Stellar and wind properties of massive stars in the central parsec of the Galaxy

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Abstract. We present a detailed spectroscopic analysis of the massive stars in the central parsec of the Galaxy. Non-LTE atmosphere models including winds and line-blanketing are computed and used to derive stellar and wind properties. The evolutionary status of the stars is discussed, and we show due to the age of the population, the most massive stars (M > 60 M\textsubscript{☉}) have disappeared. We estimate the total H and He ionising fluxes emitted by these young stars and show that they are able to account for the nebular observed emission. Finally, we discuss the spectral properties of the S-stars.

1. Introduction

The Galactic Center region contains a large number of massive stars. They are mainly found in three massive clusters: the Arches, the Quintuplet and the central cluster. The latter surrounds the super-massive black hole SgrA* while the two former are a few tens of parsecs away from it. These clusters have slightly different ages: 2.5 Myr for the Arches, 4 Myr for the Quintuplet and 6 Myr for the central cluster. This age spread is responsible for the wide variety of massive stars encountered. This is a very fortunate property which allows a sampling of the various evolutionary states of massive stars, going from main sequence objects to all kinds of Wolf-Rayet stars and to Luminous Blue Variables. Getting access to the physical properties of such a sample of massive stars represents a unique opportunity to constrain quantitatively the evolution of massive stars.

In the present study, we concentrate on the central cluster. Its massive stellar content was first unraveled by [6, 1] and [12] who discovered several luminous objects showing unusually strong H and He emission lines in the K band. At that time, no other star was known to display such a characteristic spectrum, and the objects were nicknamed “Helium stars”. The quantitative analysis of these objects by [21, 22] revealed that they were evolved massive stars with relatively cool effective temperatures, placing them close to the so-called Humphreys-Davidson limit above which stars become unstable. The development of powerful near IR observational techniques has recently widened our knowledge of the massive stars GC population. More evolved objects as well as OB stars have been discovered, including the so-called S-stars, a group of stars located within the central arc-second and orbiting the super-massive black hole with periods of a few tens of years.

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2. New population of massive stars in the Galactic Center

With the development of powerful observational techniques in the near-IR spectral range, more and more stars can be observed. In that context, 3D spectroscopy is a unique tool since it allows observations of crowded regions such as the Galactic Center central cluster. Not only 3D spectroscopy provides data for tens of stars in one single exposure, but it also allows a much better estimate of nebular contamination than long-slit spectroscopy.

The use of SINFONI in the Galactic Center has proven to be very efficient. During its first year, SINFONI has revealed a new population of massive stars. The spectral classification as well as the dynamical properties of these stars are reported in Paumard et al. (these proceedings and [23]). One of the main discoveries is the presence of numerous OB stars, something which was suspected but not confirmed so far. In addition, several faint Wolf-Rayet stars have also been observed for the first time. Fig. 1 shows a mosaic of spectra of several WR stars observed with SINFONI. It is important to realize that even for stars which have been known for several years, the new spectra are an improvement since their quality allows the detection of weak emission lines such as He II 2.189 μm or N III 2.238 μm. Such lines are extremely useful to derive stellar properties, in particular effective temperatures and abundances. We describe such an analysis and discuss its results in the following sections.

3. New atmosphere models for massive stars

The modelling of atmospheres of massive stars has experienced significant improvements in the last years. Indeed, a realistic modelling requires the inclusion of three main ingredients: first, non-LTE calculations have to be performed since the luminosity of massive stars is so large that radiative processes are dominant in the atmosphere; second, winds must be included because of the large mass loss of these stars creating large expanding envelopes; third, metals have to be included in the models, not only because lines from elements other than H and He are
observed, but also because metals strongly modify the atmospheric structure, especially the temperature structure (see [17]). The two first ingredients (non-LTE and winds) are present in most atmosphere models since the early 90’s, but the third one, referred to as line-blanketing, was missing until recently. Significant progress in both computers capabilities and numerical techniques now allow a realistic treatment of line-blanketing. Consequently, quantitative analysis of massive stars can be performed and accurate stellar and wind parameters are derived ([2, 18]).

The development of such new atmosphere models for massive stars opens new perspectives for the study of the young stars in the Galactic Center. Indeed, we have seen in the previous section that the improvements in the observational techniques allow the detection of weak lines from various metallic elements and various ionisation states. These diagnostics can now be studied quantitatively and accurate physical parameters can be derived without suffering from approximation such as the lack of line-blanketing as was the case for the pioneering studies of [21, 22]. In the next section we describe the strategy adopted in our quantitative study of SINFONI spectra with these new atmosphere models.

4. Spectroscopic analysis of Wolf-rayet stars

We have computed atmosphere models for the massive stars in the Galactic Center using the code CMFGEN ([10]). CMFGEN makes a non-LTE treatment of the atmosphere in a spherical geometry and includes winds and line-blanketing. In practice, several input parameters are given, the main ones being: effective temperature ($T_{\text{eff}}$), luminosity ($L$), mass loss rate ($\dot{M}$), terminal velocity ($v_{\infty}$), abundances. In addition, a hydrodynamic structure (velocity structure or density structure) has to be provided. Indeed, CMFGEN is not an hydrodynamical code and does not compute the structure itself, but provides the temperature structure, radiation field and emergent spectrum for a given hydrodynamical structure. In practice, the input velocity structure is given by a quasi hydrostatic velocity structure connected to a so-called $\beta$ velocity law (see [10] for a complete description).

Our general strategy to derive the stellar and wind parameters can be summarised as follows:

- Effective temperature: lines of two successive ionisation states of the same elements are used. He lines were the main indicators, while C lines (C\textsc{iii} and C\textsc{iv}) are also used in WC stars.
- Luminosity: the absolute K band magnitude is the main diagnostic. The observed value is estimated from $m_K$, the distance to the GC (7.62 kpc, see [5]) and the extinction map of [24].
- Mass loss rate: it is derived from the strength of emission lines.
- Terminal velocity: the width of emission lines is the main indicator. When P-Cygni profiles are observed, the blue-ward extension of the absorption dip also serves as an indicator.
- Abundances: they are derived from the intensity of absorption or emission lines.

Two points need to be stressed. First, a huge advantage of the Galactic Center massive stars compared to most other Galactic stars is that their distance is known accurately. Hence, the luminosity suffers from less uncertainty (which is dominated by uncertainties on the extinction). Second, the modelling of near-IR spectra is a highly degenerated problem, and the situation is in fact more complicated than the simple sketch drawn above. Indeed, most indicators depend equally on several parameters. For example, the absolute K band magnitude increases with luminosity, but also with the wind density, and thus the mass loss rate, due to free-free emission in the ionised atmosphere. The determination of stellar and wind parameters is consequently a long iterative process.

Figs. 2 and 3 show the final fits for the stars IRS16SE2 and IRS13E2. We see that in addition to the strong emission lines, weaker lines are also well reproduced. As already mentioned,
this leads to a better estimate of the stellar and wind parameters, and enables abundances determinations. We now discuss in more detail some of these parameters.

5. Masses

One of the most important parameters is the initial mass of the stars. In Wolf-Rayet stars and related objects, mass estimates are very difficult since the photosphere is not observable. Hence, standard measurement of gravity from the wing of Hydrogen lines cannot be done. The only solution is to get an estimate of the evolutionary mass, i.e. the mass obtained from evolutionary diagrams. In Fig. 4, we show such a diagram giving the Hydrogen content as a function of luminosity. The comparison of predictions of evolutionary models to the position of the GC massive stars reveals that these stars have initial masses in the range 25-60 M$_\odot$. This means that no very massive stars (M $\sim$ 100 M$_\odot$) are present. Is it an indication of an upper mass cut-off of the IMF? For a total number of 40 stars in the 25-60 M$_\odot$ mass range (number of Wolf-Rayet stars), one would expect at least 8 stars in the range 60-100 M$_\odot$ for a Salpeter IMF. This is a lower limit since [23] have shown that the mass function in the Galactic Center was top-heavy. Since we do not see any of these very massive stars, one may indeed wonder whether such a cut-off exists since a positive detection would strongly constrain the formation mechanism of the GC young stars. In particular, star formation in a self gravitating disk predicts the presence of such a cut-off ([14, 15]). However, in the present case the most likely explanation is the age of the population. Indeed, [23] showed that the young stars in the GC resulted from a burst of star formation 6±2 Myr ago. The lifetime of the most massive stars being of only a few Myr (see [19]), we naturally expect the absence of very massive objects in the population of GC massive stars.

6. Ionising radiation and the ISM properties

In the early studies of the Galactic Center massive stars, an important problem appeared: the population of young stars was too cool to account for the ionisation of the interstellar medium.
Figure 4. Hydrogen content as a function of luminosity. Solid lines are predictions of evolutionary models ([19]) and squares are values derived for Wolf-Rayet stars in the Galactic Center. Initial masses for these objects range between 25 and 60 M⊙.

this problem was first highlighted by [22]: their analysis of the brightest “He” stars revealed that they were able to produce enough H ionising photons, but were far too cool to reproduce the nebular He i emission. Indeed, [4] and [13] state that one should expect log $Q_H = 50.4$ and log $Q_{HeI} = 48.4$ ($Q_H$ and $Q_{HeI}$ being the H and Hei ionising fluxes), while [22] proved that the He stars provided log $Q_H = 50.5$ and log $Q_{HeI} < 46$.

Later, ISO observations of the Galactic Center lead [16] to the conclusion that standard stellar evolution was facing serious problems in this region. Indeed, synthesis population models at an age of 7 Myr produced much more hot stars than was observed in the GC. In addition, the observed Ne excitation was much too low compared to the prediction of photoionisation models. [16] claimed that stellar evolution produced too few cool stars.

Here, we show that this is not true any more. First, a new population of massive stars was discovered. Most of them are either Wolf-Rayet stars fainter than the first “Helium” stars, or OB stars. The latter have effective temperatures of the order 25000-35000 K, much hotter than the values of the He stars derived by [22]. The faint WR stars are also much hotter, with $T_{\text{eff}}$ as large as 54000 K. Second, the use of new atmosphere models for the analysis of the He stars lead to an upward revision of their effective temperatures. All in all, this implies that the present population of massive stars in the GC is much hotter than previously estimated, with the consequence of a harder ionising spectrum. For the whole population, we find log $Q_H = 50.7$ and log $Q_{HeI} = 49.2$, in very good agreement with the nebular estimates. We also note that the contribution of the He stars to the total H ionising luminosity has dropped to 3 %, in good agreement with the value of the synthesis population models ([16]). From that, we conclude that standard stellar evolution and the present generation of atmosphere models are perfectly adapted to study the Galactic Center massive star population.

7. The S - stars: spectroscopic properties

The so-called S-stars are the stars orbiting the super-massive black hole in the central arc-second of the Galaxy. Since the first spectroscopic identification of one of them – S2 – as a late O – early B star ([7, 8]), there has been a number of observations which have confirmed that the majority of these objects are indeed early to late B stars ([5]). Given that such stars are quite young (no more than $\sim 20$ Myr for the earliest types), their presence indicates recent star formation. But in this special environment, star formation should not happen ([20]): this is the
Figure 5. Comparison between the average $\text{Br}_\gamma$ spectrum of S2 over the last two years to template spectra of a B2V star (left) and a B1Ia star (right) from the atlas of [9]. The width of the observed line is much more compatible with a dwarf than with a supergiant classification.

“paradox of youth” in the Galactic Center ([8]).

With the accumulation of observations, better spectra of the S-stars become available. Consequently, more spectral lines are detected: in addition to the strong $\text{Br}_\gamma$ and $\text{He}^\text{i} 2.112 \mu m$ absorptions, $\text{He}^\text{i} 2.149 \mu m$, $\text{He}^\text{i} 2.164 \mu m$ and $\text{He}^\text{i} 2.184 \mu m$ are clearly seen in the spectrum of S2. This confirms the spectral classification as an early B star. With a better signal to noise ratio, the detailed shape of the $\text{Br}_\gamma$ line allows an estimate of the luminosity class of this star. Fig. 5 shows the comparison of this line in S2 (black) to template spectra for an early B dwarf and an early B supergiant (from the atlas of [9]): it is clear that the width of the line is better reproduced by the dwarf template, showing that S2 is not a supergiant. Hence, not only we confirm that spectroscopically S2 is an early B star, but we also argue that it is not a supergiant star. This is another indication of the youth of this star.

In order to solve the paradox of youth, there has been a number of proposal in the last years arguing that the S-stars are not genuine B stars but are older cool giants the envelope of which has experienced extreme changes due to the proximity of the super-massive black hole. Recently, [11] have proposed that the atmosphere of late type giants could be irradiated by some AGN activity of SgrA*. They show that depending on the strength of the irradiation, the resulting spectrum could either still show CO absorption bands, or show no CO but all H and He lines in emission. None of these models correspond to the observed spectrum of the S-stars which display absorption lines (H and He) and no CO. Another scenario proposed by [3] is that the S-stars are the core of AGB stars the envelope of which has been ripped off by tidal forces. Although attractive, this possibility suffers from quantitative problems: the rate at which tidal disruption occurs is too small to account for the number of S-stars; the luminosity of these remaining cores is too low compared to the estimated luminosity of the brightest S-stars; and special abundances are expected in such remnants, while so far the spectra of the S-stars do not differ from normal B dwarfs, i.e. stars with unprocessed He abundance.

In conclusion, the S-stars are spectroscopically B dwarfs and all the scenarios developed to explain them as older stars having experienced strong changes due to the proximity of SgrA* face quantitative problems.
8. Conclusion

We have performed detailed spectroscopic analysis of massive stars in the central parsec of the Galaxy using non-LTE atmosphere models including winds and line-blanketing. The combination of these new models with better spectra displaying more diagnostic lines than in previous study leads to an improved knowledge of the stellar and wind properties of the young stars located in the two counter-rotating disks in the Galactic Center. We show that very massive stars (with \( M \sim 100 M_\odot \)) are absent, mainly due to the age of the population: such stars have already exploded in supernovae after 6 Myr. The average effective temperature of the population is much larger than previously thought, mainly due to both the presence of hot OB and new Wolf-Rayet stars. This has important consequences for the ionisation of the ISM which can now be fully explained by the known population of young stars. This indicates that standard stellar evolution and atmosphere models, once thought to fail to explain the existence of the GC massive stars, now fully account for the observed properties of the population. Finally, we argue that the S-stars are B stars on or near the main sequence.

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