

**O Vz stars at different
metallicities: the Magellanic
Clouds and the Milky Way**

O Vz stars at different metallicities: the Magellanic Clouds and the Milky Way

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Cover Image: This image shows the stellar cluster NGC 346 in the Small Magellanic Cloud, captured by the Near-Infrared Camera (NIRCam) aboard NASA's James Webb Space Telescope (JWST). The view reveals intricate structures of gas and dust where stars and possibly planets are forming. Ionized hydrogen, heated to approximately 10,000 °C, appears in pink, while colder, dense molecular hydrogen and associated dust, at temperatures around –200 °C, are rendered in orange. These features highlight the ongoing stellar feedback and erosion of surrounding material by young stars.

Credit: NASA, ESA, CSA, O. Jones (UK ATC), G. De Marchi (ESTEC), and M. Meixner (USRA). Image processing: A. Pagan (STScI), N. Habel (USRA), L. Lenkic (USRA) and L. Chu (NASA/Ames).

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Abstract

Massive stars, owing to their intense luminosities, powerful stellar winds, generally end their lives in supernova explosions, exert a significant influence on their immediate surroundings and on galactic scales. Nevertheless, their study remains challenging: observationally, they are rare objects that are typically located in distant, heavily obscured star-forming regions, while their theoretical modeling requires accounting for complex processes such as mass loss, rotation, internal mixing, chemical composition, and their frequent multiplicity. As a result, fundamental questions regarding their formation and evolution persist.

Within this context, the O V_z subclass stands out, defined by the presence of a He II $\lambda 4686$ absorption line stronger than typically observed in normal O-type dwarfs. Traditionally, this morphology has been interpreted as an indication of proximity to the Zero-Age Main Sequence (ZAMS). However, subsequent analyses of O V and O V_z stars in different environments revealed a more complex picture: the V_z signature does not arise solely from weak stellar winds or youth, but from specific combinations of physical parameters that may favor or suppress its appearance. Building on this framework, it has been proposed that metallicity could play a key role: in metal-poor regions, the reduced wind efficiency may cause the V_z morphology to become both more common and longer-lasting.

In light of these considerations, the main objective of this Thesis is to investigate the origin and nature of O V_z stars across environments with different metallicities. By characterizing their physical properties in regions spanning a broad metallicity range, we re-examine the view that the V_z morphology reflects extremely young evolutionary stages, while placing particular emphasis on understanding how metallicity influences the frequency and persistence of this feature.

To this end, we perform a quantitative spectral analysis of O V and O V_z stars belonging to three young clusters with different metallicities: NGC 3603 in the Milky Way ($Z \approx Z_{\odot}$), NGC 346 in the Small Magellanic Cloud ($Z \approx 0.2 Z_{\odot}$), and 30 Doradus in the Large Magellanic Cloud ($Z \approx 0.5 Z_{\odot}$). The sample combines medium- and high-resolution optical spectra ($R \approx 2500 - 40000$) with $S/N > 100$. All data were processed and analyzed homogeneously using the tools of the IACOB project, allowing us to consistently derive key physical parameters: effective temperature, surface gravity, helium abundance, wind strength, radii, luminosities, and spectroscopic masses.

Our results confirm that the V_z morphology alone is not a reliable indicator of proximity to the ZAMS or of an exceptionally young evolutionary stage. Consistently, no systematic differences are found in stellar parameters or wind properties between O V and O V_z stars across the different environments analyzed. The age distributions in the three clusters show that O V_z stars span a wide range of inferred ages within the main-sequence phase, with no clear evidence that their persistence is significantly enhanced at lower metallicities. Although metallicity is expected to play a role, the limited spectral resolution of part of the dataset and the small sample available for NGC 346 prevent a quantitative assessment of how this dependence operates in practice. The present analysis, however, provides a solid observational basis upon which broader studies of young stellar populations in these regions can build.

Chapter 1

Fundamentals of massive star formation and evolution

Massive stars, traditionally defined as those with initial masses exceeding $8 M_{\odot}$, constitute a fundamental class of astrophysical objects due to their profound impact on the interstellar medium, galactic evolution, and the synthesis of heavy elements. Despite their relative rarity—accounting for less than 1% of all stars formed (Massey, 2003)—they dominate the mechanical, chemical, and radiative feedback in galaxies (Zinnecker & Yorke, 2007; Krumholz et al., 2009).

These stars exhibit extreme physical properties compared to their lower-mass counterparts. Their masses, spanning from ≥ 8 up to roughly $100 M_{\odot}$ (Heger, 2012), determine their internal structure and govern their evolutionary paths. These stars are characterized by effective temperatures between 20000 and 50000 K, although the youngest and hottest objects, such as those of spectral type O2–O3, can exceed 55000 K (Martins et al., 2005; Sabín-Sanjulián et al., 2014). Their luminosities, which can reach up to 10^6 times the solar value, place them in the upper left region of the Hertzsprung–Russell diagram, close to the Eddington limit (Zinnecker & Yorke, 2007). Their radii vary with mass and evolutionary stage, ranging from 5–20 $R_{\odot}$ on the main sequence to several hundred solar radii during the supergiant phases (Ekström et al., 2012). Despite their remarkable size and luminosity, the lifetimes of massive stars are relatively short—of the order of a few million years (5–20 Myr)—due to their high rates of hydrogen consumption through nuclear fusion (Maeder & Meynet, 2005).

Massive stars play a pivotal role in a wide range of astrophysical processes. They were likely key contributors to the reionization of the Universe (Bromm et al., 2009) and are major drivers of stellar winds and supernova explosions that enrich the interstellar medium with heavy elements (Langer, 2012). These stars are the primary sources of elements heavier than helium, distributing them into the galactic medium through their explosive deaths. This enrichment process is not only essential for the chemical evolution of galaxies but also facilitates the formation of future stellar generations (Massey, 2003; Langer, 2012).

At the end of their lives, many massive stars explode as supernovae, releasing vast amounts of energy and stellar material into space. Furthermore, some stars may collapse into neutron stars or black holes, responsible for extreme astrophysical phenomena such as long-duration gamma-ray bursts (Woosley & Bloom, 2006).

1.1 Formation of massive stars

The formation of massive stars is one of the most complex and debated processes in stellar astrophysics (Krumholz et al., 2009; Beuther, 2011). Unlike low-mass stars, whose formation is relatively well understood, the birth of massive stars presents significant theoretical and observational challenges due to their short formation timescales,

high luminosity, and intense feedback processes they generate (Zinnecker & Yorke, 2007). This section provides a detailed analysis of the massive star formation process, divided into its fundamental stages, the main theoretical models explaining their formation, and the current challenges in the field.

1.1.1 Stages of the star formation process

Researchers divide the formation of massive stars into six key stages, ranging from the initial collapse of the molecular cloud to the stabilization of the protostar on the main sequence. Classical works such as Shu (1977) and modern reviews like Lada et al. (2013) have extensively studied these stages.

- **Gravitational collapse of molecular clouds:** star formation begins with the perturbation of a molecular cloud in the interstellar medium. This disturbance can originate from shock waves generated by events like supernova explosions or collisions between molecular clouds. If the cloud's mass exceeds the critical Jeans mass, it cannot remain in hydrostatic equilibrium and begins collapsing under its gravity (Jeans, 1902; Larson, 1969). This process occurs over long timescales, on the order of millions of years. During the initial phases, the gas remains isothermal due to its transparency to infrared radiation (Shu, 1977).
- **Cloud fragmentation:** as the density increases during the collapse, the Jeans mass decreases, favoring the fragmentation of the core into multiple smaller fragments, which individually collapse, forming numerous protostars (Padoan & Nordlund, 2002). This process continues until the fragments reach a lower mass limit near $0.1 M_{\odot}$.
- **Formation of a protostellar core:** When the fragment density increases, the gas becomes opaque to infrared radiation, causing a rise in temperature and pressure at the center. The collapsing material slows down as it reaches hydrostatic equilibrium, giving rise to the protostar, which has not yet initiated nuclear fusion (Shu, 1977).
- **Gas accretion:** surrounding gas continues to fall onto the protostar, forming an accretion disk due to the gas's angular momentum. The gravitational energy released during accretion provides the protostar's characteristic luminosity and accelerates its evolution (Palla & Stahler, 1999).
- **Gas dissociation and ionization:** when the protostellar core reaches temperatures around 2000 K, molecular hydrogen dissociates, which absorbs energy and reduces the adiabatic index, causing a new dynamic collapse and progressive heating of the core (Krumholz et al., 2007).
- **Pre-main sequence phase:** finally, once accretion ceases, the protostar stabilizes and becomes a pre-main sequence star. During this phase, luminosity is mainly caused by gravitational contraction until conditions for nuclear fusion ignition are reached (Stahler, 2005).

1.1.2 Theoretical scenarios for massive star formation

While the previously described stages constitute the general framework for star formation, massive star formation presents additional challenges that require more specific and detailed explanations. Their high luminosity generates radiation pressure capable of preventing material accretion, hindering their growth. Furthermore, they form in dense, dynamic regions where the environment influences their evolution. Therefore, researchers have proposed different theoretical scenarios to explain how massive stars achieve such high masses (Tan et al., 2014).

Monolithic accretion (turbulent core)

Monolithic accretion is one of the traditional models for massive star formation. It proposes that these stars form through a process similar to lower-mass stars but with key differences due to the larger amount of available gas and the pressure exerted by the protostar. In this model, a central protostar forms from a dense core that gravitationally attracts surrounding material. Gas falls toward the protostar, increasing temperature and density, forming a circumstellar disk from which the star grows.

[Hosokawa et al. \(2010\)](#) describes how this accretion disk allows gas and dust to accumulate gradually, facilitating efficient formation. This disk also regulates the accumulation of mass, since gas cooling can induce instabilities and fragmentation in low-mass disks, whereas in massive-star disks cooling is slower due to higher temperatures, which limits fragmentation and favors the formation of a single dominant protostar. However, [Krumholz et al. \(2009\)](#) point out that thermal radiation emitted by the protostars provides feedback that can heat the surrounding gas and drive stellar winds, slowing or even halting accretion. Thus, monolithic accretion is a sensitive process, conditioned by the physical properties of the environment.

Competitive accretion

Competitive accretion proposes that massive stars form within dense stellar clusters and that the competition among multiple protostars for surrounding material is the primary driver of their formation. This model suggests that the most massive stars arise when protostars in a nearby cluster interact gravitationally, allowing them to accumulate material from the surrounding cloud through shared accretion. Stellar clusters provide an ideal environment for competitive accretion due to the high gas density and the frequent gravitational interactions between protostars.

This process implies that the most massive stars compete for the available gas, leading to stars with stronger gravity accreting more material and eventually becoming the most massive within the cluster. [Bonnell et al. \(2001\)](#) were pioneers in demonstrating how, within a dense cluster, interactions among protostars can result in the formation of massive stars through competitive accretion. The dynamic interactions within the cluster determine which protostar will become the most massive, as stars closer to the cluster center experience greater gas accumulation.

The study of young stellar clusters such as Orion ([Kroupa et al., 2018](#); [Manara et al., 2012](#)) and NGC 3603 ([Correnti et al., 2012](#)) has enabled the investigation of massive star formation under the competitive accretion model, in which several protostars compete for the gas available in the cluster, favoring stars with higher mass or gravitational potential to grow more rapidly. In these dynamic environments, the persistence of gas in protostellar disks is crucial, as it allows protostars to continue accumulating mass. Recent observations in NGC 3603 show that a significant number of pre-main sequence stars still maintain active disks and high accretion rates, even under intense levels of UV radiation ([Rogers et al., 2025](#)), supporting the viability of the competitive accretion model under realistic massive cluster conditions.

Both models offer complementary perspectives on massive star formation. Monolithic accretion emphasizes mass accumulation onto a central protostar via a stable disk, while competitive accretion highlights the influence of the environment and interactions among multiple protostars in dense clusters.

1.1.3 Additional proposed mechanisms in massive star formation

Although core accretion and competitive accretion models are the most widely accepted theories for massive star formation, various studies propose additional mechanisms that may complement or operate in specific extreme environments:

- **Fragmentation of massive accretion disks:** in this scenario, a massive protostar forms from a gas and

dust disk that can fragment due to thermal and dynamical instabilities, giving rise to multiple protostars competing for the available material. Factors such as rotation, magnetic fields, and radiation emitted by the central protostar influence this process and can accelerate star formation in disks that are denser and hotter than those surrounding lower-mass stars (Zinnecker & Yorke, 2007; Bate, 2018).

- **Bondi-Hoyle accretion in binary systems:** this describes how a lower-mass star can capture gas from a companion in binary systems based on the gravitational interaction with the gas flow in the interstellar medium. This mechanism can be efficient even in low-density environments and is associated primarily with the dynamics of circumbinary gas feeding the more massive star (Bate, 2018; Ricotti, 2007; Zinnecker & Yorke, 2007).
- **Stellar and protostellar collisions:** in dense clusters, collisions between stars and accretion disks can trigger massive stars' formation through compression and material merging. These environments' dynamic interactions facilitate direct mergers or accelerated gas accretion onto protostars (Bate, 2009; Bonnell et al., 2004).
- **N-body dynamical interactions in clusters:** in dense stellar clusters, multiple gravitational interactions can concentrate matter and promote the merging of low-mass stars or accretion in dense cores, encouraging massive star formation through collective processes (Kroupa et al., 2001; Bonnell et al., 2001).

Each of these mechanisms provides key elements to understanding how the most massive stars form. Although there is no definitive consensus yet, it is likely that several of them act simultaneously or depend on the physical environment in which star formation occurs (Zinnecker & Yorke, 2007; Motte et al., 2018).

1.2 Evolution of massive stars

The evolution of massive stars is markedly different from that of their lower-mass counterparts. These differences primarily arise from their high luminosity, short evolutionary timescales, and the significant influence of physical processes, including rotation, stellar winds, magnetic fields, and mass loss. These factors profoundly affect the internal structure, energy transport, and evolutionary pathways that these stars follow throughout their lifetimes (Chiosi & Maeder, 1986).

1.2.1 Pre-main sequence and arrival at the ZAMS

Massive star formation begins with the rapid gravitational collapse of a giant molecular cloud, characterized by high accretion rates and strong energetic feedback that affects the surroundings (Bernasconi & Maeder, 1996; Zinnecker & Yorke, 2007).

During the pre-main sequence (pre-MS) phase, gravitational contraction via the Kelvin-Helmholtz mechanism powers the star. The core quickly reaches $\sim 10^7$ K, igniting hydrogen fusion through the CNO cycle before stable hydrostatic equilibrium is reached (Maeder & Meynet, 2000). Unlike low-mass stars, massive stars may start nuclear burning while still partially embedded in their natal clouds, as rapid accretion competes with material dispersal by winds and jets (Blandford et al., 1982).

The Zero-Age Main Sequence (ZAMS) marks the onset of stable hydrogen burning in a convective core with a radiative envelope (Schaller et al., 1992; Maeder, 2008). At this stage, the star emits intense ionizing radiation that forms H II regions, influencing the surrounding interstellar medium by compressing or dispersing gas, thereby affecting nearby star formation (Walch et al., 2012). This feedback often begins before the star is visible at optical wavelengths, as it remains embedded and is primarily detected in infrared and radio bands (Mottram et al., 2011).

Recent observations from missions like TESS and Gaia have characterized young ZAMS stars' rotation and structure, suggesting that magnetic braking already influences their rotational evolution before the Main Sequence (Rajamohan, 1978).

1.2.2 Main sequence phase and the CNO cycle

Upon entering the Main Sequence (MS), massive stars reach a hydrostatic equilibrium where hydrogen fusion into helium, via the CNO cycle (Carbon-Nitrogen-Oxygen), becomes their primary energy source due to its high-temperature sensitivity (Bethe, 1939). This cycle, efficient above 15 million K and dominant beyond 20 million K, uses heavy elements as catalysts and shows an extreme temperature dependence (Kippenhahn et al., 2012).

The high energy efficiency of the CNO cycle generates a strong thermal gradient that favors convection, forming convective cores that can extend up to 40% of the stellar radius and are surrounded by radiative envelopes (Maeder, 2008). This structure facilitates efficient internal mixing, slowing hydrogen depletion and prolonging the MS phase.

The duration of the MS phase decreases with stellar mass: a $15 M_{\odot}$ star lives ~ 10 Myr, while a $60 M_{\odot}$ star only ~ 3 Myr due to its higher luminosity (Schaller et al., 1992; Ekström et al., 2012). Rotation enhances internal mixing and angular momentum transport, enriching the surface with helium and nitrogen and extending central burning (Maeder & Meynet, 2000; Brott et al., 2011). Additionally, strong radiatively driven winds ($\dot{M} \sim 10^{-6}$ – $10^{-5} M_{\odot}/\text{yr}$), sensitive to metallicity, cause mass loss that alters stellar evolution (Vink et al., 2001; Langer, 2012).

When central hydrogen is exhausted, radiation pressure no longer balances gravity, the core contracts, helium fusion ignites, and the star expands, moving in the Hertzsprung–Russell (HR) diagram toward cooler temperatures and higher luminosities (Schwarzschild & Härm, 1958).

1.2.3 Later evolutionary stages

- **Transition to the blue supergiant and helium fusion.** When the core of a massive star exhausts its hydrogen, radiation pressure decreases, causing the gravitational collapse of the core. Consequently, the temperature increases, initiating hydrogen fusion in a shell around the inert core. As a result, the outer layers expand, and the star enters the blue supergiant phase. During this stage, the core contracts, and the stellar envelope expands, increasing the luminosity. Once the core exceeds critical temperatures, helium fusion begins via the triple-alpha process. This new energy source temporarily stabilizes the core and marks the onset of a layered structure, with helium fusion in the core and hydrogen fusion in the outer shells. Depending on the initial mass and mass-loss rate, the star may evolve into a red supergiant or maintain the blue supergiant appearance (Maeder, 2008).
- **Luminous Blue Variables (LBV).** Very massive stars (25 – $30 M_{\odot}$) may enter the Luminous Blue Variable phase, characterized by instability and episodes of massive mass loss, with luminosity variations and violent eruptions, such as in the case of Eta Carinae. During this phase, the star loses much of its outer envelope, reducing its mass and preparing for the Wolf-Rayet phase (Groh et al., 2013). LBVs represent a critical phase whose subsequent evolution depends on the mass lost; some may explode directly as supernovae, while others evolve into Wolf-Rayet stars.
- **Wolf-Rayet Stars (WR).** WR stars represent an advanced stage of massive stars that have lost nearly all their hydrogen envelope. Their spectra show emission lines dominated by helium, carbon, and oxygen, products of internal nucleosynthesis exposed by extreme mass loss. They possess powerful stellar winds with speeds up to 2000 km s^{-1} (Crowther, 2007). They are progenitors of type Ib/c supernovae, and their final evolution can lead to neutron stars or black holes, depending on the remnant core mass.

- **Supernova Phase.** When the core reaches an iron composition, it no longer releases energy through fusion and collapses under its weight, triggering a supernova explosion.
 - *Type II supernova:* occurs in stars with an intact hydrogen envelope; the collapse forms a neutron star and expels the outer layers (Filippenko, 1997).
 - *Type Ib/c supernova:* associated with stars that have lost their outer hydrogen (Ib) and helium (Ic) layers, commonly Wolf-Rayet stars (Woosley & Bloom, 2006).
- **Compact Objects.** At the end of their evolution, massive stars experience core collapse, leading to the formation of compact remnants such as neutron stars or black holes, depending on the progenitor mass and core structure. These objects play a fundamental role in high-energy astrophysics and the chemical enrichment of the interstellar medium.
 - *Neutron stars:* extremely dense remnants of type II supernovae, composed almost entirely of neutrons, with radii of 10–20 km and masses up to $2.16 M_{\odot}$ (Lattimer & Prakash, 2001). They possess strong magnetic fields, and some emit pulsed radiation (pulsars). They are key for studying matter under extreme conditions and relativistic effects.
 - *Black holes:* if the remnant mass exceeds the Chandrasekhar limit ($\sim 2.16 M_{\odot}$), the core collapses into a black hole, an object with gravity so intense that not even light can escape. These black holes typically have masses between 10 and $20 M_{\odot}$ or more and feature an event horizon marking the spacetime boundary beyond which nothing can escape (Schwarzschild & Härm, 1958).

Initial Mass ($M_{\odot}$)	Final MS phase	Final outcome	Example
8 – 20	Blue or red SG	Type II SN, neutron star	Betelgeuse (Saio et al., 2023)
20 – 33	Blue SG → Red SG	Type II/Ib SN, neutron star or black hole	Sanduleak -69° 202 (SN 1987A) (Taddia et al., 2013)
33 – 40	Blue SG / Early WR	Type Ib/c SN, black hole	WR 22 (Hamann et al., 2019)
40 – 60	LBV → WR	Type Ib/c SN or direct collapse	η Carinae (Zethson et al., 2012)
≥ 60	LBV → WR	Direct collapse, black hole without visible SN	R136a1 ($\gtrsim 150 M_{\odot}$, Crowther et al., 2010)

Table 1.2.1: Evolutionary summary of massive stars according to their initial mass. Adapted from Heger (2012)

Table 1.2.1 summarizes the expected evolution of massive stars according to their initial mass. Less massive stars tend to end their lives as Type II supernovae, leaving behind a neutron star. More massive stars go through intermediate phases such as Luminous Blue Variables (LBVs) or Wolf-Rayet (WR) stars, losing a significant portion of their envelopes and exploding as Type Ib/c supernovae. The most extreme cases ($\geq 60 M_{\odot}$) may collapse directly into black holes, without a visible supernova.

1.3 The O Vz phenomenon

1.3.1 O-type stars: physical characteristics and classification

Massive O-type stars play a crucial role in the chemical and dynamical evolution of galaxies. Their strong radiative and mechanical feedback, short lifetimes, and ability to enrich the interstellar medium through stellar winds and supernovae make them key to understanding star formation, galactic evolution, and cosmic reionization.

These stars are very luminous and hot, with surface temperatures between about 30000 and 55000 K. They occupy the upper-left region of the HR diagram. Their spectra show strong hydrogen lines (Balmer series), neutral helium (He I), ionized helium (He II, especially the $\lambda 4686$ line), and metal lines from elements such as carbon, nitrogen, oxygen, and silicon. O-type spectral subtypes range from O2 (hottest and most massive) to O9.7 (coolest), allowing astronomers to classify them and estimate key physical parameters such as effective temperature, surface gravity, and mass-loss rates (Walborn et al., 2002; Martins et al., 2005).

Parameter	Range value
Effective temperature	$\sim 28000 - 55000$ K
Mass	$\sim 15 - 100 M_{\odot}$
Luminosity	$> 10^5 L_{\odot}$
Color	Intense blue (negative B–V index)
Stellar winds	Strong, line-driven

Table 1.3.1: Physical parameters of O-type stars

O-type stars typically have masses from 15 up to $100 M_{\odot}$, luminosities exceeding $10^5 L_{\odot}$, intense blue colors (very negative B–V index), and strong line-driven stellar winds. Their main physical properties are summarized in Table 1.3.1. Many also show emission or absorption features from nitrogen and carbon that aid in further spectral classification (Walborn & Fitzpatrick, 1990).

Spectral classification is a fundamental step in the study of massive stars, as it allows an empirical characterization of their basic physical properties through the analysis of their optical spectra. For O-type stars, this classification is primarily based on the relative intensities of neutral helium (He I) and ionized helium (He II) lines, which are highly sensitive to the effective temperature, while the surface gravity is mainly constrained by the profiles of the hydrogen Balmer lines.

The classical criterion to assign the spectral type in O stars is based on the ratio between the He I $\lambda 4471$ line and the He II $\lambda 4541$ line. In the earliest types (O2–O5), the He I $\lambda 4471$ line is very weak or even absent, with He II $\lambda 4541$ clearly dominating. Near type O7, both lines have similar intensities, while in later types (O9–O9.7), the He I $\lambda 4471$ line becomes dominant (Walborn et al., 2002; Sota et al., 2011). In the most extreme subtypes, nitrogen emission lines such as N IV $\lambda 4058$ and N III $\lambda 4640$ are also used to refine the classification (Walborn et al., 2002).

The luminosity class, which reflects the evolutionary state and surface gravity, is mainly determined by observing the He II $\lambda 4686$ line. This line appears strongly in absorption in dwarf stars (class V), but weakens or even appears in emission in more evolved stars (classes III, II, I), due to increasing stellar wind strength. Other useful lines for refining luminosity classification include the N III $\lambda\lambda 4634-4640-4642$ emission lines and the Si IV $\lambda 4089$ and He I $\lambda 4713$ lines, which also vary systematically with gravity (Sota et al., 2014; Apellániz et al., 2016).

Currently, advances in spectral atlases and digital tools, such as the MGB software developed by Maíz Apellániz (2019), allow for a more objective and reproducible classification. Thus, spectral classification constitutes the basis

for subsequent quantitative analysis, guiding the selection of atmospheric models and providing a preliminary evolutionary context essential to understanding the nature and evolution of massive O-type stars.

1.3.2 The Vz luminosity class

Walborn (1973a) first introduced the Vz luminosity class after observing a series of O-type dwarf stars in the Trumpler 14 cluster (Carina) that exhibited a He II $\lambda 4686$ / He II $\lambda 4541$ absorption ratio greater than that of normal dwarfs. He proposed this new luminosity subclass based on the spectral peculiarity that the He II $\lambda 4686$ absorption is deeper than both He I $\lambda 4471$ and He II $\lambda 4541$.

The author interpreted this feature as an “inverse” effect of the Of phenomenon, i.e., the behavior observed in the He II $\lambda 4686$ and N III $\lambda\lambda 4634\text{--}40\text{--}42$ lines as stars evolve toward higher luminosity classes. These lines transition from strong absorption in class V to being neutralized in class III and eventually appear in class I in emission due to infilling caused by wind-originated emission. It was, therefore, hypothesized that the peculiar dwarfs in Tr 14 possessed weaker winds and might represent a less evolved stage than standard dwarfs.

Researchers later identified even more extreme objects in the Large Magellanic Cloud (LMC), especially in very young star-forming regions such as 30 Doradus (Walborn, 1973b) and N11 (Walborn & Parker, 1992). In the latter study, they formally established the Vz class and assigned it to O stars whose He II $\lambda 4686$ line is the strongest among all He absorption lines. This class spans from early to late O spectral types.

In this context, Walborn et al. (2007) reaffirmed that O Vz stars could represent objects on (or very close to) the ZAMS, exhibiting lower luminosities and weaker winds than O V stars. Thus, Vz stars serve as the evolutionary link between the earliest stages of star formation and slightly evolved O-type dwarfs.

Sota et al. (2014) took an important step toward quantifying the Vz phenomenon, proposing that it was defined by

$$z = \frac{\text{EW}(\text{He II } 4686)}{\text{Max}[\text{EW}(\text{He I } 4471), \text{EW}(\text{He II } 4542)]} > 1.0$$

Later, Arias et al. (2016), within the framework of the Galactic O-Star Spectroscopic Survey (GOSSS, Maíz Apellániz et al., 2011), redefined the classification criterion, making it more demanding. They assigned the “z” qualifier only to spectra where the He II $\lambda 4686$ line is substantially stronger than the other He lines. In particular, an O-type dwarf is classified as Vz when:

$$z = \frac{\text{EW}(\text{He II } 4686)}{\text{EW}(\text{He II } 4542)} \geq 1.10 \quad \text{spectral types earlier than or equal to O6.5}$$

$$z = \frac{\text{EW}(\text{He II } 4686)}{\text{EW}(\text{He I } 4471)} \geq 1.10 \quad \text{spectral types later than or equal to O7.5}$$

In early-type O stars, He II $\lambda 4686$ absorption should be stronger than He II $\lambda 4541$. For type O7, He II $\lambda 4541$ is equal in strength to He I $\lambda 4471$, so in a Vz spectrum, He II $\lambda 4686$ must be stronger than both. A late-type O Vz spectrum must show He II $\lambda 4686$ stronger than He I $\lambda 4471$.

Limitations of the Vz criterion: the effect of binarity

One of the main challenges in applying the Vz criterion is the high multiplicity rate among massive stars (Barbá et al., 2010; Sana et al., 2012; Sana, 2013). Combining lines from different components can artificially mimic a

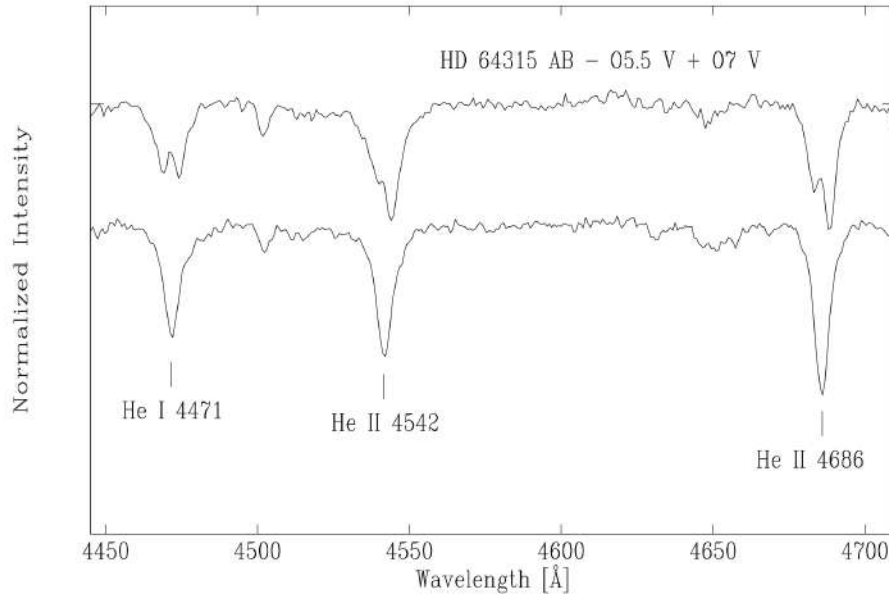


Figure 1.3.1: Two spectra of the multiple system HD 64315 illustrating how binarity can lead to a false O Vz classification. When observed during orbital conjunction, the composite spectrum yields a z parameter of 1.14. Adapted from [Arias et al. \(2016\)](#).

Vz-like spectrum in binary systems. The case of the multiple system HD 64315 (see Fig. 1.3.1) illustrates this issue.

[Lorenzo et al. \(2010\)](#) extensively studied this system, which consists of a hierarchical multiple system composed of at least two (possibly more) stars. During orbital conjunction, the composite spectrum shows a z parameter as high as 1.14 ([Arias et al., 2016](#)), leading to its classification as Vz if researchers considered only the composite spectrum. However, this value does not reflect the physical property of a single star but results from a spurious effect caused by the spectral blending of components with different spectral types.

In such systems, the early-type component usually dominates the He II $\lambda 4541$ line, while the late-type component dominates He I $\lambda 4471$. Both can contribute comparably to He II $\lambda 4686$, significantly altering the z ratio.

For this reason, the Vz criterion must be applied cautiously to binary stars. Its use should be restricted to cases where the secondary component contributes so little to the composite spectrum that it does not significantly affect the measurement of the primary star’s lines. Otherwise, there is a risk of classifying stars as Vz objects based on spectra that reflect unresolved spectral combinations rather than intrinsic physical properties.

It is estimated that more than 50–70% of O-type stars are members of multiple systems ([Sana et al., 2012](#); [Sana, 2013](#); [Moe & Di Stefano, 2017](#)). This high binarity fraction can lead to a significant number of false-positive Vz classifications.

Evolutionary evidence and physical environment

Traditionally, the Vz spectral peculiarity indicates extreme stellar youth and proximity to the ZAMS. However, subsequent studies have shown that its astrophysical interpretation is more complex. Proper characterization requires considering multiple physical parameters ([Sabín-Sanjulián et al., 2014](#); [Arias et al., 2016](#)).

[Sabín-Sanjulián et al. \(2014\)](#) conducted one of the most comprehensive studies on this topic as part of the VLT-FLAMES Tarantula Survey (VFTS) in 30 Doradus (LMC). They quantitatively analyzed a sample of 38 O Vz and 46 normal O V stars using stellar atmosphere models (FASTWIND, [Santolaya-Rey et al., 1997](#)) and automatic

spectroscopic analysis tools (IACOB-GBAT, [Simón-Díaz et al., 2011](#)). The authors found that many O Vz stars lie on or near the ZAMS, but others show characteristics of more evolved objects. Their results suggest that the Vz classification does not necessarily indicate extreme youth and that weak stellar winds—especially in low-metallicity environments like the LMC—can influence its occurrence.

In addition to the stellar wind, detailed analysis revealed that other physical parameters — such as effective temperature, surface gravity, projected rotational velocity, and spectroscopic multiplicity — can favor or inhibit the appearance of the Vz profile in stellar spectra. Therefore, the mere presence of Vz morphology cannot be interpreted unequivocally as a youth indicator.

In line with the results of [Arias et al. \(2016\)](#), O-type stars with effective temperatures below ~ 35000 K are never classified as Vz, regardless of the weakness of their winds, since the z parameter does not reach the required threshold. For this reason, all dwarfs with spectral types later than O8.5 V are justifiably excluded. On the other hand, very early-type stars with $T_{\text{eff}} \gtrsim 39000$ K can lose the Vz characteristic even before their winds reach maximum strength, indicating that strong winds do not guarantee the persistence of the Vz classification in these hotter stars. The authors noted that, in a solar metallicity environment, O stars with $T_{\text{eff}} \approx 37000$ K are the most “favored by nature” to exhibit the Vz morphology in their spectra. Their findings confirm that the appearance of such a spectral characteristic results from a subtle interaction of various physical and environmental factors, not solely from the star’s evolutionary state.

Is it possible to observe O-type stars on the ZAMS?

The detectability of O-type stars on the ZAMS has been a subject of extensive debate in the literature. Although these stars mark the onset of stable hydrogen burning in their cores, numerous studies have indicated that detecting them at this evolutionary stage is exceedingly challenging. Three primary perspectives address the issue: observational limitations, empirical evidence from population studies, and theoretical stellar evolution models.

– *Observational Limitations*

Detecting O-type stars on the ZAMS proves challenging mainly because they remain embedded within their natal environments during this evolutionary phase, making them invisible at optical wavelengths. Studies suggest that massive stars begin central nuclear fusion and reach the main sequence while still cloaked by their birth cocoons and experiencing high accretion rates—typically around $10^{-4} M_{\odot} \text{ yr}^{-1}$ or more ([Yorke, 1986](#); [Hosokawa et al., 2010](#)). In these conditions, surrounding dust absorbs their optical emission and re-emits it in the infrared, which explains why optical surveys often miss them ([Castro et al., 2014](#)).

[Walborn et al. \(2007\)](#) argues that the observation of O-type stars on the ZAMS is hindered not only by their embeddedness but also because these phases typically occur in very young, distant, and heavily reddened regions. Similarly, [Castro et al. \(2014\)](#) emphasize that massive stars near the ZAMS remain immersed in their parental clouds, preventing their detection in magnitude-limited surveys, especially in the optical. This situation introduces a significant observational bias in studies of young stellar populations.

– *Empirical evidence*

Studies have consistently reported the lack of detections of O-type stars near the ZAMS across various galactic and extragalactic environments. In the Milky Way, studies such as those by [Garmany et al. \(1982\)](#) and [Repolust et al. \(2004\)](#) demonstrated that most analyzed O-type stars are situated away from the ZAMS in terms of both age and physical parameters. More recently, [Holgado et al. \(2020\)](#) conducted a systematic study of over 400 Galactic O-type stars using the spectroscopic HR diagram (sHR), identifying a “gap” in the distribution corresponding to the theoretical location of the ZAMS. This absence of objects in the relevant region suggests a genuine scarcity of observable stars at this phase.

Similar observations have emerged in low-metallicity environments such as the Magellanic Clouds (Massey et al., 1995; Sabín-Sanjulián et al., 2014). Likewise, Massey & Johnson (1993) found consistent results in other Local Group galaxies. However, other studies, including Herrero et al. (2002); Massey et al. (2005); Mokiem et al. (2007) highlight the diversity of results across environments with varying metallicities, keeping the issue open.

– *Theoretical models and the brevity of the ZAMS phase*

Theoretical models propose that massive stars reach the ZAMS before completing the accretion process, implying that they do not enter this phase as ‘naked’ visible objects but remain covered by natal material (Hosokawa et al., 2010). In this framework, stars reach the ZAMS as a transient state during their growth, which makes them difficult to observe.

Furthermore, high-resolution evolutionary models predict that the duration of the ZAMS phase is highly brief to the most massive stars. According to Maeder & Meynet (2000) and Ekström et al. (2012), a $30 M_{\odot}$ star may pass through this stage in less than 0.5 million years. This rapid evolution, combined with embeddedness and reddening, significantly contributes to their scarce detection.

– *Alternative hypotheses and modified models*

In light of this evidence, some authors have proposed that the observational absence of O-type stars on the ZAMS could result from biases in observational samples and limitations in current theoretical models. For example, Castro et al. (2014) argue that these stars’ high reddening and rapid evolution hinder their early detection, especially in magnitude-limited surveys. Complementarily, Holgado et al. (2020) suggest that current models overestimate the accretion rates required during star formation. In their study, they propose that lower accretion rates could reconcile the theoretical location of the birthline—the limit in the HR diagram beyond which stars become optically visible—with the observed distribution. This hypothesis aims to explain the systematic absence of O-type stars with evolutionary masses between 30 and $70 M_{\odot}$ in the ZAMS region, as observed in their Galactic sample.

1.3.3 The Vz phenomenon in low-metallicity environments

Given that the Vz phenomenon depends on the intensity of stellar winds—which rely on the star’s metallicity—it is particularly relevant to study its behavior in low-metallicity environments. In these settings, winds are weaker, potentially prolonging the persistence of the Vz spectral characteristic beyond the earliest evolutionary stages.

In the LMC, Sabín-Sanjulián et al. (2014) found that stars classified as Vz tend to lie closer to the ZAMS, but many show estimated ages between 2 and 4 Myr. This finding challenges the traditional view that associates the Vz type exclusively with very young phases. They interpreted this as a consequence of low metallicity: weaker stellar winds allow stars to retain the spectral features that define the Vz type for extended periods. Therefore, the phenomenon appears more frequently and lasts longer in environments like the LMC than in the Milky Way.

However, it is essential to note that the classifications used by Sabín-Sanjulián et al. (2014) precede the stricter definition of the Vz criterion proposed by Arias et al. (2016).

Regarding the Small Magellanic Cloud (SMC), systematic studies focused on the OVz population are still lacking (Schootemeijer et al., 2021). Nevertheless, the cluster NGC 346 represents an environment of particular interest: it is one of the most massive and youngest in the Local Group and hosts nearly half of all O-type stars in the SMC (Massey et al., 1989). Its apparent youth has led to the hypothesis that it could contain a significant fraction of OVz stars, traditionally considered indicators of early evolutionary stages (Walborn & Parker, 1992). However, this direct relationship between the Vz spectral type and stellar age has not yet been firmly established or quantified.

Recent studies have begun to shed new light on this issue. [Dufton et al. \(2019\)](#), using observations from the FLAMES instrument on the VLT, analyzed a sample of O-type stars in NGC 346, determining spectral types and physical and evolutionary parameters. Their results reveal a notably young population, with ages under 2 Myr, reinforcing the relevance of this region for studying the Vz phenomenon.

On the other hand, [Rickard et al. \(2022\)](#), through UV spectra obtained with the Hubble Space Telescope, identified a single object meeting the $z > 1.1$ criterion—SSN 31 (also known as MPG 417)—and classified it as a Vz star. However, this object has an estimated age of 5 Myr, raising further questions about the relationship between the presence of the Vz spectral characteristic and stellar youth.

In this context, it is essential to critically assess whether the Vz condition can persist during more advanced phases in low-metallicity environments, challenging its traditional interpretation as a reliable indicator of youth ([Sabín-Sanjulián et al., 2014](#)).

1.4 Scope and structure of this Thesis

Understanding the formation and early evolution of massive stars remains a significant challenge due to the intrinsic complexities of both their observation and the theoretical modeling of key physical processes such as rotation, binarity, mass transfer, and convection. In this context, one of the most promising avenues to advance our knowledge of these objects is the detailed analysis of O-type stars with luminosity class Vz. These stars show a stronger He II $\lambda 4686$ absorption line compared to other typical features of the same spectral type. Researchers interpret this peculiarity as a ‘reversed Of effect.’ It is linked to stars with underdeveloped stellar winds, indicating that they are less luminous and lie close to the ZAMS.

Initially, the Vz classification was considered a reliable indicator of extreme youth. However, subsequent studies have shown that the metallicity of the environment may modulate its appearance. In low-metallicity regions, such as the Magellanic Clouds, O Vz stars are expected to be more frequent and remain in this state for longer due to the lower efficiency of mass loss via stellar winds. Observational evidence supports that, on average, O Vz stars are younger, less luminous, display higher surface gravities, and exhibit weaker winds than normal class V dwarfs. For these reasons, O Vz stars are ideal candidates for probing the physical properties of massive stars at their earliest evolutionary stages.

Based on the hypothesis that the Vz spectral feature constitutes a manifestation of the physical conditions of extremely young and minimally evolved objects—located near the ZAMS and whose atmospheres have not yet developed winds strong enough to produce the characteristic filling in the He II $\lambda 4686$ line—this study focuses on performing a quantitative spectral analysis of O V and O Vz stars in three young clusters with different metallicities: NGC 3603 in the Milky Way ($\approx Z_{\odot}$, [Harayama et al., 2008](#); [Melena et al., 2008](#)), 30 Doradus in the Large Magellanic Cloud ($\approx 0.5 Z_{\odot}$, [Mokiem et al., 2007](#); [Doran et al., 2013](#)), and NGC 346 in the Small Magellanic Cloud ($\approx 0.2 Z_{\odot}$, [Russell & Dopita, 1992](#); [Bouret et al., 2003](#); [Rickard et al., 2024](#)).

The main objective of this thesis is to derive fundamental stellar parameters—such as effective temperature, surface gravity, and helium abundance—and to evaluate how these properties vary across environments of different metallicities, with the aim of confirming or revising the hypothesis that O Vz stars represent a very early evolutionary stage.

To achieve this, quantitative spectroscopic analysis tools based on stellar atmosphere models developed within the IACOB project will be employed, complemented by current theoretical evolutionary models (see, e.g., [Brott et al. 2011](#); [Ekström et al. 2012](#)). Additionally, the positions of these stars will be analyzed in the Hertzsprung-Russell diagram and its spectroscopic counterpart, the sHR diagram, in order to estimate their evolutionary status

and evaluate the influence of metallicity on the manifestation of the Vz spectral feature.

The thesis is structured as follows: Chapter 2 introduces the sample under study, which consists of stars from three regions with different metallicities: NGC 346 in the Small Magellanic Cloud, 30 Doradus in the Large Magellanic Cloud, and NGC 3603 in the Milky Way. Chapter 3 presents the methodology, describing the spectral classification process and the quantitative spectroscopic analysis carried out with the IACOB tools, employed to determine the stellar physical parameters. Chapter 4 presents the results obtained for NGC 346, while Chapter 5 focuses on the analysis of 30 Doradus, including a comparison with the previous work by [Sabín-Sanjulián et al. \(2014\)](#). Chapter 6 is devoted to the results corresponding to NGC 3603. Finally, Chapter 7 provides a general summary of the study, highlighting the main conclusions and outlining prospects for future research.

Chapter 2

Observational sample: selection and characteristics

Understanding the properties and evolution of massive stars in environments with different metallicities is essential, given the key role these objects play in large-scale astrophysical processes, such as the reionization of the Universe (Haehnelt et al., 2001; Wyithe & Loeb, 2003). Theoretical models predict that massive stars formed in environments with higher metallic content develop stronger stellar winds, implying greater loss of mass and angular momentum compared to those born in metal-poorer environments (Mokiem et al., 2007).

In this regard, the Magellanic Clouds provide an ideal natural laboratory to study the impact of metallicity on early stellar evolution. The SMC has a metallicity of approximately $Z \approx 0.2Z_{\odot}$, while the LMC shows an intermediate value around $Z \approx 0.5Z_{\odot}$. This difference offers a unique opportunity to compare massive stellar populations under different physical conditions, including references within the Milky Way (MW).

This chapter focuses on the analysis of O-type stars, with special attention to those classified as Vz, in the star-forming regions NGC 3603, located in the MW, and NGC 346, located in the SMC. The results obtained will be compared with those of a previous study conducted in the 30 Doradus region (30 Dor, LMC) by Sabín-Sanjulián et al. (2014), who analyzed an analogous sample of O-type stars.

2.1 Sample selection

2.1.1 NGC 346 in the Small Magellanic Cloud

The sample used in this study consists of massive stars located in the NGC 346 region, a stellar cluster embedded within the H II region N66 in the SMC (Rickard et al., 2024). This region hosts approximately half of the known O-type stars in the SMC (Massey et al., 1989). With an estimated age of less than ~ 3 million years, NGC 346 represents one of the youngest and most massive stellar systems in low-metallicity environments within the Local Group, and is also the main site of active star formation in the SMC (De Marchi et al., 2011). Previous studies, such as those by Cignoni et al. (2010), have shown that star formation in this area began approximately 6 million years ago, remained active for about 3 million years, and has since gradually declined. That study also reported an apparent lack of massive stars in the upper main sequence, suggesting that some of the youngest and most massive stars may still be in the process of formation.

The preliminary sample used in this work was constructed from 40 optical spectra obtained with the Magellan Echellette spectrograph (MagE; Marshall et al. 2008), mounted on the 6.5-m Clay Telescope at Las Campanas Observatory (Chile), during several observing campaigns carried out between 2009 and 2014. The observations

and original target selection were performed by Philip Massey, Kathryn Neugent, and Nidia Morrell as part of a comparative program on massive stellar associations in the Magellanic Clouds, focused on LH 41 in the LMC and NGC 346 in the SMC.

The spectra were provided in a fully reduced form. The data reduction was carried out by the original observers using a combination of standard IRAF tasks and the MTOOLS routines developed for MagE data. As part of this work, additional processing was performed in selected cases, including continuum normalization and a consistency check of the published spectral classifications.

Within the initial sample, four stars lacked previous spectral classification. Their spectral types were determined in this work following the classification criteria of [Sota et al. \(2011, 2014\)](#). As summarized in Table 2.2.1, two objects in the preliminary sample were identified as B-type stars, and one object was classified as a peculiar O-type star exhibiting emission features (Oe); these objects were therefore excluded from the analysis. In addition, several binary or multiple systems previously reported in the literature were identified, including NGC 346-06, NGC 346-09, NGC 346-16, NGC 346-26, NGC 346-48, and NGC 346-75. Among these, NGC 346-06 corresponds to a triple system with four independent observations, while NGC 346-09 is a binary system with six individual spectra, confirming its binary nature as previously suggested by [Mokiem et al. \(2006\)](#). The sample therefore consists of 31 individual MagE spectra corresponding to apparently single O-type stars.

The sample described above was further complemented with six single-lined spectroscopic binaries (SB1) identified by [Dufton et al. \(2019\)](#), who carried out the most comprehensive analysis to date of O-type stars in NGC 346 based on FLAMES (Fibre Large Array Multi-Element Spectrograph) observations obtained with the Very Large Telescope (VLT) at the European Southern Observatory (ESO). The corresponding spectra were retrieved from the ESO public archive and correspond to objects previously classified in the literature as O- or B-type stars, following the designations adopted in that study. The spectra exhibit a combined signal-to-noise ratio (S/N) higher than 100 (slightly lower in a few cases) and cover a spectral type range from O8 to O9.5. Further details on the observing strategy and data reduction procedures are provided in [Dufton et al. \(2019\)](#).

The instrumental configurations and data properties are summarized in Table 2.1.1. For the NGC 346 region, a total of 37 spectra were considered, of which 35 correspond to O-type stars—six showing double-lined profiles and one belonging to a triple system—while the remaining two spectra correspond to B-type stars (see Subsection 2.2.1 and Table A.0.1 for spectral classification details). The fully reduced spectra are presented in Figure B.0.1.

Region	Telescope	Instrument	Setting	Resolving power	S/N	λ Range (Å)	Stars
NGC 346	LCO/Clay 6.5 m	MagE	—	4100	100-400	3200–9000	31
NGC 346	ESO/VLT 8.2 m	FLAMES	LR02	7000	>100	3960–4564	6
			LR03	8500	>100	4499–5071	

Table 2.1.1: Characteristics of the spectra employed for the NGC 346 region.

During the selection process, only spectra with S/N greater than 100 in the continuum adjacent to the diagnostic lines were considered. However, some objects with slightly lower S/N were exceptionally included, provided that the spectral lines were identifiable. Additionally, the use of the IACOB-GBAT code (see Section 3.2) enabled recalculating the effective S/N of each line during the fitting process, providing a more accurate assessment of the quality of the derived parameters.

Since spectroscopic binarity can significantly alter line profiles and, consequently, bias spectral classification, a strict visual inspection criterion was applied to restrict the sample to likely single stars. All objects with clear indications of binarity were discarded, based on references available in the literature. This filtering was particularly relevant for stars classified as type Vz, whose identification critically depends on the relative intensity of the

He II $\lambda 4686$ line, which can be affected by the presence of a binary companion.

Once the sample had been cleaned and given that the spectra were already reduced, it was possible to proceed directly with a detailed analysis. This included spectrum normalization, verification, and refinement of the spectral type based on relevant bibliographic references (e.g., Sota et al. 2011; Sota et al. 2014; Arias et al. 2016), as well as the measurement of equivalent widths of key diagnostic lines. For those objects lacking a prior spectral classification, this was determined following standard spectral classification criteria, which are described in detail in Section 1.3.

2.1.1.1 Sample representativeness

Although our aim was not to construct a complete census of the O-type population in NGC 346, we assessed the extent to which our sample reflects the distribution of known O-type dwarfs in the region. To this end, we compared our dataset with the Stellar Spectral Classification Catalog compiled by Skiff (2009), which compiles spectral classifications from the literature for stars in various regions, including NGC 346 in the SMC. In particular, Skiff provides specific references for each spectral type; for NGC 346, these include Niemela et al. (1986); Massey et al. (1989); Smith Neubig & Bruhweiler (1997); Evans et al. (2006); Lamb et al. (2016) and Dufton et al. (2019). From this catalog, we selected only the O-type stars with luminosity class V present in NGC 346. Although the catalog is not exhaustive, it constitutes one of the most comprehensive references currently available on the spectral content of the region. It allows us to assess the representativeness of our sample.

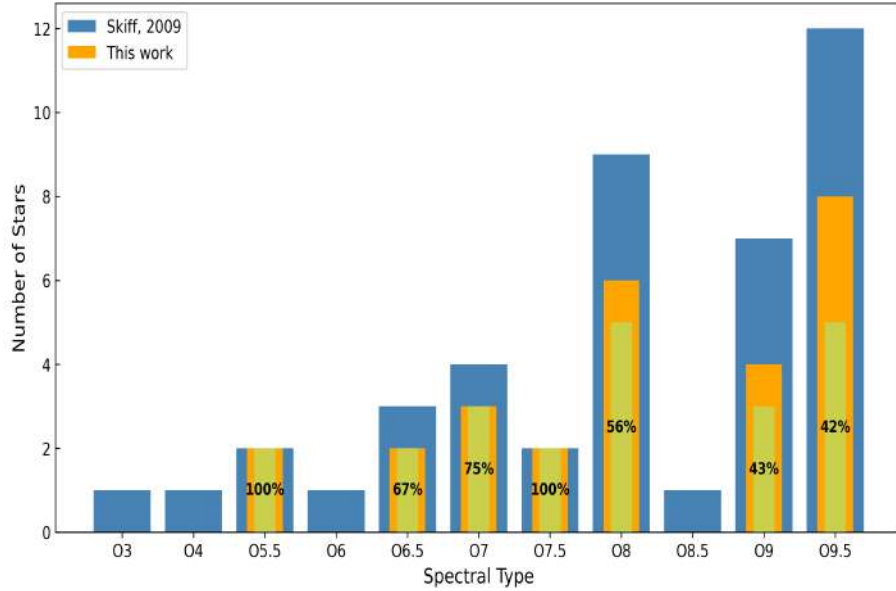


Figure 2.1.1: Comparison between our sample (orange bars) of O-type stars with luminosity class V in NGC 346 and those previously reported in the literature (Skiff, 2009, blue bars). The green bars represent the number of stars common to both samples. For each spectral subtype, the percentages indicate the fraction of stars in the Skiff catalogue that are also present in our sample.

The result of this comparison is shown in Figure 2.1.1, which presents a histogram of O-type dwarf stars in the Skiff catalog versus those analyzed in this work. The green bars indicate the stars present in both samples, with percentage labels denoting, for each spectral subtype, the proportion of Skiff catalog stars also found in our dataset. Although our sample does not uniformly cover all spectral subtypes, it spans the full range from O5.5 to O9.5 and includes a significant fraction of the most frequently observed subtypes in the Skiff catalog; for several of these

subtypes, more than 50% of the cataloged stars are represented in our dataset. While we do not claim statistical completeness, this comparison suggests that our sample reasonably reflects the overall distribution of spectral types among the known O-type dwarfs in NGC 346. This supports the relevance of our analysis for characterizing the young, massive stellar content of the region.

2.1.2 30 Doradus in the Large Magellanic Cloud

The 30 Doradus region, also known as the Tarantula Nebula, is the most active star-forming complex in the Local Group and one of the most extensively studied regions in the nearby Universe. Located in the LMC, it is rich in massive stars, young stellar clusters, and ionized structures, making it an excellent natural laboratory for investigating star formation and stellar evolution in low-metallicity environments.

Numerous studies have characterized 30 Doradus as a region of hierarchical star formation, where multiple stellar generations coexist and overlap. Through the VLT-FLAMES Tarantula Survey (VFTS, [Evans et al., 2011](#)), clusters and associations such as R136, NGC 2060, and Hodge 301 were identified, spanning ages from less than 1 Myr to more than 20 Myr ([Evans et al., 2011](#); [Schneider et al., 2018b](#)). Recent observations with the James Webb Space Telescope (JWST) have revealed even younger stellar populations ($\lesssim 0.5$ Myr), highlighting a continuous sequence of ongoing star formation ([Fahrion & De Marchi, 2024](#)). Additionally, it has been suggested that the relative number of massive stars in the region may exceed predictions from a standard initial mass function (IMF, [Schneider et al., 2018a](#)).

One topic of particular interest has been the characterization of O-type stars with Vz luminosity class, considered possible representatives of zero-age main sequence (ZAMS) objects. Using VFTS data, [Sabín-Sanjulián et al. \(2014\)](#) identified 38 O Vz stars in the 30 Doradus region. These stars exhibit intermediate effective temperatures, relatively low luminosities, and weak stellar winds. Their spatial distribution supports the interpretation that Vz stars correspond to a very early evolutionary stage on the main sequence and are preferentially associated with the youngest star-forming regions, such as R136 and NGC 2060.

The stellar sample analyzed in this thesis is drawn from the same VFTS dataset. The observations were obtained with the Fibre Large Array Multi-Element Spectrograph (FLAMES, [Pasquini et al., 2002](#)) in Medusa mode at the Very Large Telescope (VLT) in Paranal, Chile, covering the full extent of the 30 Doradus region with a field of view of approximately 25 arcminutes. From the full VFTS O-type star sample, the analysis was restricted to O-type dwarfs, predominantly luminosity class V, spanning a wide range of spectral types.

To ensure reliable results and minimize biases, only stars with high-quality spectra were considered, following the classification scheme of [Walborn et al. \(2014\)](#). In particular, objects classified in the AAA group—characterized by high S/N, low nebular contamination, and no clear evidence of spectroscopic binarity—were selected. Multiplicity information from [Sana \(2013\)](#), based on multi-epoch spectroscopy, was incorporated, and SB1 systems exhibiting large radial-velocity variations were excluded. Applying these criteria resulted in a final sample of 84 O,V stars, which is representative and well-suited for a robust analysis of their photospheric properties and surface helium abundances.

The instrumental setup and spectral characteristics are summarized in Table 2.1.2. It is worth noting that the Vz classifications adopted by [Sabín-Sanjulián et al. \(2014\)](#) predate the more stringent criteria later defined by [Arias et al. \(2016\)](#), which are adopted here for the spectral reclassification.

Region	Telescope	Instrument	Setting	Resolving power	S/N	λ Range ($\text{\AA}$)	Stars
30 Doradus	ESO/VLT 8.2 m	FLAMES	LR02	7000	~ 150	3960–4564	84
			LR03	8500	~ 150	4499–5071	
			HR15N	16000	~ 150	6442–6817	

Table 2.1.2: Characteristics of the spectra employed for the 30 Doradus region.

2.1.2.1 Sample representativeness

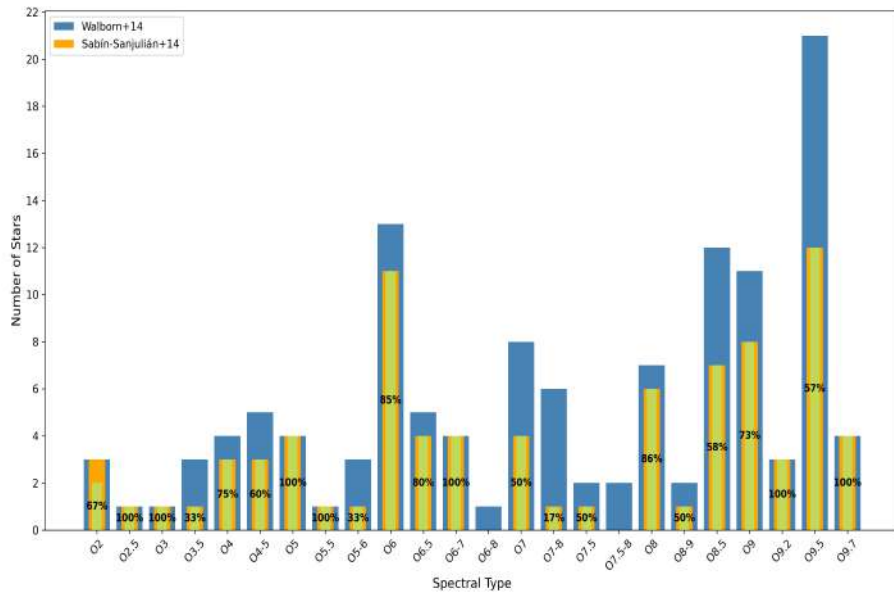


Figure 2.1.2: Comparison of O-type stars with luminosity class V in 30 Dor between our sample (orange bars) and Walborn et al. (2014) (blue bars). The green bars indicate the stars common to both samples. Percentages above each spectral subtype show the fraction of Walborn stars that are also present in our sample.

Figure 2.1.2 illustrates the spectral subtype distribution of O-type stars with luminosity class V in 30 Dor from the study of Sabín-Sanjulián et al. (2014), highlighting the comparison with the stars classified by Walborn et al. (2014). The comparison of the spectral subtypes of O-type stars in the catalog of Sabín-Sanjulián et al. (2014) with those reported by Walborn et al. (2014) shows a high degree of correspondence for most subtypes. In particular, most spectral subtypes exhibit a 100% match, whereas only the O2 subtype shows a partial correspondence of 66.7% (2 out of 3 objects). Some subtypes, such as O6-8 and O7.5-8, are not represented in Sabín-Sanjulián et al. (2014), making it impossible to evaluate the correspondence in these cases. Overall, these results indicate that the spectral subtypes in the Sabín-Sanjulián et al. (2014) sample are highly consistent with those reported by Walborn et al. (2014).

2.1.3 NGC 3603 in the Milky Way

NGC 3603 is the largest H II region in the MW, making it an ideal natural laboratory for studying this type of structure, which is also common in external galaxies. Its remarkable luminosity was first highlighted by Goss & Radhakrishnan (1969), and it is located about 6–8 kpc (Kalari et al., 2019) from the Sun in the Carina spiral arm.

When compared with 30 Doradus in the LMC, NGC 3603 is estimated to have a visual luminosity of $6.1 \times 10^5 L_{\odot}$, about five times lower than the R136 cluster. However, both have similar half-light radii of about 4 to 5 parsecs (Eisenhauer et al., 1998). A detailed study of this region requires both photometric and spectroscopic observations. The first photometric studies date back to Sher (1965) and were followed by more comprehensive works such as those by Van den Bergh (1978) and Melnick et al. (1989), which provided key information on its structure, distance (~ 7.2 kpc), and age (2–3 Myr), although with signs of considerable age spread.

For our analysis, we used spectra published by Melena et al. (2008), obtained with the 6.5 m Magellan telescopes at Las Campanas Observatory (LCO). The observations were carried out using the IMACS instrument (f/4 configuration, 600 l/mm grating) and the MagE spectrograph on April 12 and 15, 2006, respectively. The spectra cover a wavelength range from approximately 3100 to 9400 Å, with S/N between 100 and 200. Based on these data, a preliminary sample of 14 O V stars was selected.

This initial sample was complemented with observations obtained using the Magellan Inamori Kyocera Echelle spectrograph (MIKE Bernstein et al., 2003), which operates in echelle mode and provides spectral resolutions of up to $R \sim 40000$, depending on the instrumental configuration and slit width. The instrument covers a broad wavelength range, from approximately 3200 to 6700 Å. All spectra were provided through internal communication by Dr. Nidia Morrell and Dr. Phil Massey, and their instrumental characteristics are summarized in Table 2.1.3.

Telescope	Instrument	Resolving Power	λ Range (Å)	Stars
Baade 6.5 m	IMACS	2500	4000–6750	31
Clay 6.5 m	MagE	4100	3100–9400	19
Clay 6.5 m	MIKE	40000	3700–6700	4

Table 2.1.3: Instrumental characteristics for the NGC 3603 sample. Observations were obtained using the LCO telescopes.

Finally, following the same methodology applied for NGC 346, all objects presenting evidence of binarity were excluded from our analysis. In total, 54 spectra were used in this region—including 53 of spectral type O and one of type B—as shown in Table A.0.4 and displayed in Figure B.0.3.

2.1.3.1 Sample representativeness

Figure 2.1.3 illustrates the representativeness of our sample of O-type stars with luminosity class V in NGC 3603 by comparing its spectral subtype distribution with that reported in the combined studies of Melena et al. (2008) and Massey et al. (2025), which together constitute the most comprehensive optical spectroscopic characterization of NGC 3603 to date. Although our dataset does not represent a complete census, it provides a meaningful basis for evaluating the representativeness of the most common spectral subtypes.

The results show that our selection covers the most frequent O,V subtypes in a representative manner. However, the earliest subtypes (O3, O3.5, and O4) are underrepresented, while some subtypes display match percentages exceeding 100%. Despite these limitations, the sample adequately captures the diversity of the dominant O,V population in NGC 3603, supporting its suitability for the objectives of this study.

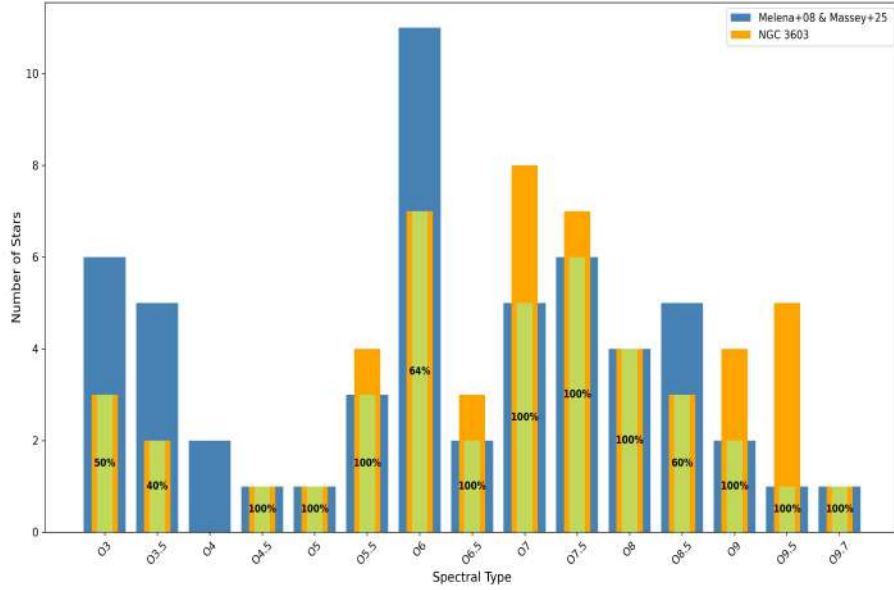


Figure 2.1.3: Comparison of O-type stars with luminosity class V in NGC 3603 between our sample (orange bars) and the combined sample of [Melena et al. \(2008\)](#) and [Massey et al. \(2025\)](#) (blue bars). The green bars indicate the stars common to both samples. Percentages above each spectral subtype represent the fraction of stars from the combined literature sample that are also present in our dataset.

2.2 Spectral classification and equivalent width measurements

The assignment of spectral types and luminosity classes for the objects in NGC 346 and NGC 3603 was carried out following the criteria described in Section 1.3, which are mainly based on the intensity ratios of characteristic lines in O-type stars. For those objects lacking a current classification in the literature, the atlases from the Galactic O-Star Spectroscopic Survey (GOSSS; [Sota et al. 2011](#), [Sota et al. 2014](#)) were used as references. The spectral classification process was performed using a visual comparative technique, which involved observing the spectra and utilizing IRAF-based tools such as `splot` and `specplot`. This methodology proved suitable even for spectra with low or moderate S/N, allowing reliable identification in most cases.

2.2.1 Stars in NGC 346

In this study, we identified four previously unclassified stars in the cluster (see Table 2.2.1). The spectral classification was carried out through a comparative approach, qualitatively evaluating the observed spectra against the GOSSS standards and applying the criteria defined in their catalog. Although the instrumental resolution might limit some spectra, the visual method was suitable for data with moderate S/N, allowing reliable classifications in most cases. It is worth noting that the spectral resolution of our sample ($R = 4100$) is higher than that of the GOSSS atlas ($R = 2500$). Therefore, we degraded the spectral resolution of the NGC 346 data using IRAF, taking into account the pixel dispersion of the GOSSS spectra ($0.7956 \text{ \AA pixel}^{-1}$), in order to ensure a consistent comparison with the classification standards.

Conceptually, the procedure consisted of two steps. First, the resolution of the original spectra was degraded to match that of the reference spectra by convolving the data with a Gaussian kernel, which approximates the instrumental response. Subsequently, the degraded spectra were resampled to the same spectral dispersion as the reference data, so that both datasets were defined on a common wavelength grid and could be directly compared.

In practice, this procedure was implemented in IRAF using the `dispcor` task, which allows the interpolation and rebinning required to obtain the final spectra with the desired resolution and dispersion. The spectral classifications from previous works are summarized in Table A.0.1.

Star	Spectral type
NGC 346-35	O9.5 III e
NGC 346-85	O9.7 V
NGC 346-76	B0.7 V
NGC 346-96	B0.7 V

Table 2.2.1: NGC 346 stars with newly classified spectral types. The stars NGC 346-35, NGC 346-76, and NGC 346-96 exhibited later spectral types within the NGC 346 sample. Since our analysis focuses exclusively on the O V stars, these three stars were excluded from the initial studies.

Spectral classification in this study required accurate measurement of the equivalent widths (EW) of specific helium lines, particularly He I $\lambda 4471$, He II $\lambda 4542$, and He II $\lambda 4686$, following the quantitative criterion proposed by Arias et al. (2016) to distinguish between O V and O Vz stars. For this, we used the IRAF task `splot` (Tody, 1993), which allows interactive integration of the absorption line profile after proper continuum normalization. The `splot` tool facilitates EW measurements by interactively integrating the area between the normalized continuum and the observed flux over a wavelength region defined by the user. This is especially useful in spectra with nebular contamination or partially blended lines, as it allows adjustment of the integration limits to exclude non-stellar contributions or instrumental effects.

Error estimation in the EW measurements was performed using a semi-empirical approach that considers the relationship between spectral resolution, line width, and the S/N of the spectrum. Following works such as Puls et al. (1996) and Gray (2005), the EW error can be approximated as:

$$\sigma_{\text{EW}} \approx \frac{\text{FWHM}}{S/N}$$

where FWHM is the full width at half maximum of the line, and S/N is the signal-to-noise ratio in the continuum near the line. This approximation is valid under the assumption of a Gaussian profile and is widely used in the spectroscopic analysis of massive stars. In cases where an accurate FWHM measurement was not available, we adopted a conservative alternative estimation directly based on the EW value:

$$\sigma_{\text{EW}} \approx \frac{\text{EW}}{S/N}$$

These expressions reflect that the precision of the EW measurement strongly depends on spectrum quality, particularly its S/N and the instrumental capacity to resolve spectral lines properly. To validate the results obtained with `splot`, we also developed a Python script that performs automatic continuum fitting and line integration. Measurements with both methods showed excellent consistency, with differences under 5%, confirming the reliability of the IRAF-based estimations even for medium-resolution and moderate S/N spectra (Gray, 2005; Puls et al., 1996).

EW measurements in this sample presented particular challenges due to contamination from nebular emission, especially for the He I $\lambda 4471$ line. Star-forming regions, such as NGC 346 and 30 Doradus, frequently exhibit nebular emission lines that can overlap with stellar absorption lines, complicating the precise determination of the EW. To minimize the effect of this contamination, we adopted the strategy of integrating only the half of the line profile that was free from significant nebular emission and subsequently doubling this value to obtain the best possible estimate of the total EW. Table A.0.2 lists the EW values and their associated uncertainties, together with the updated spectral classifications of the stars in NGC 346

2.2.2 Stars in 30 Doradus

In contrast to the approach taken for NGC 346, no new spectral classifications were performed for the 30 Doradus region. Instead, the classifications previously published by [Walborn et al. \(2014\)](#) were adopted for each object. However, to systematically identify candidate O-type Vz stars, the EW of the spectral lines He I $\lambda 4471$, He II $\lambda 4542$, and He I $\lambda 4686$ were measured in all available spectra. These measurements were carried out following the same methodology applied to NGC 346, using the `splot` task from the IRAF package and applying a consistent procedure for error estimation. Subsequently, the criterion proposed by [Arias et al. \(2016\)](#), based on the intensity ratio of the He II $\lambda 4686$ line relative to He I $\lambda 4471$ and He II $\lambda 4542$, was applied to identify objects with spectral characteristics consistent with the O Vz class. The results obtained, including the EW values, their corresponding errors, and the z parameter calculated for each star, are presented in Table A.0.3, included in the Appendix.

2.2.3 Stars in NGC 3603

Spectral classification of the stars in NGC 3603 (see Table 2.2.2) was carried out following the methodology described for NGC 346, applying the criteria defined in Section 1.3 and visually comparing the spectra with the GOSSS standards ([Sota et al., 2011, 2014](#)).

In particular, the spectra obtained with the MagE spectrograph, corresponding to stars without previous spectral classifications, were degraded in IRAF to match the resolution of the GOSSS atlas, following the procedure described in Section 2.2.1. The IMACS and MIKE spectra, which already have reliable spectral classifications in the literature, were used as provided and did not require resolution degradation.

Star	Spectral type
NGC 3603-1065	O6.5 Vz
NGC 3603-1096	O7 Vz
NGC 3603-1108	O7.5 Vz
NGC 3603-1111	O7.5 Vz
NGC 3603-911	O9 V
NGC 3603-1088	O9 V
NGC 3603-226	O9.5 V
NGC 3603-330	O9.5 V
NGC 3603-1059	O9.5 V
NGC 3603-1095	O9.5 V
NGC 3603-1076	B

Table 2.2.2: Newly classified stars in NGC 3603. The object NGC 3603-1076 was classified as a later-type star and was therefore excluded, since this work focuses exclusively on O-type stars with luminosity class V.

EW measurements of the key spectral lines used for classification were performed on all available datasets (MagE, MIKE, and IMACS), following the same methodology applied for NGC 346. The `splot` task in IRAF was used, and the same procedures for error estimation were applied. EW values, associated uncertainties, and updated spectral classifications for NGC 3603 are summarized in Table A.0.5.

Chapter 3

Methodology and tools for the quantitative spectral analysis of O stars

Over the past decade, the number of high-resolution spectroscopic observations of massive stars has increased significantly, driven by various survey programs. This growth has posed a new challenge: to analyze large volumes of spectral data in an efficient, accurate, and reproducible manner (Maíz Apellániz et al., 2011; Simón-Díaz & Herrero, 2014). In response to this need, semi-automated methodologies have been developed to extract physical parameters and chemical abundances without compromising result quality and while reducing computational time. Among the most prominent approaches are those presented by Mokiem et al. (2006); Lefever et al. (2007); Urbaneja et al. (2008); Simón-Díaz et al. (2011) and Castro et al. (2012).

In this context, quantitative spectroscopy has become a fundamental tool for the physical study of massive stars. This technique is based on the systematic comparison between observed spectra and synthetic spectra generated using atmospheric models that simulate the physical conditions of the star’s outer layers. Through this analysis, it is possible to derive key parameters, such as effective temperature, surface gravity, chemical composition, and stellar wind properties, with high precision (Hubeny & Lanz, 1995; Puls et al., 2008). It is worth noting that, except for stellar radius, most of these parameters can be determined by strategically fitting a suitable set of spectral lines (Simón-Díaz, 2020).

A representative example of this approach is the IACOB project (Simón-Díaz et al., 2011, 2014, 2015), a long-term observational program dedicated to collecting and analyzing high-resolution optical spectra ($R \gtrsim 10000$) of OB stars in the northern Galactic hemisphere. This project has generated a homogeneous, multi-epoch database that, combined with information provided by space missions such as Gaia (Global Astrometric Interferometer for Astrophysics), the International Ultraviolet Explorer (IUE), and the Far Ultraviolet Spectroscopic Explorer (FUSE), enables a detailed empirical characterization of the physical properties of these stars. Spectroscopic analysis conducted within the IACOB framework, both qualitative and quantitative, has been crucial to advancing our understanding of the evolution and nature of massive stars.

3.1 Line-broadening parameters: IACOB-BROAD

In OB-type stars, rotation is not the only mechanism responsible for spectral line broadening. As thoroughly reviewed by Simón-Díaz (2020), at least five other physical processes contribute significantly: natural broadening, thermal broadening, Stark effect (collisional), microturbulence, and macroturbulence. In particular, the linear Stark effect primarily impacts the wings of hydrogen lines and, to a lesser extent, He II lines. In contrast, the quadratic Stark effect subtly influences He I lines.

The first step in any quantitative spectroscopic analysis is the precise determination of the projected rotational velocity, $v \sin i$, by isolating its contribution from the other mechanisms that also affect line profiles. To this end, the tool IACOB-BROAD (Simón-Díaz & Herrero, 2014) is used. Developed in IDL, it combines two complementary methods: the Fourier Transform (FT) and the Goodness of Fit (GOF) approach.

The FT method is based on a mathematical property of the rotational broadening profile: its transform exhibits characteristic zeros. When a spectral line is broadened by rotation, its FT acquires a particular shape, and the first zero corresponds to the first spatial frequency, σ_1 , at which the transform vanishes. This parameter is directly related to the projected rotational velocity, $v \sin i$, through the expression

$$v \sin i (\sigma_1) = 0.66 \frac{c}{\lambda}$$

where c is the speed of light and λ is the central wavelength of the analyzed line (Carroll, 1933). In this context, σ is expressed in cycles per Å. This technique allows the rotational component to be estimated without interference from macroturbulence, provided that high-resolution spectra with a good S/N are available.

However, FT cannot completely distinguish between rotation and macroturbulence when both are present simultaneously. For this reason, IACOB-BROAD complements the analysis with a GOF method, which uses the χ^2 statistic to compare observed profiles with synthetic models generated for different combinations of $v \sin i$ and macroturbulent velocity (v_{mac}). The combination that minimizes χ^2 is considered the best estimate, reflecting the lowest discrepancy between observation and model.

Before performing the combined FT+GOF analysis, the tool allows the preprocessing of line profiles, such as local continuum renormalization or cropping of contaminated regions (e.g. nebular contamination). It is also possible to select the intrinsic profile used for convolution, either a delta function or a line profile generated by stellar atmosphere codes (Simón-Díaz & Herrero, 2014). Ideally, both methods should yield consistent estimates of $v \sin i$. When this is not the case, it may indicate that the line is affected by other phenomena not considered, such as pulsations, multiple spectral components, or complex atmospheric structures.

However, microturbulence also affects the determination of $v \sin i$ by FT. As indicated by Gray (1973), microturbulence introduces zeros in the FT at high frequencies, which can be confused with those caused by rotational broadening—especially in cases of low $v \sin i$. Simón-Díaz & Herrero (2007) present a detailed analysis of this effect in OB stars. As reported by the IACOB project, if microturbulence is not taken into account:

- (a) $v \sin i$ measurements below $\sim 40 \text{ km s}^{-1}$ should be interpreted as upper limits, especially in O stars and early B supergiants.
- (b) Macroturbulent velocities obtained through GOF should also be considered upper limits since low values (e.g., $v_{\text{mac}} \lesssim 15 \text{ km s}^{-1}$ in dwarfs) may be dominated by microturbulence.

Therefore, the combination of FT and GOF in IACOB-BROAD, along with careful handling of microturbulence, constitutes the most robust methodology to disentangle line-broadening contributions in OB stars.

3.1.1 Analysis strategy with IACOB-BROAD

To accurately determine the line-broadening parameters, such as the projected rotational velocity ($v \sin i$) and macroturbulent velocity (v_{mac}), we employed the IACOB-BROAD tool. As shown in Fig. 3.1.1, IACOB-BROAD provides three key estimates: (1) $v \sin i$ from FT, (2) $v \sin i$ from GOF, and (3) v_{mac} from GOF. These measurements allow for a more reliable separation of the rotational and macroturbulent contributions.

An important aspect of this type of analysis is the selection of spectral lines. Although the O III $\lambda 5592$ line is generally considered ideal for the determination of $v \sin i$ in O-type stars, its usefulness in our study was limited due

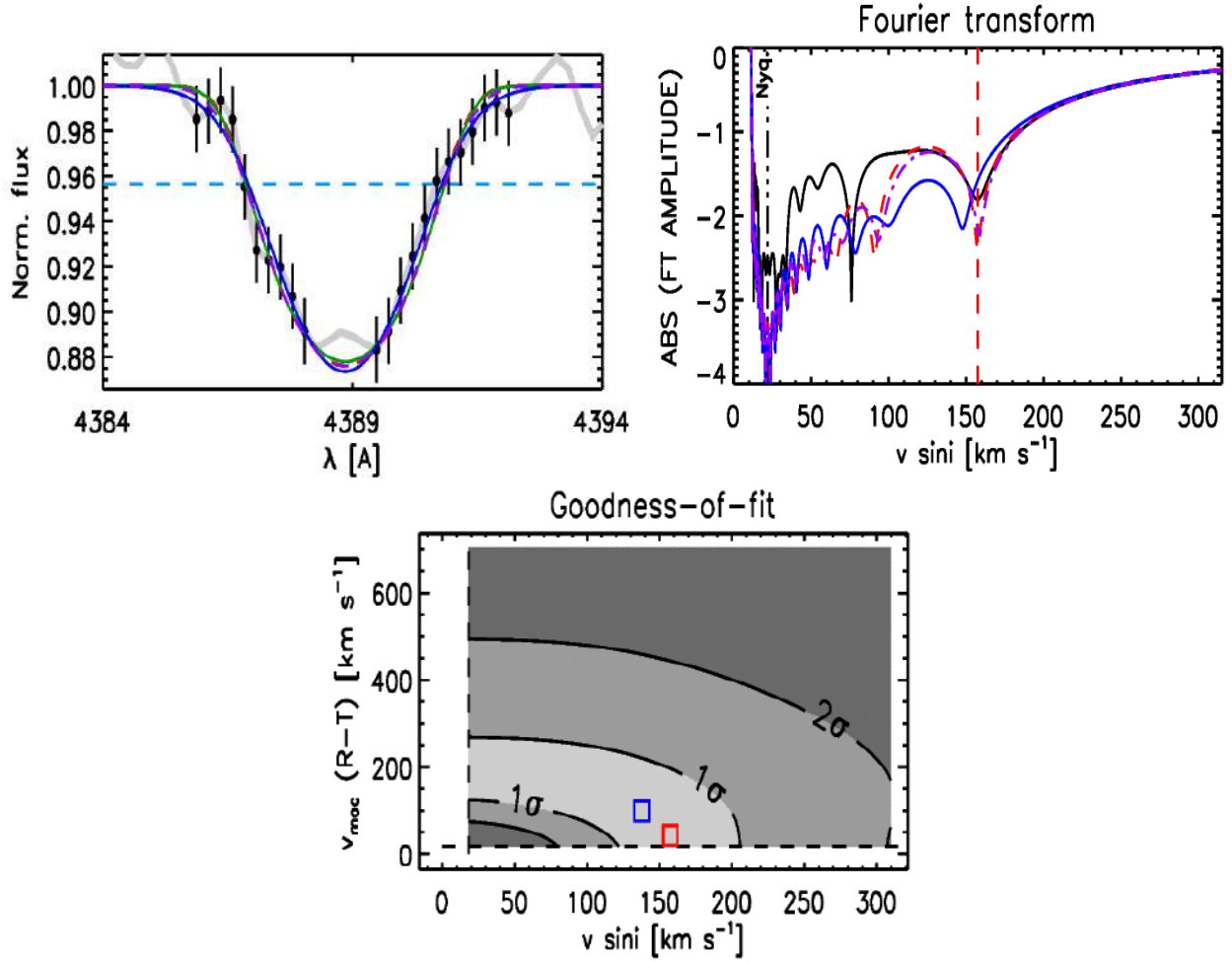


Figure 3.1.1: Example of the graphical output from IACOB-BROAD for the star NGC 3603-334 (O9.5 V), using the He I $\lambda 4388$ line. Upper left: best-fitting solution for the line profile obtained from the combined FT and GOF methods. Upper right: Fourier transform of the line profile; the observed spectrum in black, FT determination in red, and GOF fit in blue. Bottom: χ^2 distribution in the 2D space ($v \sin i$, v_{mac}) corresponding to the GOF fit. Again in red the FT determination, and in blue the GOF approximation of the minimum of the χ^2 distribution.

to the general absence of metallic lines in the spectra. Therefore, we opted to use He I lines, which, although more sensitive to the Stark broadening effect (Ramírez-Agudelo et al., 2013), have proven to be reliable when applied carefully and systematically.

Within this framework, the He I $\lambda 4388$ line was used as the primary diagnostic, occasionally supplemented by He II $\lambda 4541$ as a supporting line. It should be noted that, for low projected rotational velocities, the ability of any line to provide a reliable $v \sin i$ is limited by factors such as instrumental resolution, macroturbulence, and microturbulence (see, e.g., Sundqvist et al. 2013; Simón-Díaz & Herrero 2014). In this regime, $v \sin i$ values $\lesssim 120 \text{ km s}^{-1}$ tend to be systematically revised downward when the contribution of macroturbulence is properly taken into account, with typical corrections of the order of $\sim 25 (\pm 20) \text{ km s}^{-1}$ (Simón-Díaz & Herrero, 2014).

Simón-Díaz & Herrero (2007) have demonstrated that the FT method provides consistent results when applied to both helium and metallic lines, reinforcing the validity of the approach employed here. Furthermore, as noted by Holgado et al. (2018), the combined use of different $v \sin i$ and v_{mac} values does not introduce significant differences in the determination of physical parameters such as T_{eff} and $\log g$, provided that the synthetic spectra are properly

fitted to the observed profiles. This finding supports the systematic use of helium lines as reliable tools for the spectroscopic study of O-type stars.

Radial velocities

Before performing the quantitative spectroscopic analysis, the observed spectra must be corrected for Doppler shifts to ensure that all diagnostic lines are aligned with their laboratory wavelengths. Although this correction does not play a critical role in analysis stages based on equivalent-width measurements, it can significantly affect the determination of spectroscopic parameters when line-profile fitting techniques are applied. This correction is particularly important when estimating the surface gravity of O- and B-type stars, as this parameter is derived from fitting the wings of the hydrogen Balmer lines. Therefore, removing the Doppler shift caused by the stellar radial velocity is essential prior to running the IACOB-GBAT tool.

The radial velocities were obtained by measuring the wavelength shifts of the He,I $\lambda 4471$, He,II $\lambda 4541$, and He,II $\lambda 4686$ lines and converting them into Doppler velocities relative to their laboratory wavelengths. The resulting velocities were corrected to the heliocentric reference frame using the velocity corrections computed with the IRAF task `rvcorrect`. The final radial velocity for each star was adopted as the average of the three heliocentric-corrected line velocities.

In general, the radial velocities derived from the individual helium lines do not differ significantly from one another and are consistent within the measurement uncertainties. Small line-to-line differences may arise from uncertainties in the determination of the line centers, differences in the line formation depths, and residual nebular contamination, particularly affecting the He,I $\lambda 4471$ line. These effects are not expected to have a significant impact on the subsequent spectroscopic analysis.

3.2 Spectroscopic parameters: IACOB-GBAT

Once the observed spectrum has been prepared for analysis and the line-broadening parameters have been determined, the next step is to derive the so-called spectroscopic parameters. For O-type stars, this procedure relies on fitting synthetic profiles — previously convolved with the appropriate broadening mechanisms — to the observed hydrogen Balmer lines as well as He I and He II lines (Herrero et al., 1992, 2002; Repolust et al., 2004).

The main fundamental spectroscopic parameters obtained through this analysis include the effective temperature (T_{eff}), the surface gravity ($\log g$), and the $\log Q$ parameter, which quantifies the strength of the stellar wind. The latter becomes especially relevant in optical analyses, where lines sensitive to the mass-loss rate or the terminal wind velocity are not always present. This process also yields secondary parameters such as the helium abundance (Y_{He}), microturbulence (ξ_t), and the exponent of the wind velocity law (β). A comprehensive description of all the spectroscopic parameters mentioned here can be found in Section 3.2.4.

To carry out this analysis, we utilized the IACOB-GBAT tool, which was developed within the framework of the IACOB project. This semi-automated software replicates classical visual-fitting methods, integrating an extensive grid of atmosphere models generated with FASTWIND (Santolaya-Rey et al., 1997; Puls et al., 2005; Rivero González et al., 2012). Additionally, it incorporates IDL routines for data handling, least-squares (χ^2) fitting calculations, and result visualization. Its design allows for rapid and homogeneous analysis of large samples of O stars, providing both stellar parameters and their associated uncertainties.

In this work, we employed IACOB-GBAT to quantitatively analyze the optical spectra of our samples of O dwarf stars located in NGC 346 (SMC) and NGC 3603 (MW). It is worth noting that we did not determine stellar parameters for the objects in 30 Doradus (LMC); instead, we adopted the results from Sabín-Sanjulián et al. (2014), who derived these parameters using the same approach applied here, based on tools from the IACOB project.

Once the spectral preparation was validated, the analysis focused on parameters that can be reliably determined in the optical range (4000–5000 Å). Estimating other key physical parameters, such as stellar radius (R) or mass (M), requires additional information on distance and extinction.

3.2.1 Overview of the IACOB-GBAT methodology

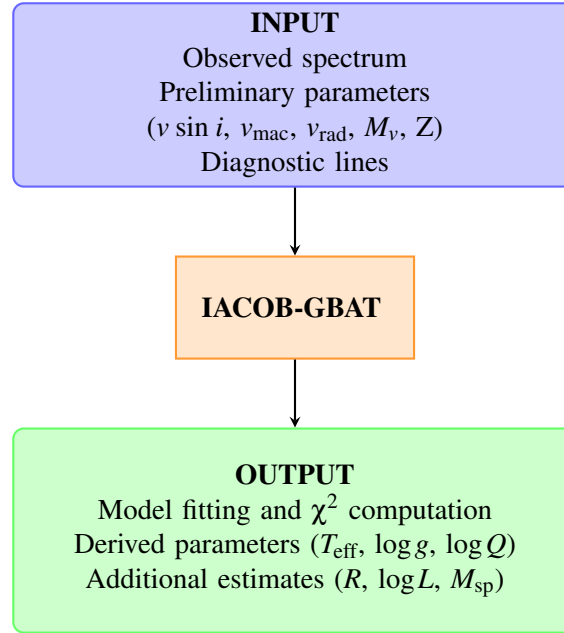


Figure 3.2.1: Schematic representation of the spectroscopic analysis process using IACOB-GBAT.

The spectroscopic analysis procedure using IACOB-GBAT (schematic in 3.2.1) is organized into several stages, which are described in detail below:

First, the user must provide the program with the essential input data, including the observed spectrum and the resolving power (R). Preliminary stellar parameters must also be supplied, such as the projected rotational velocity ($v \sin i$), the amplitude of macroturbulent broadening (v_{mac}), and, if available, the absolute visual magnitude (M_v). At this stage, the metallicity of the appropriate FASTWIND model grid is selected. The ranges of the free parameters to be fitted — typically effective temperature (T_{eff}), surface gravity ($\log g$), and wind parameter ($\log Q$) — are defined to constrain the model grid and optimize the efficiency of the analysis. The spectral H/He lines to be used for the fitting must also be specified.

In the second stage, the observed spectrum undergoes preliminary processing. Since observations may exhibit nebular contamination, continuum normalization errors, or instrumental artifacts (e.g., cosmic rays), IACOB-GBAT includes tools to correct these deficiencies. This is done through local renormalization of the lines, selection of relevant wavelength ranges, discarding or recovering affected sections, and automatic computation of the S/N in regions near the continuum. This stage may be complemented with a quick preliminary fitting using a reduced set of lines as a first reference for the complete analysis.

The third step corresponds to the evaluation of the quality of the fit. For each model in the grid, the χ^2 value per line (χ_L^2) is calculated, which measures the discrepancy between the observed profile and the synthetic model.

These values are corrected to compensate for possible systematic effects, such as continuum placement errors or intrinsic limitations of the atmospheric models, thus generating the corrected values χ_{Lc}^2 . These corrected values are then combined in a weighted manner using the weights assigned¹ to each line to obtain a global fit value:

$$\chi_T^2 = \sum (w_L \cdot \chi_{Lc}^2)$$

This global value allows the identification of the models that best reproduce the observed spectrum.

In the fourth step, probability distributions for each free parameter are built from the χ_T^2 values. These distributions are defined using the probability function:

$$p(\chi_T^2) = \exp\left(-\frac{1}{2}\chi_T^2\right)$$

This formulation assigns more weight to models that better fit the observational data. The final values of the physical parameters are computed as weighted means over these distributions. At the same time, uncertainties are estimated from the interval containing, for example, 68% of the total probability (equivalent to 1σ in a Gaussian distribution).

This probabilistic approach not only provides robust parameter estimates, but also facilitates:

- The detection of degeneracies between parameters (e.g., between $\log g$ and $\log Q$ in stars with weak winds).
- The evaluation of the impact of fixing certain parameters during fitting.
- The estimation of realistic uncertainties.

Additionally, if the absolute visual magnitude M_v is provided, the code computes the stellar radius (R), luminosity ($\log L$), and spectroscopic mass (M_{sp}) for each model in the grid. If the terminal wind velocity (v_∞) is also given, it estimates the mass-loss rate ($\dot{M}$). Finally, with the fitted values of T_{eff} and $\log g$, the tool interpolates evolutionary models to estimate the evolutionary mass (M_{ev}).

In the final stage, the code generates graphs that allow users to visualize and interpret the analysis results. These include, among others, a summary of the probability distributions for each parameter, the derived statistical values, a $\log T_{eff}$ – $\log g$ diagram with evolutionary tracks, and a detailed comparison between the observed spectrum and the synthetic models for each fitted line, explicitly marking the valid regions used in the fit.

3.2.2 Grid of FASTWIND models

The spectroscopic analysis was performed using model grids generated with the FASTWIND code, a specialized software for simulating the atmospheres of massive OB-type stars. FASTWIND computes the atmospheric structure assuming spherical geometry and homogeneous stellar winds, producing optical and infrared spectra that enable a detailed analysis of the physical properties of the stars.

As indicated in [Simón-Díaz et al. \(2011\)](#), IACOB-GBAT offers the possibility of selecting among three FASTWIND model grids, each computed for a different metallicity value.

In our case, as shown in Table 3.2.1, we selected the FASTWIND model grids corresponding to the subsolar metallicity of the SMC ($\sim 0.2 Z_\odot$) and solar metallicity, since our sample of O-type stars is mainly located in these environments. These grids include five free parameters: T_{eff} , $\log g$, Y_{He} , ξ_t , $\log Q$, with β fixed.

¹IACOB-GBAT automatically and iteratively assigns relative weights to the diagnostic lines in the computation of χ^2 , so that higher-quality lines with better S/N have a greater influence on the selection of the best-fitting model, while lines affected by noise, blends, or lower sensitivity receive lower weight.

Parameter	Range	Step size
$Z [Z_{\odot}]$	[0.2 and 1.0]	
$T_{\text{eff}} [\text{K}]$	[19 000–61 000]	1000
$\log g [\text{dex}]$	[2.1–4.5]	0.1
$\xi_r [\text{km s}^{-1}]$	[1–30]	5
Y_{He}^{a}	[0.04–0.30]	0.02
$\log Q^{\text{b}}$	[−11.0, −16.0]	~ 0.5
β	1.0	

^a $Y(\text{He}) = \text{N}(\text{He})/\text{N}(\text{H})$

^b $Q = \dot{M}(Rv_{\infty})^{-3/2}$

Table 3.2.1: Parameter space covered by the grid FASTWIND models.

3.2.3 Diagnostic Lines

Across the entire OB star domain, the wings of the Balmer lines (especially $\text{H}\gamma$ and $\text{H}\delta$) serve as the primary diagnostic for estimating surface gravity due to their sensitivity to atmospheric pressure. Additionally, lines such as $\text{H}\alpha$, $\text{He II } \lambda 4686$, and $\text{He I } \lambda 5875$ probe stellar wind properties as they respond to changes in wind density and velocity.

On the other hand, the estimation of the effective temperature strongly depends on the star’s spectral type. In mid- to late-type O stars, the classical method relies on the ratio of He I to He II lines as the primary temperature indicator (Herrero et al., 1992; Repolust et al., 2004; Holgado et al., 2018). In contrast, for very early O-type stars (O2–O3), where He I lines are weak or even absent, the diagnostic relies on N IV and N V lines (Rivero González et al., 2012; González et al., 2012). Conversely, in B-type stars, where He II lines are no longer present, Si IV–III and/or Si II–III lines are used instead (McErlean et al., 1999; Urbaneja et al., 2005; Lefever et al., 2007; Simón-Díaz, 2010).

This diversity in spectral indicators makes the careful selection of the diagnostic lines a crucial step in any quantitative analysis, as each line is sensitive to different physical parameters, such as temperature, surface gravity, or stellar wind structure.

Balmer series	He I	He II
H_{δ}	He I $\lambda 4387$	He II $\lambda 4200$
H_{γ}	He I $\lambda 4471$	He II $\lambda 4541$
H_{β}	He I $\lambda 4713$	He II $\lambda 4686$
	He I $\lambda 4922$	
	He I+II $\lambda 4026$	

Table 3.2.2: Summary of H I and He I–II diagnostic lines used in the IACOB-GBAT analysis.

In this context, Table 3.2.2 summarizes the complete list of H I and He I–II diagnostic lines considered in the IACOB-GBAT analysis for the sample of O-type stars. The selected lines correspond to those traditionally used in the spectroscopic analysis of this type of star (see, for example, Herrero et al. 1992; Repolust et al. 2004). For consistency, the same set of lines is always used in all analyses.

3.2.4 Stellar parameters

3.2.4.1 Effective temperature (T_{eff}), surface gravity ($\log g$), helium abundance (Y_{He})

As a starting point, initial values of T_{eff} and $\log g$ were selected based on previous estimates published by [Massey et al. \(2005\)](#) and [Martins et al. \(2005\)](#). The helium abundance (Y_{He}), in particular, was treated as a free parameter during the analysis, following the approach adopted in previous studies of O-type stars ([Herrero et al., 2002](#); [Ramírez-Agudelo et al., 2017](#)). Based on these parameters, chi-square (χ^2) values were calculated between the observed spectra and the generated synthetic models, thus evaluating the quality of the fit at each iteration.

For most stars in the sample, it was possible to obtain reliable estimates of T_{eff} , $\log g$, and Y_{He} , accompanied by their respective formal uncertainties. However, in some cases, limitations in the quality of the spectral data or the complexity of the stellar features prevented the precise determination of specific parameters, allowing only the establishment of upper or lower limits. It is important to note that the parameters T_{eff} and $\log g$ are not independent: when one is modified during the fitting process, the other is also affected ([Herrero et al., 1992](#); [Simón-Díaz & Herrero, 2014](#)). Consequently, the procedure implemented by IACOB-GBAT optimizes both parameters simultaneously, ensuring consistency between the obtained values and the observed spectral profiles.

3.2.4.2 Wind parameter ($\log Q$)

The wind-strength parameter Q is defined as

$$Q = \frac{\dot{M}}{(R_{\star} v_{\infty})^{3/2}}$$

This parameter is used as an indicator of wind strength in massive stars. Its definition combines the mass-loss rate and the terminal velocity of the stellar wind ([Puls et al., 1996](#)), two key properties in the evolution of such objects. Since no direct estimates of the terminal velocity (v_{∞}) are available for the stars in our sample, it was not possible to study potential differences in v_{∞} between O V and O Vz stars in detail. However, $\log Q$ can be derived directly from the spectroscopic fit, so the analysis focused on this parameter as a proxy for wind intensity.

The H α and He II $\lambda 4686$ lines are key spectroscopic features in O-type stars, commonly used to determine $\log Q$. As discussed in [Sabín-Sanjulián et al. \(2014\)](#), the core flux of the He II $\lambda 4686$ line shows apparent sensitivity to variations in $\log Q$, making it a suitable diagnostic tool for assessing wind intensity in O-type dwarf stars. Because of this, and due to the spectral range of our observations (4000–5000 Å), we employed this line as the primary diagnostic in this context.

The He II $\lambda 4686$ line is particularly relevant because, in O Vz dwarf stars, its intensity can reflect the effect of a weak stellar wind. This line presents much deeper absorption than He I $\lambda 4471$ and He II $\lambda 4541$, which is characteristic of stars with Vz luminosity class. This feature is interpreted as a lack of emission filling in the line profile due to the weak influence of the stellar wind, typical of O dwarfs with lower wind intensities ([Parker, 1992](#); [Walborn & Blades, 1997](#)). Although the He II $\lambda 4686$ line is not as prominent as in more massive or supergiant stars, in O dwarfs, it remains sensitive to wind strength, providing valuable information for fitting atmospheric models. Therefore, its use instead of H α is appropriate, especially in stars with weaker winds such as O Vz.

3.2.4.3 Wind velocity law exponent (β)

When the gas is sufficiently far from the star, it reaches a terminal velocity, v_{∞} . The atmospheric gas exhibits a velocity gradient, known as the β -velocity law, described by [Castor et al. \(1975\)](#) as:

$$v(r) = v_{\infty} \left(1 - \frac{R_*}{r} \right)^{\beta}$$

where v_{∞} is the terminal wind velocity, R_* the stellar photospheric radius, r the distance from the center of the star, and β is a free parameter that describes the slope of the velocity law. Therefore, β directly influences the modeling of wind-sensitive line profiles.

According to [Holgado et al. \(2018\)](#), the fitting procedure implemented in IACOB-GBAT does not allow robust constraints on the wind velocity-law exponent β within the typically assumed range (0.8–1.2). In addition, they show that the uncertainty in $\log Q$ is significantly reduced when β is fixed during the fitting process. Based on these results, we adopted a fixed value of $\beta = 1.0$, which is commonly assumed for O-type stars. This choice is consistent with the expected wind properties of these objects and helps to stabilize the atmospheric model fitting.

3.2.4.4 Microturbulence (ξ_t)

In the context of stellar spectroscopy, microturbulence represents small-scale random gas motions in the atmospheric layers where spectral lines form. This parameter directly affects the broadening of these lines and, thus, the determination of abundances and other physical parameters. Although many spectroscopic studies adopt a constant value for ξ_t (e.g., [Herrero et al. 2002](#); [Repolust et al. 2004](#); [Markova et al. 2014](#)), in our analysis it was considered a free parameter, following works such as [Mokiem et al. \(2005\)](#) and [Ramírez-Agudelo et al. \(2017\)](#). However, in most cases, it was only possible to derive upper or lower limits for this parameter, consistent with the limitations reported by [Holgado et al. \(2018\)](#). Although microturbulence values may be somewhat higher in early O dwarfs, this effect does not introduce significant variations in the final parameters within the typical uncertainties of the method (see also [Villamariz & Herrero, 2000](#)).

3.2.5 Fundamental Parameters: radii, luminosities, and spectroscopic masses

When the absolute magnitude in the V band (M_V) of the star is provided, the IACOB-GBAT tool can be relaunched to estimate radii, luminosities, and spectroscopic masses along with their associated uncertainties. These physical parameters are computed for each FASTWIND model within the selected subgrid, using the emergent flux, effective temperature (T_{eff}), and surface gravity ($\log g$) provided by the models, and assuming the absolute magnitude of the analyzed object. As with other stellar parameters such as T_{eff} , $\log g$, or $\log Q$, a global χ^2 distribution is constructed for each of these values.

The equations that relate the photometry of the star to the physical parameters of each FASTWIND model are based on [Kudritzki \(1980\)](#) and the Stefan–Boltzmann law, and are expressed as follows:

$$\begin{aligned} 5 \log \left(\frac{R}{R_{\odot}} \right) &= 29.57 - M_V + V \\ \log \left(\frac{L}{L_{\odot}} \right) &= 2 \log \left(\frac{R}{R_{\odot}} \right) + 4 \log \left(\frac{T_{\text{eff}}}{T_{\text{eff},\odot}} \right) \\ \log \left(\frac{M}{M_{\odot}} \right) &= 2 \log \left(\frac{R}{R_{\odot}} \right) + \log \left(\frac{g}{g_{\odot}} \right) \end{aligned}$$

These expressions allow the derivation of radius, luminosity, and mass from the combination of absolute magnitude, effective temperature, and surface gravity. Although V -band photometry is primarily used in this work, IACOB-GBAT is also adapted to perform the analysis using infrared photometry, provided the absolute magnitude in the K band (M_K) is supplied instead of M_V .

Additionally, if the terminal wind velocity (v_∞) is included in the analysis, the mass-loss rate ($\dot{M}$) can be estimated for each FASTWIND model within the grid. This value is derived from the wind-strength parameter, defined as:

$$Q = \frac{\dot{M}}{(R_\star v_\infty)^{3/2}}$$

A χ^2 distribution associated with $\dot{M}$ is also obtained, similar to the previously mentioned parameters. However, since terminal wind velocity values (v_∞) are not available for most of the O-type stars in our sample, the mass-loss rate is not computed in those cases.

3.2.6 Output of the Analysis with IACOB-GBAT

At the end of the analysis process, IACOB-GBAT provides the model that offers the best fit within the considered model grid, along with the estimated values (or upper and lower limits) for each of the six adjustable parameters, accompanied by their respective uncertainties. As part of the preprocessing, the spectral lines used as diagnostics were locally renormalized, and those affected by nebular emission or the presence of cosmic rays were discarded.

The tool also generates two illustrative graphical outputs, shown in Figures 3.2.2 and 3.2.3. The first (Figure 3.2.2) shows the fit between the observed spectral profiles and the synthetic profiles from the best-fitting model. The second (Figure 3.2.3) displays the χ^2 value distributions corresponding to each free parameter.

Figure 3.2.3 shows the χ^2 distributions obtained for the star NGC 346-38, based on the spectral fitting with FASTWIND models. Each panel shows the χ^2 values resulting from the comparison between the observed spectrum and the various models in the subgrid. The gray dots correspond to the χ^2 values of each evaluated model. The red dot indicates the parameter value of the best-fitting model (minimum χ^2), while the black curve represents the lower envelope of the distribution, i.e., the minimum χ^2 values reached across the grid. The red dashed lines indicate the total minimum value $\chi_{T\min}^2$ and the 1σ and 2σ levels relative to this minimum (calculated as $\chi_{T\min}^2 + 1$ and $\chi_{T\min}^2 + 4$, respectively; Sabín-Sanjulián et al. (2014)). To the right of Figure 3.2.3, additional information is provided in three blocks: (1) the input parameters used in the analysis, such as the star ID, the $v \sin i$ value, and the absolute visual magnitude M_V ; (2) the average derived values with their respective uncertainties, along with the parameters of the best-fit model; and (3) the star's position in the spectroscopic Hertzsprung–Russell (sHR) diagram, following the definition of Langer & Kudritzki (2014).

The final stellar parameters are obtained as weighted average values, considering only those models located within the 1σ confidence interval in the χ^2 distribution (see the red lines in Figure 3.2.3), with each model weighted by its χ^2 value. The associated uncertainties are estimated as the standard deviation within this confidence region. Additionally, when complementary information is available—such as the absolute magnitude in the V band (M_V) or the terminal wind velocity (v_∞)—the tool also estimates and presents other fundamental physical parameters: the stellar radius, luminosity, spectroscopic mass, and mass-loss rate ($\dot{M}$). The position of the star is also shown in both the Hertzsprung–Russell (HR) and sHR diagrams.

The IACOB-GBAT tool allows for precise retrieval of stellar parameters, although it is essential to consider potential degeneracies (Sabín-Sanjulián et al., 2014). In particular, for stars with weak winds, degeneracies may arise in the parameter $\log Q$, making it impossible to determine an exact value. In such cases, only an upper limit can be established. On the other hand, loss of information in the core of He I lines due to removal of nebular contamination can impact the derived values of T_{eff} , $\log g$, and helium abundances. According to Sabín-Sanjulián et al. (2014), an incorrect renormalization of the observed spectrum has a significant effect only in models with $T_{\text{eff}} \lesssim 40,000$ K, mainly affecting the surface gravity and spectroscopic masses. For hotter models, the impact of erroneous renormalization is minor, generating only slight shifts toward higher or lower values in T_{eff} , $\log g$, and M_{spec} . In general, the helium abundance and the wind parameter Q are minimally affected.

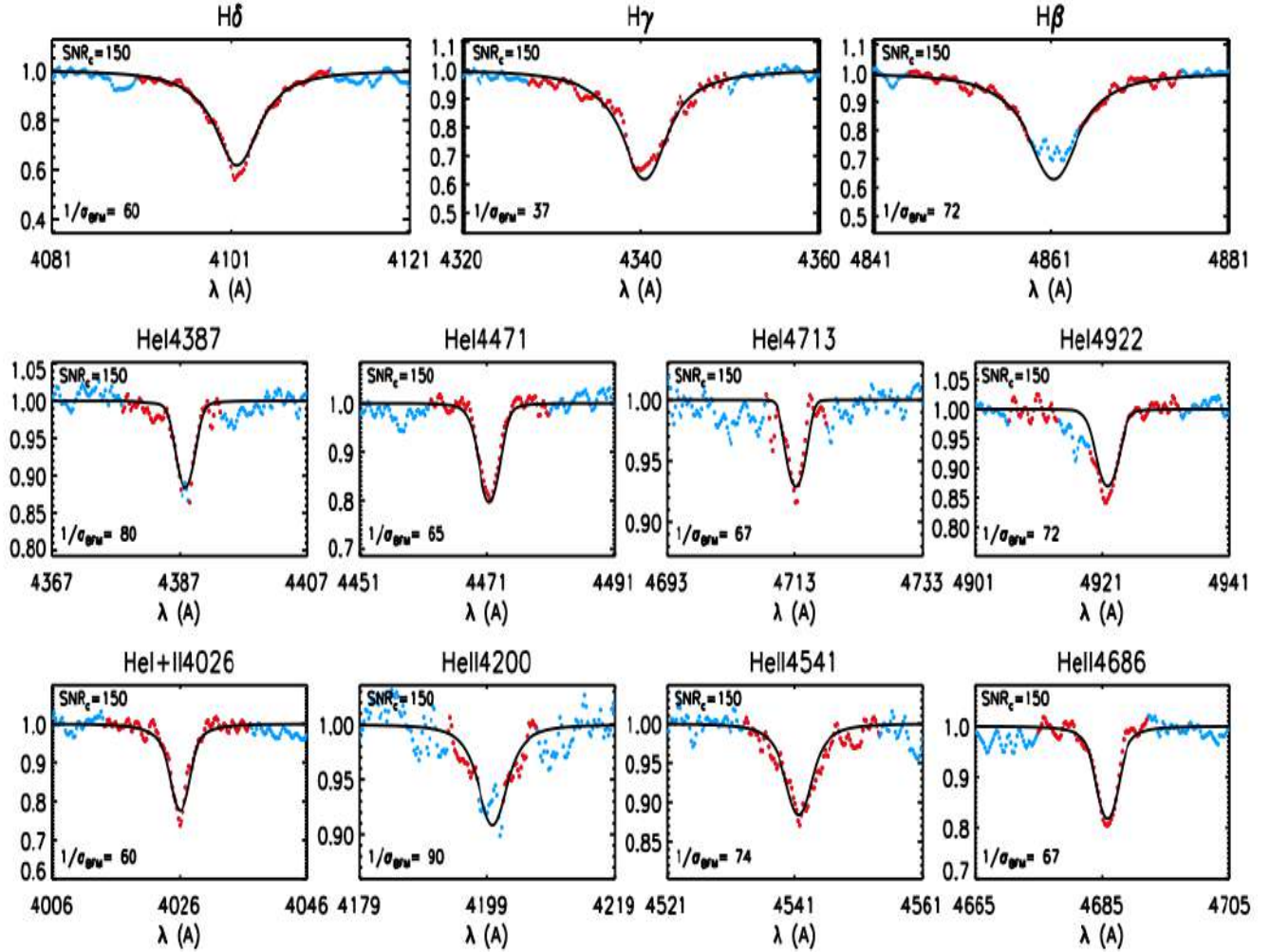


Figure 3.2.2: Example of line-profile fitting for the star NGC 346-38 (O9 V). The different diagnostic lines used in the analysis are shown in individual panels. In each panel, the spectral points considered in the fit are shown in red, while discarded points appear in blue. The synthetic profile corresponding to the model with the best global fit is shown as a black line. The quantity σ_{BFT} shown for each line represents the uncertainty associated with its contribution to the global fit.

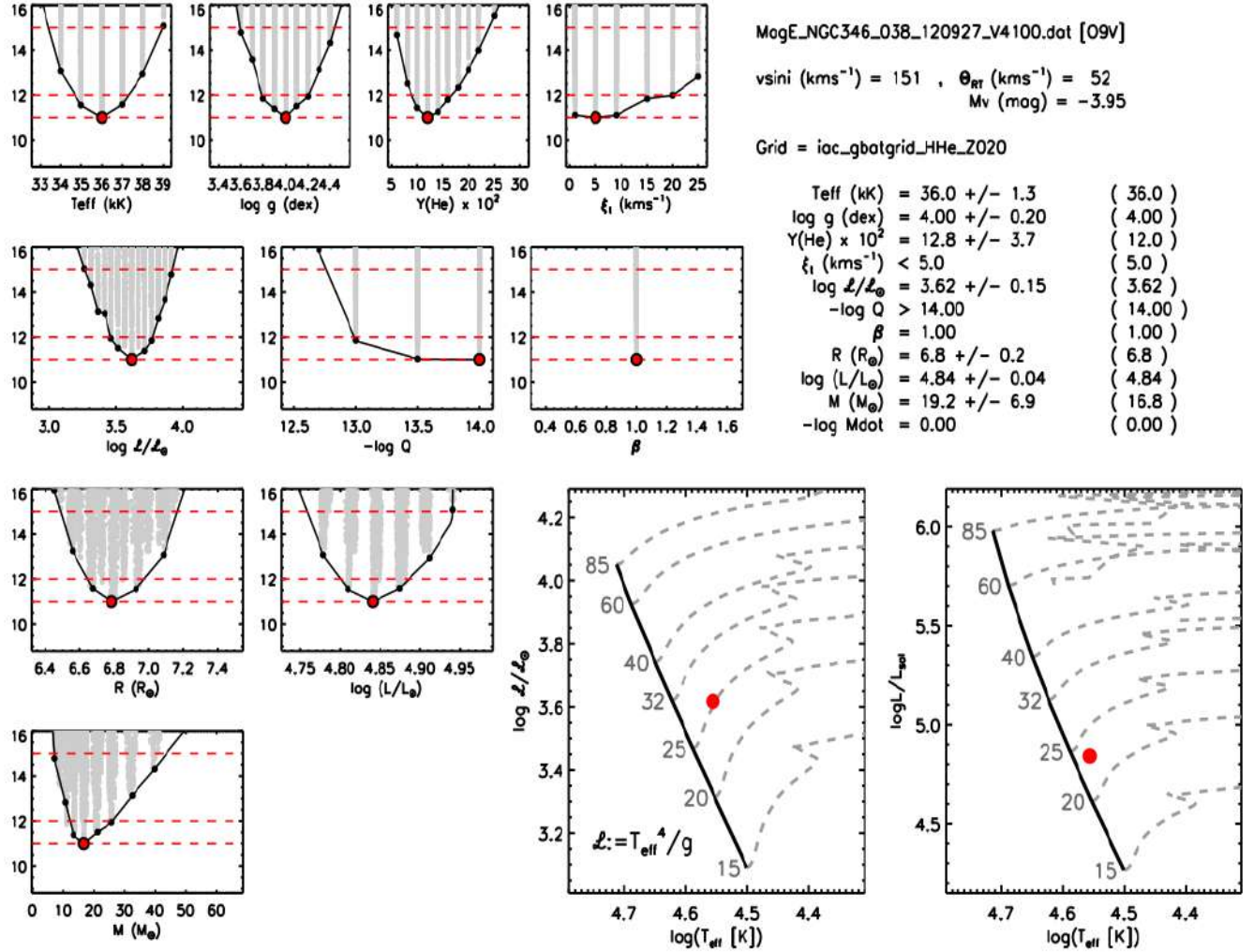


Figure 3.2.3: Example of an output plot showing the χ^2 distributions obtained for one of the O V-type stars analyzed in this thesis (NGC 346-38), based on the spectral fitting using FASTWIND models. The individual panels present the distributions for each free parameter, highlighting the model that provides the best fit.

Chapter 4

Results for the O V stars in NGC 346

This chapter presents the results of the quantitative spectral analysis performed on O-type stars of luminosity classes V and Vz located in the star-forming region NGC 346, situated in the SMC. The primary objective was to characterize their physical properties and assess potential differences between the two subclasses, with a particular focus on the distribution of effective temperature, surface gravity, helium abundance, and evolutionary status.

The following sections detail the results obtained for NGC 346 and their interpretation in the context of the origin and nature of the Vz class.

4.1 Spatial and spectral distribution of O V and O Vz stars

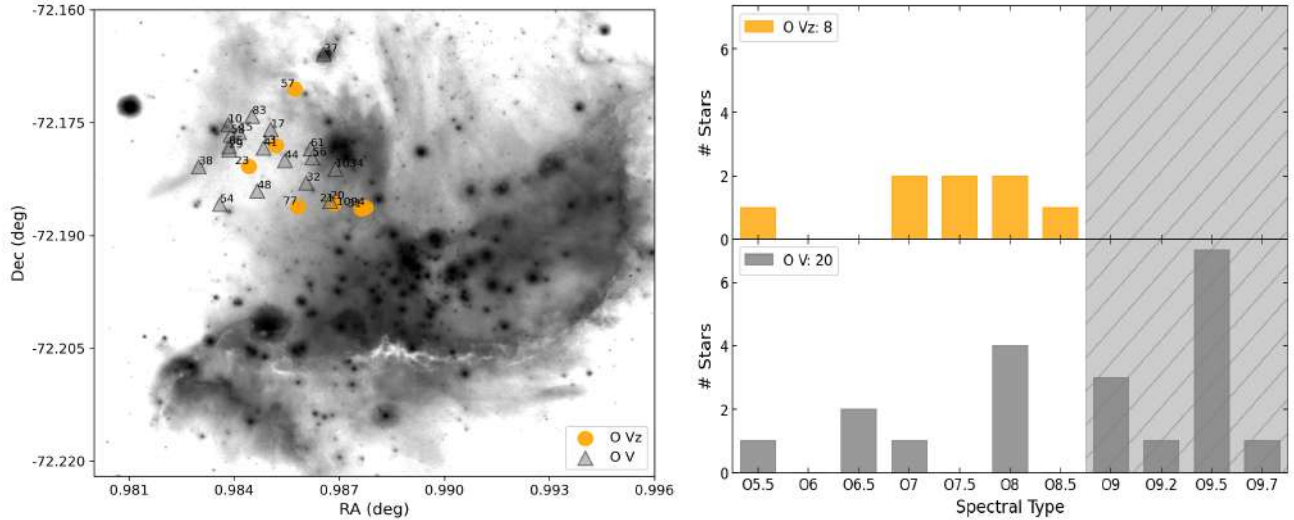


Figure 4.1.1: Left panel: Spatial distribution of O Vz stars and O V stars analyzed in the NGC 346 region. The numbers above the symbols indicate the identifier assigned to each star. Image credit: NASA, ESA, CSA, N. Habel (JPL), and P. Kavanagh (Maynooth University). Right panel: Spectral distribution of O Vz and O V stars. The gray dashed area represents the region defined by [Arias et al. \(2016\)](#), where the Vz spectral feature is absent in stars with spectral type later than O8.5.

The left panel of Figure 4.1.1 illustrates the spatial distribution of O-type stars in the sample. The analyzed objects are mainly concentrated in the northern part of the observed region.

The right panel of Figure 4.1.1 presents the spectral-type distribution of O-type stars in the NGC 346 sample. The O V population is dominated by late-type stars, peaking at spectral type O9.5. In contrast, O,Vz stars are primarily found at intermediate spectral types, between O7 and O8.5, and are scarce among the earliest subtypes. According to the quantitative classification criterion, O Vz stars represent approximately 29% of the total sample (eight objects) and are absent at spectral types later than O8.5. The remaining O V stars, accounting for about 71% of the sample, span a broader range of spectral types.

4.2 Stellar parameters derived for the O dwarf sample

The IACOB-GBAT tool was used to quantitatively analyze the optical spectra of our sample of 28 O-type dwarf stars located in the NGC 346 cluster. The motivations, methodology, and key characteristics of this tool are described in detail in Chapter 3, Section 3.2. To optimize computational time, we restricted the range of T_{eff} and $\log g$ values considered in the IACOB-GBAT analysis by using the spectral type and luminosity class calibrations from Massey et al. (1989). We used as central values those proposed in Massey’s observational calibration. We extended the corresponding range for effective temperature by ± 2000 K. Regarding the other parameters (ξ_t , Y_{He} , $\log Q$), we used the full available range, along with a fixed value of $\beta = 1.0$.

The quantitative analysis results, based on H and He line profiles, are presented for practical purposes in two main groups: first, the stellar and wind parameters, compiled in Table 4.3.1; and second, the derived absolute V magnitudes, radii, luminosities, and spectroscopic masses, included in Table 4.3.2. These tables are complemented by a series of figures in Appendix B (Figure B.0.2), where the best-fitting synthetic spectra are overplotted on the observed data for the most relevant diagnostic lines in this study. The identifier for each star-forming region and the spectral classification are indicated for each star.

4.3 Differential study of stellar parameters

This subsection analyzes key aspects of the O V and O Vz star sample in NGC 346, such as the distribution of projected rotational velocities ($v \sin i$) and the relation between surface gravity and effective temperature through the $\log g - \log T_{\text{eff}}$ diagram. The properties of stellar winds are also analyzed, determined from the spectroscopic parameter $\log Q$. Additionally, the position of the stars in the classical HR diagram is examined, which allows us to explore their evolutionary status in the context of the SMC.

Table 4.3.1: Stellar and wind parameters obtained from the quantitative analysis of our NGC 346 sample, including: (1) identifier; (2–3) updated spectral classification; (4) adopted $v \sin i$; (5–9) derived effective temperature, surface gravity, $\log Q$ parameter, helium abundance, and macroturbulence, with their respective formal uncertainties.

Star	SpT	LC	$v \sin i$ [km s ⁻¹]	T_{eff} [kK]	$\log g$ [dex]	$\log Q$ [dex]	Y(He) [dex]	ξ_t [km s ⁻¹]
NGC 346-10	O8	V	93	40.8 ± 1.5	3.79 ± 0.15	<-14.00	0.14 ± 0.05	< 1.0
NGC 346-13	O8	V _z	82	37.5 ± 1.7	4.07 ± 0.33	<-14.00	0.09 ± 0.03	< 1.0
NGC 346-15	O6.5	V	119	40.1 ± 0.9	4.15 ± 0.14	<-14.00	0.11 ± 0.02	< 9.0
NGC 346-17	O9.2	V	154	32.9 ± 0.7	3.62 ± 0.09	-13.22 ± 0.42	<0.06	< 1.0
NGC 346-20	O7	V	50	38.8 ± 1.0	3.87 ± 0.10	<-13.50	0.10 ± 0.02	< 1.0
NGC 346-21	O7	V _z	257	38.5 ± 1.0	3.96 ± 0.15	<-13.50	0.14 ± 0.03	< 1.0
NGC 346-23	O7.5	V _z	50	38.1 ± 1.1	4.05 ± 0.15	<-13.50	0.12 ± 0.03	< 9.0
NGC 346-29	O9.5	V	131	34.6 ± 0.9	4.07 ± 0.15	-13.03 ± 0.17	0.10 ± 0.02	< 1.0
NGC 346-31	O5.5	V _z	90	41.9 ± 1.0	4.00 ± 0.10	<-14.00	0.10 ± 0.02	< 9.0
NGC 346-32	O9.5	V	50	33.3 ± 1.1	3.65 ± 0.15	<-14.00	0.11 ± 0.04	< 9.0
NGC 346-37	O8	V	185	39.7 ± 1.0	4.09 ± 0.13	<13.00	0.12 ± 0.02	< 9.0
NGC 346-38	O9	V	151	36.0 ± 1.3	4.00 ± 0.20	<-14.00	0.12 ± 0.04	< 5.0
NGC 346-41	O9.5	V	109	34.1 ± 0.5	3.99 ± 0.09	<-13.50	0.12 ± 0.03	< 1.0
NGC 346-44	O8	V _n	280	38.1 ± 1.2	4.11 ± 0.18	<-13.50	0.15 ± 0.04	< 1.0
NGC 346-48	O8	V	197	33.8 ± 0.9	3.56 ± 0.16	<-13.50	0.14 ± 0.04	< 9.0
NGC 346-54	O6.5	V	50	41.3 ± 1.2	4.18 ± 0.17	<-13.50	0.20 ± 0.06	< 1.0
NGC 346-56	O8	V	96	38.2 ± 1.3	4.14 ± 0.26	<-13.50	0.14 ± 0.04	< 1.0
NGC 346-57	O7	V _z	50	39.0 ± 1.0	3.96 ± 0.15	<-14.00	0.12 ± 0.03	< 5.0
NGC 346-58	O9.5	V	224	34.5 ± 1.1	4.08 ± 0.21	<-14.00	0.14 ± 0.04	< 1.0
NGC 346-61	O9.5	V	83	32.8 ± 1.4	3.66 ± 0.25	<-13.50	<0.10	< 1.0
NGC 346-77	O7.5	V _z	50	37.3 ± 1.4	3.77 ± 0.20	<-13.50	0.13 ± 0.04	< 1.0
NGC 346-83	O9.5	V	50	33.3 ± 0.9	3.97 ± 0.20	<-13.50	0.12 ± 0.03	< 5.0
NGC 346-85	O9.7	V	108	31.9 ± 0.4	3.89 ± 0.13	-12.77 ± 0.22	0.08 ± 0.02	< 1.0
NGC 346-1034	O9.5	V	136	35.0 ± 1.3	4.19 ± 0.23	-12.64 ± 0.22	<0.06	< 1.0
NGC 346-1067	O8.5	V _z	94	36.6 ± 1.6	4.05 ± 0.28	<-14.00	0.11 ± 0.05	< 5.0
NGC 346-1094	O8	V _z	77	37.8 ± 1.3	4.10 ± 0.21	<-13.00	<0.10	< 1.0
NGC 346-1114	O9	V	236	35.7 ± 1.7	4.14 ± 0.29	<-13.50	0.11 ± 0.04	< 1.0
NGC 346-1144	O9.5	V	50	35.3 ± 1.4	4.07 ± 0.27	<-14.00	0.10 ± 0.04	< 1.0

Table 4.3.2: Absolute V magnitudes, radii, luminosities and spectroscopic masses obtained from quantitative analysis of our NGC 346 sample.

Star	SpT	LC	M_v [mag]	R [$R_\odot$]	$\log L$ [$L_\odot$]	M_{spec} [$M_\odot$]
NGC 346-10	O8	V	-4.97	10.1 ± 0.2	5.41 ± 0.05	24.5 ± 7.5
NGC 346-13	O8	Vz	-4.62	9.1 ± 0.2	5.16 ± 0.06	43.9 ± 26.3
NGC 346-15	O6.5	V	-4.76	9.2 ± 0.1	5.29 ± 0.03	46.1 ± 13.1
NGC 346-17	O9.2	V	-4.96	11.7 ± 0.1	5.15 ± 0.02	21.4 ± 4
NGC 346-20	O7	V	-4.47	8.3 ± 0.1	5.14 ± 0.03	19 ± 3.9
NGC 346-21	O7	Vz	-4.63	9 ± 0.1	5.2 ± 0.03	28.2 ± 9.1
NGC 346-23	O7.5	Vz	-4.13	7.1 ± 0.1	4.98 ± 0.03	22.1 ± 6.6
NGC 346-29	O9.5	V	-4.12	7.7 ± 0.2	4.88 ± 0.03	26.7 ± 8.7
NGC 346-31	O5.5	Vz	-4.33	7.4 ± 0.1	5.18 ± 0.03	20.1 ± 3.5
NGC 346-32	O9.5	V	-3.89	7 ± 0.1	4.73 ± 0.04	9 ± 2.2
NGC 346-37	O8	V	-4.20	7.2 ± 0.1	5.06 ± 0.03	24.5 ± 7.3
NGC 346-38	O9	V	-3.95	6.8 ± 0.2	4.84 ± 0.04	19.2 ± 6.9
NGC 346-41	O9.5	V	-3.90	7 ± 0.1	4.77 ± 0.02	17.7 ± 3.4
NGC 346-44	O8	Vn	-3.82	6.2 ± 0.1	4.86 ± 0.04	19.4 ± 7.6
NGC 346-48	O8	V	-3.82	6.7 ± 0.1	4.72 ± 0.03	6.9 ± 1.7
NGC 346-54	O6.5	V	-3.65	5.4 ± 0.1	4.89 ± 0.04	17.6 ± 6.1
NGC 346-56	O8	V	-3.44	5.2 ± 0.1	4.71 ± 0.04	16.3 ± 8
NGC 346-57	O7	Vz	-3.65	5.7 ± 0.1	4.82 ± 0.03	11.3 ± 3.5
NGC 346-58	O9.5	V	-3.68	6.2 ± 0.1	4.69 ± 0.04	19.3 ± 8.2
NGC 346-61	O9.5	V	-3.26	5.5 ± 0.2	4.49 ± 0.05	< 4.3
NGC 346-77	O7.5	Vz	-3.04	4.4 ± 0.1	4.52 ± 0.05	< 3.5
NGC 346-83	O9.5	V	-3.14	5.2 ± 0.1	4.48 ± 0.03	10.4 ± 3.9
NGC 346-85	O9.7	V	-3.55	6.3 ± 0.1	4.57 ± 0.02	12.4 ± 3.1
NGC 346-1034	O9.5	V	-4.13	7.7 ± 0.2	4.9 ± 0.04	37.6 ± 17
NGC 346-1067	O8.5	Vz	-3.62	5.8 ± 0.2	4.73 ± 0.05	16.1 ± 8.4
NGC 346-1094	O8	Vz	-3.39	5.1 ± 0.1	4.68 ± 0.04	13.2 ± 5.3
NGC 346-1114	O9	V	-3.17	4.8 ± 0.2	4.52 ± 0.06	14.1 ± 7.6
NGC 346-1144	O9.5	V	-2.92	4.3 ± 0.1	4.41 ± 0.04	9.8 ± 4.4

4.3.1 Distribution of the projected rotational velocities

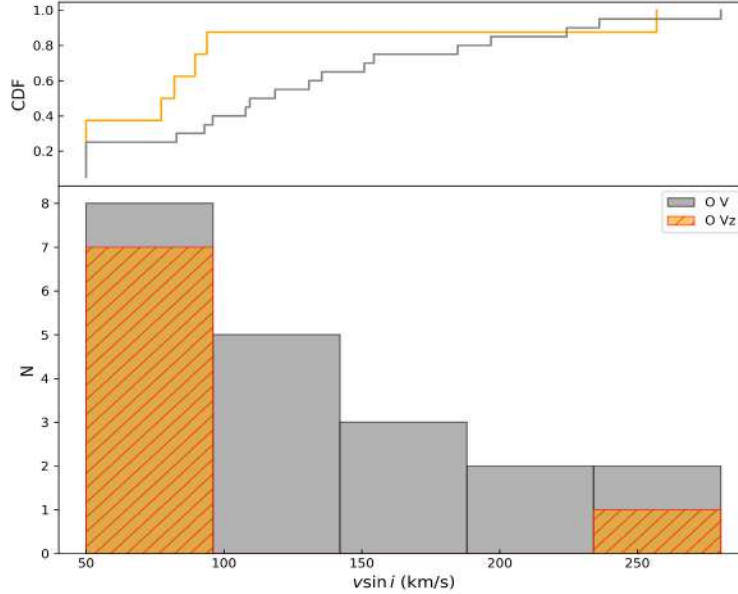


Figure 4.3.1: Distribution of projected rotational velocities ($v \sin i$) of O V and O Vz stars in the NGC 346 region. The upper panel shows the cumulative distribution functions (CDFs) of both subpopulations.

Figure 4.3.1 shows the distribution of projected rotational velocities ($v \sin i$) for O V and O Vz stars. The O V population exhibits a wide range of $v \sin i$ values, with a clear concentration below 100 km s^{-1} and a fraction of fast rotators exceeding 200 km s^{-1} . In contrast, most O Vz stars are primarily clustered in the low-velocity regime ($v \sin i < 100 \text{ km s}^{-1}$), with only a single object above this threshold. To avoid biases arising from arbitrary binning choices, the histograms were constructed using the Freedman–Diaconis criterion (Freedman & Diaconis, 1981), resulting in an optimal bin width of $\Delta v \approx 67 \text{ km s}^{-1}$.

The small sample size of O Vz stars limits the ability to draw statistically robust conclusions. This limitation is further compounded by the resolution of our spectra ($R = 4100$) and their spectral coverage ($4000\text{--}5000 \text{ \AA}$), which constrains the precise characterization of line broadening. Consequently, the determination of $v \sin i$ values below $\sim 75 \text{ km s}^{-1}$ (the instrumental limit c/R) carries significant uncertainty (see Section 3.1.1). In cases where a reliable measurement could not be obtained, a fixed value of 50 km s^{-1} was adopted for five O V stars and three O Vz stars. The presence of He I $\lambda 4387$ and He II $\lambda 4541$ lines allowed sufficiently reliable estimates of $v \sin i$ despite the spectral resolution limitations.

To assess whether the $v \sin i$ distributions of the O Vz and O V populations originate from the same underlying distribution, a Kolmogorov–Smirnov (KS, Massey Jr, 1951) test was applied. The resulting test statistic, $D = 0.52$, corresponds to the maximum separation between the cumulative distribution functions (CDFs) of the two samples (Figure 4.3.1). The associated p -value, $p = 0.06$, represents the probability of observing a difference equal to or greater than D under the null hypothesis of identical distributions. Since $p > 0.05$, the null hypothesis cannot be rejected, indicating no statistically significant differences in $v \sin i$ between O V and O Vz stars.

4.3.2 The $\log g - \log T_{\text{eff}}$ diagram

Figure 4.3.2 shows the general distribution of O V and O Vz stars in terms of effective temperature and surface gravity. In the T_{eff} histogram, as expected from their spectral classification, O Vz stars cluster predominantly

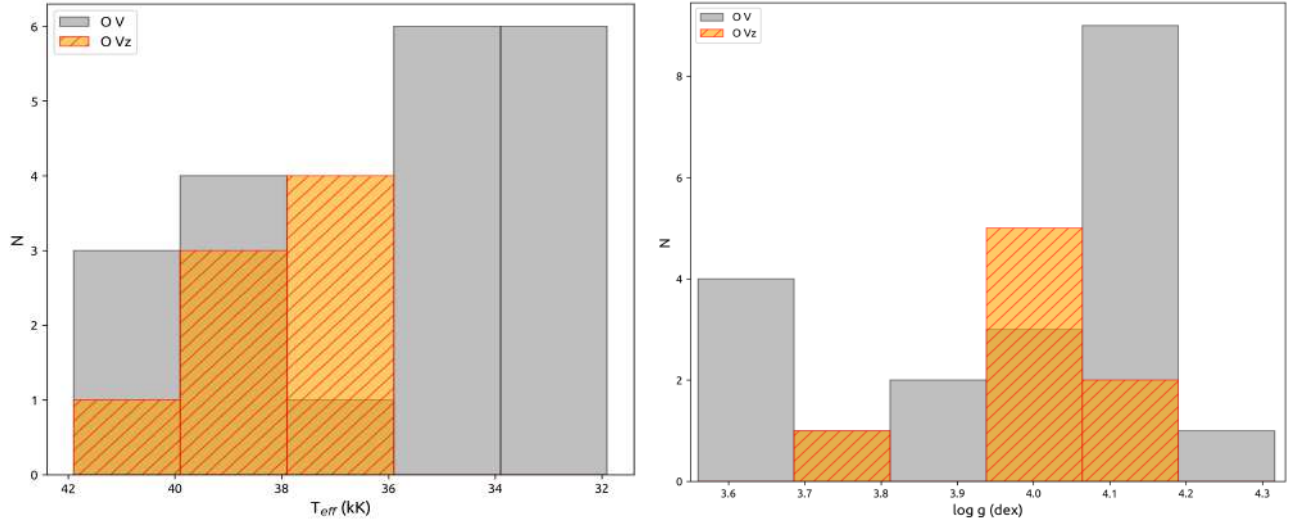


Figure 4.3.2: Distribution of effective temperatures (T_{eff} , left panel) and surface gravities ($\log g$, right panel) for O V and O Vz stars in the sample.

at intermediate and high temperatures, displaying a maximum around ~ 37 kK. In contrast, O V stars exhibit a prominent accumulation around ~ 34000 K and cover a broader temperature range, within which a partial overlap between both populations occurs.

Regarding surface gravity, O Vz stars are mostly concentrated within a relatively narrow range, between $\log g = 3.7$ and 4.2 dex. In contrast, O V stars exhibit a broader distribution in surface gravity, extending toward both lower and higher $\log g$ values. As a result, a significant overlap exists between the two subclasses, indicating that no systematic differences in surface gravity can be identified between O V and O Vz stars.

Figure 4.3.3 displays the location of the analyzed stars in the $\log g$ versus $\log T_{\text{eff}}$ plane, including the ZAMS (solid green line), evolutionary tracks (solid blue lines), and isochrones (dotted lines) covering ages up to 8 million years, based on the models of [Brott et al. \(2011\)](#). These models were computed for the characteristic metallicity of the SMC, assuming an initial rotational velocity of 180 km s^{-1} ([Dufton et al., 2019](#)).

The arrangement of the stars in this diagram reflects the trends already evident in the effective temperature and surface gravity histograms: O V stars span a broader range in both parameters, whereas O Vz stars are concentrated in narrower intervals that partially overlap with those of the O V population. Moreover, the $\log g$ – $\log T_{\text{eff}}$ diagram allows assessing their relative position with respect to the ZAMS. In this context, O Vz stars do not appear preferentially closer to the ZAMS than O V stars, as both populations are distributed along similar evolutionary tracks and isochrones. This shows that higher gravities do not systematically distinguish the Vz subclass.

4.3.3 Helium abundance

Figure 4.3.4 shows the helium abundance, $Y(\text{He})$, as a function of the effective temperature, T_{eff} , for the sample. No systematic difference in helium abundance is observed between O V and O Vz stars. Both subclasses exhibit a comparable dispersion in $Y(\text{He})$, ranging approximately from 0.08 to 0.14, with significant variability within each spectral type or T_{eff} .

Three stars, NGC 346-17, NGC 346-1034, and NGC 346-54, display helium abundances that deviate notably from theoretical predictions, with $Y(\text{He})$ values of <0.06 , <0.06 , and 0.21 , respectively. These discrepancies may reflect complex physical conditions or indicate limitations in the model assumptions for these particular objects.

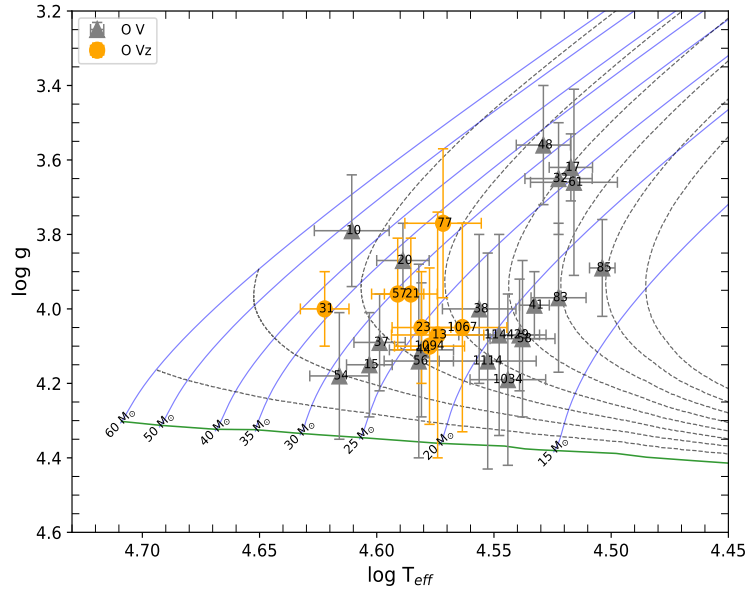


Figure 4.3.3: Results of $\log g$ vs $\log T_{\text{eff}}$ for the O V and O Vz samples in the NGC 346 region. The numbers within the symbols indicate the identifier assigned to each star. The solid green line represents the ZAMS, the solid blue lines are evolutionary tracks, and the dotted lines are isochrones up to 8 Myr, based on the models of [Brott et al. \(2011\)](#) computed for the SMC metallicity and an initial rotational velocity of 180 km s^{-1} ([Dufton et al., 2019](#)).

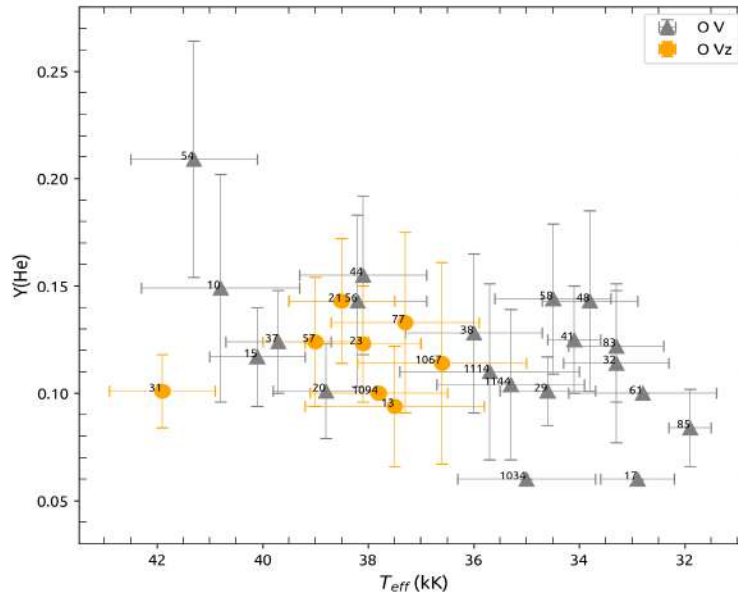


Figure 4.3.4: $Y(\text{He})$ vs T_{eff} of O Vz stars and O V stars analyzed in the NGC 346 region. Numbers next to the symbols indicate the identifier assigned to each star.

Spectral fits performed assuming a fixed $Y(\text{He}) = 0.10$, consistent with most of the sample, yielded unsatisfactory results, underscoring the need for a more detailed investigation.

4.3.4 Wind properties

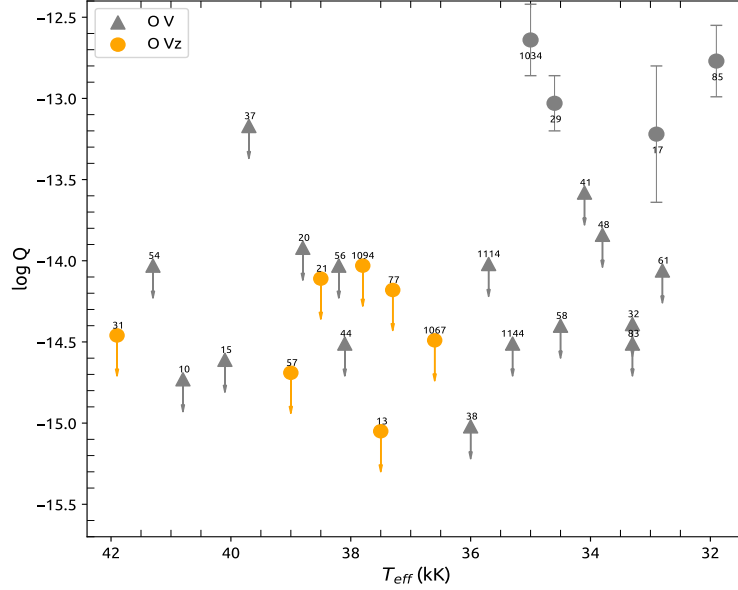


Figure 4.3.5: Wind parameter $\log Q$ vs T_{eff} for O V and O Vz stars analyzed in the NGC 346 region. Numbers above the symbols indicate the identifier assigned to each star. Downward arrows indicate upper limits for $\log Q$.

To investigate the wind properties of the analyzed sample, Figure 4.3.5 shows the derived $\log Q$ values as a function of effective temperature. The downward arrows indicate upper limits for $\log Q$, highlighting the degeneracies at lower values and the impossibility of precise determinations in such cases.

O V and O Vz stars show similar $\log Q$ distributions, with no clear separation between the two groups. The most negative $\log Q$ values, which correspond to the weakest stellar winds, show no direct association with either class. This suggests that the observed dispersion likely reflects the intrinsic variability of wind properties throughout the sample rather than systematic differences between O V and O Vz stars. As the effective temperature (which depends on gravity) of a star increases above a certain threshold, around $T_{\text{eff}} \sim 36$ kK, O Vz stars begin to display their distinctive feature at a specific $\log Q$ value, consistent with the results of Arias et al. (2016).

4.3.5 The Hertzsprung–Russell diagram

In Figure 4.3.6, we present the HR diagram, where the ZAMS (solid green line), evolutionary tracks (solid gray lines), and isochrones (dotted lines, up to 7 Myr) are plotted, based on the models of Brott et al. (2011). These models were computed for the characteristic metallicity of the SMC and an initial rotational velocity of 180 km s^{-1} (Dufton et al., 2019). Luminosities were calculated following the methodology of Hunter et al. (2007), adopting the reddening law of Bouchet et al. (1985) and assuming a constant reddening of $E(B - V) = 0.09$ (Massey et al., 1995). Bolometric corrections from Vacca et al. (1996) for temperatures above 28000 K and from Balona (1994) for lower temperatures were applied, and a distance modulus of 18.91 dex was used (Hilditch et al., 2005).

We note the apparent absence of very young stars (age $\lesssim 1$ Myr) with masses above $30 M_{\odot}$, which results in a sparsely populated region in the HR diagram between the ZAMS and the 1 Myr isochrone, in the effective temperature range above 40 kK. This outcome agrees with the recent analysis by Rickard et al. (2022), who also reported a deficiency of O-type stars near the ZAMS at the top of the HR diagram, based on a sample of 18 O V

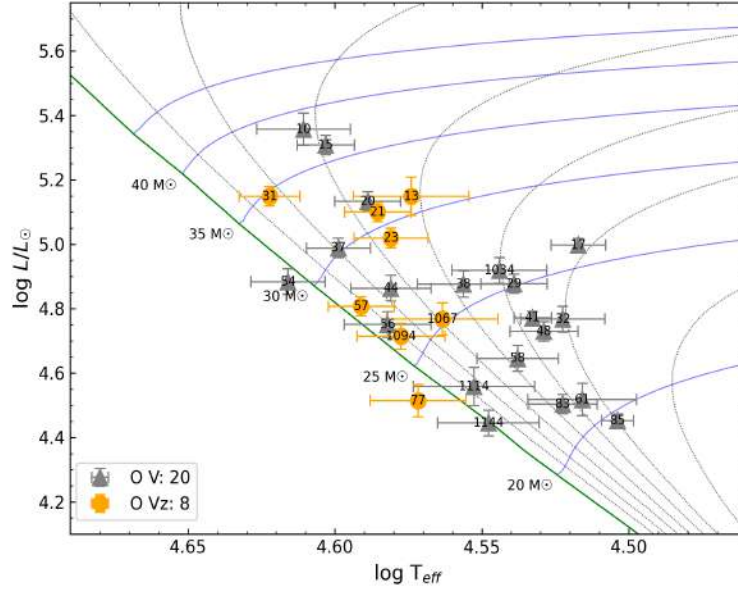


Figure 4.3.6: Hertzsprung–Russell diagram for O Vz and O V stars analyzed in the NGC 346 region. Numbers inside the symbols indicate the identifier assigned to each star. The solid green line represents the ZAMS, the solid blue lines are evolutionary tracks, and the dotted lines are isochrones up to 7 Myr, based on the models of [Brott et al. \(2011\)](#) computed for the SMC metallicity and an initial rotational velocity of 180 km s^{-1} ([Dufton et al., 2019](#)).

stars and 3 of classes II–III. On the other hand, no systematic age differences are apparent between O Vz and O V stars classified, once again suggesting that the Vz classification is not necessarily linked to youth.

4.4 Comparison with previous results in the literature

In the context of studying massive stars in low-metallicity environments, several works have significantly contributed to characterizing the physical and atmospheric properties of stars in the NGC 346 region. Among these, the studies by [Mokiem et al. \(2006\)](#); [Dufton et al. \(2019\)](#); [Rickard et al. \(2022\)](#) and [Rickard et al. \(2024\)](#) stand out.

[Mokiem et al. \(2006\)](#) conducted a spectroscopic analysis of 31 early O- and B-type stars in the SMC, 21 of which belong to NGC 346, using the FASTWIND code in combination with an automated fitting procedure based on a genetic algorithm. On the other hand, [Dufton et al. \(2019\)](#) analyzed a larger sample of 247 stars in NGC 346, including approximately 47 O-type stars, based on observations from the VLT-FLAMES survey. Their analysis employed TLUSTY atmospheric models, the Fourier transform technique to measure $v \sin i$, and the BONNSAI tool to estimate masses and ages from consistent evolutionary models

[Rickard et al. \(2022\)](#) focused on the analysis of stellar winds of an almost complete sample of O-type stars in the core of NGC 346. Using ultraviolet spectra obtained with the Hubble Space Telescope (STIS), along with optical and photometric data, they analyzed 19 O-type stars using the PoWR code. Finally, [Rickard et al. \(2024\)](#) addressed the determination of physical parameters (T_{eff} , $\log g$, $v \sin i$) of 34 OB stars in the cluster core by applying a Bayesian technique over a grid of synthetic atmospheric models. These studies provide a useful tool for evaluating our results.

Figure 4.4.1 compares the physical parameters derived in this study for O-type stars in NGC 346 with the ranges of values reported for O V stars in previous works ([Mokiem et al., 2006](#); [Dufton et al., 2019](#); [Rickard et al., 2022](#),

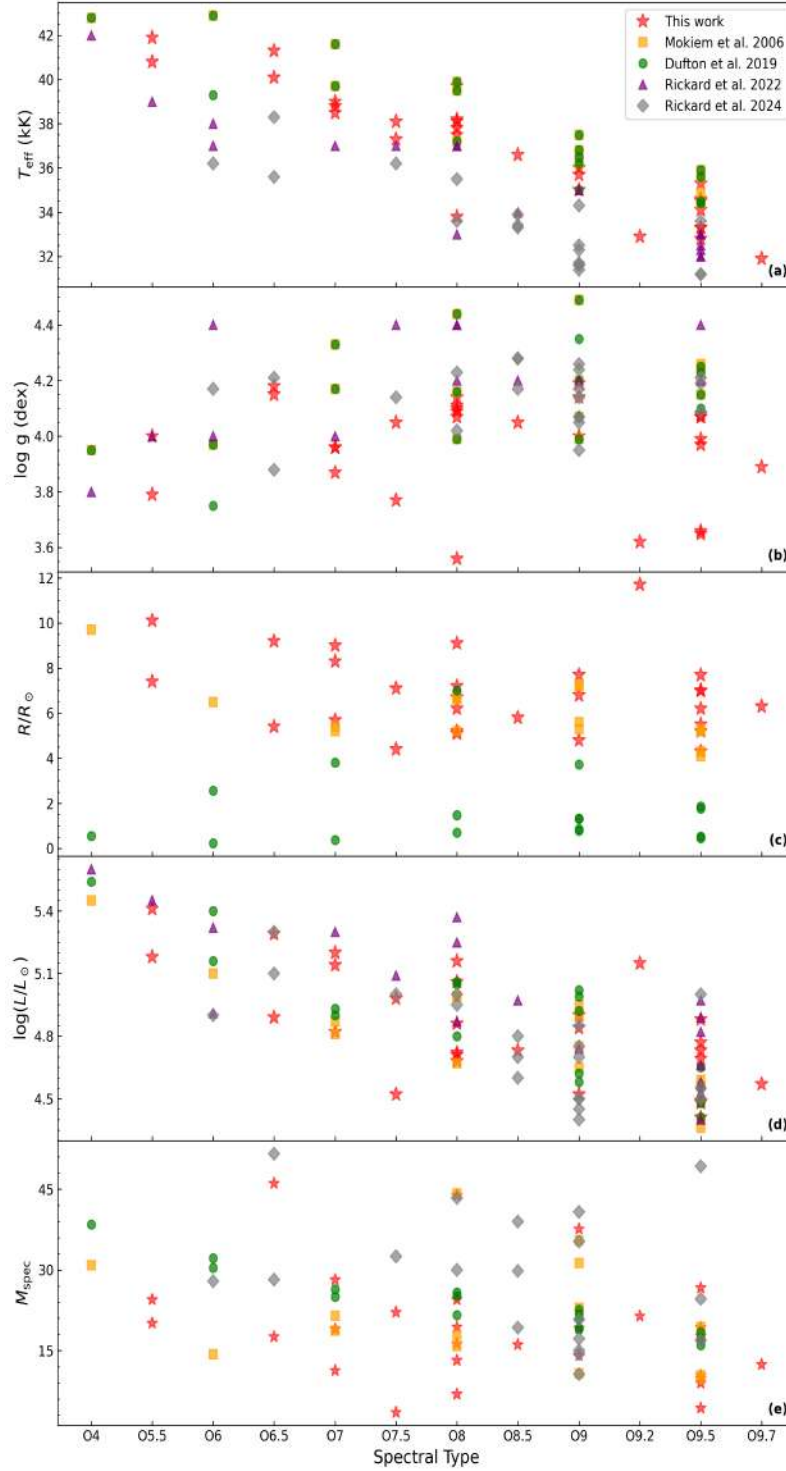


Figure 4.4.1: Comparisons of the stellar parameters derived in this work with those reported by Mokiem et al. (2006, orange squares), Dufton et al. (2019, green circles), Rickard et al. (2022, purple triangles), and Rickard et al. (2024, gray diamonds). From top to bottom, the panels show: (a) effective temperature, (b) surface gravity, (c) stellar radius, (d) luminosity, and (e) spectroscopic mass.

2024). In particular, we examine the behavior of effective temperature, surface gravity, stellar radius, luminosity, and spectroscopic mass as a function of spectral type. The comparison is made in a general sense, without matching individual stars by coordinates, focusing instead on the typical values and trends reported for main-sequence O-type stars in the NGC 346. Overall, the physical parameters derived for our sample are consistent with the expected behavior for O-type dwarfs, with effective temperature decreasing toward later subtypes and surface gravities falling within the typical ranges for low-metallicity environments.

The stellar radii are likewise consistent with previous studies, predominantly lying between 7 and 10 $R_{\odot}$, while the luminosities corresponding to intermediate subtypes remain within the reported uncertainties, without showing systematic differences between the O V and O Vz populations. Finally, a few anomalous cases of spectroscopic masses are identified, with values below 10 $M_{\odot}$ (NGC 346–61, SpT = O9.5 V; NGC 346–77, SpT = O7.5 Vz) and another above 45 $M_{\odot}$ (NGC 346–15, SpT = O6.5 V), a behavior that has also been previously documented by Rickard et al. (2024).

4.5 Mass discrepancy

Mass is the most fundamental parameter of a star, playing a crucial role across virtually all fields of astrophysics. However, obtaining reliable mass estimates for massive O-type stars has proven particularly challenging. Since the early work of Herrero et al. (1992), it has been observed that evolutionary masses (M_{evol}) tend to be higher than spectroscopic masses (M_{spec}) in O-type stars. Subsequent studies have confirmed this trend, although with variations depending on the sample and the model considered. For example, Sabín-Sanjulián et al. (2017) and Ramírez-Agudelo et al. (2017) did not find significant systematic discrepancies in O-type dwarfs in the LMC or O-type supergiants in 30 Dor, although some individual objects showed deviations.

Markova et al. (2018) demonstrated that for low-luminosity Galactic stars ($\log L/L_{\odot} < 5.3$) and $M_{\text{init}} \lesssim 30 M_{\odot}$, the spectroscopic masses are systematically between 24% and 40% lower than the evolutionary ones, especially when considering the sHR. For the rest of the sample, the agreement is reasonable. Additional studies in the LMC, the MW, and the SMC have also reported discrepancies that depend on rotation, metallicity, and atmospheric models (Heap et al., 2006; Mokiem et al., 2007; Hohle et al., 2010). This phenomenon has also been observed in B-type stars (Searle et al., 2008) and in OB objects in the SMC (Bouret et al., 2021; Bernini-Peron et al., 2024). Proposed causes include errors in distance measurements, insufficient treatment of stellar mass loss, omission of turbulent pressure in atmospheric models, and simplifications in evolutionary models, such as neglecting rotation, convective overshooting, or binary interactions (González-Torà et al., 2025).

4.5.1 Determination of evolutionary masses

To estimate evolutionary masses, we used a grid of evolutionary tracks computed for the SMC metallicity with an initial rotational velocity of $v_{\text{ini}} = 180 \text{ km s}^{-1}$, as provided by Brott et al. (2011). The procedure was implemented via a Python code that performs linear interpolation on the $\log(L/L_{\odot})$ vs. $\log T_{\text{eff}}$ diagram, using the individual values of effective temperature and stellar luminosity obtained from observed visual magnitudes, bolometric corrections, distance to NGC 346, and atmospheric parameters derived from the spectroscopic analysis with IACOB-GBAT (such as T_{eff} and $\log g$).

Once each star was located on the evolutionary diagram, the code identified the closest evolutionary tracks and interpolated between them to derive the corresponding evolutionary mass. In cases where stars lay outside the domain covered by the evolutionary tracks (i.e., outside the temperature and luminosity range defined by the models), direct interpolation was not feasible. To solve this, a nearest-neighbor search was implemented: the Euclidean distance between the star’s position and all points in the evolutionary grid was calculated, and the evolutionary

mass of the closest point was adopted. This procedure enabled masses to be derived even for stars slightly outside the modeled range, thereby avoiding the loss of information when comparing M_{spec} and M_{evol} . The results are presented in Table 4.5.1.

Star	SpT	LC	M_{spec}	M_{evol}
NGC 346-10	O8	V	25 ± 8	38 ± 4
NGC 346-13	O8	Vz	44 ± 26	32 ± 6
NGC 346-15	O6.5	V	46 ± 13	37 ± 3
NGC 346-17	O9.2	V	21 ± 4	26 ± 1
NGC 346-20	O7	V	19 ± 4	32 ± 1
NGC 346-21	O7	Vz	28 ± 9	31 ± 2
NGC 346-23	O7.5	Vz	22 ± 7	30 ± 2
NGC 346-29	O9.5	V	27 ± 9	25 ± 2
NGC 346-31	O5.5	Vz	20 ± 4	35 ± 1
NGC 346-32	O9.5	V	9 ± 2	24 ± 1
NGC 346-37	O8	V	25 ± 7	30 ± 1
NGC 346-38	O9	V	19 ± 7	26 ± 2
NGC 346-41	O9.5	V	18 ± 3	24 ± 1
NGC 346-44	O8	Vn	19 ± 8	28 ± 2
NGC 346-48	O8	V	7 ± 2	24 ± 1
NGC 346-54	O6.5	V	18 ± 6	30 ± 3
NGC 346-56	O8	V	16 ± 8	27 ± 3
NGC 346-57	O7	Vz	11 ± 4	28 ± 2
NGC 346-58	O9.5	V	20 ± 8	24 ± 2
NGC 346-61	O9.5	V	<4	21 ± 2
NGC 346-77	O7.5	Vz	<4	20 ± 3
NGC 346-83	O9.5	V	10 ± 4	21 ± 1
NGC 346-85	O9.7	V	12 ± 3	20 ± 1
NGC 346-1034	O9.5	V	38 ± 17	26 ± 2
NGC 346-1067	O8.5	Vz	16 ± 8	25 ± 3
NGC 346-1094	O8	Vz	13 ± 5	26 ± 3
NGC 346-1114	O9	V	14 ± 8	23 ± 3
NGC 346-1144	O9.5	V	10 ± 4	22 ± 2

Table 4.5.1: Comparison of spectroscopic and evolutionary masses for the sample of O-type dwarf stars in the NGC 346 region. Columns: (a) identifier, (b) spectral type, (c) luminosity class, (d) M_{spec} , (e) M_{evol} .

4.5.2 M_{spec} vs. M_{evol}

In order to assess the consistency between evolutionary and spectroscopic mass estimates, Fig. 4.5.1 compares both quantities for all the stars in our sample, without distinguishing between O V and O Vz objects. Most evolutionary masses are concentrated in the range $20\text{--}28 M_{\odot}$, with a few stars at higher masses above $30 M_{\odot}$. Spectroscopic masses are distributed between 8 and $30 M_{\odot}$. The general trend is that $M_{\text{evol}} > M_{\text{spec}}$ in most cases, especially for stars with spectroscopic masses below $23 M_{\odot}$. This result is consistent with the mass discrepancy reported in previous studies (Repolust et al., 2004; Massey et al., 2005), and could be related to incompleteness or simplifications in evolutionary models (e.g., omission of rotation or binarity) or to systematic uncertainties in estimating $\log g$, which directly affect the calculation of M_{spec} .

4.5.3 Mass variations with T_{eff} and $\log g$

Figure 4.5.2 shows how the ratio $M_{\text{spec}}/M_{\text{evol}}$ varies as a function of effective temperature and surface gravity.

For NGC 346, the ratio between the spectroscopic and evolutionary masses ($M_{\text{spec}}/M_{\text{evol}}$) shows no clear dependence on effective temperature. The data points are widely scattered along the $\log T_{\text{eff}}$ axis, and the Pearson correlation coefficient ($r = 0.198$, $p = 0.332$) confirms that there is no statistically significant correlation. Consequently, only approximately 4% of the observed variability in the mass ratio can be attributed to differences in effective temperature ($R^2 = 0.039$).

In contrast, the relation between $M_{\text{spec}}/M_{\text{evol}}$ and surface gravity exhibits a more noticeable pattern. Stars with lower surface gravities tend to show larger mass discrepancies, which gradually decrease as $\log g$ increases. This trend is supported by

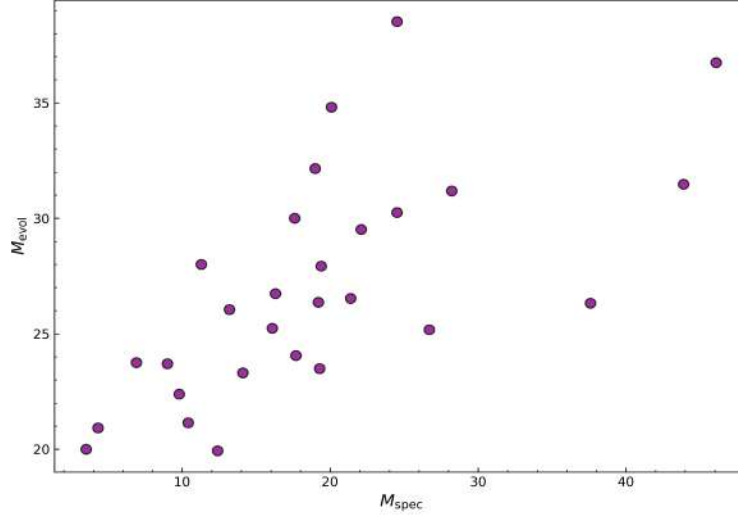


Figure 4.5.1: Comparison of spectroscopic (M_{spec}) and evolutionary (M_{evol}) masses for the complete stellar sample analyzed in this region.

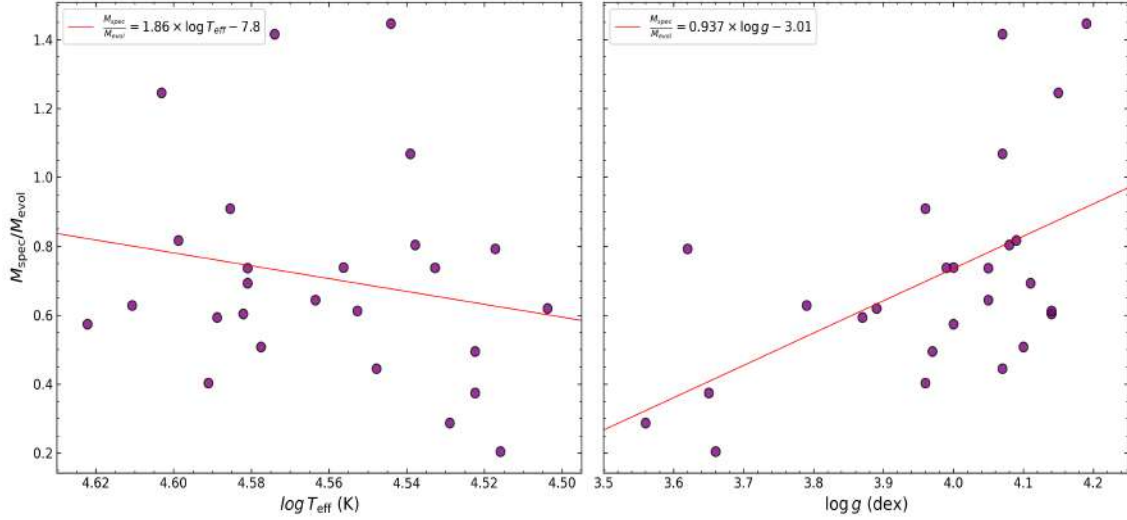


Figure 4.5.2: Spectroscopic-to-evolutionary mass ratio ($M_{\text{spec}}/M_{\text{evol}}$) as a function of effective temperature (left panel) and surface gravity (right panel) for the complete stellar sample analyzed in this region. A linear regression is shown in both panels.

the Pearson correlation ($r = 0.536$, $p = 0.005$) and the coefficient of determination ($R^2 = 0.288$), indicating that approximately 29% of the variability in the mass ratio can be explained by surface gravity.

4.6 Concluding remarks

In NGC 346, O Vz stars account for approximately 29% of the sample, while O V stars constitute 71%, dominated by late spectral types, peaking at O9.5. O Vz stars are concentrated in intermediate spectral types, between O7 and O8.5.

The analysis of projected rotational velocities ($v \sin i$) indicates that O V stars span a wide range, with a concentration below 100 km s^{-1} and a fraction of fast rotators ($> 200 \text{ km s}^{-1}$), whereas most O Vz stars are slow rotators ($< 100 \text{ km s}^{-1}$).

A Kolmogorov–Smirnov test suggests no statistically significant differences between the $v \sin i$ distributions of the two sub-populations.

Concerning the surface helium abundance, $Y(\text{He})$, no systematic differences are observed between the O V and O Vz subclasses. Both exhibit a comparable dispersion, with values approximately ranging from 0.08 to 0.14, and significant variability within each spectral type. Only three stars —NGC 346-17, NGC 346-1034, and NGC 346-54— show atypical abundances, which is attributed to limitations in the models employed for these objects.

In the $\log g$ – $\log T_{\text{eff}}$ plane, O Vz stars occupy intermediate to high temperatures (~ 37 kK), while O V stars span a broader range and partially overlap with the O Vz population. O Vz stars show $\log g \approx 3.7$ – 4.2 , coinciding with some O V stars, although the latter extend to lower values. There is no evidence that O Vz stars are systematically closer to the ZAMS than O V stars. Wind properties, evaluated through $\log Q$, show similar distributions for both classes, with O Vz stars displaying their distinctive feature at $T_{\text{eff}} \gtrsim 36$ kK.

The Hertzsprung–Russell diagram reveals a scarcity of very young stars ($\lesssim 1$ Myr) with masses above $30 M_{\odot}$, leaving a sparsely populated region between the ZAMS and the 1 Myr isochrone for $T_{\text{eff}} > 40$ kK, consistent with previous studies.

The ratio $M_{\text{spec}}/M_{\text{evol}}$ shows no clear dependence on effective temperature, but a clearer trend with surface gravity, with larger mass discrepancies at lower $\log g$ that decrease as $\log g$ increases.

Chapter 5

Comparative analysis of O V stars in 30 Doradus

This section presents a comparative analysis between the spectral classifications obtained in this work and those published by [Sabín-Sanjulián et al. \(2014\)](#). While the latter identified Vz stars based on Walborn’s classical criterion, relying on the depth of the He II $\lambda 4686$ absorption line, our study adopts a more recent and quantitative approach. Specifically, we apply the methodology proposed by [Arias et al. \(2016\)](#), which is based on the measurement of the equivalent widths (EWs) of selected He I and He II lines.

This methodological difference allows us to explore how the identification of O V and O Vz stars varies depending on the criterion used, and to evaluate whether the use of EWs leads to a more precise and homogeneous classification of O Vz objects. Accordingly, this section analyzes the identification and properties of O Vz stars in 30 Doradus in comparison with the results obtained for NGC 346.

This study does not include a new determination of the physical parameters of the 30 Doradus stars. Instead, it adopts the results from the detailed spectroscopic analysis by [Sabín-Sanjulián et al. \(2014\)](#), who used the IACOB-GBAT and FASTWIND codes, consistent with the methodology employed here. The publicly available data from that study include uncertainties for only some of the parameters. For further details on the derived stellar parameters and individual spectral fits, the reader is referred to Appendix A (Tables A.1 and A.2) and Appendix B (Figures B.1–B.3) of that study.

5.1 Spectral reclassification of Vz stars

The application of the updated classification criterion resulted in a slightly different distribution of O V and O Vz stars compared to that presented by [Sabín-Sanjulián et al. \(2014\)](#). In particular, our results show about a 12% decrease in the number of stars classified as O Vz, with a total of 28 objects identified under this category (compared to the 38 reported by [Sabín-Sanjulián et al. \(2014\)](#)), and 56 classified as O V (compared to 46 in that study). Thus, O Vz stars represent 33% of the total sample. As shown in Figure 5.1.1, displaying the distribution of stars as a function of spectral type, our results indicate that O Vz stars are primarily concentrated in intermediate spectral types (O6–O8.5), whereas O V stars span a broader spectral range.

Figure 5.1.2 compares the spatial distribution of O Vz and O V stars in 30 Doradus. The left panel shows the classification by [Sabín-Sanjulián et al. \(2014\)](#), while the right panel presents the results obtained in this work for the same stellar sample. Although the total number of objects classified as O Vz decreases by about 12% when applying the new criterion, our results are qualitatively consistent with those of [Sabín-Sanjulián et al. \(2014\)](#). In both cases, O Vz stars appear as a smaller fraction of the total sample, tending to be located in regions of recent star formation (i.e., the ionizing clusters NGC 2060 and 2070 [Walborn et al., 2014](#)). The central zone is dominated by O V stars, some O Vz stars are also identified, even in more peripheral areas.

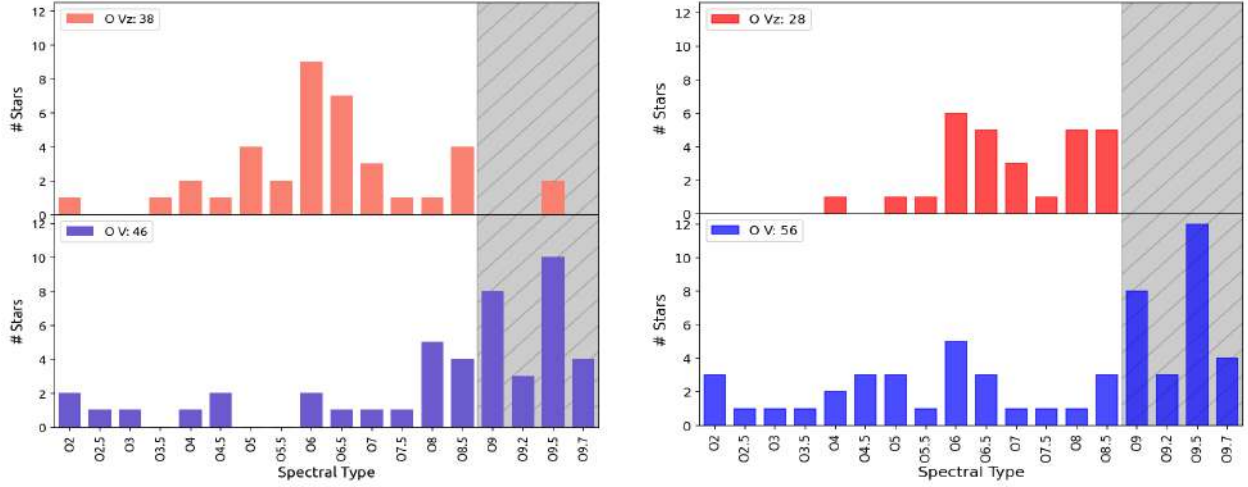


Figure 5.1.1: Spectral distribution of O Vz and O V stars analyzed in the 30 Doradus region by Sabín-Sanjulián et al. (2014) (left panel) and this study (right panel). The gray dashed area represents the region defined by Arias et al. (2016), where the Vz spectral feature is absent in stars with spectral type later than O8.5.

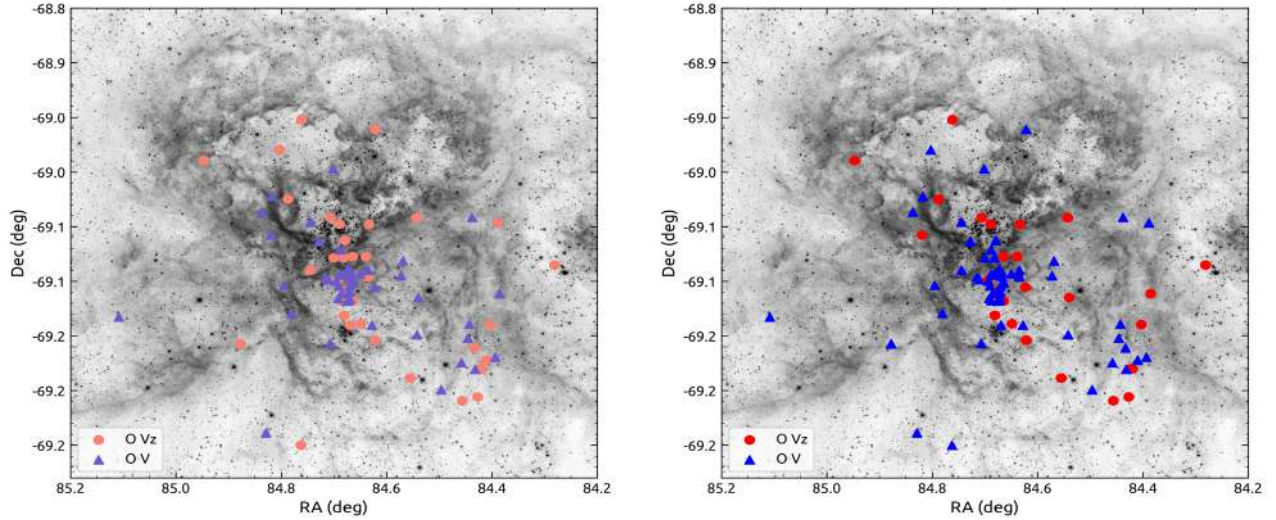


Figure 5.1.2: Spatial distribution of O Vz (red circles) and O V (blue triangles) stars analyzed in the 30 Doradus region by Sabín-Sanjulián et al. (2014) (left panel) and this work (right panel).

5.1.1 Comparison of the Hertzsprung-Russell diagrams

To compare our results with those obtained by Sabín-Sanjulián et al. (2014), we reconstructed the HR diagram presented in their study, applying our new spectral classification of Vz objects. Figure 5.1.3 shows two versions of the HR diagram for 30 Doradus: the left panel represents the morphological classifications of Sabín-Sanjulián et al. (2014), while the right panel includes the reconstruction performed in this work using the criteria established by Arias et al. (2016). Both diagrams incorporate the ZAMS as a continuous green line, along with isochrones calculated for ages up to 6 million years, based on the models of Brott et al. (2011) adjusted to the metallicity of the LMC and an initial rotational velocity of 171 km s^{-1} (Sabín-Sanjulián et al., 2014).

In their analysis, Sabín-Sanjulián et al. (2014) identified three well-defined temperature zones:

- *Zone 1* ($T_{\text{eff}} \leq 35000 \text{ K}$): only O V stars are found.

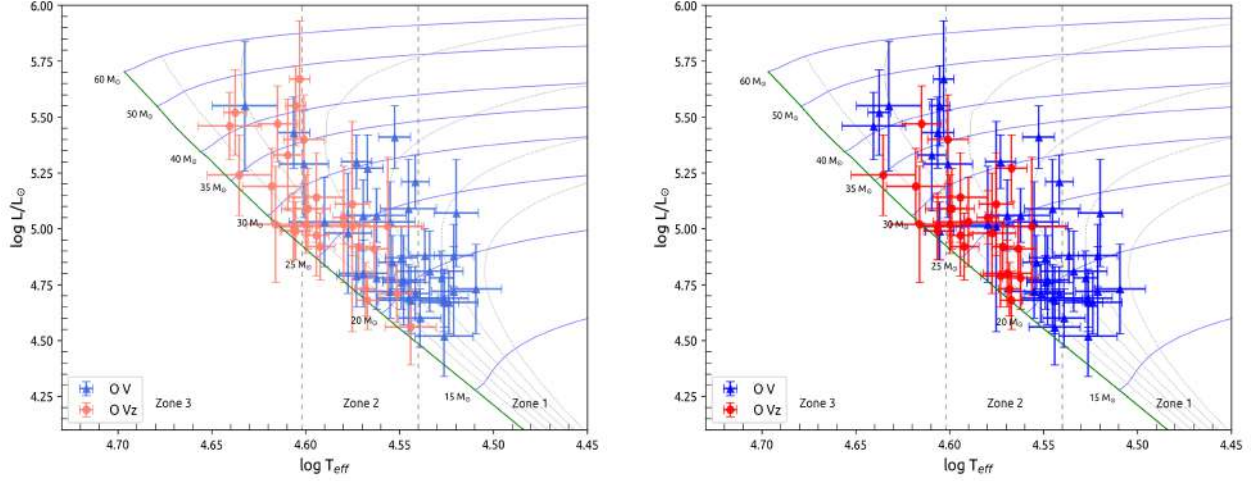


Figure 5.1.3: Hertzsprung-Russell diagram for the O Vz and O V samples in 30 Doradus, analyzed by Sabín-Sanjulián et al. (2014) (left panel) and in this study (right panel). The solid green line represents the ZAMS, the solid blue lines are evolutionary tracks, and the dotted lines are isochrones up to 6 Myr, based on the models of Brott et al. (2011) computed for the LMC metallicity and an initial rotational velocity of 171 km s^{-1} (Sabín-Sanjulián et al., 2014). Zone 1: $T_{\text{eff}} \leq 35000 \text{ K}$. Zone 2: $35000 \text{ K} \leq T_{\text{eff}} \leq 40000 \text{ K}$. Zone 3: $T_{\text{eff}} \geq 40000 \text{ K}$.

- Zone 2 ($35000 \leq T_{\text{eff}} \leq 40000 \text{ K}$): a comparable number of O V and O Vz stars are observed.
- Zone 3 ($T_{\text{eff}} \geq 40000 \text{ K}$): O Vz stars predominate, with very few O V present.

Our results are consistent with expectations for Zone 1, as only O V stars are detected in the lower temperature range. However, Zones 2 and 3 show distributions that differ from those reported by Sabín-Sanjulián et al. (2014). In Zone 2, O Vz stars dominate over O V stars, in contrast to the expected comparable numbers of both classes. In Zone 3, O V stars constitute the majority, accompanied by a few examples of the O Vz subclass.

With our reclassification, a global behavior similar to that found by Sabín-Sanjulián et al. (2014) is observed: O Vz stars tend to be located at the lower part of the diagram (with respect to the ZAMS), while O V stars concentrate in the upper part. In particular, the absence of O Vz objects with temperatures below 35000 K (Zone 1), associated with spectral types later than O8.5, is consistent with predictions from atmospheric models indicating that the He II $\lambda 4686$ line cannot surpass the absorption strength of He I $\lambda 4471$ at those temperatures, even in the presence of weak winds (Arias et al., 2016). This explains why, in this regime, only O V class stars are observed, as both in Sabín-Sanjulián et al. (2014) and in our results.

A more detailed examination of the age distribution, however, reveals a generally similar behavior. In our study, O Vz stars are not exclusively concentrated in regions associated with very young ages; instead, they are also identified in more evolved zones of the diagram, with ages between 2 and 4 Myr. Similarly, O V stars are found near the ZAMS, with ages less than 2 Myr, suggesting some overlap between both spectral classes.

However, it is essential to highlight the notable differences in the number of O Vz stars located in advanced evolutionary stages. While Sabín-Sanjulián et al. (2014) identified 16 O Vz objects older than 2 Myr (see their Table 4), applying our stricter classification criteria reduces that number to only 10 stars. This decrease, equivalent to a 37% reduction, reflects a decline in the incidence of the O Vz phenomenon at older ages.

Regarding the mass distribution, the HR diagram reveals a significant difference between both studies. While Sabín-Sanjulián et al. (2014) found that some O Vz stars reached high masses ($\sim 38\text{--}50 M_{\odot}$), in our analysis the O Vz population spans a narrower range, between 20 and $30 M_{\odot}$.

5.1.2 Comparison of the spectroscopic Hertzsprung-Russell diagrams

Figure 5.1.4 presents a comparison between the sHRD in the 30 Doradus region, as published by Sabín-Sanjulián et al. (2014) (left panel) and those obtained in this work (right panel). Both diagrams include O Vz and O V stars. The evolutionary tracks (solid blue lines) and isochrones (dashed lines) are the same as those shown in Figure 5.1.3.

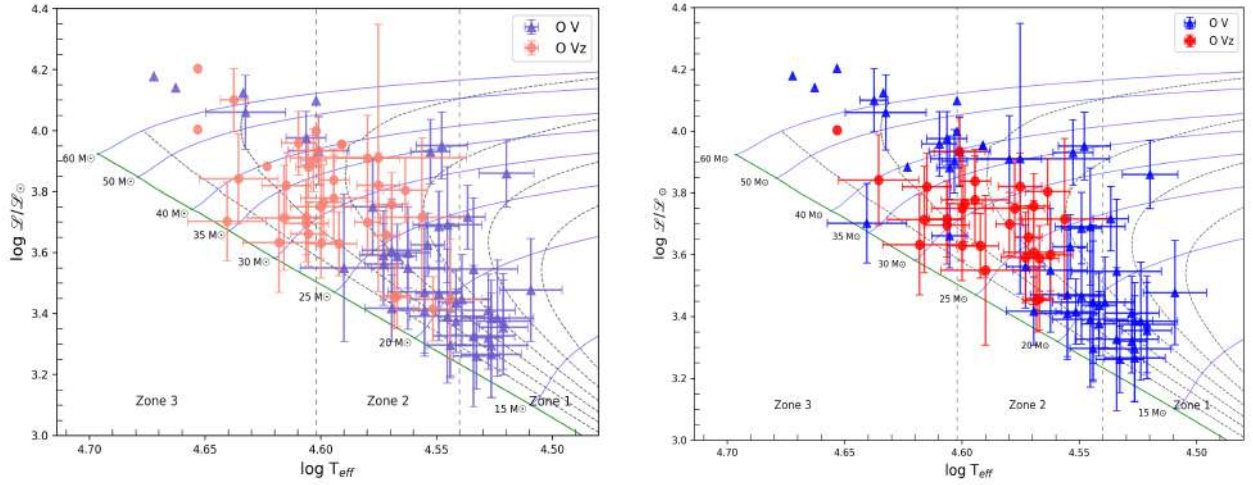


Figure 5.1.4: Spectroscopic Hertzsprung-Russell diagram for the O V and O Vz samples, analyzed by Sabín-Sanjulián et al. (2014) (left panel) and in this study (right panel). The solid green line represents the ZAMS, the solid blue lines are evolutionary tracks, and the dotted lines are isochrones up to 6 Myr, based on the models of Brott et al. (2011) computed for the LMC metallicity and an initial rotational velocity of 171 km s^{-1} (Sabín-Sanjulián et al., 2014). Zone 1: $T_{\text{eff}} \leq 35000 \text{ K}$. Zone 2: $35000 \text{ K} \leq T_{\text{eff}} \leq 40000 \text{ K}$. Zone 3: $T_{\text{eff}} \geq 40000 \text{ K}$.

The spectroscopic diagram provides information based on effective temperature ($\log T_{\text{eff}}$) and spectroscopic luminosity, defined as

$$\log \mathcal{L} \equiv \log \left(\frac{L}{L_{\odot}} \right)_{\text{spec}} = 4 \log T_{\text{eff}} - \log g - 10.61$$

the latter being a quantity directly dependent on effective temperature and the inverse of surface gravity. Both parameters are derived directly from quantitative spectroscopic analysis without the need to know the star's distance (Langer & Kudritzki, 2014).

In both panels, O Vz stars are located, on average, farther from the ZAMS compared to what is observed in the HR diagrams. In fact, most O Vz objects lie above 1 Myr, and consistently cluster within the 1–4 Myr range. In contrast, O V stars span a broader age range, including some cases with ages below 1 Myr. O V stars are distributed over a wider range of effective temperatures and spectroscopic luminosities, with some clustering in the lower right part of the diagram, where luminosities vary between 3.3 and 3.7 dex. Conversely, O Vz stars are concentrated in a more restricted range of effective temperatures, with spectroscopic luminosities between 3.5 and 3.8 dex.

5.1.3 Wind properties

Figure 5.1.5 shows the stellar wind strength, described by the parameter $\log Q$, as a function of the effective temperature (T_{eff}) for O-type stars classified as V and Vz. The left panel corresponds to the results of Sabín-Sanjulián et al. (2014), while the right panel presents those obtained in this work. When analyzing the different temperature zones, as expected, the Vz characteristic does not appear in any star within Zone 1, not even in those with low $\log Q$ values. In Zones 2 and 3, a considerable number of stars classified as O V exhibit wind strengths, or upper limits in $\log Q$, comparable to those observed in some O Vz stars. This suggests that, at least within Zones 2 and 3, there is no consistent correlation between wind strength and the O V/O Vz spectral classification.

Consequently, although wind strength seems to play a role in the appearance of the Vz classification (as might be expected), the results suggest that additional factors are involved, particularly within the temperature range of Zones 2 and 3. As highlighted by Sabín-Sanjulián et al. (2017), ultraviolet observations (1100–1800 Å), which include spectral lines more sensitive to wind variations than H α and He II $\lambda 4686$, are required to better disentangle the O V and O Vz groups and to confirm these findings.

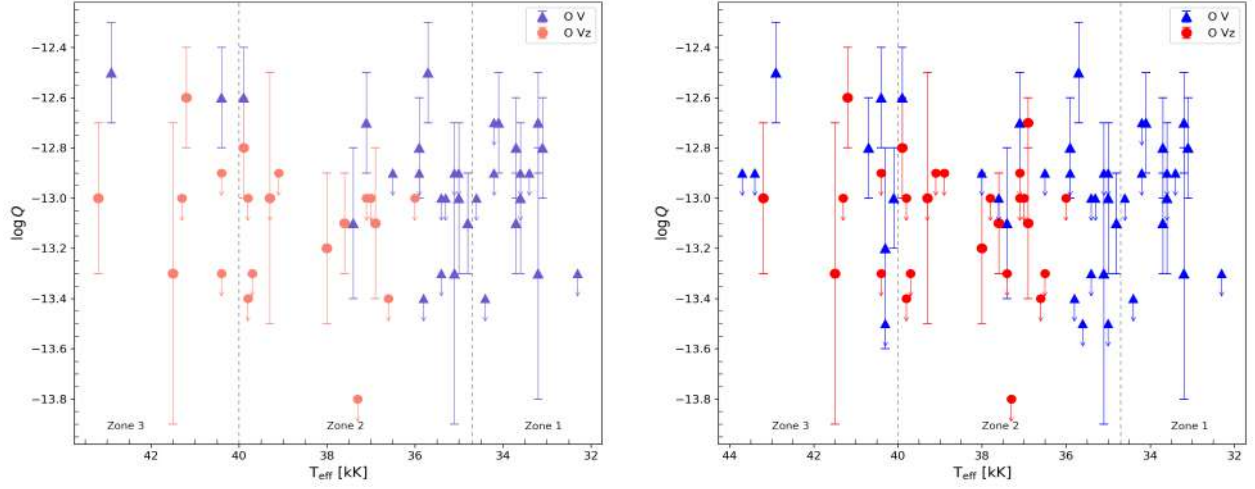


Figure 5.1.5: Wind strength parameter $\log Q$ vs T_{eff} for the O V and O Vz samples, analyzed by Sabín-Sanjulián et al. (2014) (left panel) and in this study (right panel). Downward arrows indicate upper limits for $\log Q$. Zone 1: $T_{\text{eff}} \leq 35000$ K. Zone 2: $35000 \text{ K} \leq T_{\text{eff}} \leq 40000$ K. Zone 3: $T_{\text{eff}} \geq 40000$ K.

5.2 Comparative study of stellar physical parameters in 30 Doradus and NGC 346

5.2.1 Distribution of the projected rotational velocity

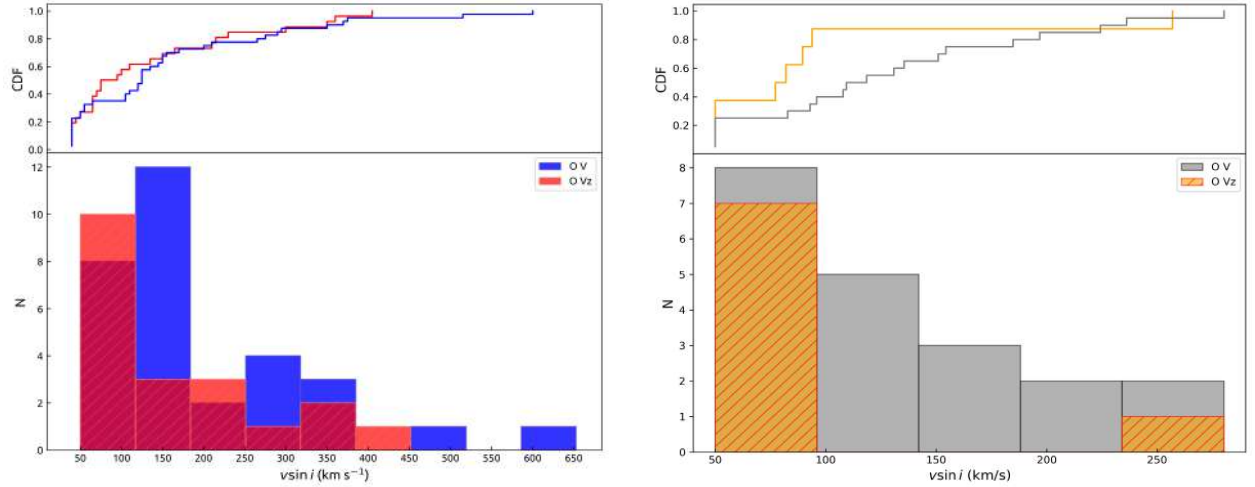


Figure 5.2.1: Distribution of projected rotational velocities ($v \sin i$) for O V and O Vz stars in 30 Doradus (left panel) and NGC 346 (right panel). The two subpopulations are indicated by the colors shown in the legend. The upper part of each panel shows the corresponding cumulative distribution functions (CDFs).

Figure 5.2.1 shows the distribution of projected rotational velocities for O V and O Vz stars in 30 Doradus (left panel) and NGC 346 (right panel). For consistency between the two regions, we adopt a bin width of $\Delta v \simeq 67 \text{ km s}^{-1}$, corresponding to that used for NGC 346. The $v \sin i$ distribution in 30 Doradus suggests the presence of two rotational regimes: a dominant group of slow rotators, with projected velocities of approximately $50\text{--}170 \text{ km s}^{-1}$, and a less populated group of fast rotators with $v \sin i$ in the range $\sim 250\text{--}350 \text{ km s}^{-1}$. Both subpopulations, O V and O Vz, are present in these rotational regimes. The

O V stars span the full velocity range and reach the highest values in the sample ($\approx 500\text{--}600 \text{ km s}^{-1}$). In contrast, the O Vz stars are primarily concentrated in the low-to-intermediate rotation domain, with few objects above 300 km s^{-1} .

Analogously to the analysis performed for NGC 346, a Kolmogorov–Smirnov test was applied to the $v \sin i$ distributions of the O V and O Vz subpopulations in 30 Doradus. The test statistic, $D = 0.18$, and the associated p -value, $p = 0.58$, indicate that no statistically significant differences are observed between the two populations.

5.2.2 Fundamental stellar parameters

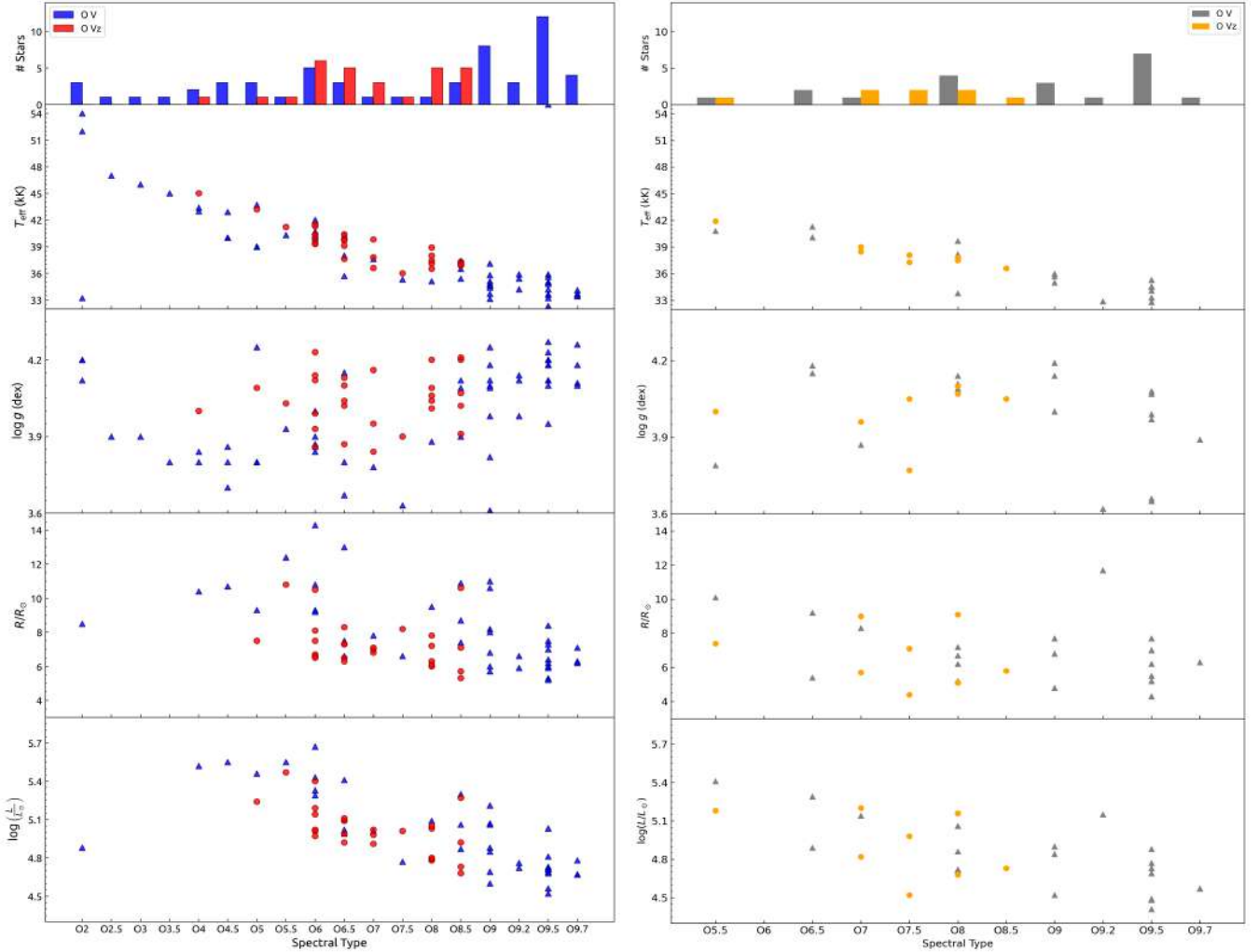


Figure 5.2.2: Comparison of stellar parameters as a function of spectral type for O V and O Vz stars in 30 Doradus (left) and NGC 346 (right). The top panel shows the spectral-type distribution of both populations. The subsequent panels display, from top to bottom, the effective temperature, surface gravity, stellar radius, and luminosity.

Figure 5.2.2 shows a comparison of stellar parameters: effective temperature (T_{eff}), surface gravity ($\log g$), relative radius ($R/R_{\odot}$), and luminosity ($\log(L/L_{\odot})$), as a function of spectral type, derived for O V and O Vz stars in 30 Doradus (left panel) and NGC 346 (right panel).

As expected for main-sequence O stars, the effective temperature decreases progressively toward later spectral subtypes. In this context, O Vz stars tend to occupy the range of intermediate effective temperatures. The surface gravity spans values

of $\log g \sim 3.6\text{--}4.2$ dex, consistent with those reported for dwarf O stars in environments such as the SMC and 30 Doradus (Bouret et al., 2003; Massey et al., 2005; Mokiem et al., 2006; Massey et al., 2009; Sabín-Sanjulián et al., 2014).

Similarly, both stellar radius and luminosity increase toward earlier spectral subtypes, reflecting their direct dependence on T_{eff} and stellar size. No systematic separation is observed between the O V and O Vz subclasses in any of these parameters. Consequently, O Vz stars do not exhibit subluminous characteristics nor do they show systematically smaller radii compared to their O V counterparts.

5.2.3 Helium abundance

The projected rotational velocity ($v \sin i$) is a key parameter in studies of surface helium abundance in massive stars. Observational studies, such as the VLT-FLAMES Survey, reveal a general trend of increased nitrogen and helium enrichment with higher rotation rates (Hunter et al., 2008). However, this relationship is not strictly linear: some stars exhibit high rotational velocities but low enrichment, while others are slow rotators with high enrichment, suggesting the influence of additional processes, such as binary history or specific evolutionary events (Hunter et al., 2008; Brott et al., 2011).

More recently, Martínez-Sebastián et al. (2025, IACOB project XIII) showed that a significant fraction of Galactic O-type stars with moderate rotation velocities ($v \sin i \leq 150 \text{ km s}^{-1}$) exhibit elevated surface helium abundance ($Y_{\text{He}} \geq 0.12$), but unexpectedly low nitrogen abundances, challenging classical stellar evolution models that assume single stars with no binary interaction (Rivero González et al., 2012; Grin et al., 2017). Such a pattern is better explained by mass-transfer processes in binary systems, in which the mass gainer acquires helium-enriched material but shows comparatively lower nitrogen enhancement due to partial mixing following the transfer episode.

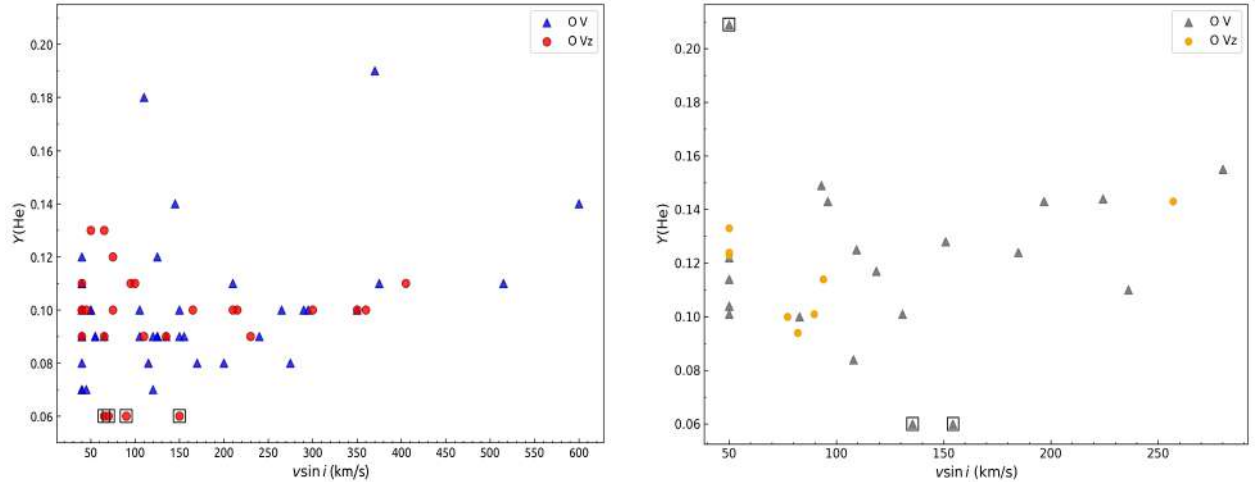


Figure 5.2.3: Distribution of helium abundance $Y(\text{He})$ as a function of projected rotational velocity ($v \sin i$) for O V and O Vz stars in 30 Doradus (left) and NGC 346 (right). The two populations are distinguished by the colors indicated in the legend. Black squares highlight stars with anomalous surface helium abundances.

Within this theoretical and observational framework, Figure 5.2.3 shows the relationship between surface helium abundance ($Y(\text{He})$) and projected rotational velocity ($v \sin i$) for O V and O Vz stars in 30 Doradus (left panel) and NGC 346 (right panel). In 30 Doradus, the helium abundance $Y(\text{He})$ exhibits a large dispersion at low rotational velocities ($< 100 \text{ km s}^{-1}$), spanning both low ($\sim 0.06\text{--}0.08$) and high ($\sim 0.12\text{--}0.13$) values. At higher rotational velocities ($> 220 \text{ km s}^{-1}$), the $Y(\text{He})$ values cluster around ~ 0.10 , without reaching abundances higher than those already observed in the low-rotation regime. Consequently, no monotonic increase of $Y(\text{He})$ with rotation is evident.

To explore possible non-linear behaviors between helium abundance and rotation, a LOWESS (Locally Weighted Estimated Scatterplot Smoothing) smoothing was applied, which allows global trends in the data to be identified without assuming a specific functional relationship. The resulting smoothing is consistent with an approximately constant helium abundance across the entire $v \sin i$ range and does not reveal a systematic increase in the high-rotation regime.

This behavior is reflected in the correlation coefficients: the Pearson coefficient ($r_P \simeq 0.29$, $p \simeq 0.015$) indicates a weak linear correlation, while the Spearman coefficient ($r_S \simeq 0.16$, $p \simeq 0.18$) is not statistically significant, confirming the absence of a monotonic relation between the two variables.

In NGC 346 (SMC), helium enrichment is observed at low rotational velocities, remaining nearly constant across the full $v \sin i$ range. The mean surface helium abundance is 0.1165 ± 0.016 for O Vz stars and 0.1197 ± 0.033 for the O V population, indicating that, despite some dispersion, helium values remain relatively uniform across the subpopulations. This behavior is supported by the correlation analysis, as neither the Pearson nor the Spearman correlation coefficients reveal a significant relation between projected rotational velocity and surface helium abundance ($r_P = 0.12$, $p = 0.55$; $r_S = 0.16$, $p = 0.41$), confirming that helium enrichment is not correlated with rotation in this region.

The black squares highlight stars exhibiting anomalous surface helium abundances compared to the rest of the sample, as discussed in Section 4.3.3. In these cases, quantitative spectroscopic analysis only allowed for the determination of upper limits, because the minimum of the χ^2 distribution was located at the edge of the FASTWIND model grid, whose helium abundance limits are $Y(\text{He}) = [0.04, 0.30]$ (see Table 3.2.1). Previous studies, such as Sabín-Sanjulián et al. (2014), have suggested that these low abundances may result from the presence of undetected companions, whose contribution to the total flux dilutes the helium lines and produces artificially reduced $Y(\text{He})$ values. Alternatively, these estimates may be affected by inherent limitations of the spectra, including low S/N, strong nebular contamination, or particularly weak He I lines.

Finally, when comparing the O V and O Vz subclasses in both regions, no systematic differences are observed in the surface helium abundance: both slow and fast rotators can exhibit helium enrichment or low $Y(\text{He})$ levels, regardless of whether they belong to the O V or O Vz class. This indicates that the Vz subclass is not directly associated with a higher or lower helium abundance as a function of $v \sin i$.

5.2.4 Mass ratio ($M_{\text{spec}}/M_{\text{evol}}$) as a function of evolutionary mass

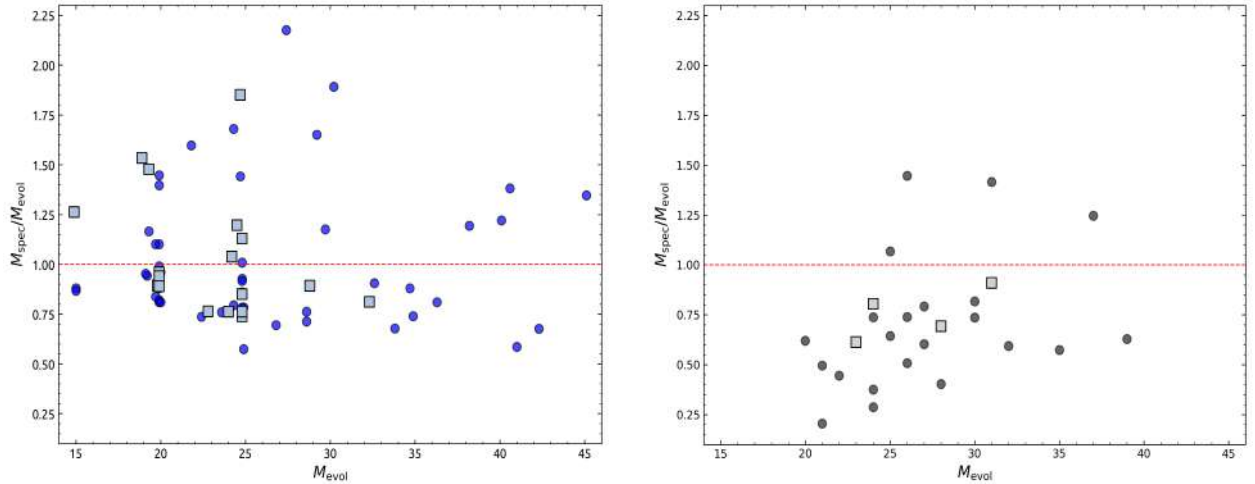


Figure 5.2.4: Comparison between the spectroscopic-to-evolutionary mass ratio ($M_{\text{spec}}/M_{\text{evol}}$) and the evolutionary mass (M_{evol}) for O dwarf population. Rapid rotators ($v \sin i > 200 \text{ km s}^{-1}$) are highlighted with squares. 30 Doradus (left panel) and NGC 346 (right panel).

Figure 5.2.4 shows the relationship between evolutionary mass (M_{evol}) and spectroscopic mass (M_{spec}) for the O V star population in 30 Doradus (left panel) and NGC 346 (right panel). The squares indicate stars with high rotation ($v \sin i > 200 \text{ km s}^{-1}$). The red horizontal line marks the equality line, where $M_{\text{spec}} = M_{\text{evol}}$. In 30 Doradus, approximately 64% of the stars exhibit $M_{\text{spec}} < M_{\text{evol}}$, a phenomenon known as the “mass discrepancy”. High-rotation objects are distributed throughout the sample; some display $M_{\text{spec}}/M_{\text{evol}} < 1$, while others have values close to or exceeding unity, indicating that rotation may contribute to the scatter but is not the sole factor influencing the discrepancy. In general, stars with $M_{\text{evol}} < 30 M_{\odot}$ tend to show M_{spec} values below M_{evol} , albeit with considerable variability, making it challenging to identify a clear trend in the relationship between the two mass estimates. This behavior is consistent with the findings of Sabín-Sanjulián et al. (2017), who reported

localized discrepancies between the two mass determinations without a discernible global pattern in the sample.

In the NGC 346 region, nearly 80% of the sample shows $M_{\text{spec}} < M_{\text{evol}}$, with $M_{\text{spec}}/M_{\text{evol}}$ typically spanning the range 0.25–1. For high-rotation stars, all objects lie below the theoretical equality line, indicating that $M_{\text{spec}} < M_{\text{evol}}$, although the differences are small and fall within the observed scatter in the sample ($\sigma \sim 0.30$). Therefore, these are not considered significant deviations from the general trend. This distribution suggests that rapid rotation does not necessarily cause a systematic mass discrepancy; its impact depends on additional factors.

5.3 Concluding remarks

In 30 Doradus, the application of the quantitative classification criterion reduced the number of O Vz stars by 12 % compared to the classical study of [Sabín-Sanjulián et al. \(2014\)](#), resulting in 28 O Vz versus 56 O V stars. The O Vz stars are primarily concentrated in intermediate spectral types (O5–O7), whereas the O V stars span a broader diversity of subtypes.

The analysis of projected rotational velocities ($v \sin i$) indicates that O V stars exhibit a considerable dispersion of values, with a concentration below 100 km/s and some fast rotators (> 200 km/s), while the majority of O Vz stars are slow rotators (< 100 km/s). A Kolmogorov–Smirnov test reveals no statistically significant differences between the $v \sin i$ distributions of the two subpopulations.

Surface helium abundances ($Y(\text{He})$) show a wide dispersion at low rotational velocities (< 100 km/s), encompassing both low (~ 0.06 – 0.08) and high (~ 0.12 – 0.13) values. At higher velocities (> 220 km/s), the values cluster around ~ 0.10 , without indicating a systematic increase with rotation. No significant differences are observed between the O V and O Vz subclasses, suggesting that the Vz characteristic is not directly associated with higher or lower surface helium abundance.

In the Hertzsprung–Russell diagram (HRD), O Vz stars tend to occupy the lower region relative to the ZAMS, whereas O V stars are concentrated in the upper region. A more detailed inspection shows that some O Vz stars reach ages of 2–4 Myr, while some O V stars remain close to the ZAMS (< 2 Myr). Furthermore, there is a scarcity of very massive stars ($> 30 M_{\odot}$) with ages $\lesssim 1$ Myr, resulting in a sparsely populated area between the ZAMS and the 1 Myr isochrone. In the spectroscopic HR diagram (sHRD), the O V population exhibits greater dispersion in effective temperatures and spectroscopic luminosities, whereas the O Vz stars occupy a narrower range ($\log \mathcal{L} \approx 3.4$ – 3.8 dex).

The analysis of stellar wind properties, evaluated through $\log Q$, indicates that in the intermediate and high-temperature regimes ($T_{\text{eff}} > 35$ kK), there is no clear correlation between wind strength and the O Vz subclass. Overall, the $\log Q$ distributions are similar for O V and O Vz stars, suggesting that the Vz characteristic is not systematically associated with weaker winds.

The comparison between spectroscopic and evolutionary masses shows that most O V stars have $M_{\text{spec}} < M_{\text{evol}}$. High-rotation objects are found across the full sample, and while some reach mass ratios close to or above unity, suggesting that rotation contributes to the observed scatter, it is not the dominant factor. Stars with $M_{\text{evol}} < 30 M_{\odot}$ generally exhibit lower spectroscopic masses, with significant dispersion and no clear overall trend.

Chapter 6

Results for the O V stars in NGC 3603

This chapter presents the results of the quantitative spectral analysis applied to O-type stars belonging to the V and Vz luminosity classes, located in the NGC 3603 star-forming region in the MW. The analysis follows a methodology analogous to that applied in NGC 346, allowing for a homogeneous comparison between stellar populations and the assessment of evolutionary and physical differences associated with variations in metallicity and other environmental properties. In particular, the aim was to compare the behavior of the Vz phenomenon in the Galaxy and the Magellanic Clouds.

The following sections present the results obtained, together with their interpretation in the context of understanding the and nature of stars classified as Vz.

6.1 Spatial and spectral distribution of O V and O Vz stars

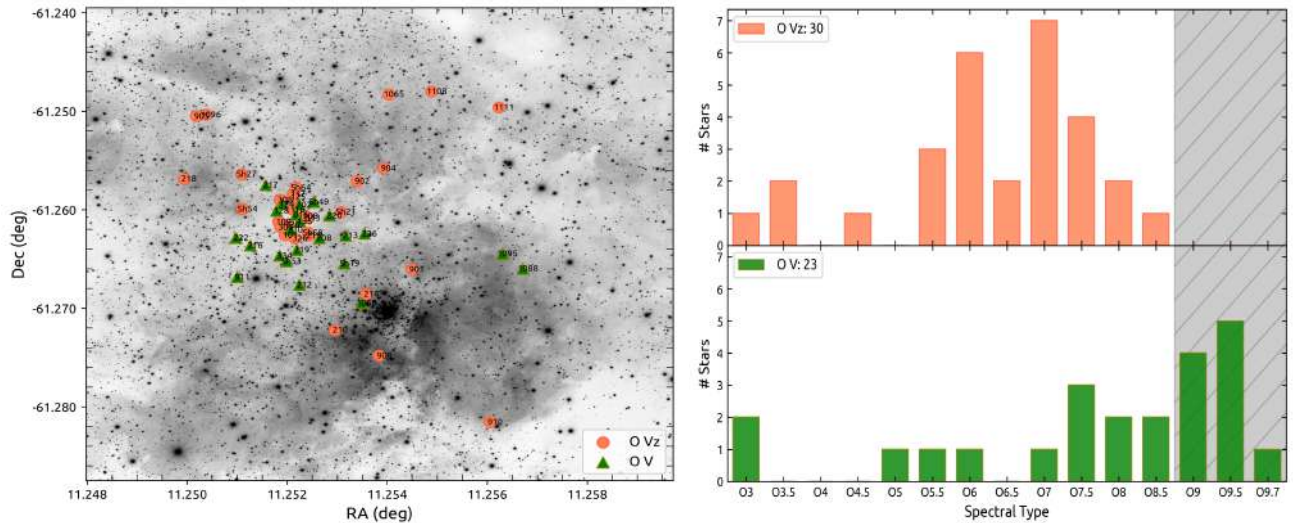


Figure 6.1.1: Left panel: Spatial distribution of O Vz stars and O V stars analyzed in the NGC 3603 region. The numbers within the symbols indicate the identifier assigned to each star. Image Credit: ESO/VLT/FORS. Right panel: Spectral distribution of O Vz and O V stars. The gray dashed area represents the region defined by [Arias et al. \(2016\)](#), where the Vz spectral feature is absent in stars with spectral type later than O8.5.

The left panel of Figure 6.1.1 shows the spatial distribution of O Vz stars (reddish-orange circles) and O V stars (green triangles) analyzed in the NGC 3603 region, overlaid on a background image obtained with the VLT/FORS instrument. Both

subclasses are mainly concentrated toward the northern and eastern parts of the field, with a few Vz objects located in the periphery. Numerically, O Vz stars outnumber O V stars in the sample.

The presence of massive, young stars located away from the cluster core has been documented in various massive star-forming regions. Studies of complexes such as 30 Doradus (Sabbi et al., 2012) and Cygnus OB2 (Wright et al., 2014) show that these populations include stars situated in diffuse substructures surrounding the main cluster. Similarly, analyses from the MYStIX project reveal the existence of young stellar populations distributed in an extended manner around massive clusters (Feigelson et al., 2013). In the particular case of NGC 3603, previous studies have evidenced the presence of massive stars beyond the main core (Harayama et al., 2008; Pang et al., 2013), supporting the possibility of an extended or dispersed formation in its immediate environment.

The right panel of Figure 6.1.1 shows the spectral subtype distribution of O Vz (reddish-orange bars, top panel) and O V (green bars, bottom panel) stars. Out of the 53 stars analyzed in NGC 3603, 30 are classified as O Vz and 23 as O V. A clear difference between the two subclasses is apparent: most O Vz stars are concentrated in the intermediate spectral types (O5.5–O7.5), peaking at O7. In contrast, O V stars are distributed over a broader spectral range, with lower representation at intermediate subtypes and occasional absence among the earliest types.

6.2 Stellar parameters derived for the O dwarf sample

For the quantitative analysis of the optical spectra of our sample of 53 O-type dwarf stars in NGC 3603, the IACOB-GBAT tool was used, following a methodology similar to that previously applied to NGC 346. To optimize computational time, the range of values considered for the effective temperature (T_{eff}) and surface gravity ($\log g$) in the analysis was restricted, using the spectral type and luminosity class calibrations of Martins et al. (2005) as a reference. Specifically, the central values proposed by this observational calibration were adopted, expanding the effective temperature range by ± 3000 K. For the other free fitting parameters, microturbulence (ξ_t), helium abundance (Y_{He}), and wind-strength parameter ($\log Q$), the full available range was used, while keeping the value of β fixed at 1.0, as was done for NGC 346.

The results of the analysis for NGC 3603 are presented in two sets: the stellar and wind parameters, compiled in Table 6.2.1, and the derived absolute V magnitudes, radii, luminosities, and spectroscopic masses, included in Table 6.2.2. $\log g$ values higher than 4.2 dex were marked with an asterisk, as they may indicate the presence of undetected binary systems (Sabián-Sanjulián et al., 2014). This consideration is important for the interpretation of the results, especially when placing the stars in the $\log g - T_{\text{eff}}$ diagram and when computing spectroscopic and evolutionary masses (see Section 6.6).

Finally, Appendix B include a Figure B.0.4 corresponding to the spectral fits performed for this region, following the same structure and criteria applied to NGC 346.

Table 6.2.1: Stellar and wind parameters obtained from the quantitative analysis of our NGC 3603 sample, including: (1) identifier; (2–3) updated spectral classification; (4) adopted $v \sin i$; (5–9) derived effective temperature, surface gravity, $\log Q$ parameter, helium abundance, and macroturbulence, with their respective formal uncertainties.

Star	SpT	LC	$v \sin i$ [km s ⁻¹]	T_{eff} [kK]	$\log g$ [dex]	$\log Q$ [dex]	Y(He) [dex]	ξ_r [km s ⁻¹]
NGC 3603-16	O3	V((f))	223	40.7 ± 2.5	3.40 ± 0.13	<-14.00	0.25 ± 0.12	1–20
NGC 3603-101	O6.5	Vz	173.1	36.5 ± 1.4	3.70 ± 0.19	<-13.00	<0.06	1.0–20.0
NGC 3603-102	O8.5	V	168.4	34.2 ± 1.4	3.90 ± 0.33	<-14.00	0.13 ± 0.05	<9.0
NGC 3603-108	O4.5	Vz	157.3	38.5 ± 1.5	3.72 ± 0.16	<-13.00	<0.08	1–20
NGC 3603-109	O8	Vz	150.1	35.9 ± 0.9	3.53 ± 0.13	<-14.00	0.11 ± 0.03	>20.0
NGC 3603-116	O3.5	V((f))z	164.1	43.5 ± 2.2	3.81 ± 0.21	<-13.50	0.16 ± 0.07	>20.0
NGC 3603-117	O5.5	V((f))z	257.2	38.2 ± 1.5	3.51 ± 0.15	<-14.00	0.18 ± 0.08	>20.0
NGC 3603-120	O6	Vz	167.5	38.2 ± 1.2	3.55 ± 0.16	<-14.00	0.17 ± 0.06	1–20
NGC 3603-124	O6	V	102.8	39.3 ± 3.8	4.09 ± 0.25	<-13.50	<0.06	1–20
NGC 3603-125	O6	V((f))z	133.5	39.0 ± 1.5	3.95 ± 0.30	-13.14 ± 0.54	<0.06	1–20
NGC 3603-128*	O9	V	156.8	35.7 ± 3.4	>4.50	<-13.00	<0.08	1–20
NGC 3603-135	O8	V	306.7	33.1 ± 1.2	3.36 ± 0.13	<-13.50	0.13 ± 0.06	1–20
NGC 3603-208	O5	V	139.5	40.5 ± 1.5	3.52 ± 0.13	<-13.50	0.19 ± 0.07	>20.0
NGC 3603-210	O7	Vz	262.6	36.5 ± 1.1	3.56 ± 0.16	<-13.00	0.10 ± 0.03	>20.0
NGC 3603-212	O5.5	V	296.6	36.7 ± 1.2	3.43 ± 0.15	<-14.00	0.13 ± 0.07	1–20
NGC 3603-213	O9	V	117.9	34.7 ± 1.2	3.75 ± 0.21	<-13.50	0.11 ± 0.04	1–20
NGC 3603-214	O5.5	Vz	158.4	38.4 ± 1.7	3.68 ± 0.24	<-14.00	0.16 ± 0.08	1–20
NGC 3603-215	O7	Vz	212.6	36.4 ± 1.6	3.65 ± 0.22	<-13.50	>0.18	1–20
NGC 3603-216	O7.5	V	161	37.2 ± 2.3	3.89 ± 0.47	<-14.00	0.18 ± 0.10	1–20
NGC 3603-217	O7	V	203.8	35.3 ± 1.3	3.53 ± 0.21	<-13.50	0.20 ± 0.09	>15.0
NGC 3603-218	O6.5	Vz	123.9	39.9 ± 0.9	4.11 ± 0.14	<-13.00	0.08 ± 0.01	>20.0
NGC 3603-219	O8	V	326.3	35.6 ± 1.6	4.11 ± 0.28	<-13.50	<0.08	>20.0
NGC 3603-220	O7.5	V	192.5	33.2 ± 1.1	3.54 ± 0.17	-12.76 ± 0.14	<0.06	<1.0
NGC 3603-222	O9.7	V	167.6	34.9 ± 1.9	4.15 ± 0.33	<-13.00	0.19 ± 0.07	1–20
NGC 3603-226	O9.5	V	94.3	31.8 ± 1.4	3.97 ± 0.32	<-13.50	<0.08	1–20
NGC 3603-305	O3.5	Vz	198.7	41.0 ± 1.6	3.69 ± 0.14	<-13.00	0.11 ± 0.04	>20.0
NGC 3603-308	O6	V((f))z	170.1	38.1 ± 0.6	3.78 ± 0.10	-13.26 ± 0.49	<0.06	<1.0
NGC 3603-313	O6	Vz	218.5	38.6 ± 3.0	4.06 ± 0.40	-12.96 ± 0.39	<0.06	1–20
NGC 3603-326	O8.5	Vz	140.5	35.1 ± 1.9	3.95 ± 0.37	<-14.00	0.13 ± 0.07	1–20
NGC 3603-330	O9.5	V	122.2	34.2 ± 2.8	4.12 ± 0.34	<-13.00	0.16 ± 0.08	1–20
NGC 3603-334	O9.5	V	157.5	33.5 ± 1.5	3.87 ± 0.22	<-13.50	0.13 ± 0.04	<1.0
NGC 3603-901	O7.5	Vz	109.7	39.0 ± 4.4	>4.10	<-14.00	<0.08	1–20
NGC 3603-902	O7	Vz	127.3	38.6 ± 1.7	4.07 ± 0.36	<-13.00	<0.08	1–20
NGC 3603-904	O7	Vz	136.1	37.8 ± 1.7	3.81 ± 0.31	-13.37 ± 0.46	>0.22	<1.0
NGC 3603-905*	O5.5	V((f))z	135.4	37.7 ± 3.4	>4.40	<-14.00	<0.06	1–20
NGC 3603-908	O7	Vz	189.6	39.8 ± 2.3	3.95 ± 0.31	<-13.50	0.14 ± 0.07	1–20
NGC 3603-910	O7	V((f))z	187.7	38.0 ± 1.5	3.95 ± 0.29	<-14.00	<0.06	1–20
NGC 3603-911	O9	V	163.2	34.2 ± 1.3	3.59 ± 0.21	<-13.50	<0.08	1–20
NGC 3603-1059	O9.5	V	100	32.0 ± 2.0	4.18 ± 0.22	-12.46 ± 0.15	0.16 ± 0.09	1–20
NGC 3603-1065	O6.5	Vz	113	39.6 ± 1.6	3.85 ± 0.24	<-13.50	0.13 ± 0.05	1–20
NGC 3603-1088	O9	V	213.7	35.2 ± 2.4	3.64 ± 0.45	<-14.00	>0.18	1–20
NGC 3603-1095	O9.5	V	119.6	33.4 ± 1.8	3.90 ± 0.32	<-14.00	0.17 ± 0.07	1–20
NGC 3603-1096	O7	Vz	293.5	35.3 ± 1.4	4.07 ± 0.27	<-14.00	0.10 ± 0.04	1–20
NGC 3603-1108	O7.5	Vz	116.6	36.0 ± 1.6	3.82 ± 0.25	<-14.00	0.13 ± 0.06	1–20
NGC 3603-1111	O7.5	Vz	122.4	36.7 ± 1.7	3.83 ± 0.28	<-13.50	0.16 ± 0.07	1–20
NGC 3603-Sh19	O3	V((f))	200.6	40.5 ± 3.1	3.77 ± 0.46	-12.61 ± 0.21	<0.08	1–20
NGC 3603-Sh21	O6	V((f))z	192.4	38.1 ± 1.5	3.56 ± 0.20	<-14.00	>0.22	>20.0
NGC 3603-Sh27	O7.5	Vz	219.6	37.7 ± 2.2	3.96 ± 0.48	<-14.00	>0.20	1–20
NGC 3603-Sh49	O7.5	V	285.8	36.0 ± 2.3	3.70 ± 0.50	<-14.00	<0.10	>20.0
NGC 3603-Sh53	O8.5	V	100	35.1 ± 1.1	3.81 ± 0.22	<-13.50	0.11 ± 0.02	<1.0
NGC 3603-Sh54	O6	Vz	213.7	37.5 ± 1.5	3.60 ± 0.20	<-14.00	0.10 ± 0.03	>15.0
NGC 3603-Sh58	O8	Vze	227.7	37.2 ± 1.6	3.76 ± 0.26	<-13.50	0.16 ± 0.08	1–20
NGC 3603-Sh64	O3	V((f))z	167.2	41.8 ± 3.5	3.53 ± 0.16	<-13.50	0.14 ± 0.06	1–20

(*) Stars with $\log g$ values higher than 4.2 dex.

Table 6.2.2: Absolute V magnitudes, radii, luminosities and spectroscopic masses obtained from quantitative analysis of our NGC 3603 sample.

Star	SpT	LC	M_v [mag]	R [$R_\odot$]	$\log L$ [$L_\odot$]	M_{spec} [$M_\odot$]
NGC 3603-16	O3	V((f))	-5.42	12.8 $\pm$ 0.6	5.56 $\pm$ 0.05	17.7 $\pm$ 2.1
NGC 3603-101	O6.5	Vz	-4.81	10.1 $\pm$ 0.2	5.19 $\pm$ 0.05	23.5 $\pm$ 11.2
NGC 3603-102	O8.5	V	-3.60	26.7 $\pm$ 0.6	4.63 $\pm$ 0.05	—
NGC 3603-108	O4.5	Vz	-5.29	12.1 $\pm$ 0.2	5.45 $\pm$ 0.05	29.9 $\pm$ 11.2
NGC 3603-109	O8	Vz	-4.60	9.1 $\pm$ 0.2	5.09 $\pm$ 0.03	11.6 $\pm$ 3.0
NGC 3603-116	O3.5	V((f))z	-4.62	8.2 $\pm$ 0.2	5.32 $\pm$ 0.06	17.7 $\pm$ 6.5
NGC 3603-117	O5.5	V((f))z	-4.88	10.1 $\pm$ 0.2	5.28 $\pm$ 0.03	13.1 $\pm$ 2.5
NGC 3603-120	O6	Vz	-4.42	8.1 $\pm$ 0.2	5.09 $\pm$ 0.03	9.5 $\pm$ 2.3
NGC 3603-124	O6	V	-4.21	7.3 $\pm$ 0.2	5.04 $\pm$ 0.05	31.8 $\pm$ 17.1
NGC 3603-125	O6	V((f))z	-4.37	7.9 $\pm$ 0.2	5.09 $\pm$ 0.04	25.1 $\pm$ 14.2
NGC 3603-128	O9	V	-3.67	6.0 $\pm$ 0.4	4.71 $\pm$ 0.12	26.3 $\pm$ 18.0
NGC 3603-135	O8	V	-4.08	7.7 $\pm$ 0.2	4.79 $\pm$ 0.04	<4.2
NGC 3603-208	O5	V	-4.68	9.0 $\pm$ 0.2	5.26 $\pm$ 0.03	10.3 $\pm$ 1.6
NGC 3603-210	O7	Vz	-4.36	8.2 $\pm$ 0.2	5.01 $\pm$ 0.03	9.6 $\pm$ 2.9
NGC 3603-212	O5.5	V	-4.88	10.4 $\pm$ 0.2	5.23 $\pm$ 0.03	12.1 $\pm$ 2.9
NGC 3603-213	O9	V	-4.14	7.5 $\pm$ 0.2	4.86 $\pm$ 0.04	13.4 $\pm$ 5.4
NGC 3603-214	O5.5	Vz	-4.51	8.4 $\pm$ 0.2	5.13 $\pm$ 0.05	16.7 $\pm$ 7.9
NGC 3603-215	O7	Vz	-3.23	4.8 $\pm$ 0.1	4.56 $\pm$ 0.05	<3.4
NGC 3603-216	O7.5	V	-3.90	6.5 $\pm$ 0.3	4.85 $\pm$ 0.07	19.3 $\pm$ 14.1
NGC 3603-217	O7	V	-3.58	5.8 $\pm$ 0.1	4.66 $\pm$ 0.05	<3.9
NGC 3603-218	O6.5	Vz	-4.11	6.8 $\pm$ 0.1	5.02 $\pm$ 0.03	23.1 $\pm$ 7.0
NGC 3603-219	O8	V	-3.77	6.2 $\pm$ 0.2	4.75 $\pm$ 0.04	22.2 $\pm$ 11.0
NGC 3603-220	O7.5	V	-3.72	6.5 $\pm$ 0.1	4.64 $\pm$ 0.03	6.2 $\pm$ 1.7
NGC 3603-222	O9.7	V	-3.83	6.6 $\pm$ 0.3	4.75 $\pm$ 0.06	29.1 $\pm$ 17.7
NGC 3603-226	O9.5	V	-3.34	5.6 $\pm$ 0.2	4.44 $\pm$ 0.05	13.2 $\pm$ 7.1
NGC 3603-305	O3.5	Vz	-4.75	9.3 $\pm$ 0.2	5.31 $\pm$ 0.04	14.8 $\pm$ 4.5
NGC 3603-308	O6	V((f))z	-4.43	8.2 $\pm$ 0.1	5.09 $\pm$ 0.02	15.2 $\pm$ 3.0
NGC 3603-313	O6	Vz	-4.26	7.5 $\pm$ 0.2	5.04 $\pm$ 0.05	28.6 $\pm$ 16.2
NGC 3603-326	O8.5	Vz	-3.77	6.3 $\pm$ 0.2	4.73 $\pm$ 0.06	17.9 $\pm$ 11.6
NGC 3603-330	O9.5	V	-3.38	5.6 $\pm$ 0.2	4.55 $\pm$ 0.06	20.2 $\pm$ 10.8
NGC 3603-334	O9.5	V	-3.52	5.9 $\pm$ 0.1	4.58 $\pm$ 0.05	10.7 $\pm$ 4.6
NGC 3603-901	O7.5	Vz	-4.62	9.0 $\pm$ 0.8	5.19 $\pm$ 0.12	53.0 $\pm$ 42.4
NGC 3603-902	O7	Vz	-4.19	7.3 $\pm$ 0.2	5.01 $\pm$ 0.05	23.3 $\pm$ 12.7
NGC 3603-904	O7	Vz	-5.59	14.0 $\pm$ 0.4	5.55 $\pm$ 0.05	57.8 $\pm$ 33.3
NGC 3603-905	O5.5	V((f))z	-5.09	11.2 $\pm$ 1.0	5.34 $\pm$ 0.16	—
NGC 3603-908	O7	Vz	-4.60	8.6 $\pm$ 0.3	5.21 $\pm$ 0.06	30.0 $\pm$ 17.6
NGC 3603-910	O7	V((f))z	-5.21	11.7 $\pm$ 0.3	5.40 $\pm$ 0.05	54.4 $\pm$ 29.1
NGC 3603-911	O9	V	-4.26	8.1 $\pm$ 0.2	4.90 $\pm$ 0.05	10.5 $\pm$ 4.3
NGC 3603-1059	O9.5	V	-3.08	5.1 $\pm$ 0.3	4.34 $\pm$ 0.06	15.9 $\pm$ 6.3
NGC 3603-1065	O6.5	Vz	-4.53	8.3 $\pm$ 0.2	5.18 $\pm$ 0.05	20.6 $\pm$ 9.5
NGC 3603-1088	O9	V	-4.65	9.5 $\pm$ 0.4	5.09 $\pm$ 0.07	21.9 $\pm$ 15.9
NGC 3603-1095	O9.5	V	-3.65	6.2 $\pm$ 0.2	4.62 $\pm$ 0.06	13.3 $\pm$ 7.0
NGC 3603-1096	O7	Vz	-4.38	8.0 $\pm$ 0.3	5.08 $\pm$ 0.07	<9.2
NGC 3603-1108	O7.5	Vz	-4.25	7.7 $\pm$ 0.2	4.95 $\pm$ 0.05	16.7 $\pm$ 7.5
NGC 3603-1111	O7.5	Vz	-4.66	9.2 $\pm$ 0.3	5.14 $\pm$ 0.05	25.0 $\pm$ 12.9
NGC 3603-Sh19	O3	V((f))	-4.98	10.5 $\pm$ 0.5	5.38 $\pm$ 0.08	36.0 $\pm$ 25.7
NGC 3603-Sh21	O6	V((f))z	-4.32	7.8 $\pm$ 0.2	5.05 $\pm$ 0.04	<7.0
NGC 3603-Sh27	O7.5	Vz	-3.66	5.8 $\pm$ 0.2	4.77 $\pm$ 0.08	20.7 $\pm$ 15.4
NGC 3603-Sh49	O7.5	V	-4.34	8.2 $\pm$ 0.4	4.87 $\pm$ 0.07	20.2 $\pm$ 14.7
NGC 3603-Sh53	O8.5	V	-4.65	9.5 $\pm$ 0.2	5.08 $\pm$ 0.04	24.4 $\pm$ 10.9
NGC 3603-Sh54	O6	Vz	-4.22	7.5 $\pm$ 0.2	4.99 $\pm$ 0.04	9.6 $\pm$ 3.6
NGC 3603-Sh58	O8	Vze	-3.80	6.1 $\pm$ 0.1	4.81 $\pm$ 0.04	11.4 $\pm$ 4.3
NGC 3603-Sh64	O3	V((f))z	-5.68	14.1 $\pm$ 0.7	5.70 $\pm$ 0.09	24.7 $\pm$ 5.7

6.3 Differential study of stellar parameters

In this section, a detailed study of the fundamental properties of the sample of O V and O Vz stars in NGC 3603 is carried out. The distribution of projected rotational velocities ($v \sin i$) is examined, as well as the relationship between surface gravity and effective temperature through the $\log g$ versus $\log T_{\text{eff}}$ diagram. In addition, the characteristics of the stellar winds are analyzed using the spectroscopic parameter $\log Q$. Finally, the location of the stars in the sHRD is evaluated.

6.3.1 Distribution of the projected rotational velocities

Figure 6.3.1 presents a histogram showing the distribution of $v \sin i$ values in our sample of O-type stars, distinguishing between luminosity classes V and Vz.

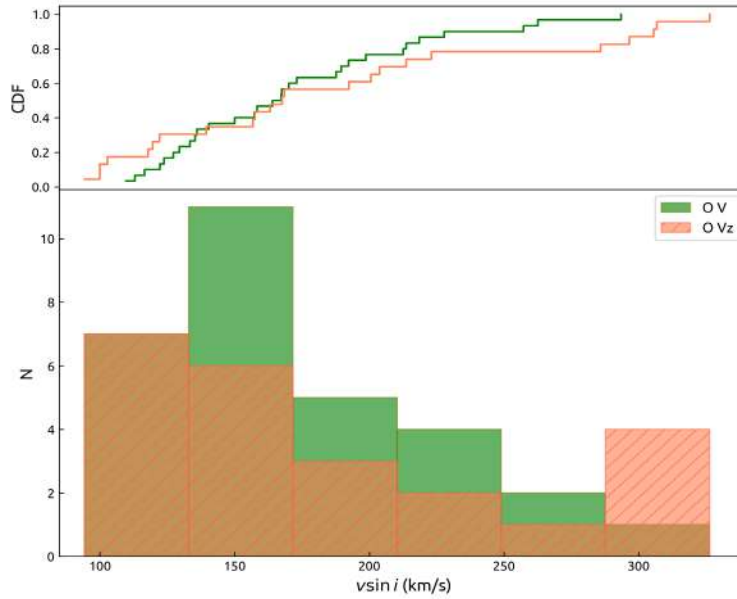


Figure 6.3.1: Distribution of projected rotational velocities ($v \sin i$) of O V and O Vz stars in the NGC 3603 region. The upper panel shows the cumulative distribution functions (CDFs) of both subpopulations.

The distribution of projected rotational velocities ($v \sin i$), shown in Figure 6.3.1, was analyzed using histograms constructed with a binning defined by the Freedman–Diaconis rule (Freedman & Diaconis, 1981). In this case, the adopted bin width is $\Delta v \approx 44 \text{ km s}^{-1}$.

Classical studies of main-sequence O stars in the MW have reported bimodality in the distribution of projected rotational velocities, interpreted as the coexistence of slow and fast rotator populations (e.g., (Conti & Ebbets, 1977; Penny, 1996; Howarth et al., 1997; Berlanas et al., 2020, 2025)). In particular, the seminal work by Conti & Ebbets (1977) identified a minimum in the distribution around $v \sin i \sim 200 \text{ km s}^{-1}$, separating the two populations.

In contrast to what has been reported in the literature for other populations of main-sequence O stars, the distribution analyzed in this work does not show a clearly defined bimodality. Instead, an asymmetric distribution is observed, dominated by a peak around $v \sin i \sim 150 \text{ km s}^{-1}$ and a tail toward high rotational velocities, with only a small number of objects exhibiting $v \sin i \gtrsim 250 \text{ km s}^{-1}$.

On the other hand, no O-type stars with $v \sin i$ values below $\sim 90 \text{ km s}^{-1}$ are observed, which can be explained by instrumental limitations. For spectra obtained with MagE ($R = 4100$), the minimum reliable measurement threshold is $\sim 75 \text{ km s}^{-1}$, while for IMACS ($R = 2500$) it is $\sim 120 \text{ km s}^{-1}$. In cases where $v \sin i$ could not be reliably determined, fixed values were adopted following standard practice: 50 km s^{-1} for MagE and 100 km s^{-1} for IMACS. This strategy was applied to two O V stars (NGC 3603-1059, NGC 3603-Sh53).

Finally, a Kolmogorov–Smirnov (KS) test applied to the cumulative distribution functions (CDFs) of $v \sin i$ for the O V and O Vz subpopulations, shown in the upper panel of Figure 6.3.1, yields $D = 0.20$ and $p = 0.56$. Consequently, no statistically significant differences are detected between the two groups.

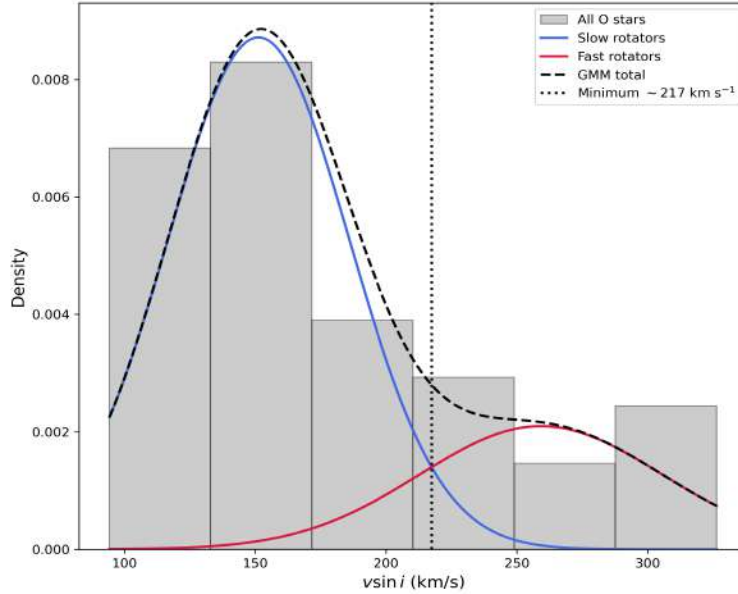


Figure 6.3.2: Distribution of projected rotational velocities ($v \sin i$) for the total sample of O stars. The blue and red curves show the two Gaussian components obtained from a Gaussian Mixture Model (GMM) fit, associated with a dominant population of slow rotators and a secondary population of fast rotators, respectively. The black dashed curve represents the total distribution resulting from the superposition of both components. The position of the minimum between the two Gaussians ($\sim 218 \text{ km s}^{-1}$) is indicated by a vertical dotted line.

In order to quantitatively explore the possible presence of rotational subpopulations, Gaussian Mixture Models (GMM) were employed, as shown in Figure 6.3.2. These models describe the observed distribution as the superposition of one or more Gaussian distributions. When fitting a two-component model, a dominant population of slow rotators is obtained, with a mean projected rotational velocity of $\langle v \sin i \rangle \approx 151 \text{ km s}^{-1}$ and a dispersion of $\sim 35 \text{ km s}^{-1}$, together with a secondary population of fast rotators, characterized by $\langle v \sin i \rangle \approx 259 \text{ km s}^{-1}$ and a dispersion of $\sim 46 \text{ km s}^{-1}$, which accounts for approximately 24% of the sample.

However, the comparison between the unimodal and bimodal models using the Bayesian Information Criterion (BIC), which penalizes the increase in the number of free parameters of the model, in this case, the introduction of a second Gaussian component with its own mean, dispersion, and relative weight, indicates that the two-component model is not statistically favored over a single-component model ($\Delta\text{BIC} \approx -0.3$). Therefore, these results do not provide statistically robust evidence for a well-defined bimodality in the $v \sin i$ distribution.

6.3.2 The $\log g - \log T_{\text{eff}}$ diagram

Figure 6.3.3 shows the distribution of effective temperatures (left panel) and surface gravities (right panel) for the sample of O V and O Vz stars, belonging to the NGC 3603 region. In the T_{eff} histogram, although the highest effective temperature reached by Vz stars is 43.5 kK, the majority of them concentrated around 38 kK. This peak in the distribution corresponds to intermediate spectral types (O5–O7). The earliest types are relatively rare among the Vz stars. In contrast, the O V stars present a more extended distribution, with a less pronounced peak near 34 kK.

Regarding surface gravity, O Vz stars exhibit $\log g$ values distributed primarily between 3.5 and 4.1 dex, a range that overlaps with that of O V stars, which cover a broader interval including higher values. This shared distribution indicates that

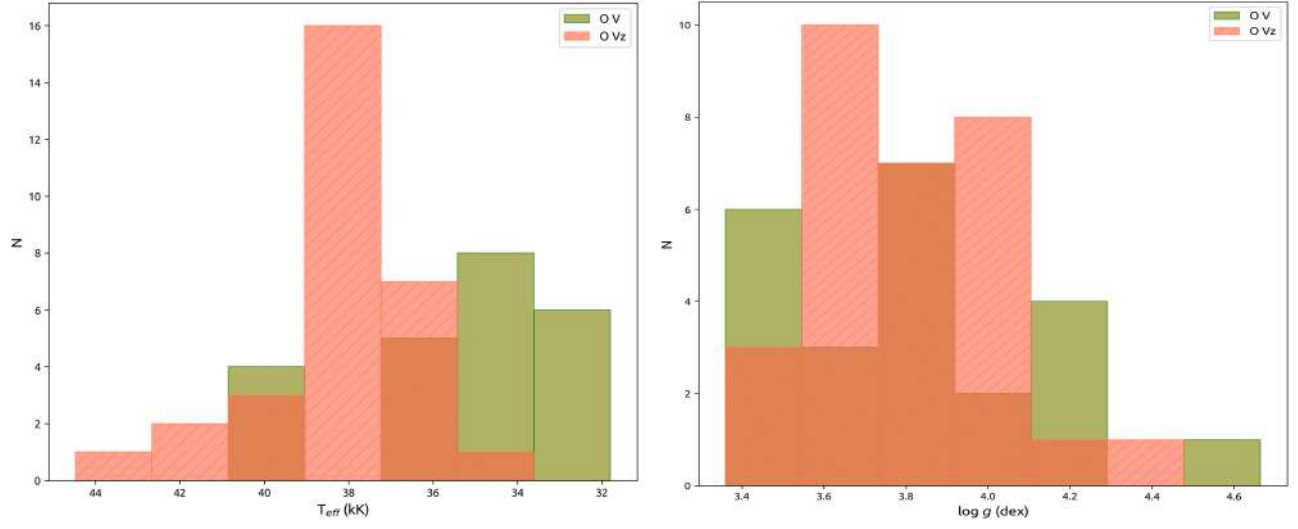


Figure 6.3.3: Distribution of effective temperatures (T_{eff} , left panel) and surface gravities ($\log g$, right panel) for O Vz and O V stars in the sample.

there is no systematic difference in surface gravity between the two subclasses and is consistent with the findings in 30 Dor (Sabín-Sanjulián et al., 2014).

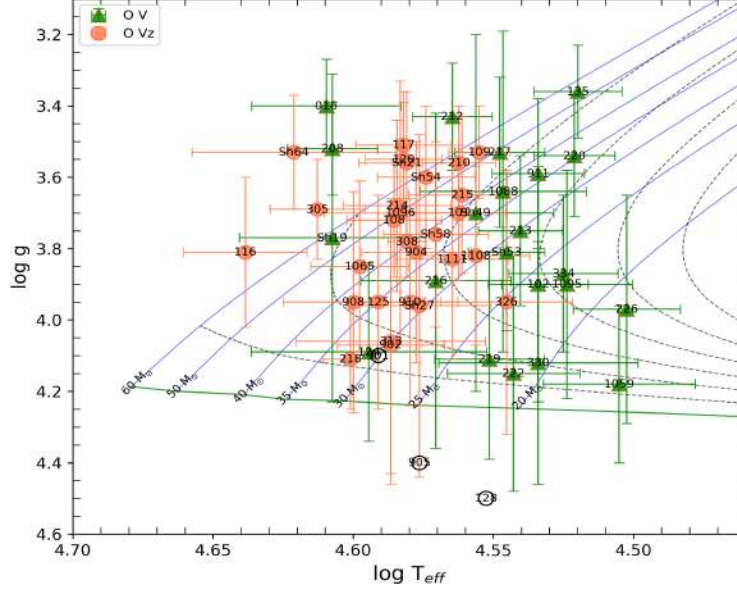


Figure 6.3.4: Results of $\log g$ vs $\log T_{\text{eff}}$ for the O Vz and O V samples in the NGC 3603 region. The numbers within the symbols indicate the identifier assigned to each star. The solid green line represents the ZAMS, the solid blue lines are evolutionary tracks, and the dotted lines are isochrones up to 6 Myr, based on the models of Brott et al. (2011) computed for MW metallicity and an initial rotational velocity of 200 km s^{-1} . Symbols appear empty when only a lower or upper limit for $\log g$ could be determined.

Figure 6.3.4 shows the distribution of the analyzed stars in the $\log T_{\text{eff}}$ versus $\log g$ plane for NGC 3603. The blue curves represent rotating evolutionary tracks computed by Brott et al. (2011) for MW metallicity conditions and $v_{\text{ini}} = 200 \text{ km s}^{-1}$, together with dotted isochrones (dashed lines) reaching up to 6 Myr. The solid green line indicates the ZAMS.

The OVz stars are mainly located in the left region of the diagram ($\log T_{\text{eff}} \approx 4.55\text{--}4.62$ and $\log g > 3.5$ dex), where a considerable fraction of O V stars also lies within the same range of surface gravity. Both subclasses therefore exhibit a comparable distribution in $\log g$, with no evidence to support that OVz stars systematically display higher values or are preferentially located closer to the ZAMS. This conclusion remains valid even when accounting for the uncertainties in $\log g$, which are typically around 0.22 dex (median) and can reach up to ~ 0.27 dex in individual cases.

In three cases (NGC 3603-128, NGC 3603-901, and NGC 3603-905), open symbols indicate that only upper or lower limits on $\log g$ could be determined. This situation reflects the degeneracy between T_{eff} and $\log g$, common in spectra where He I lines disappear and He II lines saturate. According to [Sabián-Sanjulián et al. \(2014\)](#), this degeneracy generates flat regions in the χ^2 maps, making precise estimation of T_{eff} difficult. In these cases, GBAT only provides a lower limit for the temperature, which may bias results toward higher gravities.

This issue has also been examined by [Holgado et al. \(2020\)](#), who show that He II lines lose sensitivity at very high temperatures and intermediate gravities. Under these conditions, the fits may converge toward degenerate solutions that can moderately underestimate T_{eff} and overestimate $\log g$ in some cases. Values for which GBAT provides only an upper limit should be taken with caution. In future analysis versions, these values could be confirmed through simultaneous fits with other spectral indicators (e.g., metal ions such as N III or C IV) or by using complementary tools to reduce current degeneracies. Nonetheless, these represent the best results attainable with our current analysis.

6.3.3 Helium abundance

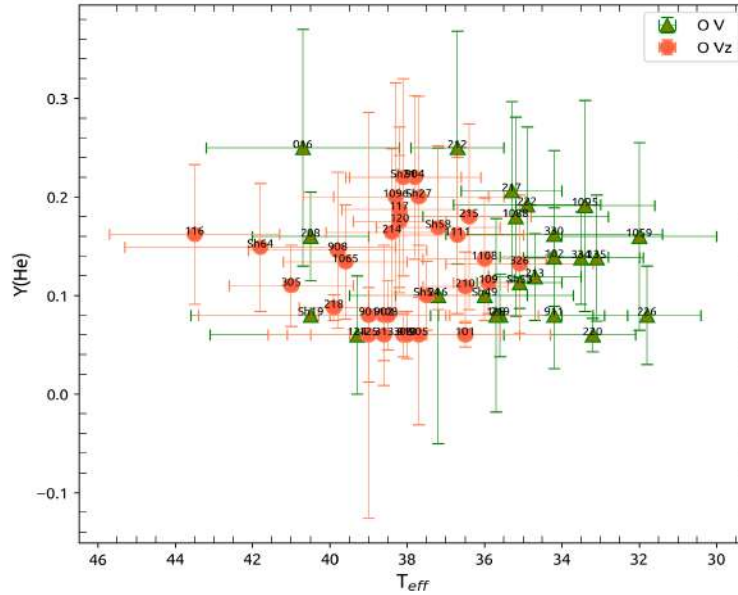


Figure 6.3.5: $Y(\text{He})$ vs T_{eff} of OVz stars and O V stars analyzed in the NGC 3603 region. Numbers above the symbols indicate the identifier assigned to each star.

Figure 6.3.5 shows the distribution of the surface helium abundance, $Y(\text{He})$, as a function of T_{eff} , for OVz stars and O V stars in NGC 3603. At first glance, both classes cover similar helium abundance ranges, approximately from low values (~ 0.06) to enriched values (~ 0.3 , in extreme cases). In O V stars, the helium abundance is distributed rather uniformly across the temperature range, albeit with significant dispersion. Two objects stand out due to their extreme enrichment: NGC 3603-016 and NGC 3603-212, both with $Y(\text{He}) = 0.25$. No clear correlation is identified between spectral class and a helium abundance.

Figure 6.3.6 illustrates the relationship between rotation and surface composition for the NGC 3603 sample. No direct correlation is observed between rotational velocity and surface helium abundance. A few fast-rotating stars ($v \sin i \geq$

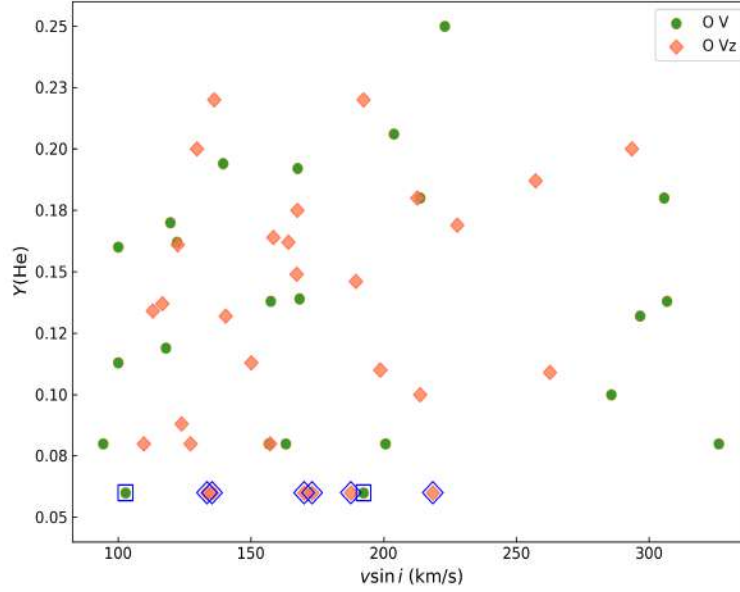


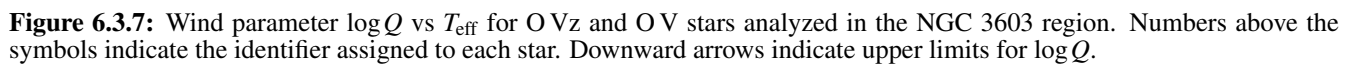
Figure 6.3.6: Distribution of helium abundance $Y(\text{He})$ as a function of projected rotational velocity ($v \sin i$) for O V and O Vz stars. Blue symbols represent stars with a lower limit of $Y(\text{He}) < 0.06$, derived from GBAT analysis.

250 km s^{-1}) exhibit relatively low $Y(\text{He})$ levels, likely due to their youth (age $< 3 \text{ Myr}$), which limits the efficiency of rotational mixing (Ramírez-Agudelo et al., 2017; Holgado et al., 2018). Conversely, some stars with elevated helium abundances do not show particularly high rotational velocities, suggesting that additional factors may be influencing the surface helium enrichment.

As for the NGC 346 stars, a lower limit $Y(\text{He}) < 0.06$ was also estimated for some NGC 3603 stars based on GBAT analysis, represented by blue symbols in Figure 6.3.6. Nebular contamination in NGC 3603, caused by the intense UV radiation from its massive stars that ionizes the surrounding gas, can partially fill in the spectral lines and contribute to some He I lines appearing particularly weak. As previously discussed in Subsection 5.2.3, there are limitations that may affect the determination of the upper limits of the helium abundance. Overall, the dispersion observed in $Y(\text{He})$ within NGC 3603 reflects the combined action of multiple factors.

6.3.4 Wind properties

Figure 6.3.7 shows the distribution of the parameter $\log Q$ as a function of effective temperature (T_{eff}) for O Vz and O V stars in NGC 3603. Downward arrows indicate upper limits for $\log Q$, highlighting degeneracies at the lower values and the impossibility of obtaining precise determinations in those cases. Contrary to what might be expected based on spectral class, no clear distinction is observed between the O Vz and O V subclasses in terms of $\log Q$ values: both cover similar ranges, approximately from $\log Q \sim -15.3$ to -12.5 , and present comparable dispersion.



Due to the high and anomalous extinction in NGC 3603 (Melena et al., 2008), which differs from typical values in the MW, the sHR was employed instead of the classical HR diagram. The sHR allows stellar parameters to be estimated independently of apparent luminosity and, therefore, of extinction correction, making it particularly suitable for characterizing the massive and young stellar population of the region.

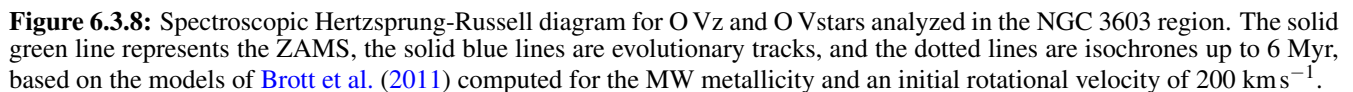


Figure 6.3.8 shows the sHR diagram of O-type V and Vz stars in NGC 3603. In this plane, the vertical axis corresponds to the spectroscopic luminosity, defined as $\mathcal{L} = T_{\text{eff}}^4/g$ (Langer & Kudritzki, 2014). For reference, evolutionary tracks (blue solid lines) and isochrones (grey dotted lines) computed from the models of Brott et al. (2011), assuming a representative Galactic chemical composition and an initial rotational velocity of $v_{\text{ini}} = 200 \text{ km s}^{-1}$, are included. The green line indicates the ZAMS.

For this region, O Vz stars are concentrated at high effective temperatures and exhibit spectroscopic luminosities within the approximate range $\log \mathcal{L} \sim 3.6\text{--}4.2$. In contrast, O V stars display a much more extended distribution along the luminosity axis, although a fraction of them reaches values comparable to those of the O Vz population.

A significant lack of objects located very close to the ZAMS above $\approx 27 M_{\odot}$ is observed. This deficit does not appear to be exclusive to NGC 3603: recent studies in other massive star-forming regions of the MW, show a similar pattern, revealing a systematic decrease of stellar population in the immediate vicinity of the ZAMS for intermediate–high masses ($\approx 30\text{--}70 M_{\odot}$; Holgado et al. 2020; Berlanas et al. 2025).

A small subset of objects exhibits $\mathcal{L} > 4.2$ dex, namely NGC 3603-016 ($\log \mathcal{L} = 4.43$ dex), NGC 3603-Sh 64 ($\log \mathcal{L} = 4.34$ dex), NGC 3603-208 ($\log \mathcal{L} = 4.30$ dex), NGC 3603-212 ($\log \mathcal{L} = 4.22$ dex), and NGC 3603-117 ($\log \mathcal{L} = 4.21$ dex). All of them correspond to early spectral types (O3–O5.5), characterised by very weak He I lines. In these cases, a possible explanation is that the scarcity of He I lines limits the ability to constrain the He I/He II ionization balance, the primary diagnostic of T_{eff} , which increases the uncertainty in its determination. As a consequence, the spectral fits tend to converge toward higher temperatures ($\gtrsim 40 \text{ kK}$), increasing the T_{eff}^4 term in the definition of $\mathcal{L}$ and shifting these stars to anomalously high spectroscopic luminosity values.

Regarding the age distribution, differences are observed between the O V and O Vz populations. The O Vz stars are strongly concentrated in the 2–3 Myr interval, with a single object at ≤ 1 Myr and none above 4 Myr. In contrast, we find only one O V star at ≤ 1 Myr, while the remainder of the population is continuously distributed up to the 4–5 Myr range. These results indicate that, although the Vz morphology does not constitute an unambiguous indicator of proximity to the ZAMS, most O Vz stars correspond to young populations and are concentrated around the 2–3 Myr isochrone.

6.4 Stellar parameters as a function of spectral type

Figure 6.4.1 presents the relationships between the physical parameters and spectral type, allowing us to assess the consistency of the NGC 3603 O Vz and O V stellar population with known evolutionary trends and with results reported for other massive star-forming regions in the MW and the MCs.

As expected, the effective temperature (T_{eff}) decreases toward later spectral subtypes. O Vz stars are confined to relatively high temperatures, in agreement with previous studies (Sabín-Sanjulián et al., 2014; Arias et al., 2016). Within the spectral-type range where O V and O Vz stars overlap, however, no systematic differences in T_{eff} are evident between the two subclasses.

The distribution of surface gravity values ($\log g$) indicates that O V and O Vz stars occupy similar ranges, with no significant systematic differences. This suggests that O Vz stars do not exhibit higher gravities than their O V counterparts, consistent with the results reported by Sabín-Sanjulián et al. (2014). Three stars, NGC 3603-128 (SpT = O9 V), NGC 3603-901 (SpT = O7.5 Vz), and NGC 3603-905 (SpT = O5.5 V((f))z), for which only upper limits on $\log g$ could be derived, were excluded from this and subsequent analyses (see Figure 6.3.4). The derived stellar radii and luminosities decrease toward later spectral subtypes. Two stars, NGC 3603-102 (SpT = O8.5 V) and NGC 3603-904 (SpT = O7 Vz), were omitted from the corresponding figure because the wings of their Balmer lines could not be reliably fitted, resulting in unrealistically large radii. Consequently, both stars were excluded from this and subsequent analyses.

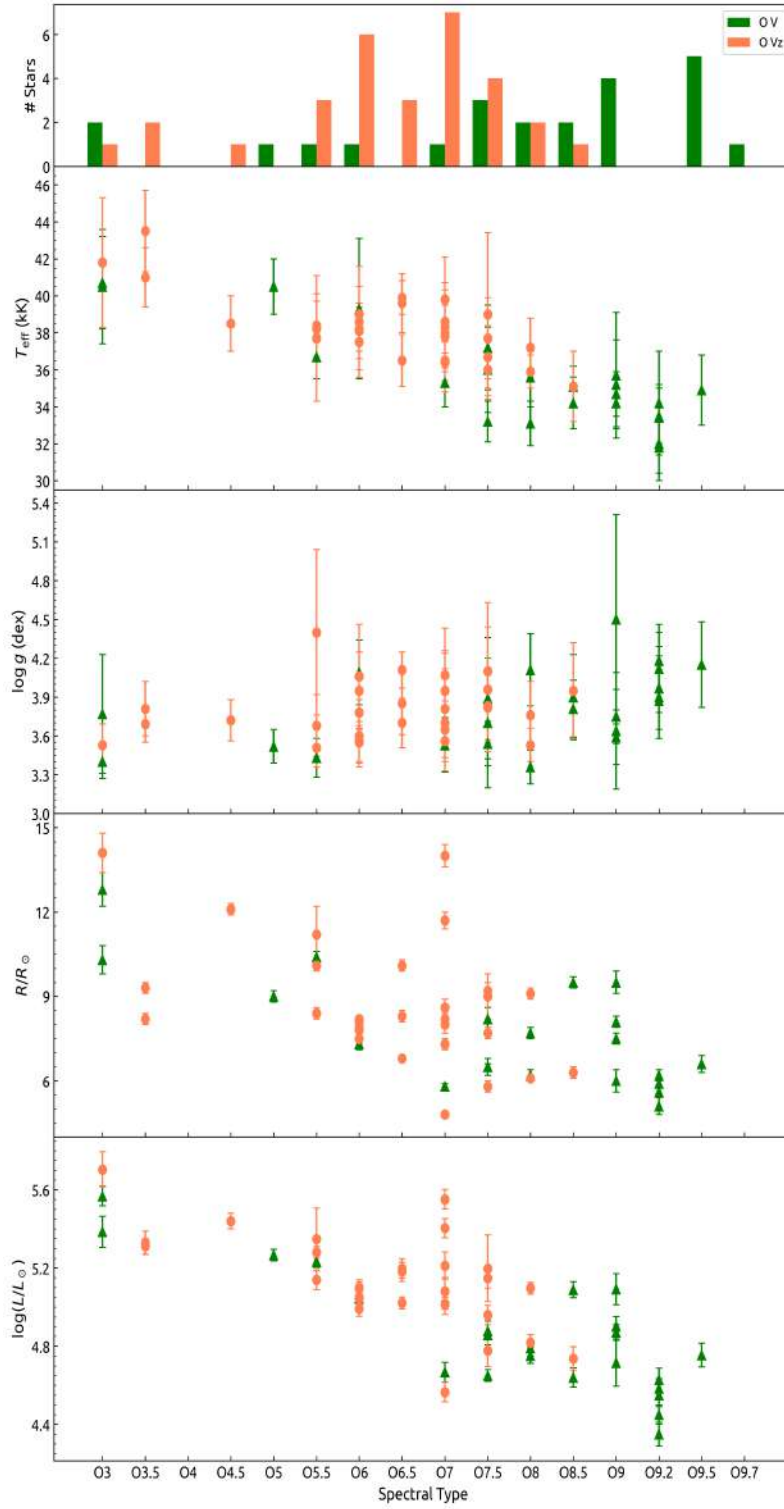


Figure 6.4.1: Stellar parameter distributions for O V and O Vz stars in NGC 3603 as a function of spectral subtype. The top panel shows the number of stars per spectral subtype. From top to bottom, the remaining panels display the effective temperature (T_{eff}), surface gravity ($\log g$), stellar radius ($R/R_{\odot}$), and luminosity ($\log(L/L_{\odot})$), including their associated uncertainties.

6.5 Comparison with previous results in the literature

To contextualize and validate the results of this study, it is useful to compare them with previous research. For this purpose, we selected the works by [Holgado et al. \(2018\)](#), (yellow squares) and [Berlanas et al. \(2025\)](#), (green circles), as both carry out spectroscopic analyses of a similar nature, even employing the same computational tools.

The study by [Holgado et al. \(2018\)](#), within the IACOB project framework, performed a homogeneous spectroscopic analysis of a representative sample of Galactic O stars, including objects from the OWN project (High-resolution spectroscopic monitoring survey of Southern Galactic O- and WN-type Stars, [Barbá et al., 2017](#)). On the other hand, [Berlanas et al. \(2025\)](#) conducted a detailed analysis of 54 apparently single O stars in the Car OB1 association, located in the Carina Nebula, one of the most active star formation regions in the MW. The study is based on high-resolution spectra from the Gaia-ESO Survey (GES [Gilmore et al., 2022](#)) and the LiLiMaRlin database ([Apellániz et al., 2018](#)), which integrates observations from projects like OWN, IACOB, NoMaDS ([Pellerin et al., 2012](#)), and CAFÉ-BEANS ([Negueruela et al., 2014](#)). Additionally, they used Gaia DR3 ([Lindgren et al., 2021](#)) astrometric information and the BONNSAI tool ([Schneider et al., 2014](#)) to estimate evolutionary masses and ages.

Figure 6.5.1 summarizes this comparison, showing the stellar parameters derived for the NGC 3603 sample alongside the corresponding values reported in previous studies. Overall, the stellar parameters derived for the stars in NGC 3603 show reasonable agreement with the values reported by [Holgado et al. \(2018\)](#) and [Berlanas et al. \(2025\)](#), considering the associated uncertainties and the limitations imposed by the sample size for specific spectral subtypes. We note that no values for stellar radius, luminosity, or spectroscopic mass are provided by [Holgado et al. \(2018\)](#), and therefore these parameters cannot be directly compared with that study.

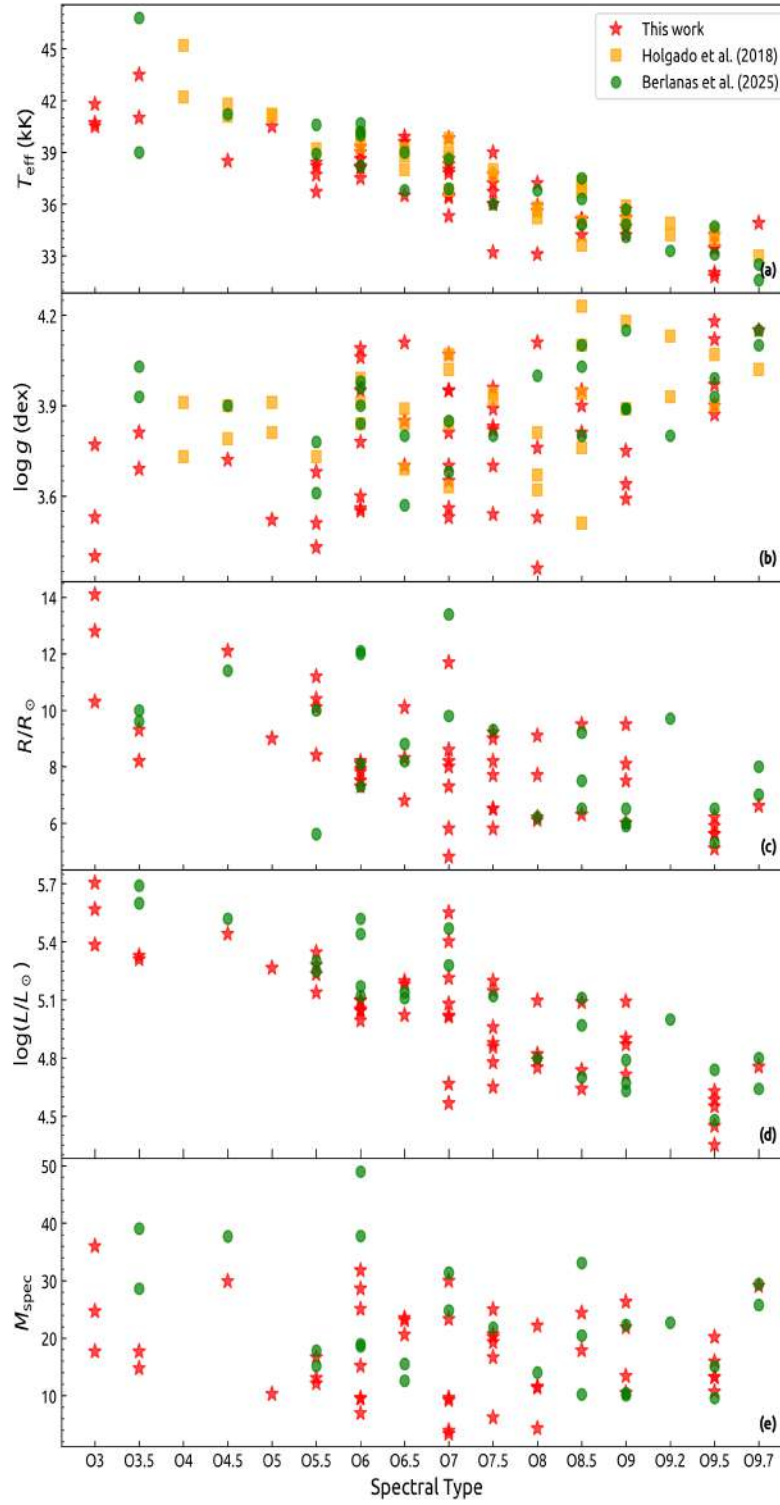


Figure 6.5.1: Comparison of the stellar parameters derived in this work (red stars) with those reported by Holgado et al. (orange squares 2018) and Berlanas et al. (green circles 2025). From top to bottom, the panels show: (a) effective temperature, (b) surface gravity, (c) stellar radius, (d) luminosity, and (e) spectroscopic mass.

6.6 Mass discrepancy

6.6.1 Determination of evolutionary masses

Evolutionary masses were determined from the position of each object in the spectroscopic HR diagram by comparing the values derived from $(\log T_{\text{eff}}, \log \mathcal{L})$ with the evolutionary tracks of [Brott et al. \(2011\)](#), calculated for Galactic metallicity and an initial rotational velocity of $v_{\text{ini}} = 200 \text{ km s}^{-1}$. The mass assigned to each star corresponds to the evolutionary track that best reproduces its location in the sHR, interpolating between adjacent tracks when necessary. Table 6.6.1 lists the values obtained for each object.

Table 6.6.1: Comparison of spectroscopic (M_{spec}) and evolutionary (M_{evol}) masses for the sample of O-type dwarf stars in the NGC 3603 region. Columns: (a) identifier, (b) spectral type, (c) luminosity class, (d) M_{spec} , (e) M_{evol} .

Star	SpT	LC	M_{spec}	M_{evol}
NGC 3603-16	O3	V((f))	18 ± 2	60
NGC 3603-101	O6.5	Vz	24 ± 11	39 ± 12
NGC 3603-102	O8.5	V	—	24 ± 14
NGC 3603-108	O4.5	Vz	32 ± 10	49 ± 10
NGC 3603-109	O8	Vz	12 ± 3	54 ± 9
NGC 3603-116	O3.5	V((f))z	18 ± 7	60 ± 7
NGC 3603-117	O5.5	Vz	13 ± 3	60 ± 5
NGC 3603-120	O6	Vz	10 ± 2	60 ± 7
NGC 3603-124	O6	V	32 ± 17	31 ± 10
NGC 3603-125	O6	V((f))z	25 ± 14	32 ± 13
NGC 3603-128	O9	V	26 ± 18	15 ± 15
NGC 3603-135	O8	V	<4.3	55 ± 10
NGC 3603-208	O5	V	10 ± 2	60 ± 2
NGC 3603-210	O7	Vz	10 ± 3	55 ± 10
NGC 3603-212	O5.5	V	12 ± 3	60 ± 6
NGC 3603-213	O9	V	13 ± 5	30 ± 11
NGC 3603-214	O5.5	Vz	17 ± 8	53 ± 13
NGC 3603-215	O7	Vz	<3.4	43 ± 13
NGC 3603-216	O7.5	V	19 ± 14	32 ± 16
NGC 3603-217	O7	V	<3.9	49 ± 12
NGC 3603-218	O6.5	Vz	23 ± 7	32 ± 7
NGC 3603-219	O8	V	22 ± 11	23 ± 9
NGC 3603-220	O7.5	V	6 ± 2	36 ± 11
NGC 3603-222	O9.7	V	29 ± 18	21 ± 8
NGC 3603-226	O9.5	V	13 ± 7	19 ± 9
NGC 3603-305	O3.5	Vz	15 ± 5	60 ± 4
NGC 3603-308	O6	V((f))z	15 ± 3	41 ± 8
NGC 3603-313	O6	Vz	29 ± 16	30 ± 14
NGC 3603-326	O8.5	Vz	18 ± 12	25 ± 14
NGC 3603-330	O9.5	V	20 ± 11	21 ± 8
NGC 3603-334	O9.5	V	11 ± 5	23 ± 7
NGC 3603-901	O7.5	Vz	53 ± 42	30 ± 16
NGC 3603-902	O7	Vz	23 ± 13	30 ± 13
NGC 3603-904	O7	Vz	58 ± 33	38 ± 14
NGC 3603-905	O5.5	V((f))z	—	20 ± 15
NGC 3603-908	O7	Vz	30 ± 18	38 ± 13
NGC 3603-910	O7	V((f))z	54 ± 29	32 ± 12
NGC 3603-911	O9	V	11 ± 4	37 ± 13
NGC 3603-1059	O9.5	V	16 ± 6	17 ± 2
NGC 3603-1065	O6.5	Vz	21 ± 10	43 ± 12
NGC 3603-1088	O9	V	22 ± 16	38 ± 16
NGC 3603-1095	O9.5	V	13 ± 7	22 ± 10
NGC 3603-1096	O7	Vz	<9.2	50 ± 14
NGC 3603-1108	O7.5	Vz	17 ± 8	31 ± 12

Table 6.6.1: Continued.

Star	SpT	LC	M_{spec}	M_{evol}
NGC 3603-1111	O7.5	Vz	25 ± 13	33 ± 12
NGC 3603-Sh19	O3	V((f))	36 ± 26	57 ± 15
NGC 3603-Sh21	O6	V((f))z	< 7.0	60 ± 9
NGC 3603-Sh27	O7.5	Vz	21 ± 15	31 ± 16
NGC 3603-Sh49	O7.5	V	20 ± 15	37 ± 17
NGC 3603-Sh53	O8.5	V	24 ± 11	29 ± 9
NGC 3603-Sh58	O8	Vze	11 ± 4	38 ± 13
NGC 3603-Sh64	O3	V((f))z	25 ± 6	60 ± 2

6.6.2 Mass ratio ($M_{\text{spec}}/M_{\text{evol}}$) as a function of evolutionary mass

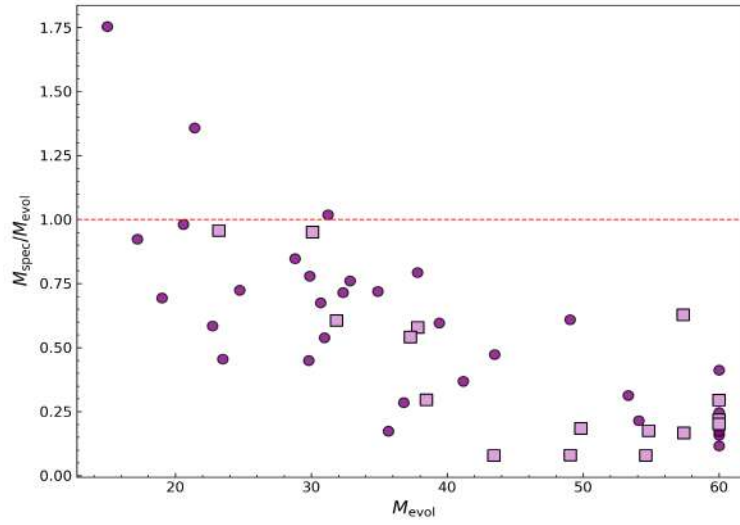


Figure 6.6.1: Comparison between the spectroscopic-to-evolutionary mass ratio ($M_{\text{spec}}/M_{\text{evol}}$) and the evolutionary mass (M_{evol}) for dwarf population, regardless of the V or Vz subclass. Rapid rotators ($v \sin i > 200 \text{ km s}^{-1}$) are highlighted with squares.

Figure 6.6.1 shows the ratio $M_{\text{spec}}/M_{\text{evol}}$ as a function of evolutionary mass (M_{evol}), with squares highlighting rapidly rotating objects ($v \sin i > 200 \text{ km s}^{-1}$). During the analysis, one star in the sample, NGC 3603-905 (SpT = O5.5 V((f))z), did not allow a reliable determination of its spectroscopic mass, as the values derived for $\log g$ and R were physically inconsistent. Three objects, NGC 3603-901 (SpT = O7.5 Vz), NGC 3603-904 (SpT = O7 V), and NGC 3603-910 (SpT = O7 V((f))), were identified as outliers and were excluded from this comparison and from subsequent analyses. These stars yield spectroscopic masses that are anomalously high for O-type dwarfs, significantly exceeding the values expected for their spectral types. Such discrepancies are most likely driven by uncertainties in the derived surface gravities and radii, which directly propagate into the spectroscopic mass estimates. Given the absence of independent evidence supporting such high masses, these objects were excluded to avoid biasing the comparison.

Overall, the $M_{\text{spec}}/M_{\text{evol}}$ ratio is less than 1, indicating that spectroscopic masses are generally lower than evolutionary masses, especially in more massive stars. A strong and statistically significant anti-correlation is found between the mass ratio $M_{\text{spec}}/M_{\text{evol}}$ and the evolutionary mass. The Pearson correlation coefficient ($r = -0.76$) and the extremely low p -value ($p = 3.97 \times 10^{-10}$) indicate that the mass

discrepancy becomes more pronounced toward higher evolutionary masses. Approximately 60% of the observed dispersion in $M_{\text{spec}}/M_{\text{evol}}$ can be attributed to its dependence on the evolutionary mass.

No systematic trends are observed between $M_{\text{spec}}/M_{\text{evol}}$ and projected rotational velocity. A Kolmogorov–Smirnov test comparing fast and slow rotators yields $D = 0.37$ with $p = 0.09$, indicating that the distributions of the mass ratio do not differ significantly. This suggests that the mass discrepancy is not solely associated with projected rotation, and that other factors, such as binary evolution or limitations in spectroscopic analysis, may also play a role.

6.6.3 Mass variations with T_{eff} and $\log g$

Figure 6.6.2 shows the ratio between the spectroscopic and evolutionary masses ($M_{\text{spec}}/M_{\text{evol}}$) as a function of $\log T_{\text{eff}}$ (left panel) and $\log g$ (right panel). These representations allow us to examine how the mass discrepancy depends on the fundamental stellar parameters

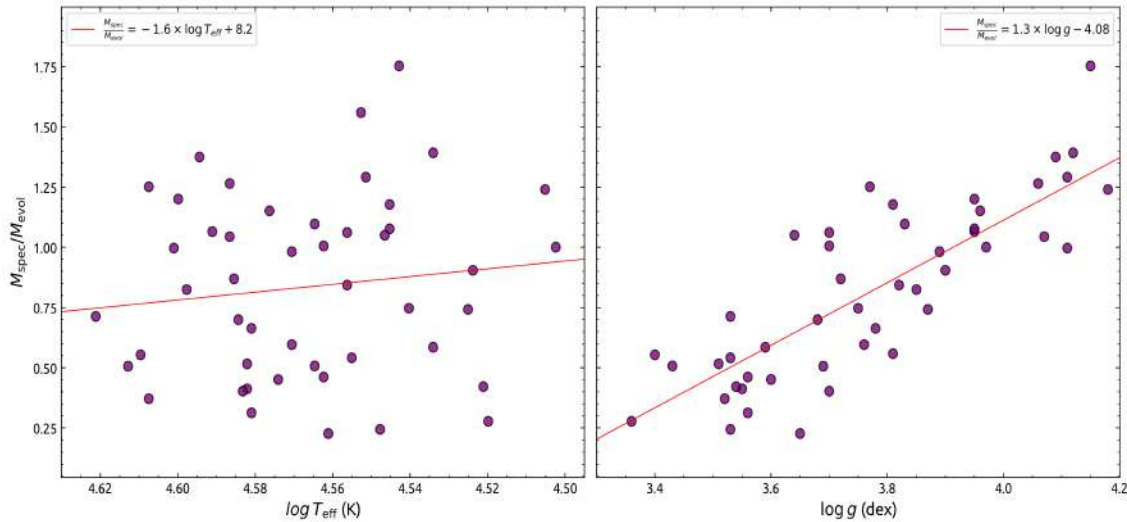


Figure 6.6.2: Spectroscopic-to-evolutionary mass ratio ($M_{\text{spec}}/M_{\text{evol}}$) as a function of effective temperature (left panel) and surface gravity (right panel) for the complete stellar sample analyzed in this region. A linear regression is shown in both panels.

In the case of the relation with effective temperature, no clear trend is observed. The data are widely scattered along the $\log T_{\text{eff}}$ axis. The Pearson correlation ($r = -0.159$, $p = 0.280$) indicates that the relationship is weak and statistically not significant, suggesting that effective temperature does not explain the observed variability in the $M_{\text{spec}}/M_{\text{evol}}$ ratio.

In contrast, the relation between $M_{\text{spec}}/M_{\text{evol}}$ and $\log g$ shows a more defined pattern. Stars with lower surface gravity generally exhibit larger mass discrepancies, while these discrepancies progressively decrease as $\log g$ increases. The Pearson correlation ($r = 0.897$, $p \ll 0.001$) and the coefficient of determination ($R^2 = 0.805$) indicate that approximately 80% of the variability in the mass ratio can be explained by surface gravity, confirming that this stellar property is closely related to the magnitude of the observed mass discrepancy.

6.7 Concluding remarks

In NGC 3603, following the application of the quantitative classification criterion, the sample comprises 30 O Vz stars and 23 O V stars. The O Vz stars are primarily concentrated in intermediate spectral types (O5.5–O7.5), whereas the O V stars display a more heterogeneous distribution, with lower density in the intermediate range and occasional absence in the earliest types.

The analysis of projected rotational velocities ($v \sin i$) reveals an asymmetric distribution, peaking around 150 km/s with a tail toward higher velocities, without evidence of a clearly defined bimodality. The Kolmogorov–Smirnov test indicates that there are no statistically significant differences between the $v \sin i$ distributions of the O V and O Vz subclasses.

Regarding surface helium abundance, $Y(\text{He})$, no systematic differences are observed between O V and O Vz stars. Both subclasses exhibit considerable dispersion, with values approximately ranging from 0.06 to 0.3 in extreme cases. No direct correlation is identified between rotational velocity and helium abundance, suggesting that factors other than rotation-induced mixing may contribute to surface enrichment.

The HRD and sHRD diagrams show that O Vz stars tend to occupy high effective temperatures, with spectroscopic luminosities between 3.6 and 4.2 dex. In contrast, O V stars are distributed over a wider range of luminosities and ages (up to 4–5 Myr), while most O Vz stars are concentrated between 2 and 3 Myr. Additionally, a notable scarcity of very massive stars ($> 27 M_{\odot}$) near the ZAMS is observed, consistent with patterns reported in other massive Galactic clusters.

The analysis of stellar wind properties shows no systematic differences between O V and O Vz stars, indicating that the Vz characteristic is not consistently associated with weaker winds.

Finally, the comparison between spectroscopic and evolutionary masses ($M_{\text{spec}}/M_{\text{evol}}$) indicates that most stars have $M_{\text{spec}} < M_{\text{evol}}$, especially the most massive objects. While no clear trends are observed with effective temperature, the mass discrepancy progressively decreases with increasing surface gravity.

Chapter 7

Conclusions and future perspectives

This Thesis presented a comparative analysis of a sample of O-type dwarf stars, with a particular emphasis on characterizing the Vz phenomenon, across three massive star-forming regions located in galaxies with different metallicities: NGC 346 in the Small Magellanic Cloud, 30 Doradus in the Large Magellanic Cloud, and NGC 3603 in the Milky Way.

Our sample consisted of 165 O-type dwarf stars, with 28 (17%) located in NGC 346, 84 (51%) in 30 Doradus, and 53 (32%) in NGC 3603. Of the total sample, 66 stars (40%) fulfill the criteria of the O Vz class, while the remaining 99 stars (60%) correspond to the O V class. Within each region, the fraction of O Vz stars is 29% (8/28) in NGC 346, 33% (28/84) in 30 Doradus, and 57% (30/53) in NGC 3603. The identification of Vz stars was carried out by applying the quantitative criterion proposed by [Arias et al. \(2016\)](#), which uses the comparison of the equivalent widths of the He II $\lambda 4686$, He II $\lambda 4541$, and He I $\lambda 4471$ lines.

The quantitative spectroscopic analysis was carried out using IACOB-BROAD ([Simón-Díaz & Herero, 2014](#)) as a first step, a tool employed to determine the projected rotational velocities ($v \sin i$) and to quantify the macroturbulent broadening present in the spectra. Subsequently, we used the IACOB Grid-Based Automatic Tool ([Simón-Díaz et al., 2011](#)), which provides a fast and automated procedure for deriving stellar and wind parameters in OB stars. The combination of both tools enabled us to obtain effective temperatures, surface gravities, helium abundances, wind parameter Q values, radii, luminosities, spectroscopic masses, and line-broadening parameters. These results allowed us to establish a comparative framework to evaluate the physical properties and nature of O Vz stars relative to O V stars, and to explore whether these characteristics varied as a function of the metallicity of their environment.

The main findings are summarized below, followed by several conclusions based on these results.

7.1 On the Vz spectral feature and the stellar youth

The hypothesis that originally motivated the introduction of the “z” qualifier in the spectral classification of O-type dwarfs was based on the idea of an inverse Of effect—namely, that the unusually strong He II $\lambda 4686$ absorption was evidence of reduced wind infill in that line. Within this framework, O Vz objects appeared as less evolved than “normal” dwarfs and were therefore expected to be located closer to the ZAMS ([Walborn & Blades, 1997](#)).

Over the following years, this idea led some authors to associate the spectral Vz classification with ZAMS O stars. However, later studies of O V stars, both in 30 Doradus (Sabín-Sanjulián et al., 2014) and in the Milky Way (Arias et al., 2016), revealed a more complex scenario, demonstrating that the Vz feature does not depend exclusively on stellar winds; instead, certain combinations of physical parameters may favor or inhibit its appearance.

Nonetheless, the Vz subclass continued to be considered representative of the youngest objects in the O-type population. To explain the results in 30 Doradus, Sabín-Sanjulián et al. (2014) proposed a hypothesis related to environmental metallicity: low metallicity leads to weaker stellar winds, allowing the Vz feature to persist longer; consequently, in low-metallicity environments such as the Magellanic Clouds, a larger fraction of O Vz stars is expected, and many of them might display advanced ages.

To test this hypothesis, we examined the physical and evolutionary properties of O V and O Vz stars in environments with different metallicities, analyzing their distribution in the $\log g$ – $\log T_{\text{eff}}$, $\log Q$ – $\log T_{\text{eff}}$, and $\log(L/L_{\odot})$ – $\log T_{\text{eff}}$ diagrams. These diagrams allowed us to assess whether O Vz stars are indeed younger, exhibit lower luminosities, show higher surface gravities, and possess weaker winds than O V stars.

Based on this comparative analysis, we find that metallicity may influence the manifestation of the Vz feature, but its effect does not seem to follow the behavior anticipated by the hypothesis Sabín-Sanjulián et al. (2014). We do not observe an increase in the abundance of O Vz stars toward lower metallicities, nor a systematic concentration of Vz objects at more advanced evolutionary stages. Instead, each region shows a different internal age distribution, without a coherent global trend that can be attributed solely to metallicity. In NGC 3603, the highest-metallicity region, most Vz objects fall in the ~ 2 –3 Myr interval; in 30 Doradus, with intermediate metallicity, the number of Vz stars decreases toward older ages; and in NGC 346, some Vz stars appear at relatively evolved positions and other with ages ≤ 1 Myr. Figure 7.1.1 summarizes these differences across the three samples.

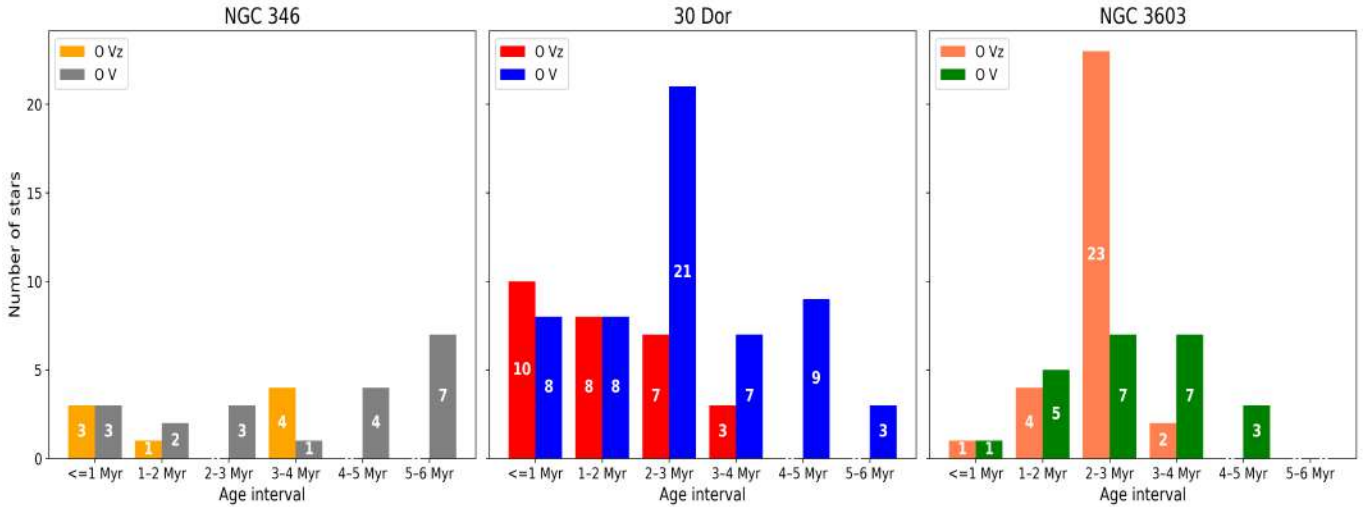


Figure 7.1.1: Age distribution of O V and O Vz stars in the studied regions. The numbers inside the bars indicate the number of stars in each category.

When considering the three regions together, approximately 21% of the O Vz stars have ages ≤ 1 Myr, while the majority of the sample ($\sim 65\%$) lies in the 1–3 Myr age range. For more evolved ages

(3–4 Myr), the fraction of O Vz stars remains low, representing only $\sim 14\%$ of the total O Vz population. When analysed by region, these older O Vz stars account for $\sim 7\%$ (2/30) of the O Vz population in NGC 3603, $\sim 11\%$ in 30 Doradus, and $\sim 50\%$ in NGC 346. Although these differences are noticeable, the comparison should be interpreted with caution given the small-number statistics in some regions.

At this point, it is essential to consider the limitations that may affect the interpretation of these age distributions. The samples from NGC 346 and NGC 3603 are relatively small, restricting our ability to extract firm population-level trends. In NGC 3603, the high extinction implies that part of the youngest population may remain undetected in the optical, potentially biasing the observed age distribution. In NGC 346, the scarcity of objects amplifies statistical fluctuations. In contrast, the 30 Dor sample is likely more complete (Evans et al., 2011), which may partly explain the clearer internal patterns observed there. Given these constraints, our data do not allow us to confirm or reject metallicity-dependent hypotheses regarding the persistence or prevalence of the Vz morphology.

Within these limitations, however, one conclusion does emerge robustly from all three regions. The O Vz morphology does not constitute a reliable indicator of proximity to the ZAMS. In every environment analyzed, Vz stars span an age range extending from very young objects up to ~ 4 Myr. Thus, while metallicity may influence the conditions under which the Vz morphology appears, it does not seem to play a crucial role in determining how long this feature persists in the spectrum. Expanding the samples and incorporating observations across multiple wavelength regimes will be essential to refining our understanding of how the Vz phenomenon depends on age, metallicity, and other environmental factors.

7.2 Are there systematic differences in the stellar parameters of the O V and O Vz populations?

Figure 7.2.1 shows the distribution of the main stellar parameters for the complete sample of O V and O Vz stars from the three studied regions, grouping all subclasses without distinguishing by metallicity. To construct these histograms, the bin width was estimated using the Freedman–Diaconis criterion (Freedman & Diaconis (1981), in order to obtain a statistically consistent representation and to avoid both oversmoothing and the loss of structure in the distributions.

In the spectral type (SpT) distribution, O Vz stars are distributed across intermediate subtypes, from approximately O5.5 to O8.5, whereas O V stars cover a broader range, including earlier subtypes. The distributions of projected rotational velocity ($v \sin i$) are qualitatively similar for both subclasses, characterized by the presence of both slow ($\leq 100 \text{ km s}^{-1}$) and fast ($\geq 200 \text{ km s}^{-1}$) rotators. O V and O Vz stars are represented in both regimes, with no evidence of rotational segregation between the subclasses. Although the highest rotational velocities are more common among O V stars (26 stars with $v \sin i \geq 200 \text{ km/s}$) than among O Vz stars (15 stars), the presence of a significant number of O Vz objects in this high- $v \sin i$ regime demonstrates that rapid rotation alone does not determine the appearance of the Vz spectral feature.

Regarding effective temperature (T_{eff}), O Vz stars are predominantly concentrated within intermediate and higher ranges. In contrast, O V stars display a broader spread, consistent with the findings of Sabín-Sanjulián et al. (2014). Surface gravities ($\log g$) show no significant differences between the subclasses, exhibiting substantial overlap; in particular, O Vz stars do not display higher values than normal O dwarfs.

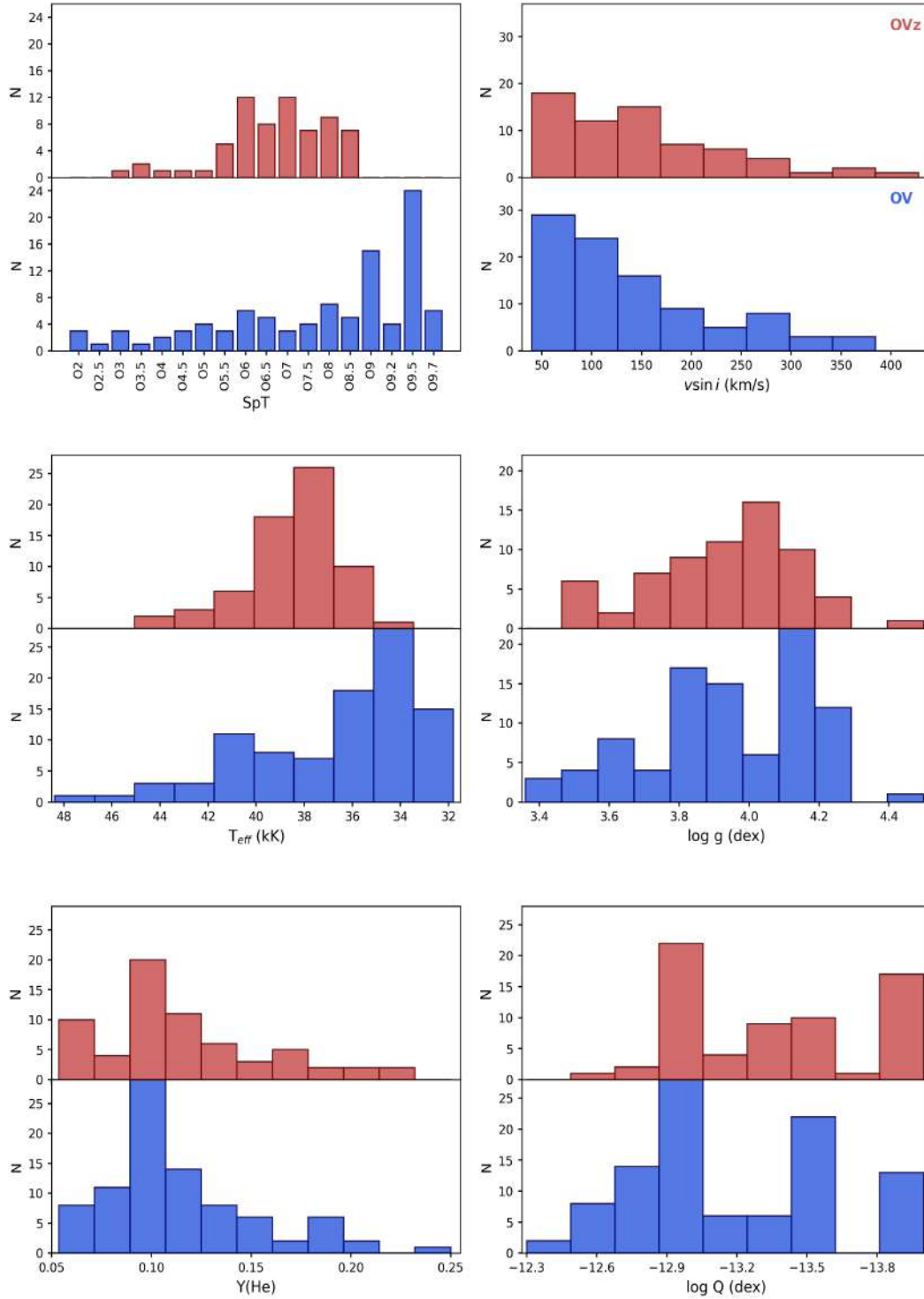


Figure 7.2.1: Distribution of the main stellar parameters for the complete sample of O V and O V z stars in the three studied regions. From left to right and top to bottom, the panels show: spectral type (SpT), projected rotational velocity ($v \sin i$), effective temperature (T_{eff}), surface gravity ($\log g$), surface helium abundance ($Y(\text{He})$), and wind-strength parameter ($\log Q$). All subclasses are grouped together without distinguishing metallicity.

Similarly, the helium surface abundance ($Y(\text{He})$) does not show systematic differences between O V and O Vz stars. The relation between $Y(\text{He})$ and $v \sin i$ (see Figs 5.2.3 and 6.3.6) reinforces this picture: both slow and fast rotators exhibit either low or high abundances, suggesting that the observed behavior does not correspond to a simple correlation between rotation and surface enrichment, nor does it support the existence of systematic differences between O V and O Vz in this parameter.

The stellar wind diagnostics display a pattern consistent with the previous results. The values of the $\log Q$ parameter span comparable ranges in both subclasses, without revealing apparent differences in wind strength, indicating that O dwarfs generally possess relatively weak winds.

7.2.1 Considerations on the limitations of the study

It is relevant to consider the limitations inherent to spectroscopic data and analysis methods, as these factors may introduce significant biases into spectral classification and the derivation of physical parameters. Nebular contamination in the Balmer and He I lines artificially reduces the depth of the absorption cores, leading to an underestimation of equivalent widths (EWs). This effect can bias the determination of stellar parameters such as T_{eff} , $\log g$, and helium abundance, and is particularly critical for the classification of Vz stars. A reduced EW of He I $\lambda 4471$ can make He II $\lambda 4686$ appear more dominant, thus introducing a bias that may result in erroneous Vz classification, increasing the total number of such objects in the spectral type range O7–O8.5.

Since this work employs spectra obtained at varying resolutions (see Tables ?? and 2.1.3), the analysis by Berlanas et al. (2017) is especially relevant. These authors show, based on comparisons between high-resolution spectra (IACOB-OWN, $R \gtrsim 25,000$) and low-resolution spectra (GOSSS, $R \sim 2,500$), that the derived fundamental parameters, such as T_{eff} and $\log g$, exhibit only minor variations associated with spectral resolution, and that these differences remain within the typical uncertainties of the analysis methods. In this sense, although our sample is not homogeneous in terms of resolution, the results of Berlanas et al. (2017) suggest that this condition does not significantly compromise the determination of stellar parameters.

Beyond the limitations of this study, the results presented in this Thesis indicate that the fundamental parameters of the O Vz population are, in general, comparable to those of O V stars. Likewise, not all O Vz stars are systematically less luminous than normal O dwarfs, and their radii fall within ranges similar to those of O V stars, with no evidence of a tendency toward smaller values.

7.3 Future work

A natural extension of this work is to increase the level of detail in the spectral analysis by obtaining higher-resolution spectra with broader wavelength coverage. Although the results of Berlanas et al. (2017) indicate that resolution does not introduce significant systematic variations in parameters such as T_{eff} and $\log g$, a higher resolution ($R \gtrsim 10,000$) would allow for a more precise characterization of the line-profile shapes and a better separation of the different broadening sources, for example, distinguishing more clearly the rotational component from non-rotational contributions such as macroturbulence, which translates into more robust determinations of $v \sin i$. In parallel, an extended spectral range reduces the uncertainties in the fundamental parameters by increasing the number of available diagnostic lines

([Berlanas et al., 2017](#)).

In this context, NGC 3603 is an ideal environment to deepen quantitative spectral analysis and to expand the sample across multiple wavelength ranges. The acquisition of high-resolution optical spectra will enable a more detailed characterization of the line profiles and a clearer separation of the various broadening mechanisms, as well as improving the diagnostics of weak winds. Likewise, incorporating ultraviolet observations is essential, as this range provides access to resonance lines that are highly sensitive to wind structure and mass-loss rate, allowing for a more robust characterization of the weak-wind regime. Complementarily, near-infrared information will increase the completeness of the sample by enabling the identification and analysis of very young massive stars that remain hidden in the optical due to strong extinction; moreover, relevant diagnostic lines for quantitative analysis remain accessible in this range. In this way, a multi-band strategy will support progress toward a more complete and homogeneous characterization of the massive-star population in NGC 3603.

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Appendix A

Tables

Table A.0.1: Stellar sample in NGC 346.

Star	Identifier	RA (J2000)	Dec (J2000)	V	Spectral Type	Comments
NGC 346-06 [†]	MPG 342	00:59:00.01	-72:10:37.7	13.66	O5-6 V((f)) (1–7)	Binary (SB3) (7)
NGC 346-09 [†]	MPG 324	00:58:57.36	-72:10:33.4	14.02	O4 V((f+)) (3)	Binary (4)
NGC 346-10	MPG 368	00:59:01.77	-72:10:30.9	14.18	O5.5 V((f+)) (1); O4-5 V((f)) (2); O6 V((f)) (7)	
NGC 346-13	MPG 487	00:59:06.71	-72:10:41.0	14.53	O8 V (1)	
NGC 346-15	MPG 396	00:59:02.88	-72:10:34.7	14.39	O7 V (1)	
NGC 346-16 [†]	MPG 470	00:59:05.94	-72:10:33.6	13.78	O8.5 III (1); O8 V (8)	Eclipsing Binary (8)
NGC 346-17	MPG 476	00:59:06.16	-72:10:33.3	14.19	O6 V (8)	
NGC 346-20	MPG 602	00:59:12.28	-72:11:07.7	14.68	O7 V (1); O6.5 V((f)) (7)	
NGC 346-21	MPG 615	00:59:12.66	-72:11:08.8	14.52	O8 V (1); O7 V (7)	
NGC 346-23	MPG 417	00:59:03.93	-72:10:50.9	15.02	O7.5 V((f)) (1–7); O7.5 Vz (8)	
NGC 346-26 [†]	MPG 495	00:59:07.29	-72:10:25.1	15.13	O8 V (1); O9 V (7)	Binary (SB2), this work
NGC 346-29	MPG 370	00:59:01.86	-72:10:43.1	15.03	O9.5 V (1–7)	Binary (SB1) (7)
NGC 346-31	MPG 655	00:59:15.48	-72:11:11.4	14.82	O6 V (1); O5 V+OB (5); OC5-6 Vz (7)	
NGC 346-32	MPG 549	00:59:09.80	-72:10:58.8	15.26	O8 V (1); O9.5 V (7)	
NGC 346-35 ^{†♦}	MPG 508	00:59:08.11	-72:10:45.1	15.51	—	—
NGC 346-37	MPG 593	00:59:11.61	-72:09:57.3	14.95	O5.5 V (1); O8 V (3)	High Mass X-ray Binary (6)
NGC 346-38	MPG 330	00:58:58.74	-72:10:51.1	15.20	O7.5 V (1); O9 V (7)	
NGC 346-41	MPG 455	00:59:05.41	-72:10:42.1	15.25	O9.5 V (1–5); B0 V (7)	
NGC 346-44	MPG 500	00:59:07.59	-72:10:48.1	15.33	O6 V (1); O8 Vn (7)	
NGC 346-48	MPG 445	00:59:04.76	-72:11:02.7	15.33	O8 V (1)	Binary (SB1) (7)
NGC 346-54	MPG 356	00:59:00.92	-72:11:09.0	15.50	O6.5 V (1); O6.5 Vz (7)	
NGC 346-56	MPG 561	00:59:10.43	-72:10:46.8	15.34	O8 V (1–7)	
NGC 346-57	MPG 523	00:59:08.65	-72:10:13.9	15.50	O7 Vz (3)	
NGC 346-58	MPG 375	00:59:02.02	-72:10:36.0	15.47	O9.5 V (8)	
NGC 346-61	MPG 557	00:59:10.25	-72:10:42.4	15.89	O9.5 V (1–7)	
NGC 346-75 [†]	MPG 519	00:59:08.50	-72:11:12.4	16.05	O9 V (1–3)	Binary (SB2), this work
NGC 346-76 ^{†♦}	MPG 427	00:59:04.20	-72:10:25.2	15.97	—	—
NGC 346-77	MPG 529	00:59:08.92	-72:11:10.2	16.11	O7.5 V((f)) (1)	
NGC 346-83	MPG 429	00:59:04.23	-72:10:26.9	16.01	O9.5 V (8)	
NGC 346-85 [♦]	MPG 371	00:59:01.87	-72:10:41.4	15.60	—	—
NGC 346-96 ^{†♦}	MPG 366	00:59:01.64	-72:10:43.6	15.77	—	—
NGC 346-1034	Star 1034	00:59:12.81	-72:10:52.3	15.02	O9.5–B0 V (7)	
NGC 346-1051 [†]	Star 1051	01:00:13.61	-72:12:44.6	15.22	O9 V (7)	Binary (SB2), this work
NGC 346-1067	Star 1067	00:58:22.90	-72:17:51.4	15.53	O9 V (7)	
NGC 346-1094	Star 1094	00:59:15.87	-72:11:10.7	15.76	O8 V (7)	
NGC 346-1114	Star 1114	01:00:18.26	-72:07:51.8	15.98	O9 V (7)	
NGC 346-1144	Star 1144	00:59:11.66	-72:14:24.7	16.23	O9.5 V (7)	

[†] Stars not considered in our analysis.

[♦] Stars that had no previous spectral classification.

Cross-references to identifiers are listed in the second column: MPG (Massey et al., 1989), Star # (Dufton et al., 2019).

(1) Massey et al. (1989); (2) Walborn et al. (2000); (3) Evans et al. (2006); (4) Mokiem et al. (2006); (5) Heydari-Malayeri & Selier (2010); (6) Antoniou et al. (2019); (7) Dufton et al. (2019); (8) Rickard et al. (2022).

It is worth noting that works prior to Rickard et al. (2022) did not apply the quantitative classification criteria for the O Vz spectral subclass, and therefore the classification of such stars in these references should be considered with caution.

Star	He I $\lambda 4471$		He II $\lambda 4542$		He II $\lambda 4686$		z	Spectral Type
	EW	σ	EW	σ	EW	σ		
NGC 346-10	0.26	0.01	0.72	0.01	0.73	0.01	1.02	O5.5 V((f+))
NGC 346-13	0.46	0.01	0.42	0.01	0.73	0.01	1.58	O8 Vz
NGC 346-15	0.46	0.01	0.99	0.01	0.84	0.01	0.86	O6.5 V
NGC 346-17	0.64	0.01	0.20	0.01	0.44	0.01	0.69	O9.2 V
NGC 346-20	0.42	0.01	1.00	0.01	0.77	0.01	0.77	O7 V
NGC 346-21	0.55	0.01	0.48	0.01	0.62	0.01	1.10	O7 Vz
NGC 346-23	0.60	0.01	0.59	0.01	0.79	0.01	1.32	O7.5 Vz
NGC 346-29	0.80	0.01	0.78	0.01	0.53	0.01	0.66	O9.5 V
NGC 346-31	0.26	0.01	0.77	0.01	0.87	0.01	1.13	O5.5 Vz
NGC 346-32	0.77	0.01	0.41	0.01	0.55	0.01	0.72	O9.5 V
NGC 346-37	0.49	0.03	1.03	0.01	0.69	0.01	0.67	O8 V
NGC 346-38	0.74	0.01	0.71	0.02	0.75	0.01	1.01	O9 V
NGC 346-41	0.80	0.01	0.33	0.01	0.50	0.01	0.62	O9.5 V
NGC 346-44	0.73	0.01	1.14	0.01	0.85	0.01	0.75	O8 Vn
NGC 346-48	0.63	0.01	0.77	0.01	0.75	0.01	0.98	O8 V
NGC 346-54	0.43	0.01	1.01	0.01	0.96	0.01	0.95	O6.5 V
NGC 346-56	0.70	0.01	0.78	0.01	0.81	0.01	1.04	O8 V
NGC 346-57	0.52	0.02	0.78	0.01	0.93	0.02	1.19	O7 Vz
NGC 346-58	0.86	0.01	0.40	0.01	0.64	0.01	0.74	O9.5 V
NGC 346-61	0.70	0.02	0.36	0.02	0.65	0.02	0.93	O9.5 V
NGC 346-77	0.59	0.01	0.61	0.02	0.71	0.01	1.16	O7.5 Vz
NGC 346-83	0.83	0.01	0.27	0.01	0.48	0.01	0.57	O9.5 V
NGC 346-85	0.77	0.01	0.12	0.01	0.40	0.01	0.52	O9.7 V
NGC 346-1034	0.77	0.01	0.38	0.01	0.49	0.01	0.63	O9 V
NGC 346-1067	0.30	0.01	0.44	0.02	0.70	0.02	1.51	O8.5 Vz
NGC 346-1094	0.58	0.02	0.50	0.01	0.68	0.01	1.18	O8 Vz
NGC 346-1114	0.69	0.02	0.30	0.02	0.58	0.02	0.84	O9 V
NGC 346-1144	0.46	0.02	0.28	0.01	0.47	0.01	1.01	O9.5 V

Table A.0.2: Measured equivalent widths (with their errors) of the spectral lines of He I and He II, along with the assigned parameter z to identify the spectral feature Vz in the analyzed stars in NGC 346.

Table A.0.3: Measured equivalent widths (with their errors) of the spectral lines of He I and He II, along with the assigned parameter z to identify the spectral feature Vz in the analyzed stars in 30 Doradus.

Star	He I $\lambda 4471$		He II $\lambda 4542$		He II $\lambda 4686$		z	Spectral Type
	EW	σ	EW	σ	EW	σ		
14	0.61	0.01	0.54	0.01	0.75	0.01	1.23	O8.5 Vz
65	0.64	0.02	0.59	0.02	0.83	0.02	1.30	O8 V(n)z
67	0.62	0.02	0.31	0.02	0.66	0.02	1.07	O9.5 V
74	0.89	0.02	0.41	0.02	0.66	0.02	0.74	O9 Vn
89	0.54	0.01	0.83	0.01	1.03	0.02	1.24	O6.5 V((f))z Nstr
96	0.48	0.01	0.77	0.01	0.77	0.01	1.00	O6 V((n))((fc))
110	0.31	0.01	0.52	0.01	0.72	0.01	1.39	O6 V((n))z
117	0.41	0.01	0.78	0.02	0.99	0.02	1.27	O6 Vz
123	0.46	0.01	0.85	0.01	1.08	0.01	1.27	O6.5 Vz
130	0.73	0.02	0.38	0.01	0.66	0.02	0.90	O8.5 V((n))
132	0.68	0.01	0.45	0.01	0.72	0.01	1.05	O9.5 V
138	3.01	0.02	0.40	0.01	0.67	0.01	0.22	O9 Vn
149	0.82	0.02	0.40	0.02	0.69	0.02	0.84	O9.5 V
154	0.77	0.01	0.59	0.01	0.72	0.01	0.94	O8.5 V
168	0.73	0.01	0.69	0.01	0.92	0.01	1.26	O8.5 Vz
169	0.11	0.01	0.63	0.01	0.33	0.01	0.53	O2.5 V(n)((f*))
216	0.13	0.01	0.73	0.01	0.72	0.01	0.99	O4 V((fc))
249	0.73	0.01	0.63	0.01	0.81	0.01	1.06	O8 Vnz
250	0.78	0.01	0.39	0.01	0.67	0.01	0.85	O9.2 V((n))
252	0.65	0.01	0.65	0.01	0.90	0.01	1.38	O8.5 Vz
266	0.64	0.01	0.69	0.01	0.79	0.01	1.14	O8 V((f))z
280	0.81	0.01	0.45	0.01	0.66	0.01	0.82	O9 V((n))
285	0.75	0.01	0.61	0.01	0.78	0.01	1.03	O7.5 Vnnn
355	0.19	0.01	0.76	0.01	0.78	0.01	1.03	O4 V((n))((fc))
356	0.48	0.01	0.71	0.01	0.87	0.01	1.24	O6 V(n)z
361	0.49	0.01	0.43	0.01	0.55	0.01	1.14	O8.5 Vz
369	0.49	0.01	0.13	0.01	0.42	0.01	0.86	O9.7 V
380	0.25	0.01	0.64	0.01	0.90	0.01	1.42	O6-7 Vz
382	1.45	0.01	0.74	0.01	0.89	0.01	0.62	O4-5 V((fc))
385	0.19	0.01	0.71	0.01	0.56	0.01	0.78	O4-5 V((n))((fc))
392	0.29	0.01	0.62	0.01	0.77	0.01	1.24	O6-7 V((f))z
398	0.39	0.01	0.64	0.01	0.74	0.01	1.16	O5.5 V((n))((f))z
418	0.24	0.01	0.78	0.02	0.93	0.01	1.19	O5 V((n))((fc))z
419	0.75	0.01	0.39	0.01	0.57	0.01	0.75	O9 V(n)
468	0.18	0.01	0.64	0.01	0.54	0.01	0.84	O2 V((f*))+OB
470	0.18	0.01	0.70	0.01	0.85	0.01	1.22	O6 V((f))z
472	0.28	0.01	0.80	0.01	0.94	0.01	1.17	O6 Vz
483	0.66	0.01	0.23	0.01	0.39	0.01	0.59	O9 V
484	0.47	0.01	0.47	0.01	0.40	0.01	0.86	O6-7 V((n))
488	0.32	0.01	0.72	0.01	0.78	0.01	1.07	O6 V((f))
491	0.34	0.01	0.72	0.01	0.70	0.01	0.97	O6 V((fc))
493	0.57	0.01	0.45	0.01	0.57	0.01	1.01	O9 V
494	0.67	0.02	0.66	0.02	0.85	0.01	1.27	O8 V(n)z
506	0.22	0.01	0.78	0.01	0.62	0.01	0.80	ON2 V((n))((f*))
498	0.98	0.01	0.21	0.02	0.38	0.01	0.39	O9.5 V
511	0.30	0.01	0.90	0.01	0.96	0.01	1.07	O5 V((n))((fc))
521	0.74	0.01	0.43	0.01	0.61	0.01	0.82	O9 V(n)
536	0.33	0.02	0.67	0.01	0.83	0.02	1.24	O6 Vz
537	0.17	0.01	0.64	0.01	0.44	0.01	0.70	O5 V((fc))
549	0.46	0.01	0.67	0.02	0.92	0.02	1.38	O6.5 Vz
550	2.11	0.01	0.78	0.01	0.82	0.01	0.39	O5 V((fc))

Table A.0.3: continued.

Star	He I $\lambda 4471$		He II $\lambda 4542$		He II $\lambda 4686$		z	Spectral Type
	EW	σ	EW	σ	EW	σ		
554	0.65	0.02	0.24	0.02	0.41	0.01	0.63	O9.7 V
560	0.63	0.01	0.17	0.01	0.49	0.01	0.78	O9.5 V
560	0.63	0.01	0.17	0.01	0.49	0.01	0.78	O9.5 V
577	0.92	0.01	0.69	0.02	0.81	0.01	0.88	O5 V((fc))
581	1.32	0.01	0.65	0.01	0.71	0.01	0.54	O4-5 V((fc))
582	0.64	0.02	0.24	0.01	0.55	0.02	0.86	O9.5 V((n))
586	0.05	0.01	0.81	0.01	0.92	0.01	1.13	O4 V((n))((fc))z
592	1.03	0.02	0.24	0.02	0.40	0.02	0.39	O9.5 Vn
597	0.76	0.01	0.52	0.01	0.75	0.01	0.99	O8-9 V(n)
601	0.32	0.01	0.76	0.01	0.82	0.01	1.08	O5-6 V((n))
611	0.66	0.01	0.72	0.01	0.87	0.01	1.19	O8 V(n)z
621	1.58	0.01	0.51	0.01	0.62	0.01	0.39	O2 V((f*))
627	0.88	0.01	0.24	0.01	0.54	0.01	0.61	O9.7 V
638	0.69	0.01	0.66	0.01	0.91	0.01	1.32	O8.5 Vz
639	0.93	0.01	0.25	0.01	0.51	0.01	0.55	O9.7 V
649	0.73	0.01	0.35	0.01	0.61	0.01	0.84	O9.5 V
660	0.95	0.02	0.25	0.02	0.44	0.01	0.46	O9.5 Vnn
677	0.52	0.02	0.27	0.02	0.53	0.02	1.02	O9.5 V
679	0.56	0.02	0.19	0.01	0.36	0.01	0.65	O9.5 V
704	0.76	0.02	0.33	0.01	0.62	0.02	0.81	O9.2 V(n)
706	0.53	0.01	0.74	0.01	0.81	0.01	1.09	O6-7 Vnn
722	0.70	0.01	0.66	0.01	0.89	0.01	1.28	O7 Vnnz
724	0.40	0.02	0.81	0.04	0.83	0.04	1.02	O7 Vnn
746	0.45	0.01	0.73	0.01	0.63	0.01	0.87	O6 Vnn
751	0.66	0.02	0.62	0.02	0.89	0.02	1.35	O7-8 Vnnz
755	0.69	0.01	0.72	0.01	0.76	0.01	1.06	O3 Vn((f*))
761	0.66	0.01	1.11	0.01	1.14	0.01	1.02	O6.5 V((n))((f)) Nstr
768	0.74	0.02	0.52	0.02	0.64	0.02	0.86	O8 Vn
770	0.63	0.02	0.75	0.02	0.86	0.02	1.15	O7 Vnnz
775	0.89	0.02	0.46	0.02	0.70	0.02	0.79	O9.2 V
778	0.81	0.03	0.21	0.02	0.53	0.03	0.66	O9.5 V
797	0.50	0.01	0.76	0.01	0.73	0.01	0.96	O3.5 V((n))((fc))
849	0.59	0.01	0.82	0.01	1.03	0.01	1.26	O7 Vz
892	0.86	0.01	0.54	0.01	0.80	0.01	0.93	O9 V

Table A.0.4: NGC 3603 stars.

Star	RA (J2000)	Dec (J2000)	V	Spectral Type
NGC 3603-16	11:15:07.825	-61:15:37.84	13.55	O3 V (1); O3 V((f)) (3)
NGC 3603-101	11:15:07.068	-61:15:45.32	14.03	O6.5 V((f)) (2); O6.5 Vz (3)
NGC 3603-102	11:15:08.073	-61:15:34.24	15.32	O8.5 V (2); O8.5 V/O9c (3)
NGC 3603-103 [†]	11:15:06.237	-61:15:36.58	13.11	O3 V((f)) (2); O3 III((f*)) (3)
NGC 3603-108	11:15:08.513	-61:15:38.30	13.72	O5.5 V (2); O4.5 V (3)
NGC 3603-109	11:15:06.588	-61:15:40.40	13.89	O7 V (2); O8 V (3)
NGC 3603-116	11:15:07.593	-61:15:35.96	14.13	O3.5 V((f)), (3)
NGC 3603-117	11:15:07.623	-61:15:30.24	14.17	O6 V (2); O5.5 V((f))z (3)
NGC 3603-120	11:15:07.211	-61:15:41.50	14.37	O6 V (3)
NGC 3603-124	11:15:06.815	-61:15:33.95	14.54	O6 V (3)
NGC 3603-125	11:15:07.630	-61:15:31.35	14.51	O6 V((f))
NGC 3603-128	11:15:06.422	-61:15:36.42	14.78	O9 V (3)
NGC 3603-135	11:15:08.106	-61:15:40.30	14.76	O8 V (3)
NGC 3603-208	11:15:09.503	-61:15:46.37	14.16	O5 V
NGC 3603-210	11:15:10.654	-61:16:20.00	14.52	O7 V (3)
NGC 3603-212	11:15:08.085	-61:16:03.46	14.69	O5.5 V
NGC 3603-213	11:15:11.392	-61:15:45.49	14.83	O9 V
NGC 3603-214	11:15:12.902	-61:16:06.81	14.97	O5.5 V (3)
NGC 3603-215	11:15:08.756	-61:15:45.45	15.13	O7 V (3)
NGC 3603-216	11:15:04.542	-61:15:49.09	15.15	O7.5 V (3)
NGC 3603-217	11:15:05.661	-61:15:27.03	15.17	O7 V
NGC 3603-218	11:14:59.784	-61:15:24.77	15.20	O6.5 V (3)
NGC 3603-219	11:15:07.897	-61:15:50.73	15.24	O8 V (3)
NGC 3603-220	11:15:10.251	-61:15:38.20	15.25	O7.5 V (3)
NGC 3603-222	11:15:03.525	-61:15:46.26	15.52	O9.7 V (3)
NGC 3603-226 [♦]	11:15:12.761	-61:15:44.81	15.88	—
NGC 3603-305	11:15:06.749	-61:15:42.43	13.87	O3.5 V (3)
NGC 3603-308	11:15:06.707	-61:15:32.42	14.15	O6 V((f)) (3)
NGC 3603-313	11:15:08.690	-61:15:39.01	14.62	O6 V (3)
NGC 3603-326	11:15:07.772	-61:15:46.51	15.41	O8.5 V
NGC 3603-330 [♦]	11:15:07.429	-61:15:43.36	15.50	—
NGC 3603-334	11:15:06.661	-61:15:52.77	15.83	O9.5 V (3)
NGC 3603-901	11:15:16.184	-61:15:57.79	15.38	O7.5 Vz
NGC 3603-902	11:15:12.238	-61:15:25.55	15.64	O7 V
NGC 3603-904	11:15:14.137	-61:15:20.85	15.14	O7 V
NGC 3603-905	11:15:00.689	-61 15:01.88	15.30	O5.5 V((f))z
NGC 3603-908	11:15:13.835	-61:16:29.36	15.66	O7 V
NGC 3603-910	11:15:21.802	-61:16:53.59	15.18	O7 V((f))
NGC 3603-911 [♦]	11:15:03.608	-61:16:00.59	15.87	—
NGC 3603-1059 [♦]	11:15:12.565	-61:16:10.15	16.02	—
NGC 3603-1065 [♦]	11:15:14.514	-61:14:53.91	16.07	—
NGC 3603-1076 ^{†♦}	11:15:13.879	-61:15:58.34	16.15	—
NGC 3603-1088 [♦]	11:15:24.175	-61:15:57.56	16.25	—
NGC 3603-1095 [♦]	11:15:22.697	-61:15:52.12	16.31	—
NGC 3603-1096 [♦]	11:15:01.356	-61:15:01.32	16.31	—
NGC 3603-1108 [♦]	11:15:17.606	-61:14:52.84	16.39	—
NGC 3603-1111 [♦]	11:15:22.449	-61:14:58.62	16.41	—
NGC 3603-Sh19	11:15:11.317	-61:15:55.63	13.69	O3 V((f)) (2-3)
NGC 3603-Sh21	11:15:11.074	-61:15:36.85	14.82	O6 V((f)) (2)
NGC 3603-Sh27	11:15:03.921	-61:15:23.06	15.09	O7.5 V (2)
NGC 3603-Sh47 [†]	11:15:09.353	-61:16:02.07	12.75	O4 V (2); O3.5 III(f) (3)
NGC 3603-Sh49	11:15:09.129	-61:15:33.18	14.67	O7.5 V (2)

Table A.0.4: continued.

Star	RA (J2000)	Dec (J2000)	V	Spectral Type
NGC 3603-Sh53	11:15:07.148	-61:15:54.86	14.53	O8.5 V (2)
NGC 3603-Sh54	11:15:03.976	-61:15:35.72	14.62	O6 V (2)
NGC 3603-Sh58	11:15:08.699	-61:15:44.49	14.99	O8 Ve (2)
NGC 3603-Sh64	11:15:07.822	-61:15:27.93	13.59	O3 V((f)) (2)

† Stars not considered in our analysis.

♦ Stars that had no previous spectral classification.

Spectral Type references: (1) [Drissen et al. \(1995\)](#); (2) [Melena et al. \(2008\)](#); (3) [Massey et al. \(2025\)](#).

Table A.0.5: Measured equivalent widths (with their errors) of the spectral lines of He I and He II, along with the assigned parameter z to identify the spectral feature Vz in the analyzed stars in NGC 3603.

Star	He I $\lambda 4471$		He II $\lambda 4542$		He II $\lambda 4686$		z	Spectral Type
	EW	σ	EW	σ	EW	σ		
NGC 3603-16	0.03	0.01	0.87	0.01	0.62	0.01	0.71	O3 V((f))
NGC 3603-101	0.45	0.01	0.61	0.01	0.81	0.01	1.32	O6.5 Vz
NGC 3603-102	0.80	0.02	0.49	0.02	0.71	0.02	0.88	O8.5 V
NGC 3603-108	0.28	0.01	0.70	0.01	1.03	0.01	1.45	O4.5 Vz
NGC 3603-109	0.47	0.01	0.61	0.01	0.83	0.01	1.34	O8 Vz
NGC 3603-116	0.14	0.01	0.94	0.02	1.16	0.02	1.23	O3.5 V((f))z
NGC 3603-117	0.34	0.01	0.75	0.02	0.89	0.01	1.19	O5.5 V((f))z
NGC 3603-120	0.24	0.02	0.85	0.03	0.95	0.02	1.11	O6 Vz
NGC 3603-124	0.63	0.01	0.25	0.01	0.50	0.01	0.79	O6 V
NGC 3603-125	0.42	0.02	0.70	0.02	0.79	0.02	1.13	O6 V((f))z
NGC 3603-128	0.88	0.01	0.43	0.01	0.36	0.01	0.40	O9 V
NGC 3603-135	0.77	0.03	0.98	0.02	0.92	0.02	0.94	O8 V
NGC 3603-208	0.21	0.01	0.75	0.02	0.72	0.02	0.96	O5 V
NGC 3603-210	0.57	0.02	0.58	0.02	0.77	0.02	1.32	O7 Vz
NGC 3603-212	0.35	0.03	0.86	0.03	0.89	0.03	1.03	O5.5 V
NGC 3603-213	0.78	0.03	0.42	0.02	0.57	0.02	0.72	O9 V
NGC 3603-214	0.40	0.03	0.77	0.03	0.95	0.04	1.22	O5.5 Vz
NGC 3603-215	0.43	0.02	0.36	0.02	0.73	0.02	1.70	O7 Vz
NGC 3603-216	0.30	0.03	0.82	0.05	0.90	0.03	1.09	O7.5 V
NGC 3603-217	0.70	0.02	0.87	0.03	0.81	0.02	0.92	O7 V
NGC 3603-218	0.53	0.01	0.51	0.01	0.84	0.01	1.57	O6.5 Vz
NGC 3603-219	0.96	0.01	0.30	0.01	0.84	0.01	0.87	O8 V
NGC 3603-220	0.83	0.02	0.25	0.02	0.63	0.02	0.75	O7.5 V
NGC 3603-222	0.67	0.02	0.29	0.02	0.60	0.02	0.88	O9.7 V
NGC 3603-226	0.85	0.04	0.06	0.02	0.35	0.02	0.40	O9.5 V
NGC 3603-305	0.19	0.02	0.52	0.02	0.73	0.02	1.40	O3.5 Vz
NGC 3603-308	0.34	0.01	0.59	0.01	0.83	0.01	1.41	O6 V((f))z
NGC 3603-313	0.89	0.02	0.78	0.02	1.16	0.02	1.31	O6 Vz
NGC 3603-326	0.54	0.01	0.36	0.01	0.60	0.01	1.12	O8.5 Vz
NGC 3603-330	1.16	0.01	0.28	0.02	0.17	0.01	0.14	O9.5 V
NGC 3603-334	0.63	0.02	0.28	0.02	0.61	0.02	0.96	O9.5 V
NGC 3603-901	0.55	0.01	0.51	0.01	0.83	0.01	1.51	O7.5 Vz
NGC 3603-902	0.69	0.02	0.59	0.03	0.93	0.03	1.33	O7 Vz
NGC 3603-904	0.26	0.01	0.55	0.02	0.72	0.02	1.30	O7 Vz
NGC 3603-905	0.48	0.01	0.40	0.01	0.74	0.01	1.54	O5.5 V((f))z
NGC 3603-908	0.42	0.04	0.57	0.05	1.09	0.05	1.91	O7 Vz
NGC 3603-910	0.43	0.01	0.62	0.01	0.84	0.01	1.34	O7 V((f))z
NGC 3603-911	0.69	0.04	0.25	0.03	0.63	0.03	0.91	O9 V
NGC 3603-1059	0.88	0.05	0.26	0.02	0.38	0.04	0.43	O9.5 V
NGC 3603-1065	0.38	0.02	0.61	0.03	0.83	0.03	1.37	O6.5 Vz
NGC 3603-1088	0.87	0.03	0.41	0.03	0.65	0.03	0.75	O9 V
NGC 3603-1095	0.80	0.03	0.20	0.03	0.61	0.02	0.76	O9.5 V
NGC 3603-1096	0.49	0.04	0.58	0.03	0.88	0.04	1.52	O7 Vz
NGC 3603-1108	0.61	0.02	0.54	0.02	0.80	0.02	1.31	O7.5 Vz
NGC 3603-1111	0.60	0.02	0.59	0.02	0.77	0.02	1.29	O7.5 Vz
NGC 3603-Sh19	0.00	0.00	0.68	0.02	0.54	0.02	0.79	O3 V((f))
NGC 3603-Sh21	0.41	0.01	0.74	0.02	0.94	0.02	1.27	O6 V((f))z
NGC 3603-Sh27	0.72	0.01	0.61	0.01	0.83	0.01	1.15	O7.5 Vz
NGC 3603-Sh49	0.93	0.02	0.56	0.02	0.67	0.02	0.72	O7.5 V

Table A.0.5: continued.

Star	He I $\lambda 4471$		He II $\lambda 4542$		He II $\lambda 4686$		z	Spectral Type
	EW	σ	EW	σ	EW	σ		
NGC 3603-Sh53	0.71	0.01	0.51	0.02	0.68	0.02	0.96	O8.5 V
NGC 3603-Sh54	0.29	0.01	0.62	0.01	0.96	0.01	1.54	O6 Vz
NGC 3603-Sh58	0.75	0.01	0.56	0.01	0.86	0.01	1.14	O8 Vze
NGC 3603-Sh64	0.00	0.00	0.62	0.01	0.71	0.01	1.14	O3 V((f))z

Appendix B

Figures

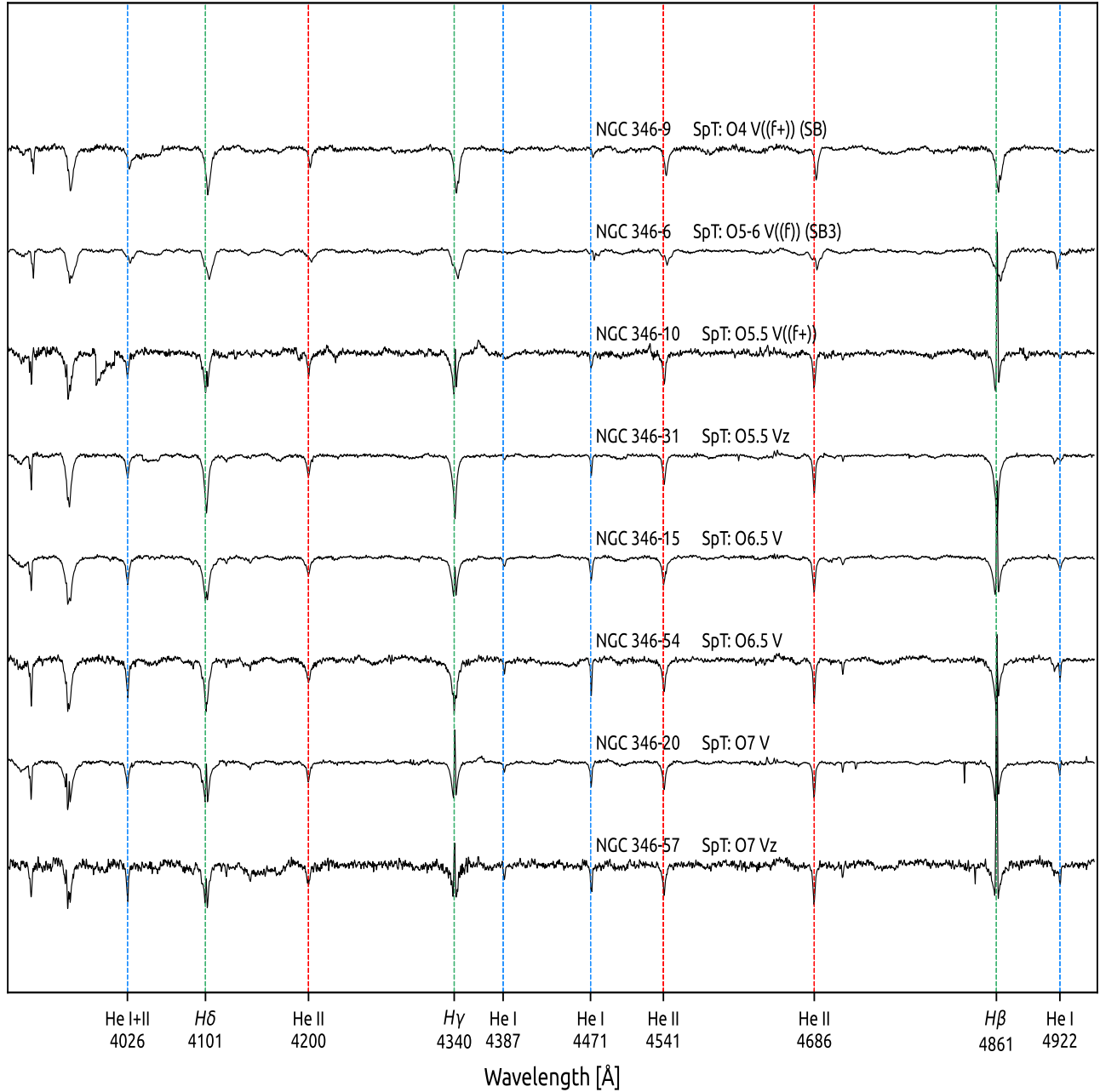


Figure B.0.1: Normalized spectra of the analyzed stars in NGC 346. The principal He I, He II, and Balmer lines employed in the quantitative analysis are indicated. The corresponding spectral types are displayed next to each stellar identifier.

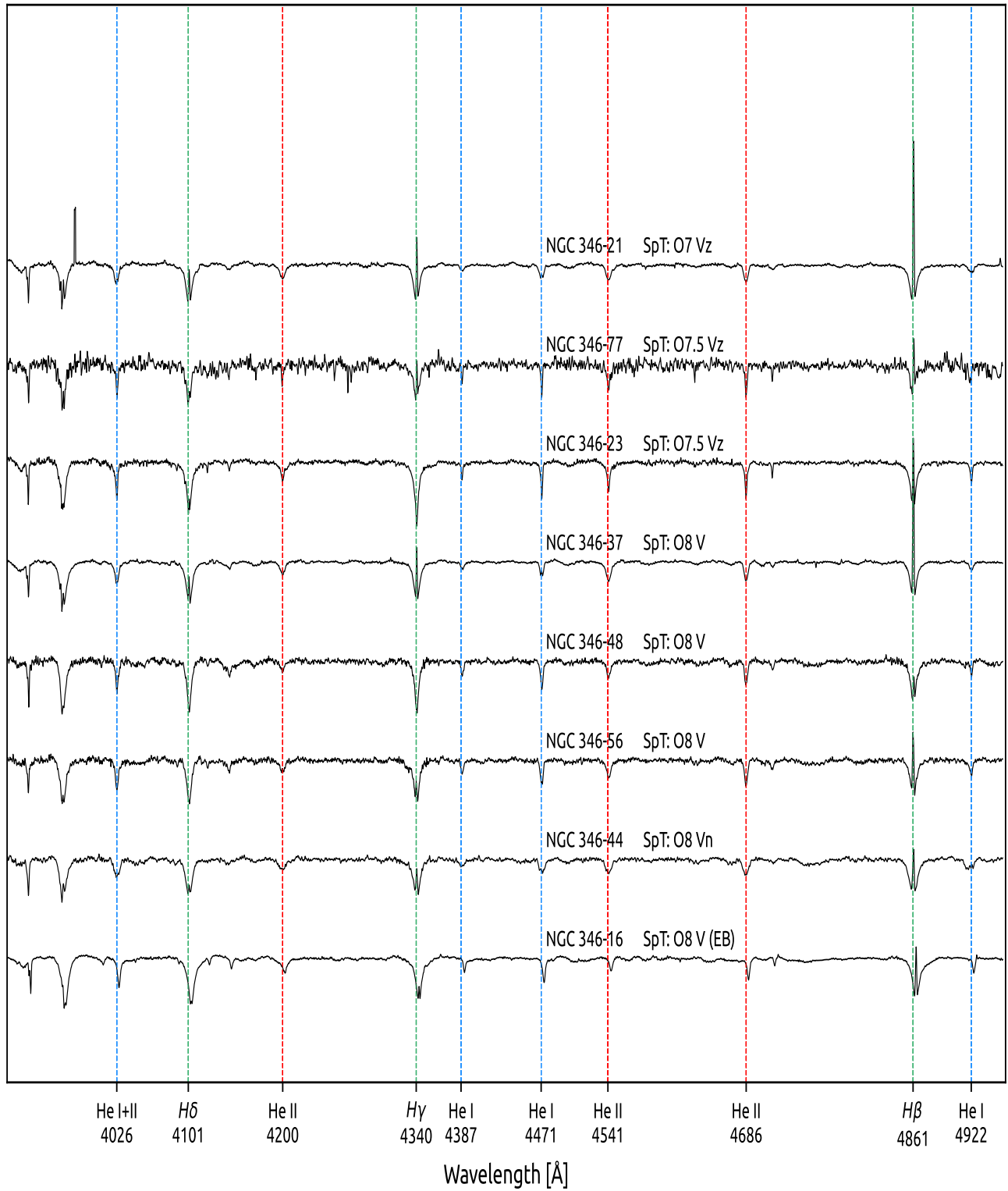


Fig. B.0.1 continued.

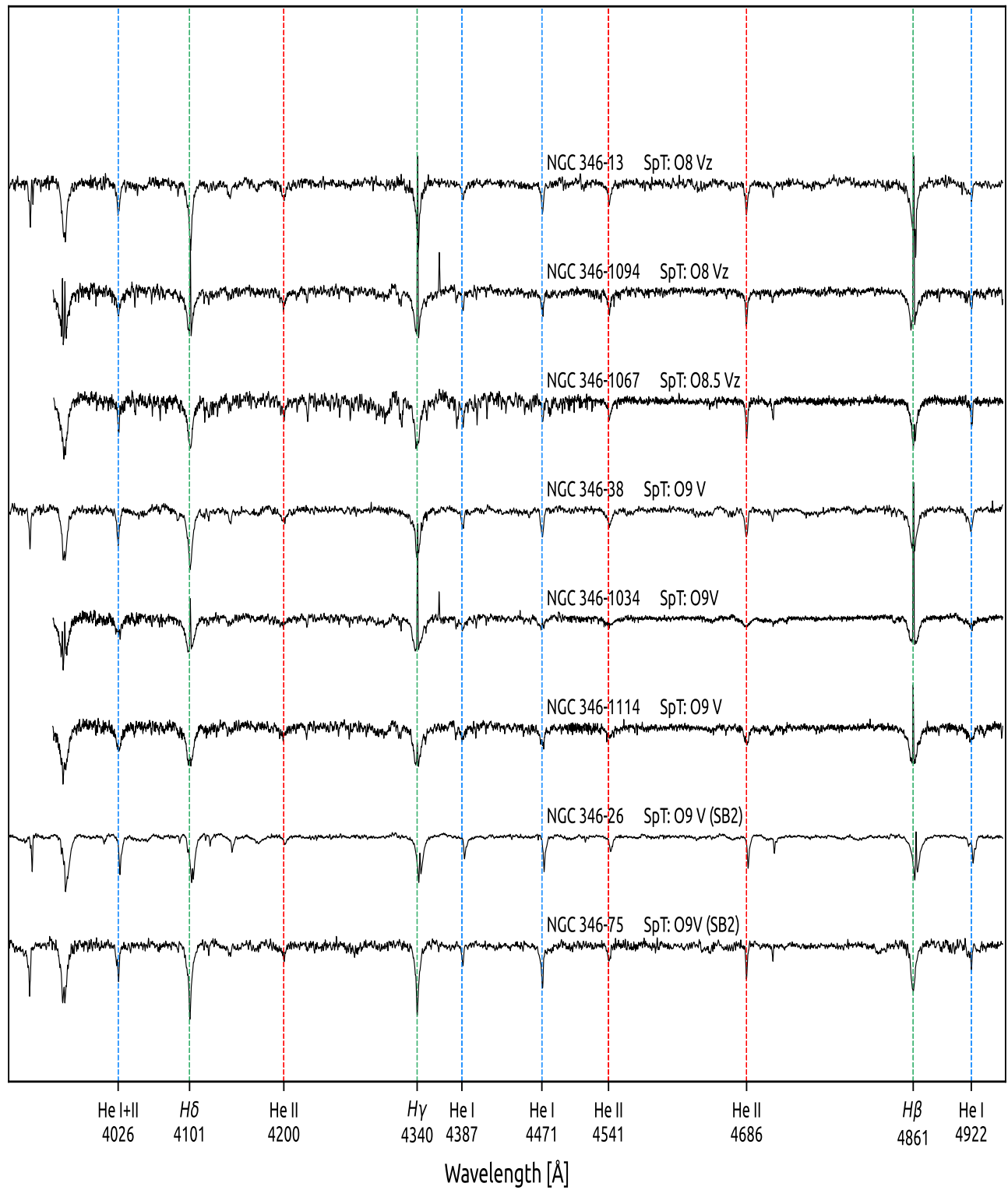


Fig. B.0.1 continued.

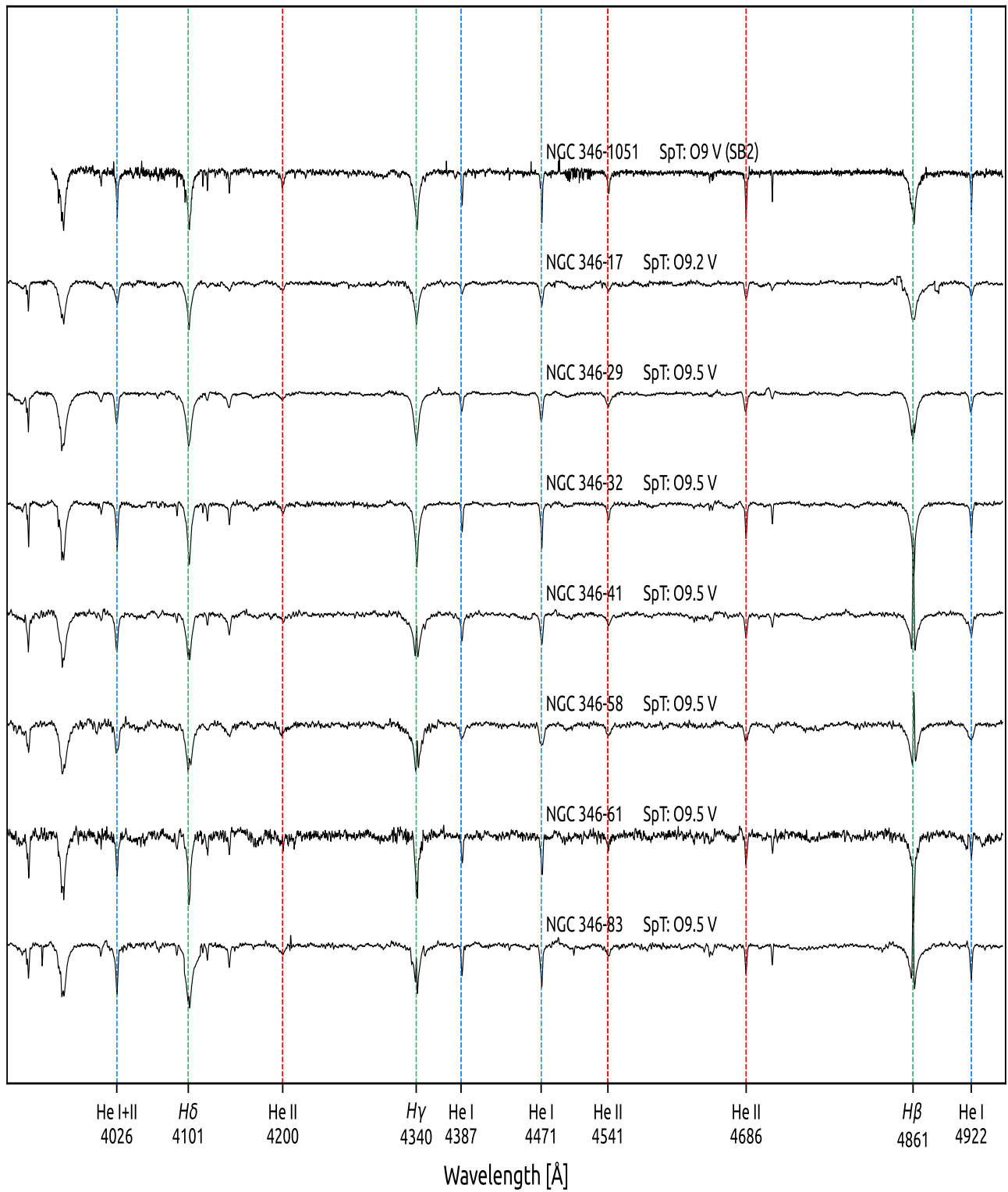


Fig. B.0.1 continued.

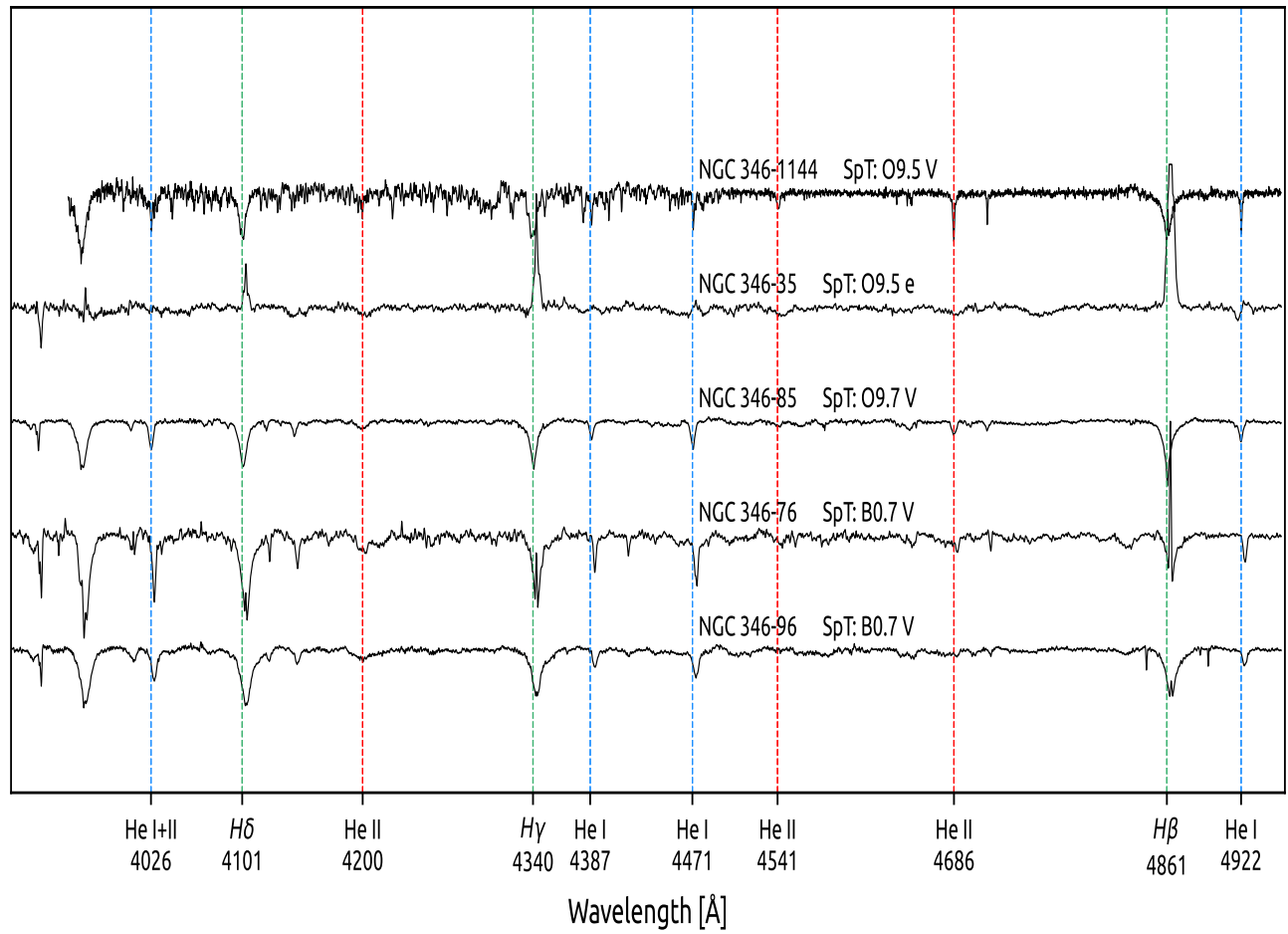


Fig. B.0.1 continued.

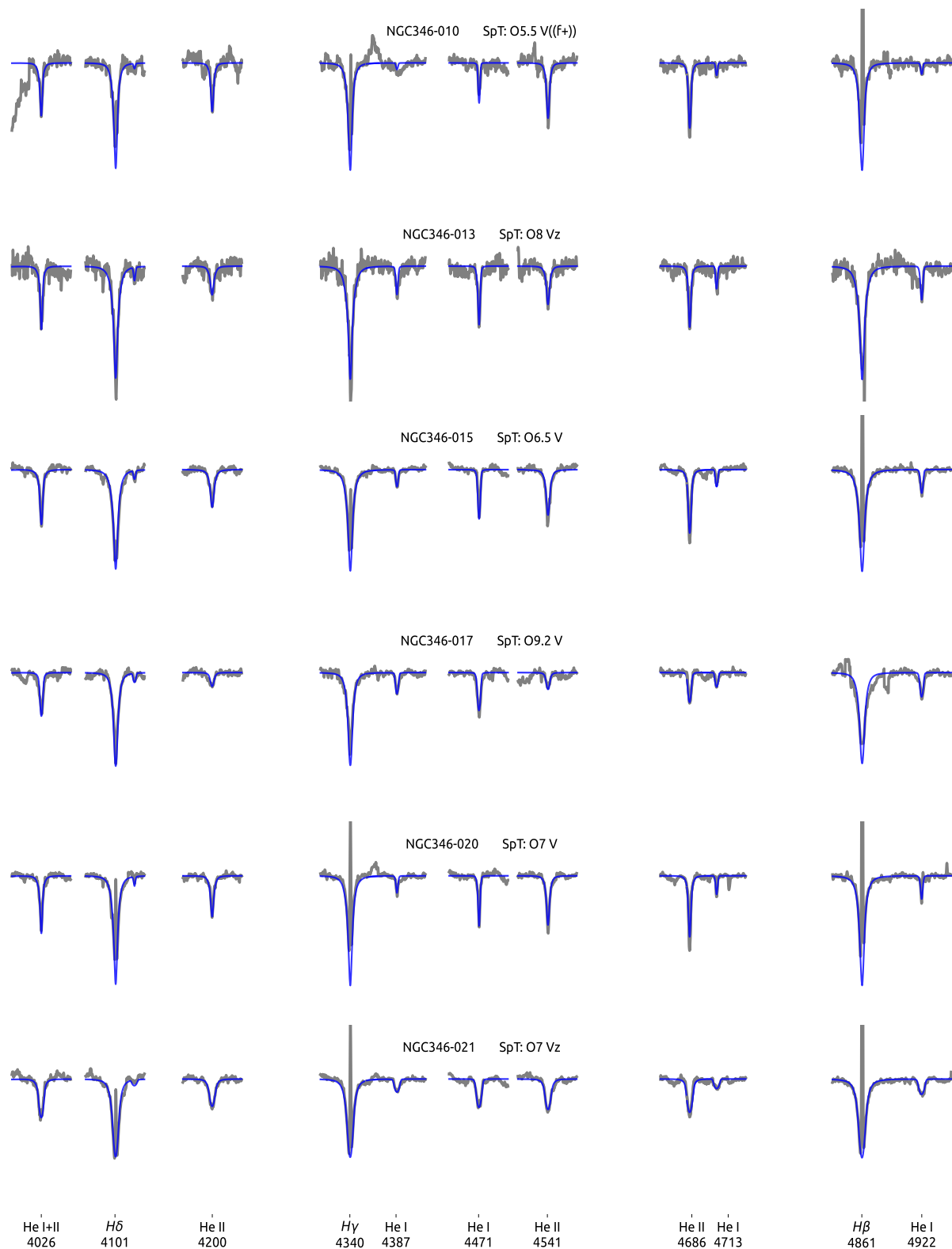


Figure B.0.2: Observed spectra (gray) and best fitting model (blue) for the main diagnostic lines of O-type stars in NGC 346. The sample is sorted following Table 4.3.1.

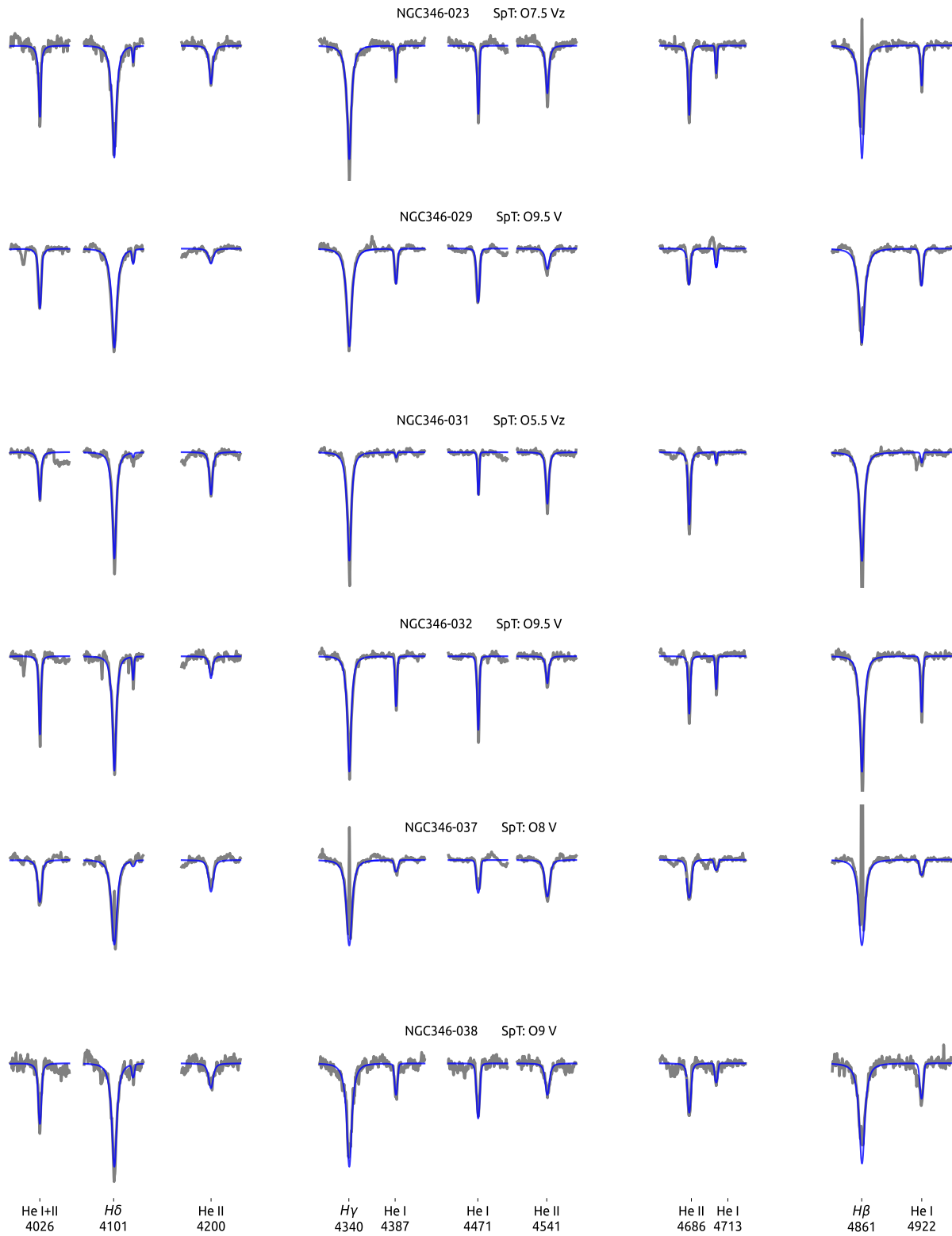


Fig. B.0.2 continued.

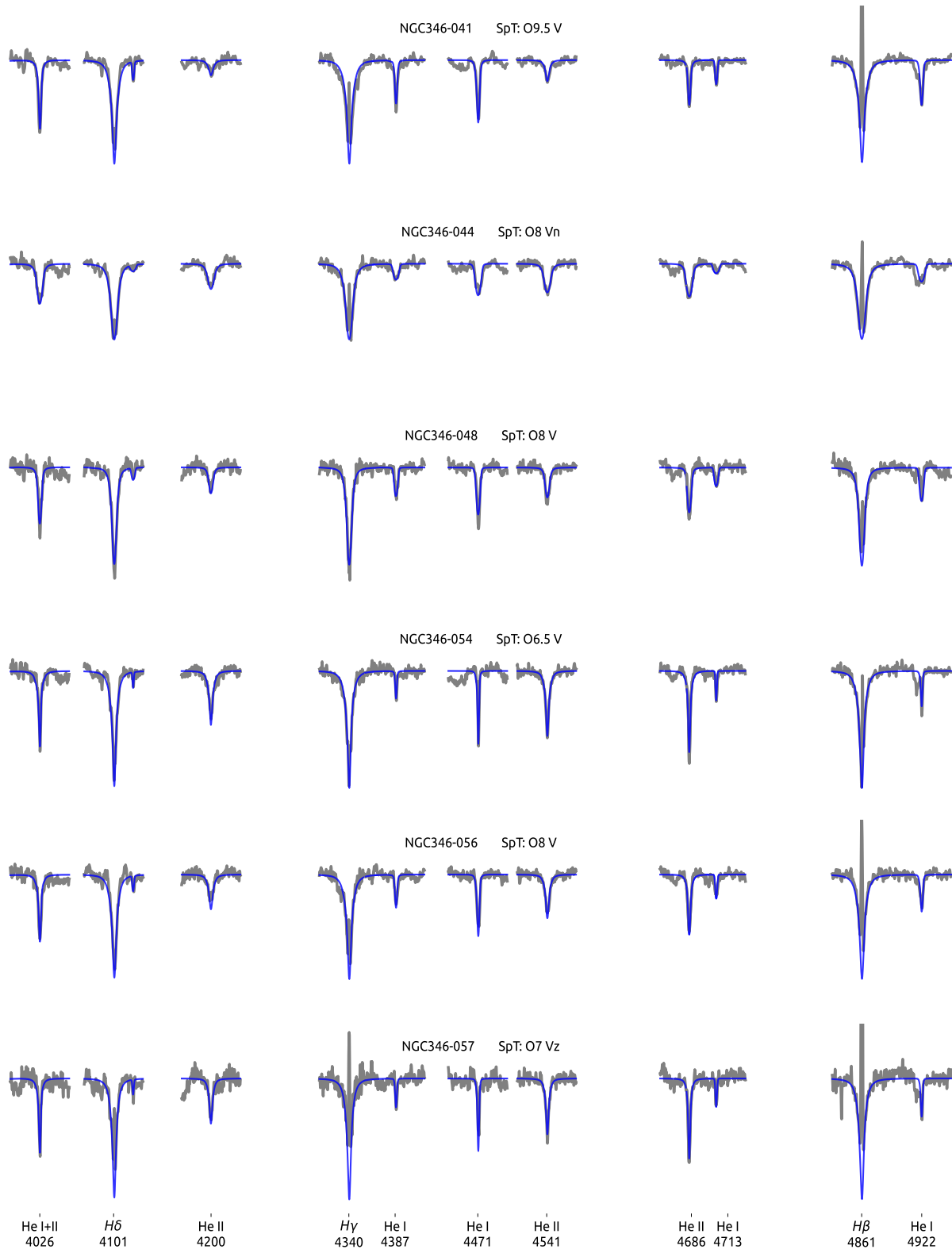


Fig. B.0.2 continued.

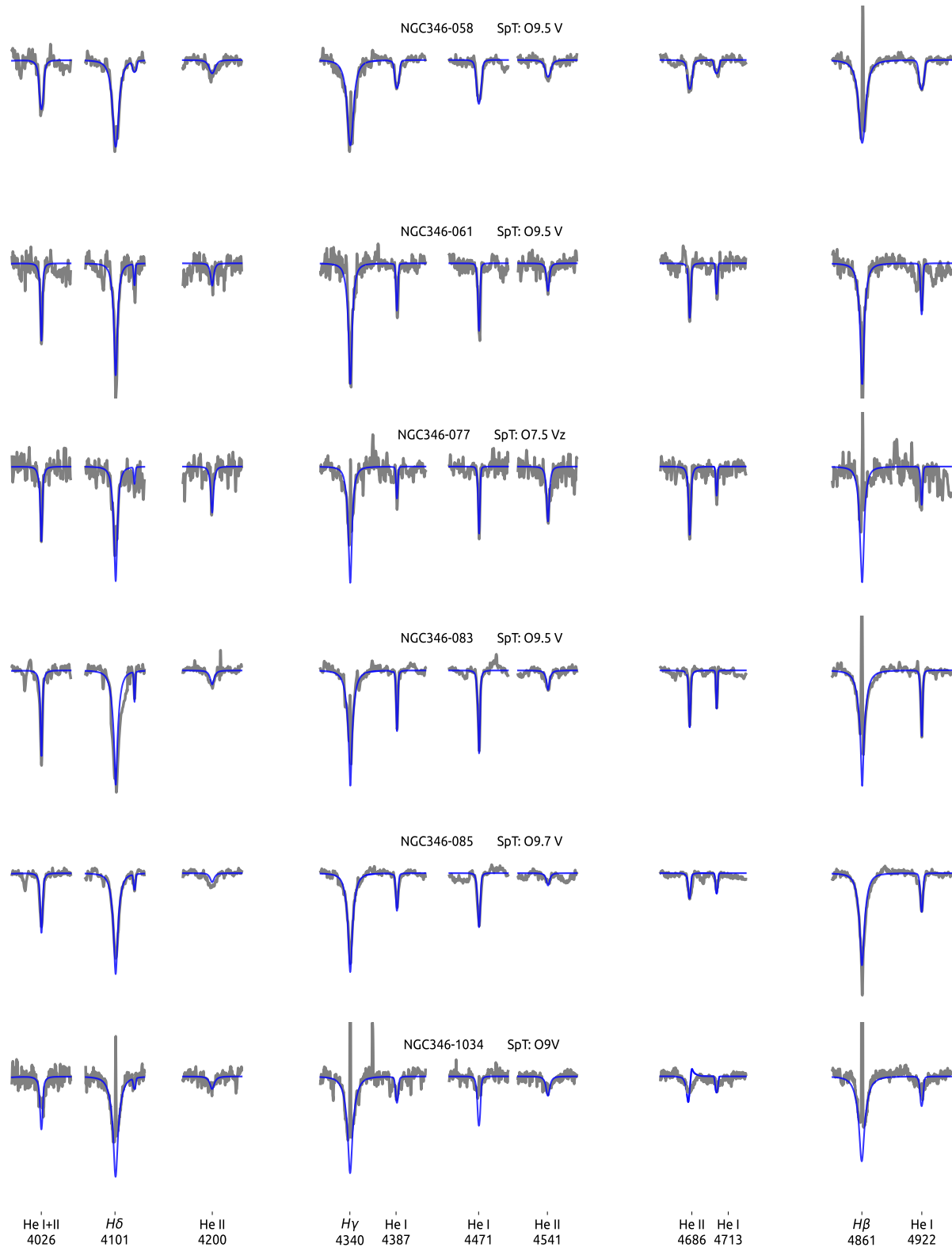


Fig. B.0.2 continued.

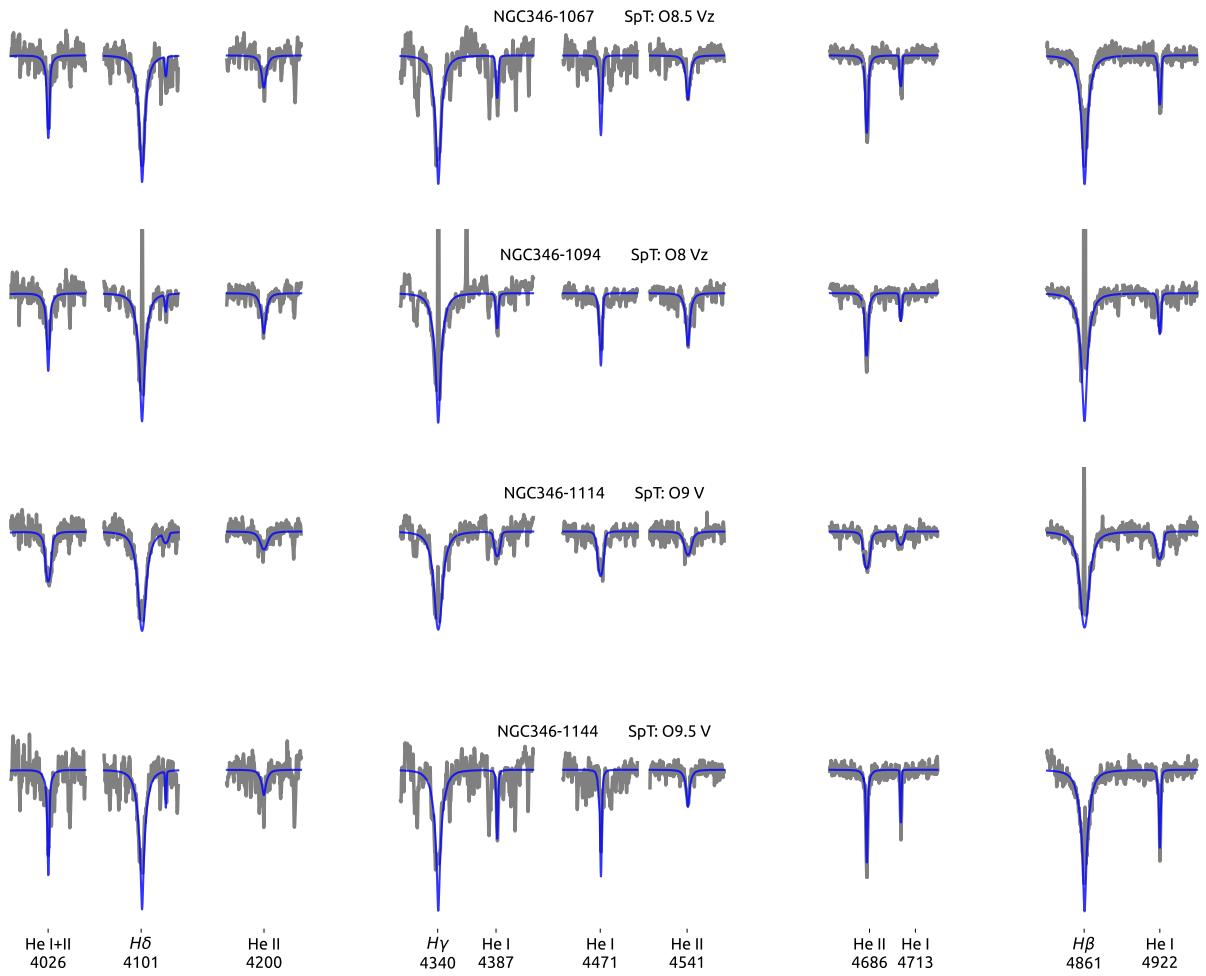


Fig. B.0.2 continued.

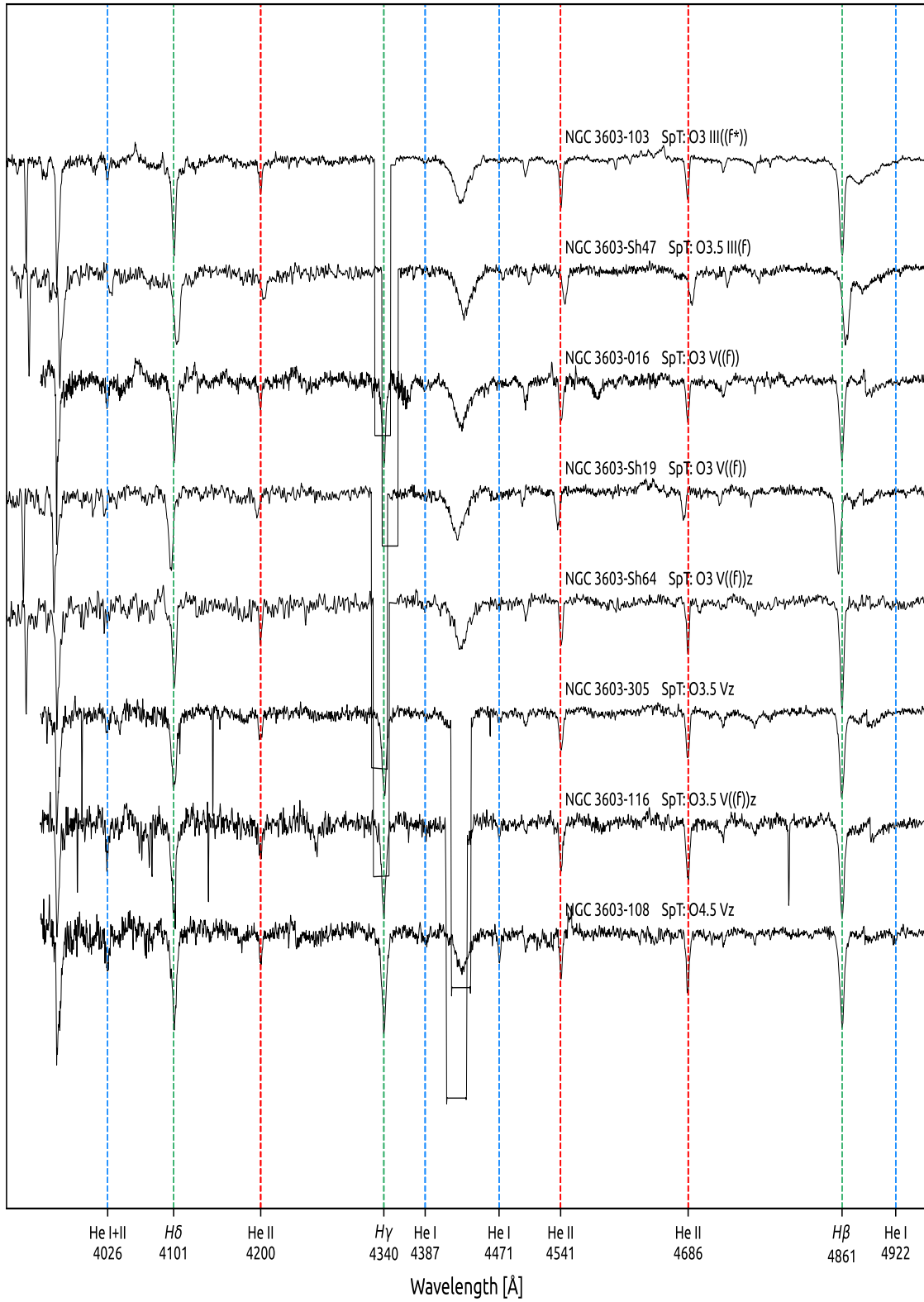


Figure B.0.3: Normalized spectra of the analyzed stars in NGC 3603. The principal He I, He II, and Balmer lines employed in the quantitative analysis are indicated. The corresponding spectral types are displayed next to each stellar identifier. The discontinuity near the center of the spectrum is an instrumental artifact caused by the gap between CCD detectors.

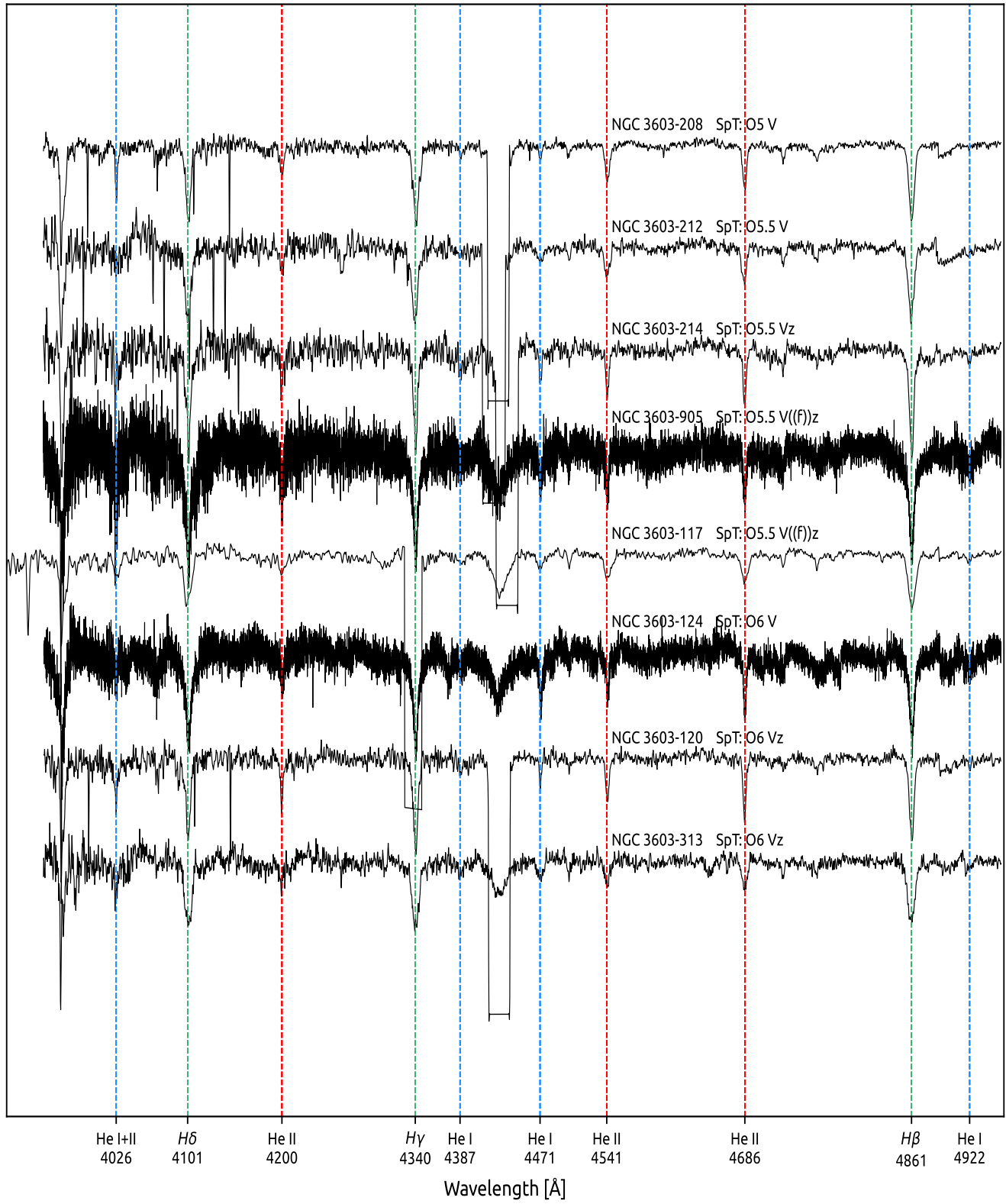


Fig. B.0.3 continued.

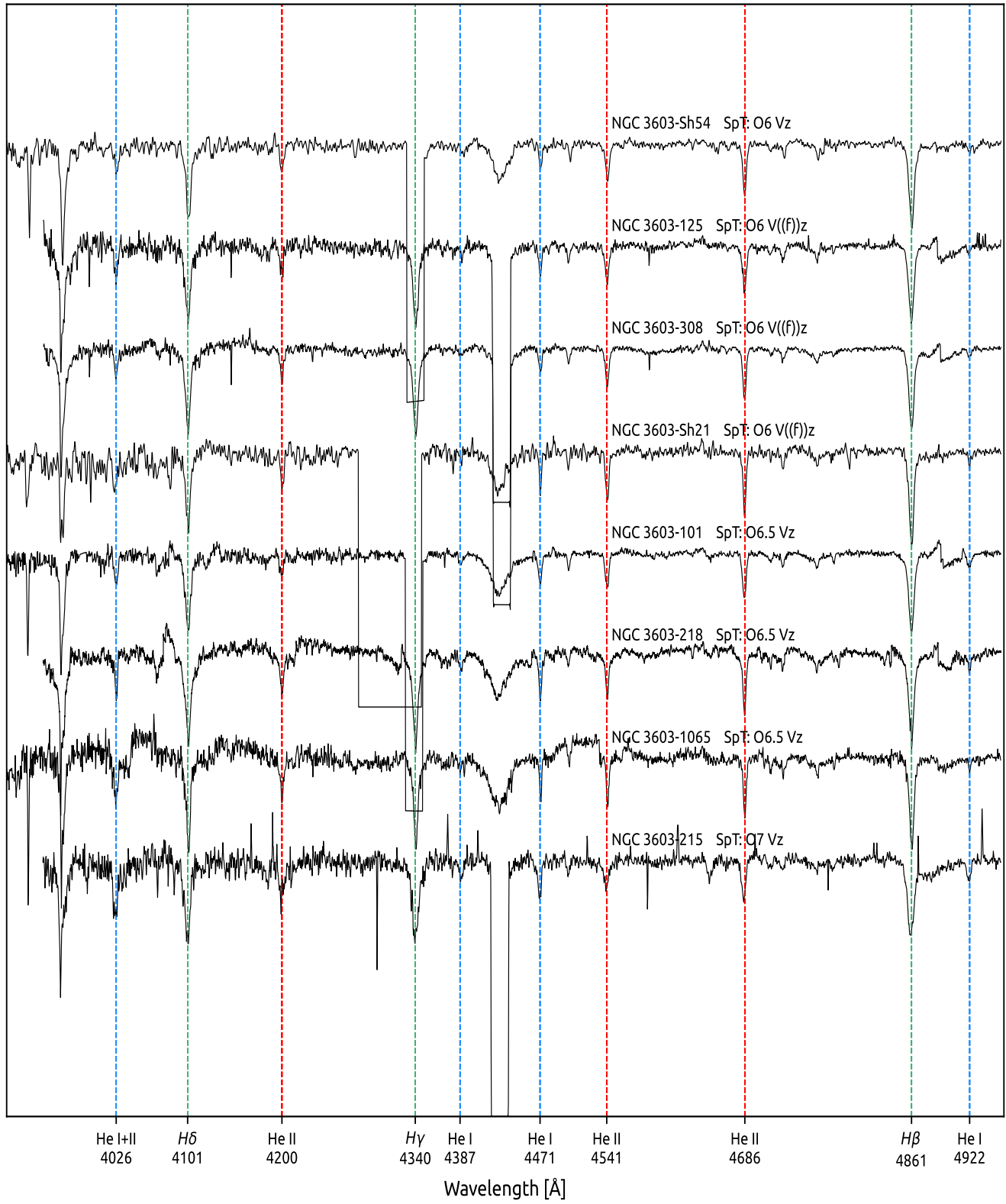


Fig. B.0.3 continued.

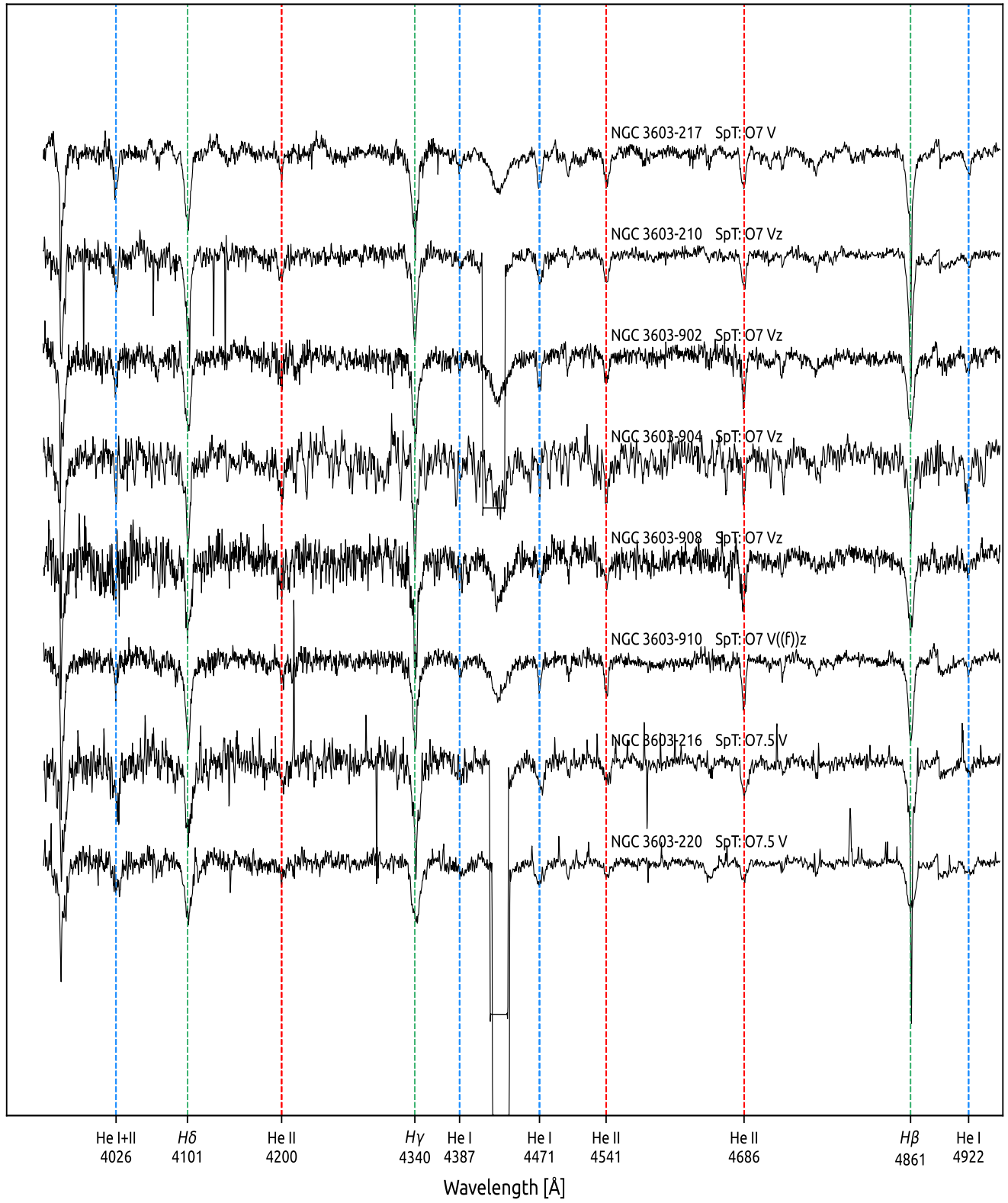


Fig. B.0.3 continued.

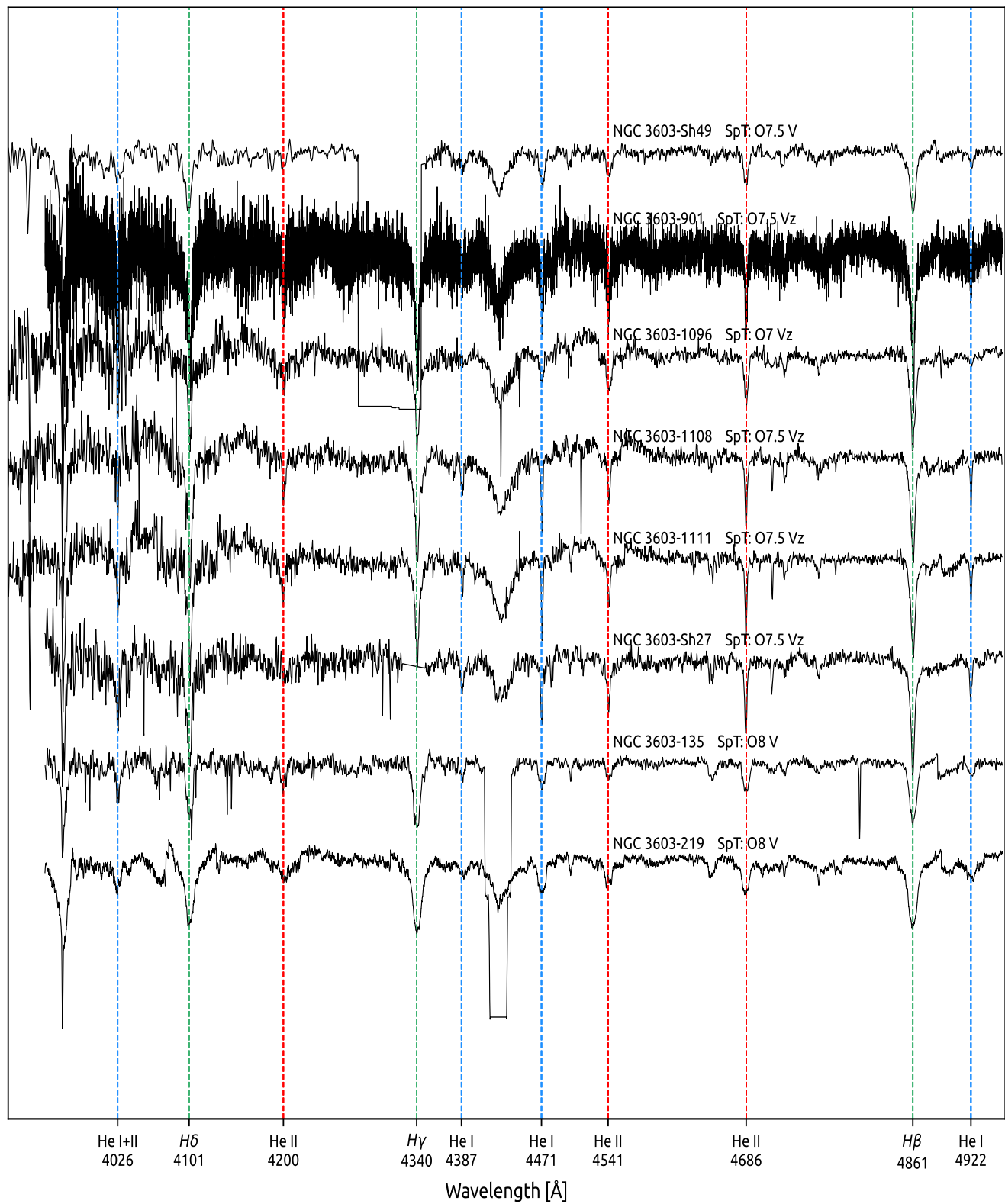


Fig. B.0.3 continued.

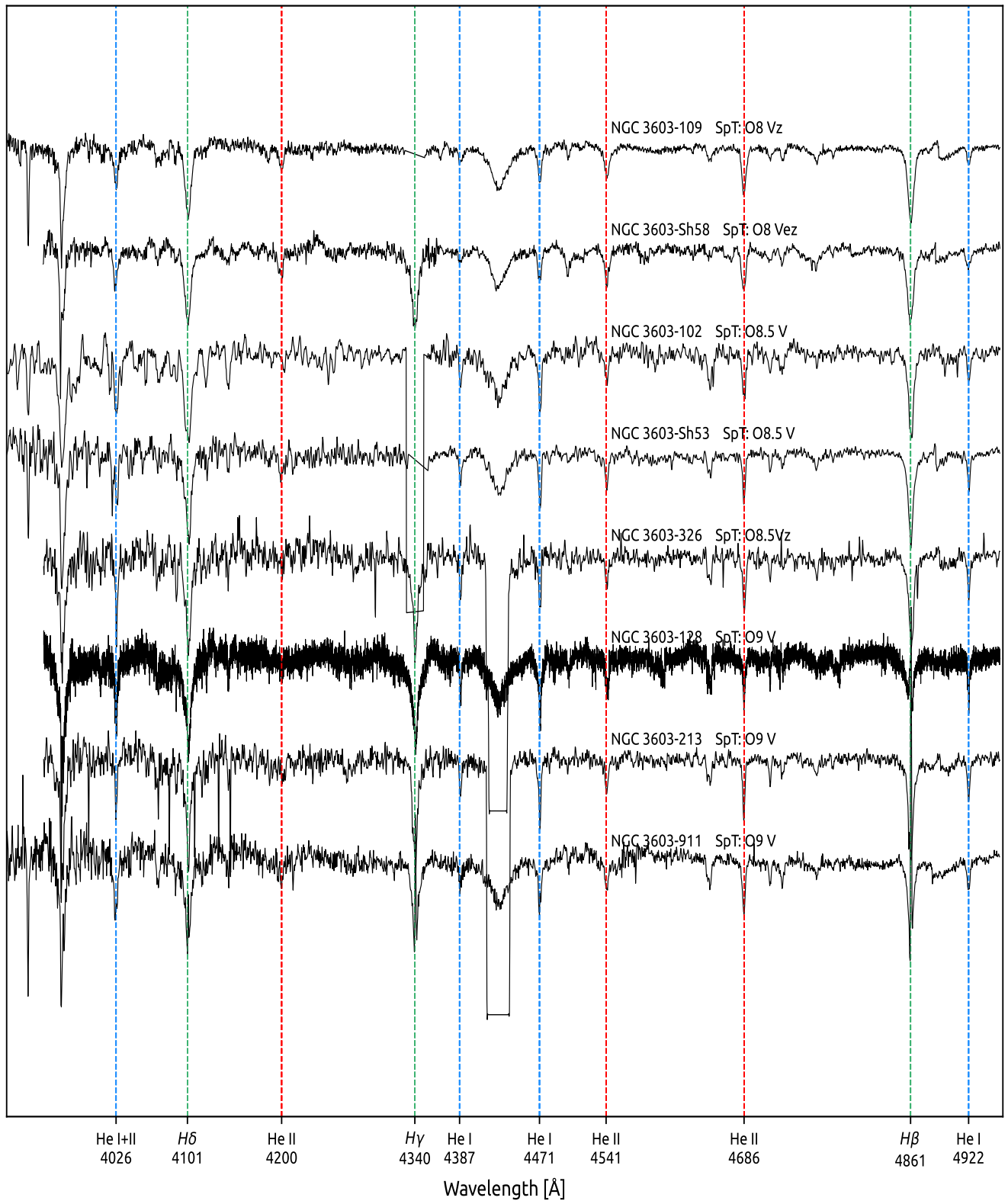


Fig. B.0.3 continued.

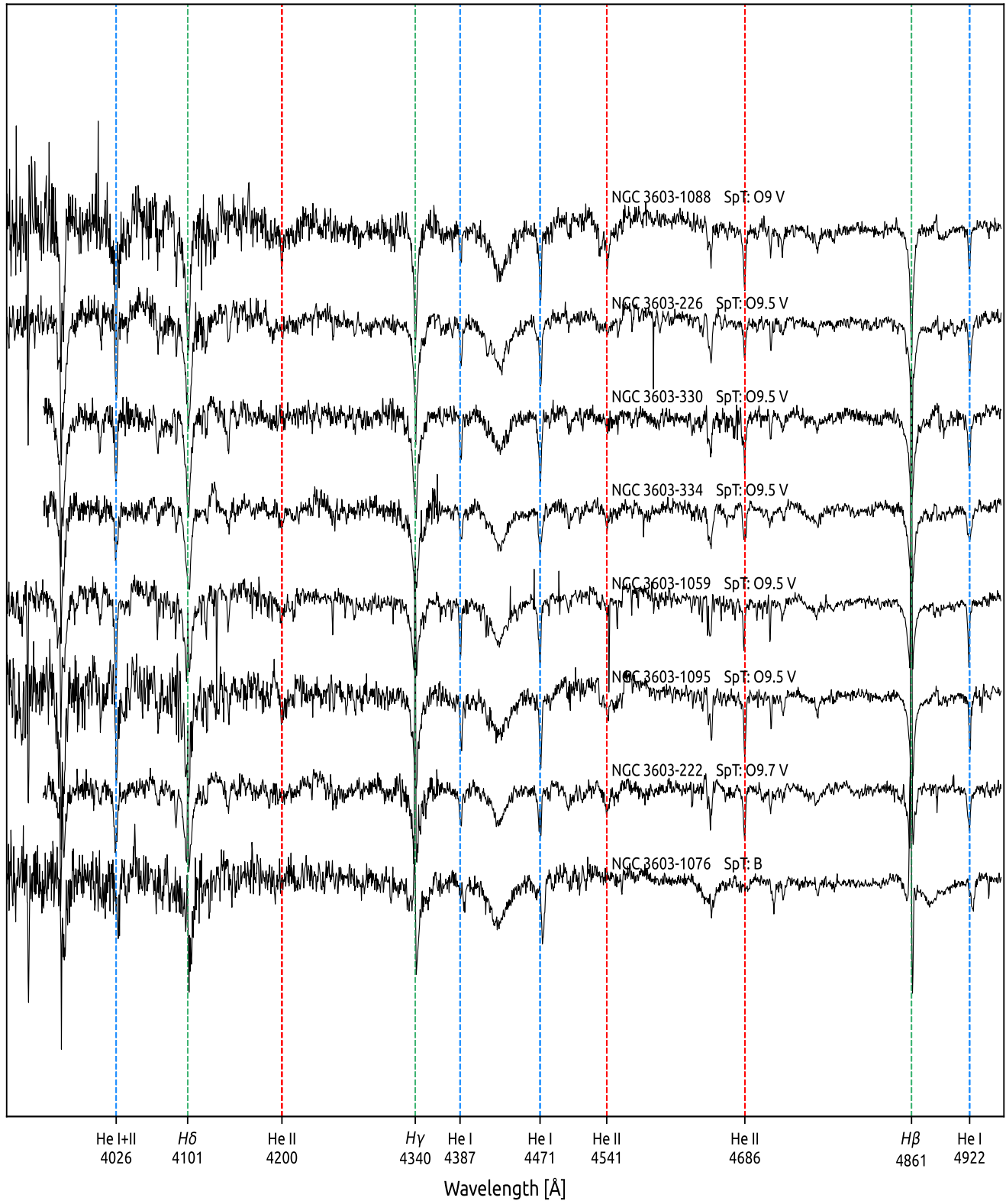


Fig. B.0.3 continued.

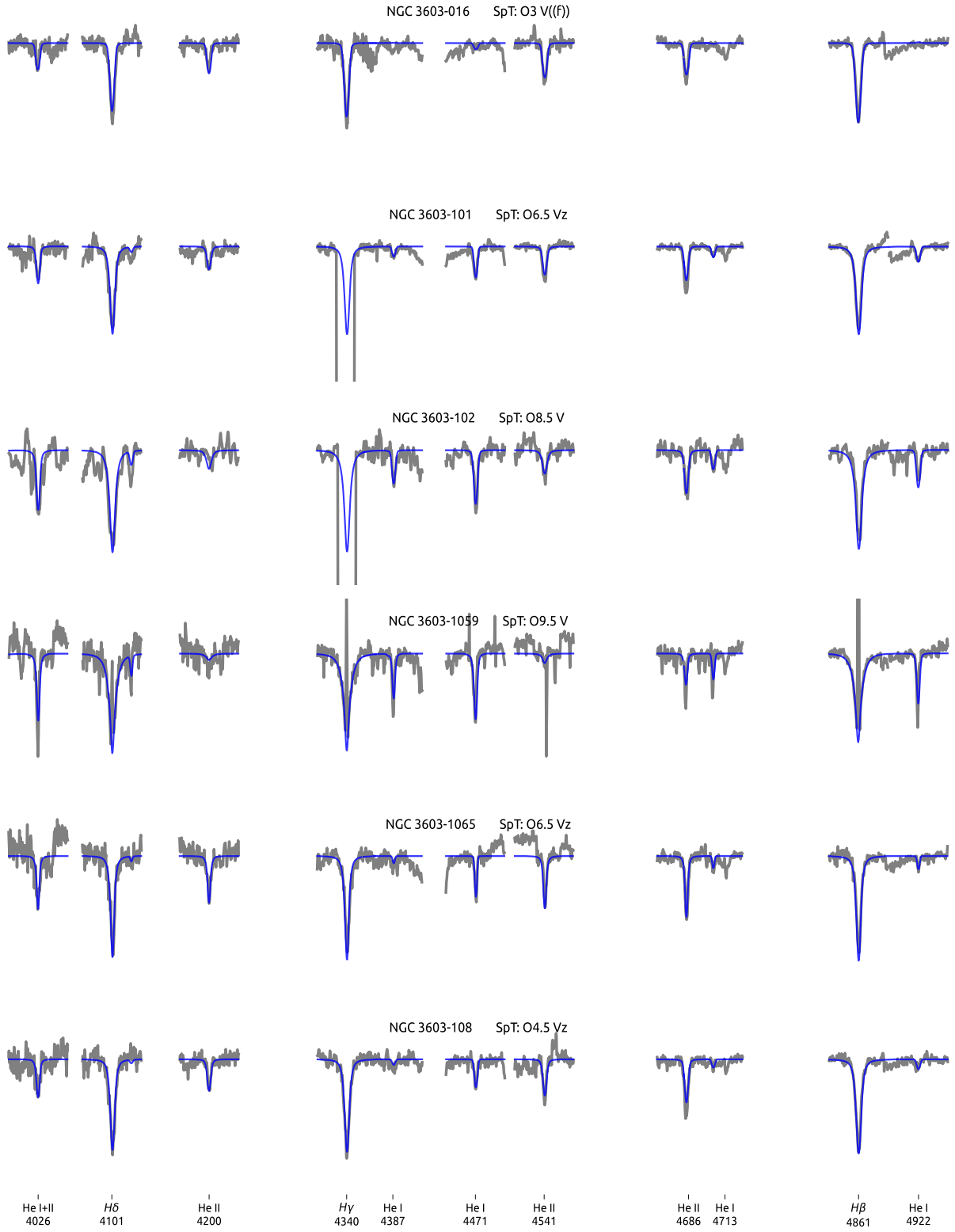


Figure B.0.4: Observed spectra (gray) and best fitting model (blue) for the main diagnostic lines of O-type stars in NGC 3603. The sample is sorted following Table 6.2.1.

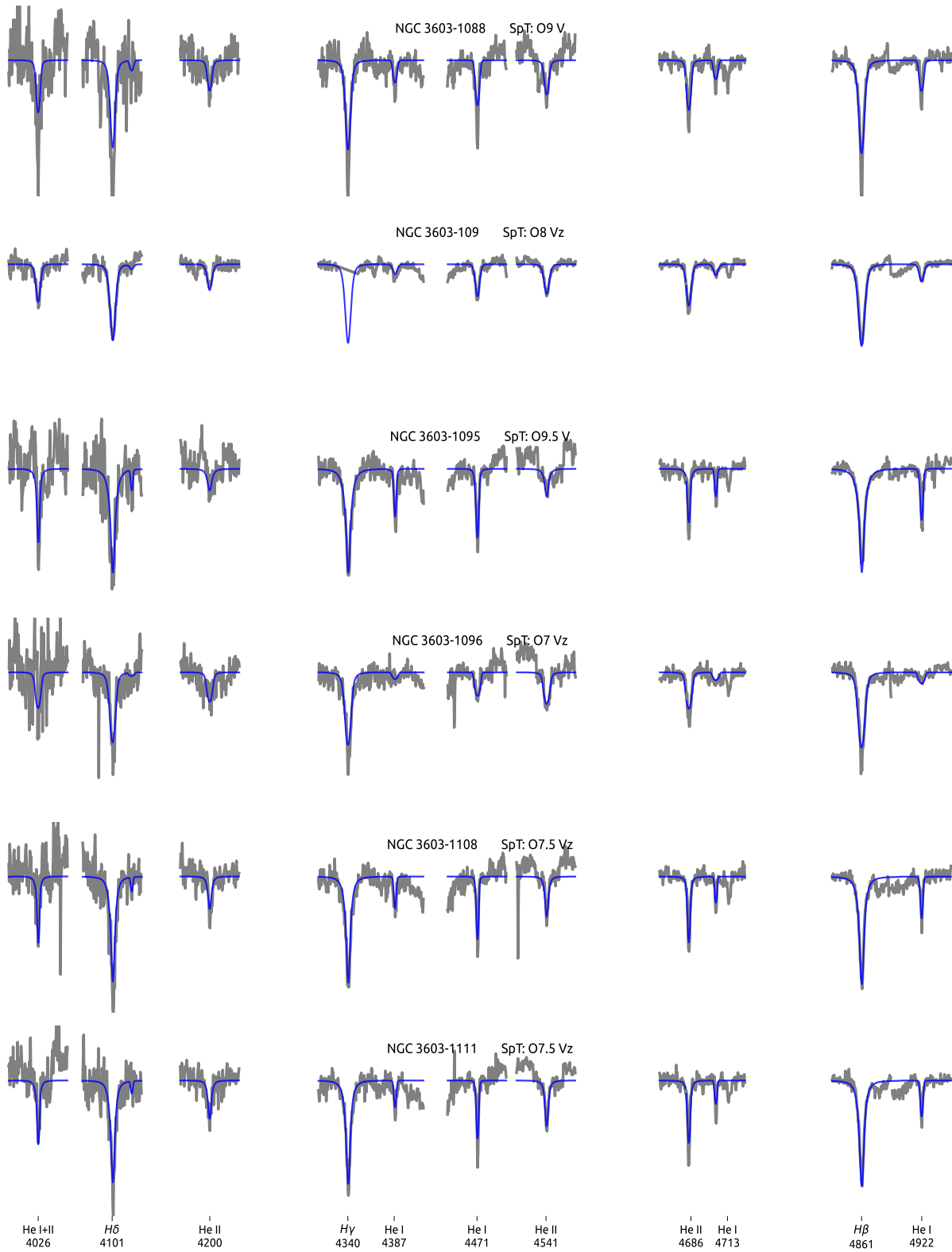


Fig. B.0.4 continued.

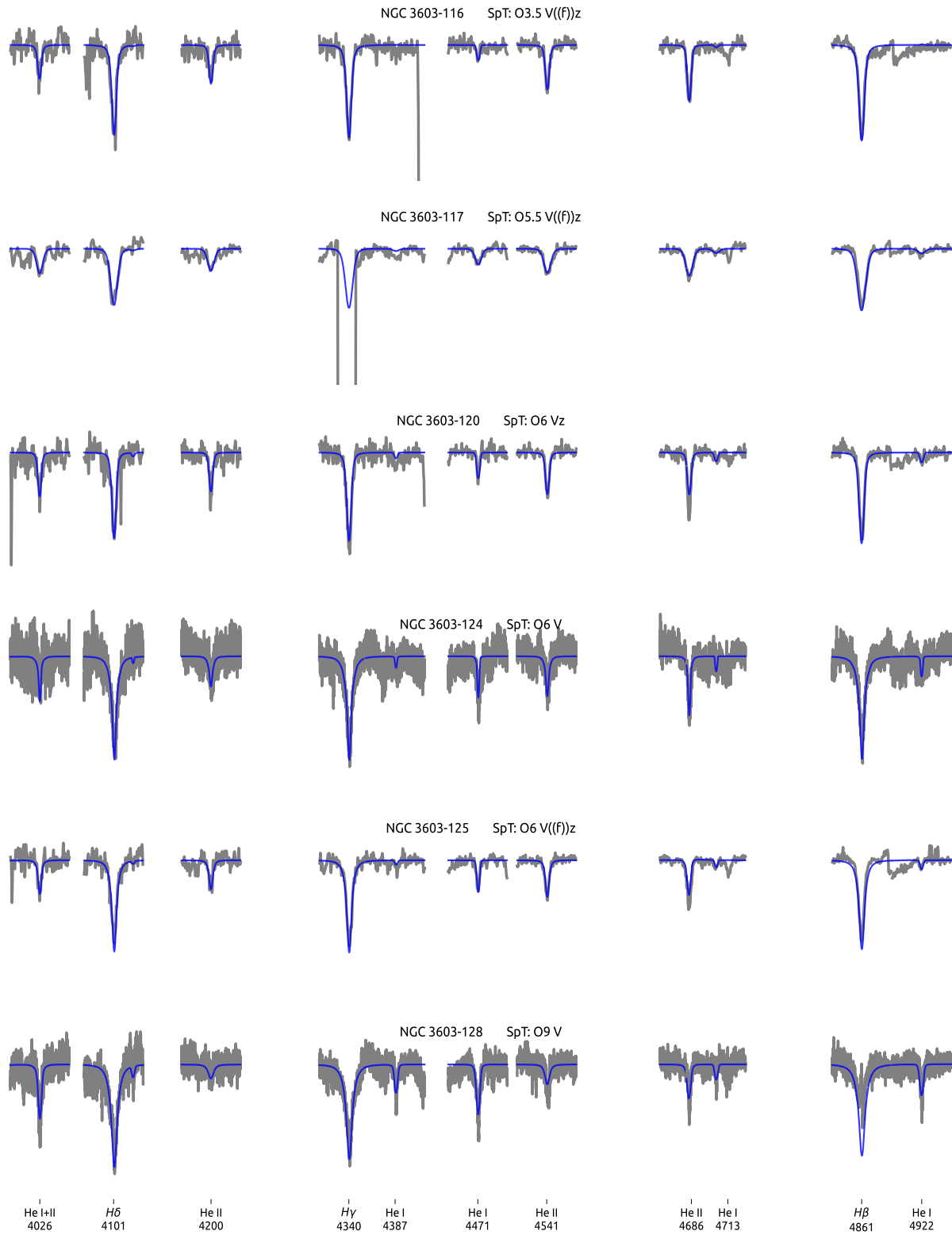


Fig. B.0.4 continued.

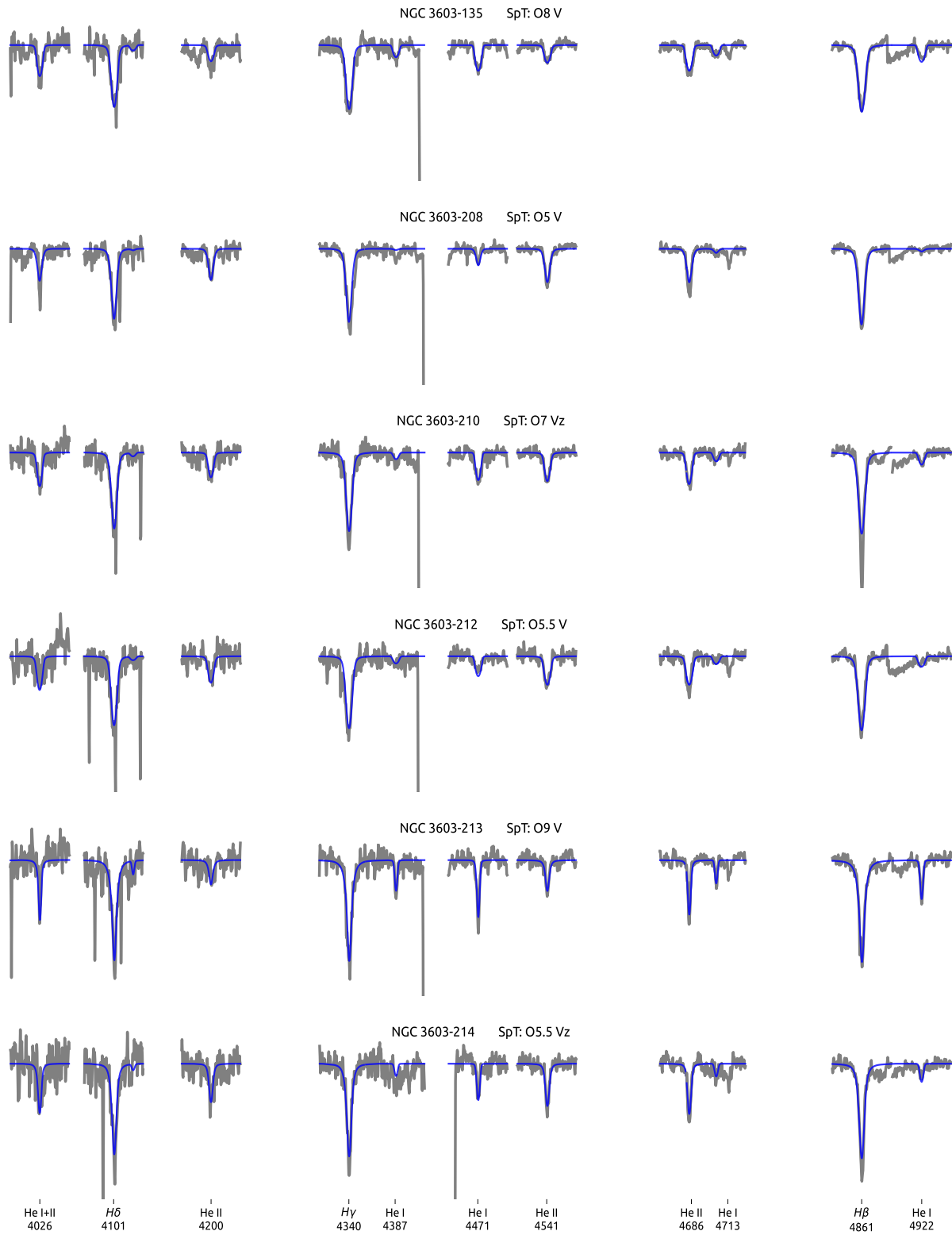


Fig. B.0.4 continued.

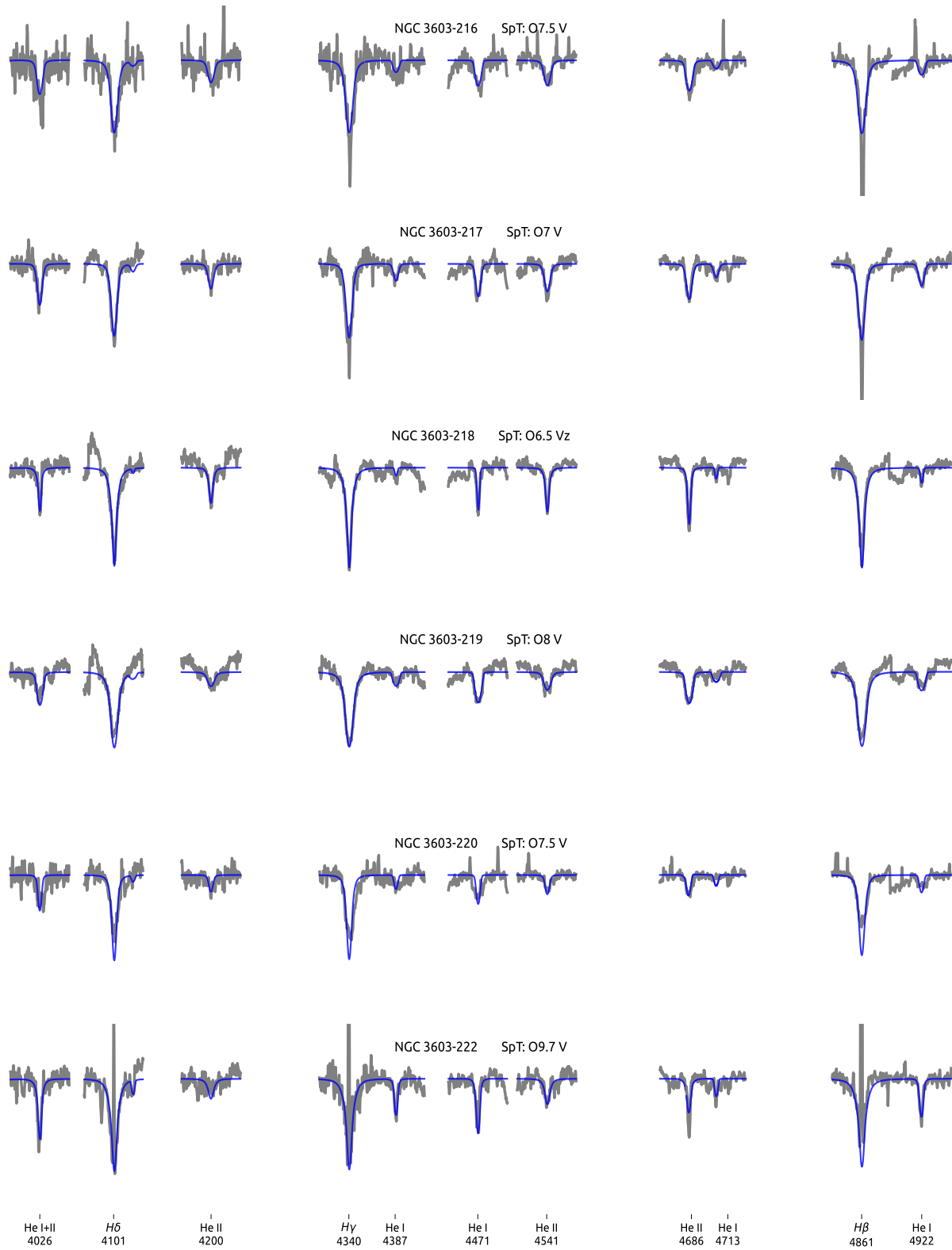


Fig. B.0.4 continued.

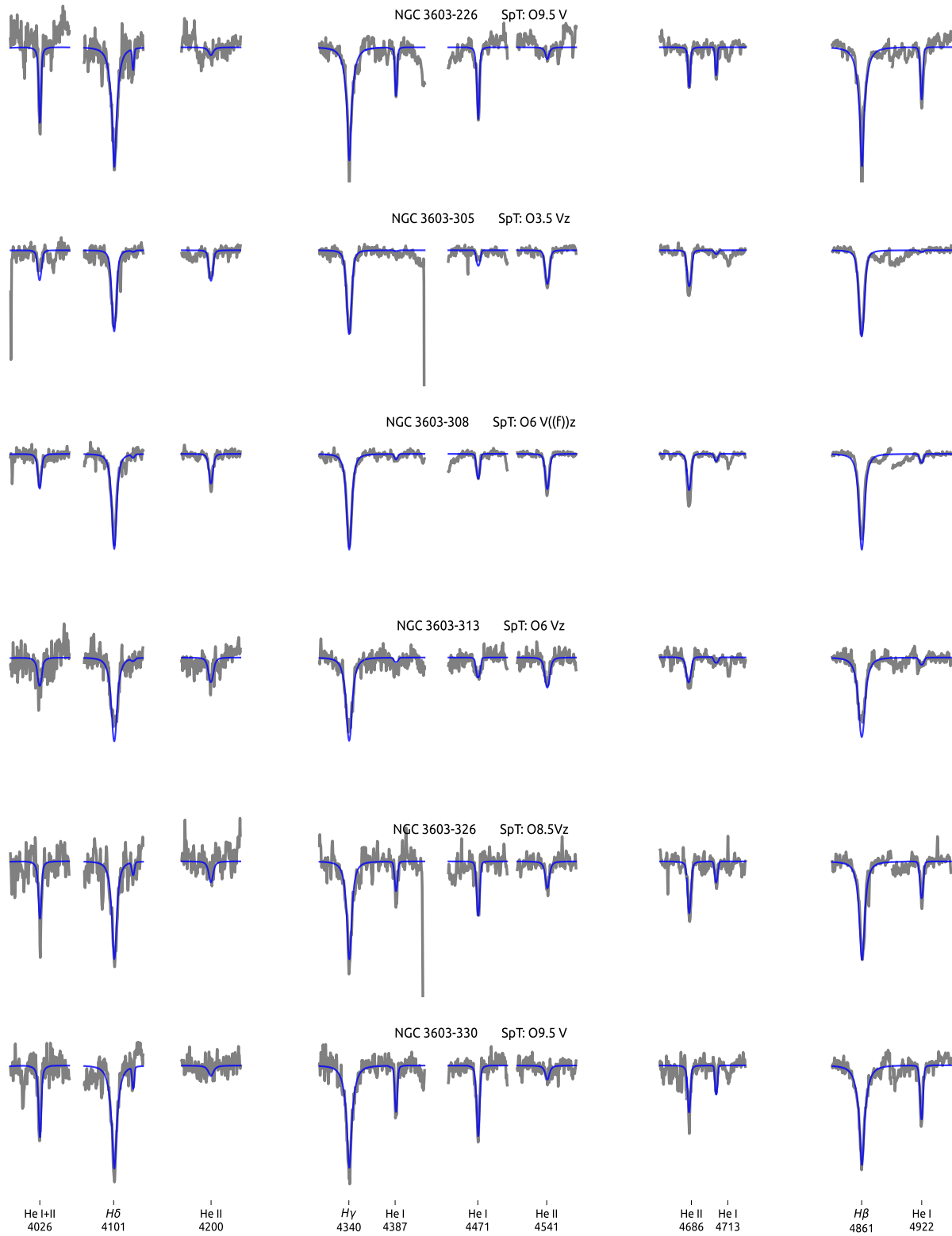


Fig. B.0.4 continued.

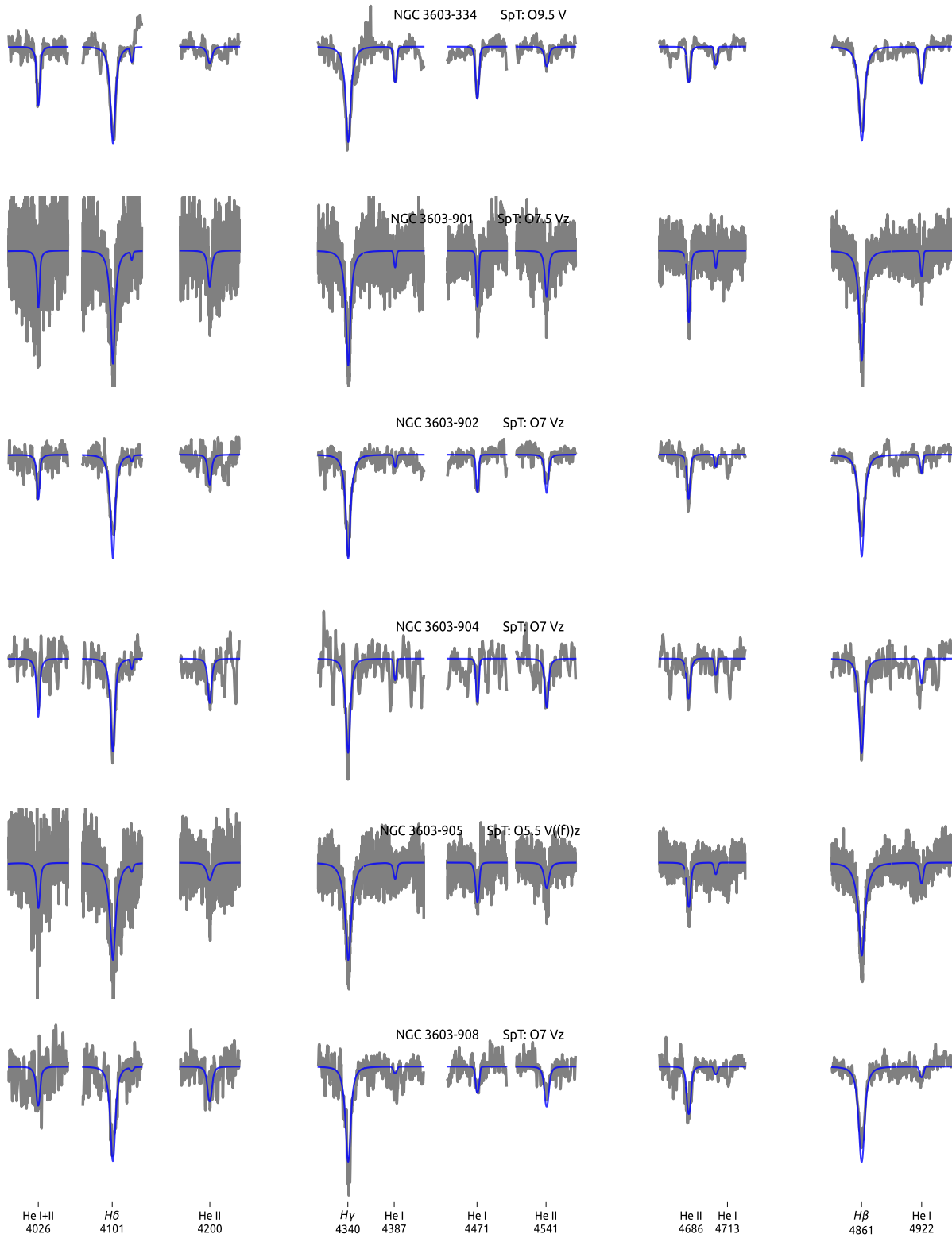


Fig. B.0.4 continued.

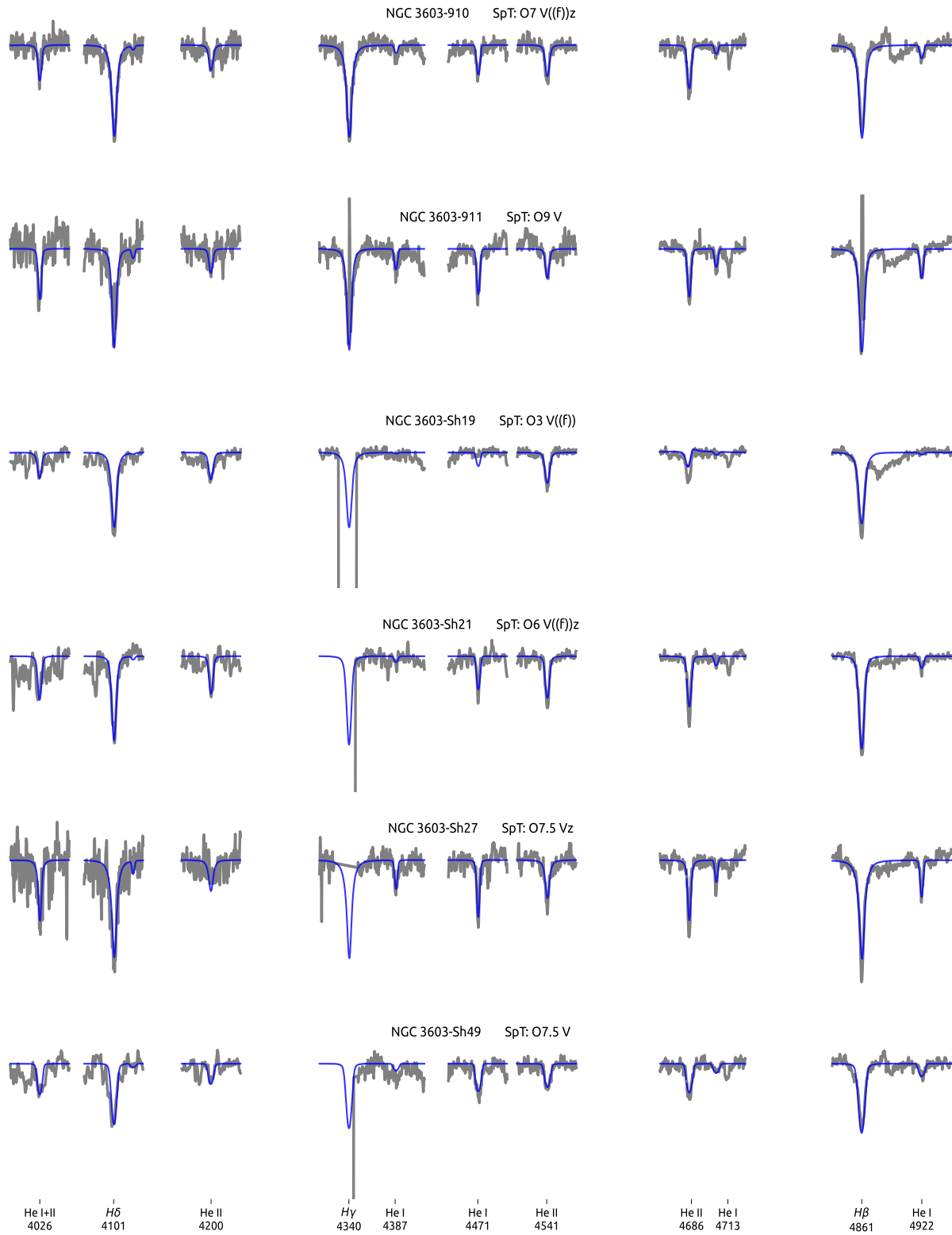


Fig. B.0.4 continued.

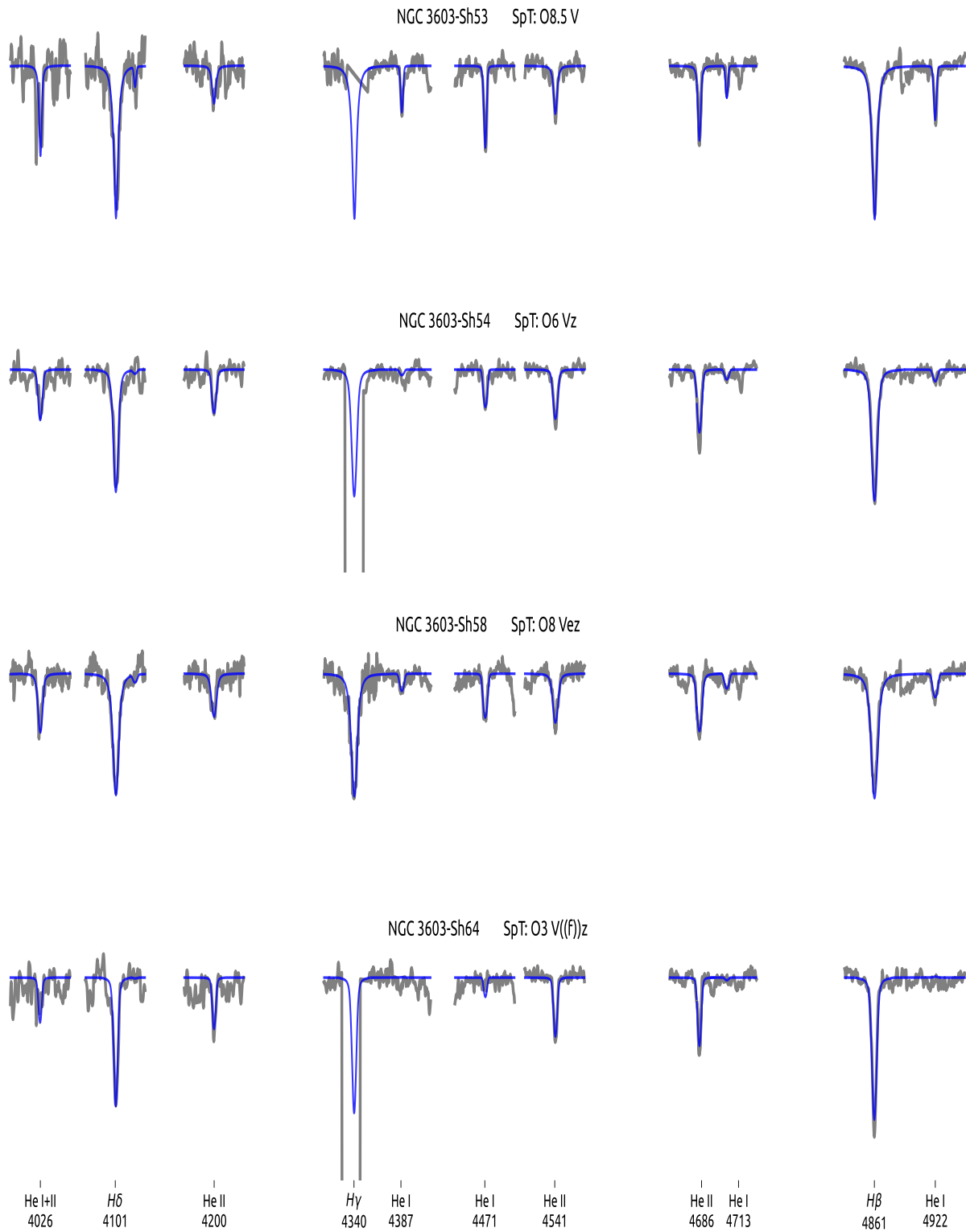


Fig. B.0.4 continued.