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Studying bright, massive stars in the era of large telescopes. I. General context

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Abstract

Stars of spectral type O play a key role in many processes in our Galaxy and beyond. However, there are still a number of open issues about these massive and luminous objects that need to be ad-dressed. Several of these questions require (long-term) spectroscopic monitoring that is difficult to achieve with the highly-demanded equipment on most modern professional instruments. However, these kinds of studies offer an opportunity for collaborations between amateur spectroscopists and professional astrophysicists.

Keywords : Stars: massive – stars: fundamental parameters – stars: emission-line – stars: winds, outflows – stars: binaries: general.

1. Introduction

O-type stars are hot (more than 30000 K), luminous (between 30000 and 3000000 times the solar luminosity) and massive (more than 10 solar masses) objects. With these extreme properties, O-type stars and massive stars in general, play a key role in the processes that shape the Universe (see e.g. the review by Nazé 2006). For instance, because of their high temperatures and extreme luminosities, O-type stars produce a large amount of UV radiation that ionizes the interstellar material in their vicinity, thus creating the well-known H II regions (emission nebulae containing ionized hydrogen such as the Orion or Rosette nebulae). The large luminosity is also responsible for the acceleration of their stellar wind (see Sect. 4).

Because of their high luminosities, these massive stars have rather short lifetimes (for astronomical standards) of order 10 million years (see Sect. 2 & 3). At the end of their life, they explode as supernovae, ejecting large amounts of material and energy into the interstellar medium.

At low spectral resolution, O-type stars can be identified thanks to their relatively low number of spectral lines and their blue colours. At higher spectral resolution, their spectral type, which reflects directly the surface temperature of the star, can be determined thanks to the ratio between the strengths of two helium lines: the neutral helium line He I λ 4471 and the singly ionized helium line He II λ 4542 lines (see e.g. Gray 2000). Hotter O-stars, i.e., stars with "earlier" spectral types (O2 – O6.5), have an atmosphere that is more ionized and display hence a stronger He II line. "Later" spectral types (O7.5 – B0), on the contrary, display weaker He II features in their spectra. The two lines have equal strength at spectral type O7.

In this article, I review the general properties of these stars and discuss how these properties are determined. Special emphasis is put on the powerful stellar winds which are unique features of these massive stars. Finally, some peculiar classes of O-type stars that display spectral variability are introduced and I highlight some aspects where amateur astronomers can make important contributions and help their professional colleagues achieve a deeper understanding of these stars.

2. The determination of the stellar mass

There are several techniques that allow determining the mass of a star. By far the most accurate and least model-dependent approach is based on the study of binary systems. Indeed, in a binary system, the radial velocity, i.e., the velocity component along the line of sight towards the observer, of each star changes periodically as the stars move around their common centre of mass. As a result of the Doppler effect, these changes of the radial velocity translate into a change of the wavelengths of the spectral lines of each binary component (see Fig. 1) with an amplitude that depends on the product of the stellar mass of its companion times the sine of the inclination

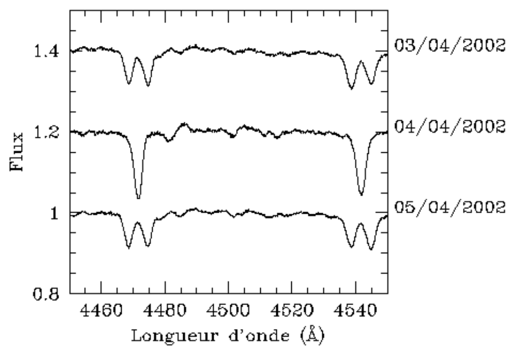

Fig. 1: Spectroscopic observations of the O-type binary HD165052 for three different dates illustrating the shift in wavelength of the lines of both stars as they move around their common centre of mass (Linder et al. 2007).

angle between the orbital plane and the line of sight. For instance, the amplitude of the radial velocity curve of binary component 1 is proportional to

$$\frac{M_2 \sin i}{(M_1 + M_2)^{2/3}},$$

where M_1 and M_2 are the masses of components 1 and 2 respectively, and i is the inclination angle of the orbit with respect to the line of sight (i = 90° standing for the line of sight being actually inside the orbital plane, i.e., edge-on eclipsing systems). Conversely, the amplitude of the radial velocity curve of component 2 is obtained by simply interchanging the indices 1 and 2 in the equation above. Hence, if we can measure the spectral signatures of both binary components and hence their radial velocities (i.e. we are dealing with a so-called SB2 binary system, such as in Fig. 1), we can eventually determine the quantities $M_1 \, sin^3 \, i$ and $M_2 \, sin^3 \, i$.

The determination of absolute masses requires the knowledge of the orbital inclination angle i. The latter can be determined if the binary system displays photometric eclipses, i.e., for values of i not too far away from 90°, by fitting a geometrical model of the binary system to its observed light-curve[1] (see Fig. 2).

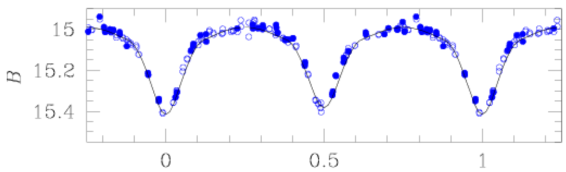

Fig. 2: Photometric light-curve of the very massive eclipsing binary system WR 20a in the *B* filter, along with the best fit model that allows to determine the inclination of the orbital plane with respect to the line of sight and to show that this system consists of two stars of about 82 solar masses each (Rauw et al. 2007).

Currently, the most massive stars that have been reliably weighed in this way have masses around 80 solar masses (Rauw et al. 2005). There are a few candidates of even more massive objects (up to 150 solar masses, De Becker et al. 2006, Schnurr et al. 2008), but these values are more uncertain.

A second technique, that allows estimating the mass of a star, is the mass-luminosity relation. The latter is an empirical relation that was established based on the results from the study of a large sample of eclipsing binary systems. For massive main-sequence stars, such as the O-type stars considered here, this relation is approximately given by

$$L \propto M^{\alpha}$$

[1] In some cases, the orbital inclination can also be obtained by combining the information of the spectroscopic orbit with astrometric measurements of the apparent position of the stars on the plane of the sky. This happens when the binary system is either very nearby (making it a visual binary) or more distant, but very-wide (making it an astrometric binary that can be resolved by high-angular resolution observations). This technique provides interesting results for low-mass stars (see e.g. Martin et al. 1998), but is less successful for more massive stars because of the scarcity of suitable systems.

where α ≈ 3 for stars between about 1 and 10 solar masses, whilst α ≈ 2 for stars more massive than 10 solar masses. It is the latter relation, implying that the luminosity increases with a large power of the mass, which explains the short lifetimes of the most massive stars. Indeed, to produce their huge luminosity, these objects need to “consume” their nuclear fuel at a much faster rate than the Sun.

The mass-luminosity relation can be used to get a rough estimate of the mass of a star, based on its observed luminosity. However, this technique is rather crude, especially for very distant objects, and fails completely if we are actually observing an unresolved multiple system, where the luminosity is not produced by a single star, but rather by a binary star or even a compact stellar cluster (see e.g. Maíz Apellániz et al. 2007). Moreover, because massive stars are rather rare objects and because only a few percent of the spectroscopic binary systems display eclipses, there are only a handful massive eclipsing binaries and the empirical mass-luminosity relation is thus rather poorly constrained in the higher-mass range.

The third method, frequently used to estimate the mass of a star, is the spectral analysis with a model-atmosphere code (e.g. Marcolino et al. 2009). This approach consists in computing synthetic spectra accounting for the physical processes inside the stellar atmosphere and adjusting this model to the observed spectrum. Among the model parameters, one finds the surface effective temperature T_{eff}, the stellar luminosity L and the surface gravity g. The former two parameters are related through the simple relation

$$L = 4\pi\sigma\ R^2 T_{eff}^4 ,$$

where σ is the Stefan-Boltzmann constant (5.67 10^{-8} W m^{-2} K^{-4}), whilst the surface gravity is given by

$$g = \frac{G \cdot M}{R^2} ,$$

where G is the gravitational constant (6.67 10^{-11} m^3 kg^{-1} s^{-2}).

Therefore, if we know the distance of a star, hence its luminosity, we can use its best-fit effective temperature to derive its radius and from the best-fit value of the surface gravity, we

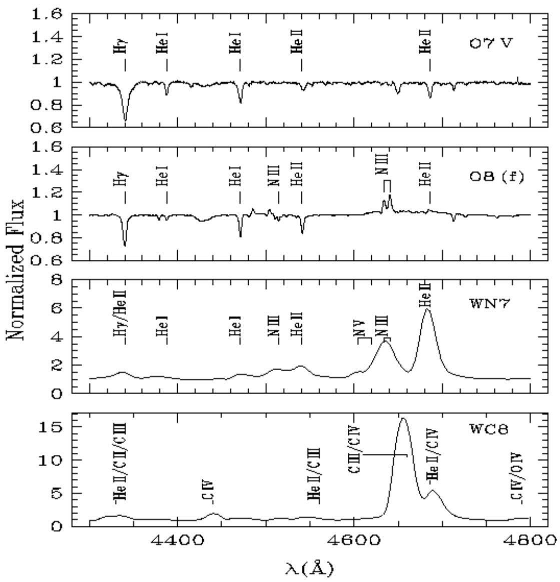

Fig. 3: A sequence of spectra of massive stars showing the evolution from a main-sequence O-star to an Of supergiant and subsequent Wolf-Rayet stages (respectively the nitrogen-rich WN and the carbon-rich WC stages).

eventually infer the stellar mass. This method is however dependent on the stellar atmosphere model and is also often hampered by a poor knowledge of the distance of the star.

3. The evolution of massive stars

Stars, whether massive or low-mass, produce their energy through nuclear reactions in their core. During the so-called main-sequence lifetime, these reactions transform hydrogen into helium. In massive stars, the evolution is also influenced by the stellar wind that progressively removes the outer layers of the star. As a reaction to this mass-loss, the stellar core shrinks and material that was initially part of the convective core reaches the stellar surface. At this stage, the stellar atmosphere hence contains the chemical elements that are products (helium) and/or by-products (nitrogen) of the nuclear reactions that once occurred in the stellar interior. In parallel, the nuclear reactions in the core shift towards the production of increasingly heavier elements. First, helium is "burned" to produce carbon and oxygen. Then, carbon is consumed to produce neon and magnesium, etc. As the processed material reaches the stellar surface, the changes in the composition of the stellar atmosphere leave their signature in the stellar spectrum and the enhanced metal content of the atmosphere leads to a stronger stellar wind. The star thus progressively evolves from a main-sequence O-star into an Of supergiant, displaying some (usually) weak emission lines in its spectrum, and eventually becomes a Wolf-Rayet star, first of spectral type WN, then WC (see Fig. 3).

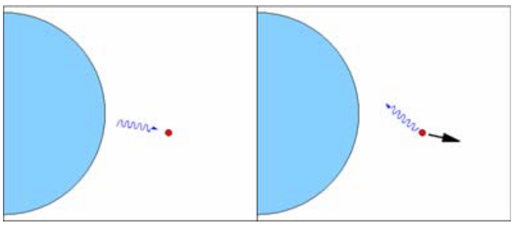

Fig. 4: Schematic illustration of the interaction between a stellar photon and an atom in the atmosphere of the star leading to the formation of a stellar wind. The atom absorbs a photon coming from the photosphere (left) and re-emits it in an arbitrary direction (right). The net result is an outwards acceleration of the atom along the radial direction.

Finally, once the nucleosynthesis in the stellar core has produced an iron core, there is no possibility to produce energy by further nuclear reactions. At this level, the stellar core collapses and the star explodes as a supernova, leaving a neutron star or black hole behind. Let us stress that the above scenario applies to single massive stars (see e.g., Maeder et al. 2008). In massive binary systems, the stellar evolution is a lot more complex because of the possibility for the two stars to exchange mass and/or angular momentum (see e.g., Langer et al. 2008).

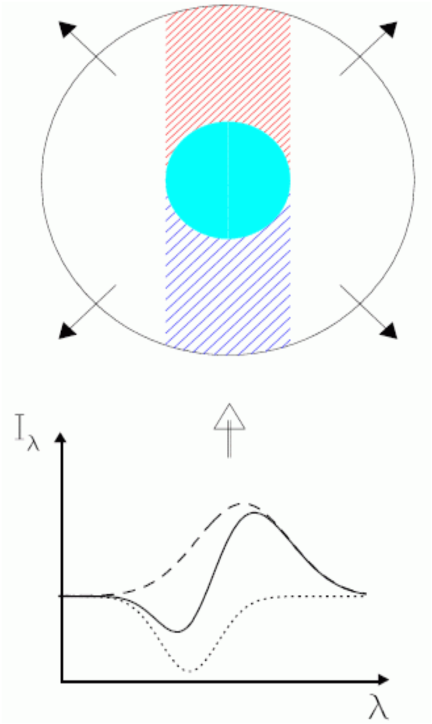

Fig. 5: Schematic view of the formation of a P-Cygni type line profile. The observer is looking at a spherically expanding wind from below in this figure (direction of the white arrow). Everywhere in the wind, the material absorbs photons from the photosphere beneath and re-emits them into an arbitrary direction. The blue-shaded material is moving towards the observer (hence producing a blue-shifted absorption, illustrated by the dotted line) whilst the red-shaded material is hidden by the stellar body and the side lobes of the stellar wind have on average zero velocity and produce thus an un-shifted emission line (dashed line). The combination of these features eventually leads to the P-Cygni type profile (solid line).

4. Stellar winds and their consequences

In the previous sections, we have frequently mentioned the effects of stellar winds. It is now time to state more explicitly what this is all about. Stellar winds in hot massive stars are driven by radiation pressure, i.e., it is the exchange of momentum between the photons from the stellar surface and the atoms in the stellar atmosphere that produces the acceleration of these atoms and leads to the formation of the stellar wind (see Fig. 4).

The stellar wind of a massive star carries substantial amounts of material at high velocity. The typical mass-loss rates of O-type stars are of order 10^{-6} solar masses per year and can reach 10^{-4} solar masses per year in the most extreme massive stars. The material in the stellar wind moves at a velocity of order 1000 to 5000 km/s (see e.g. Nazé 2006 for a review). Hence, the stellar winds of massive stars carry a huge amount of kinetic power and have therefore an important impact on the surroundings of these stars, leading for instance to the formation of circumstellar bubbles or to the triggering of new generations of lower mass stars.

The existence of an outwards expanding spherical stellar wind can be inferred from the spectra (especially in the ultraviolet domain) of massive stars through the presence of P-Cygni type profiles (see Fig. 5) or strong emission lines (see Fig. 3).

The above picture is however too simplistic. Over recent years it has been shown that the winds of massive stars are usually not homogeneous, but have structures that are either large scale structures or small-scale clumps (see Fig. 6), or both. This situation has various consequences: (1) the effective mass-loss rate of a clumpy wind is lower than for a homogeneous one with identical emission line strength (e.g. Martins 2009) and (2) the existence of structures can lead to substantial temporal variability of the lines that are formed inside the stellar wind (Eversberg et al. 1998, Howarth et al. 1998).

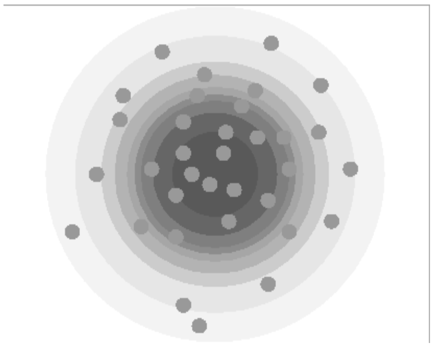

Fig. 6: Schematic representation of a clumpy stellar wind.

An important consequence of the existence of stellar winds associated with massive stars is the collision of these winds in massive binaries. In fact, when two massive stars form a binary, their winds interact somewhere in between the two stars, and this interaction produces a wealth of observational signatures over a wide range of wavelengths (from the gamma-rays and X-rays to the radio domain; see e.g., Rauw 2008). This phenomenon is intensively studied by astrophysicists and the most efficient approach is through multi-wavelength studies[2]. Amateur astronomers can make important contributions in this field, as is nicely illustrated by the MONS spectroscopic monitoring campaign orchestrated by Thomas Eversberg and friends (see Eversberg 2009). This campaign allowed collecting unique data for the long-period (7.94 years) colliding-wind system WR 140 (WC7 + O4-5) around its periastron passage in early 2009.

5. Some peculiar O-type stars and how amateurs can help us understand these objects

Massive stars are rare objects and as such, one could consider that they are all peculiar objects. Still, among the massive stars, there are some categories that deserve a particular interest, because they exhibit some special features in their spectrum and/or because their

[2] For more details see e.g. http://www.gaphe.ulg.ac.be/col_e.html

spectrum is variable. In this section, we briefly review two such categories, the Oe and the Of?p stars. We subsequently discuss the possible contributions of amateur spectroscopists to this research and we provide a non-exhaustive list of stars in the northern hemisphere that are of interest in the context of collaboration between amateurs and professionals.

In the previous section, we have seen that the winds of massive stars are nowadays understood to harbour considerable structures. These structures can be either small (compared to the dimensions of the star) or large. In the case of so-called Oe stars, the structure is most probably a large-scale one. There are only eight such stars known in our Galaxy and their distinctive feature is that their spectra exhibit a large number of double-peaked emission lines (Negueruela et al. 2004, see also Fig. 8). The Oe stars are usually considered to form an extension of the Be stars (Porter & Rivinius 2003) towards somewhat more massive and hotter stars. In Be stars, the double-peaked emissions are attributed to the stellar wind being concentrated near the stellar equator in a rotating disk-like structure. By analogy, the same situation is likely to apply to Oe stars (see Fig. 7).

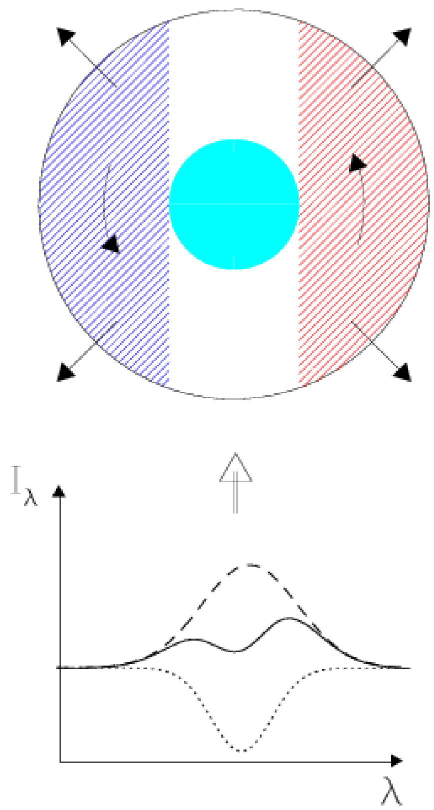

Fig. 7: Illustration of the formation of a double-peaked emission line in the spectrum of a star surrounded by a co-rotating equatorial wind.

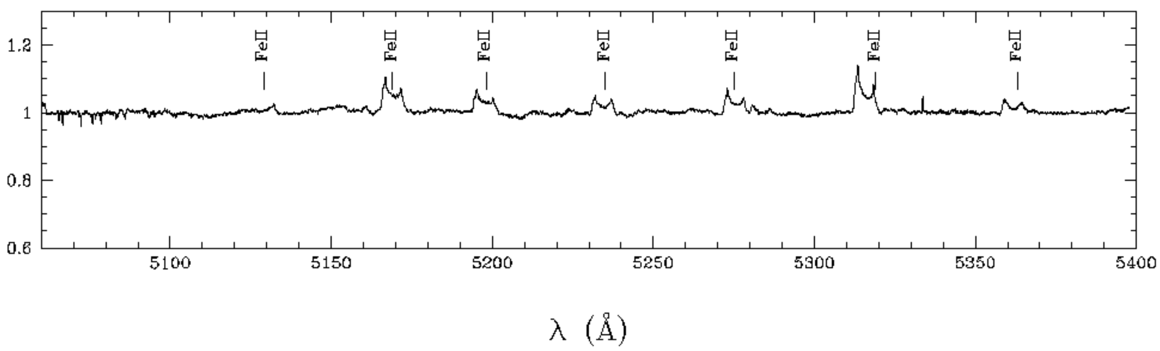

Fig. 8: Small part of the optical spectrum of the Oe star HD45314 displaying a large number of double-peaked emission lines. The lines in this specific spectral domain are due to singly ionized iron (Fe II).

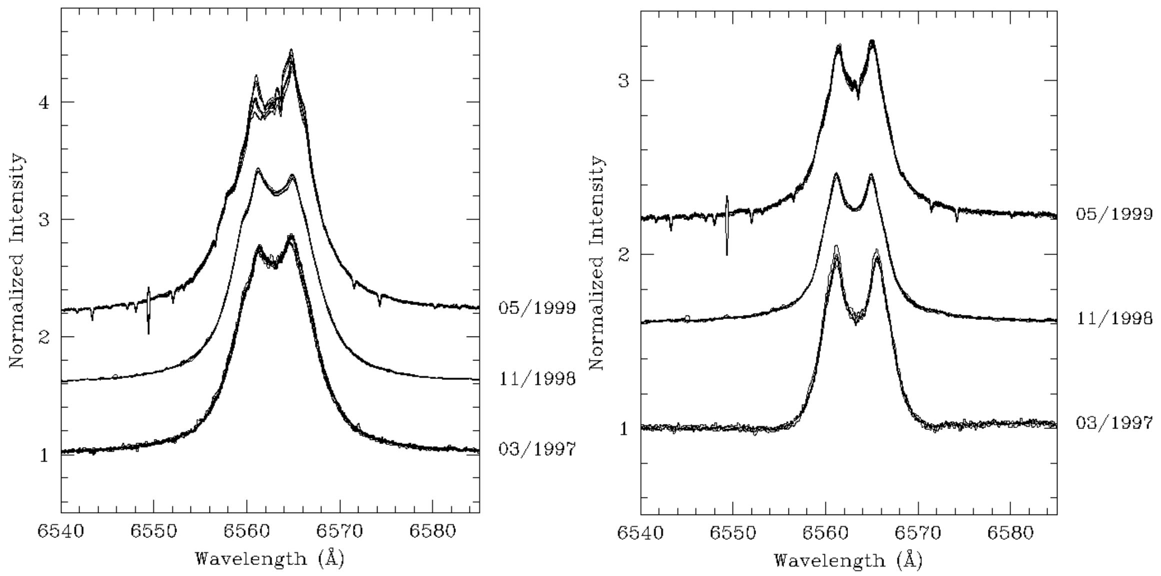

Fig. 9: Illustration of the changing Hα line in the spectrum of the O9.5Ve star HD45314 (left) and the O9.5IVe star HD60848 (right). The spectra taken during a given observing campaign (typically a week) are overplotted, whilst the data from the various campaigns (between 1997 and 1999) are shifted vertically. The figure clearly illustrates the lack of short-time variations, but the obvious presence of long-term changes both in line intensity and morphology (see also Rauw et al. 2007b).

However, the mere existence or absence of an equatorial disk in the case of Oe stars is still a matter of controversy. Important clues can be obtained from the temporal behaviour of the emission lines in the spectra of Oe stars. In fact, in Be stars, these lines are highly variable, often as a result of the existence of moving density waves in the disk itself (Porter & Rivinius 2003). Similar variations of the equivalent width of the Balmer emission lines and the ratio of the violet emission peak over the red emission peak have been observed at least in two Oe stars: HD45314 and HD60848 (Rauw et al. 2007b, see Fig. 9). However, the long-term behaviour of these stars still needs to be explored in much more detail. Important steps

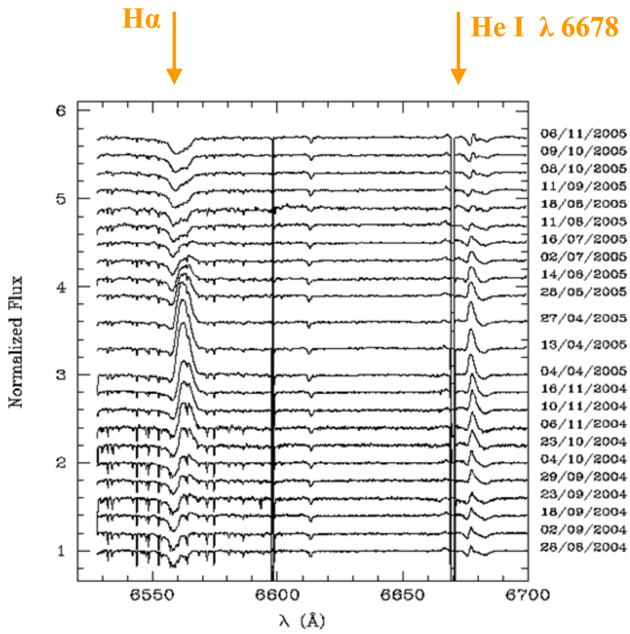

Fig. 10: The changes in the red spectrum of the Of?p star HD191612. Note especially the Hα and He I λ 6678 lines that vary between an absorption dominated profile and a P-Cygni type morphology.

towards such a study were taken during the MONS campaign mentioned above, when these two stars were more or less regularly monitored over 3 months.

The Of?p category is even more scarce than the Oe class, since only three objects of this kind are currently known within our Galaxy (Nazé et al. 2008). These are HD108, HD148937 and HD191612. This class was originally defined by an unusual strength of some carbon emission lines compared to neighbouring nitrogen emissions. However, over recent years, spectroscopic monitoring revealed that these objects display substantial spectroscopic variability as illustrated in the case of HD191612 by Fig. 10. Not only are these stars variable, apparently changing between a low and high-emission state, but most of all, this variability was found to be cyclic with periods of about seven days in the case of HD148937, 538 days for HD191612 and 55 years (!) for HD108 (see Nazé et al. 2008). The interest in these objects was even more stimulated by the discovery of a rather strong magnetic field in HD191612 (Donati et al. 2006). Magnetic fields are difficult to measure in massive stars and only a few cases are known with certainty. However, the impact of a magnetic field on the stellar wind can be quite substantial. In fact, such a field can potentially control the flow of the wind material leading to a stellar wind compressed near the magnetic equator. Such a feature is likely responsible for the variability of the very young O-star θ^1 Ori C (Stahl et al. 1996). If the magnetic axis is inclined with respect to the rotation axis and/or if the rotation axis is precessing (see Fig. 11), the compressed high-density part of the wind (i.e. where most of the emission lines form) will be seen by the observer under a changing inclination and this could possibly explain the spectacular spectral variations observed in these stars. However, only a continuous monitoring of their variability over a long time-scale (especially for HD108) will allow us to eventually establish the origin of the variations of these objects.

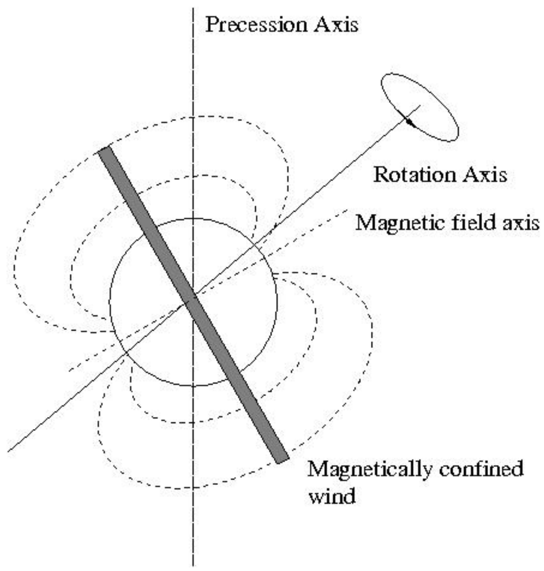

Fig. 11: Sketch of a possible interpretation of the variations of Of?p stars. The precession of the rotation axis (e.g. as a result of the action of binary companion) a star with a magnetically confined wind changes the orientation of the confined wind with respect to the direction towards the observer.

Many of these peculiar objects are relatively bright (often brighter than magnitude 8) and usually, a spectral resolution of order 10000 is sufficient for our purpose.
Monitoring the spectra of these stars is important since the temporal information provides complementary clues to understand the physics behind their peculiarities. Whilst this kind of monitoring is thus potentially very rewarding, it is quite difficult to organize in practice for professional astronomers. The reasons are multiple:

- Professional astronomers rarely have permanent access to a telescope.
- The time scales over which the stars must be investigated are often rather long (several months, sometimes even years) and are incompatible with (typically) short observing runs lasting for only a few nights.
- Over the recent decades most efforts in the field of professional astrophysics have been invested to (1) the developments of very big telescopes which are ideally suited for the study of very faint (often extragalactic) sources and (2) the design of very specialized instrumentations devoted to a specific research field such as the search and investigation of extra-solar planets.

For all these reasons, the spectroscopic monitoring of massive stars offers an interesting opportunity for a fruitful collaboration between amateur spectroscopists and professionals.

- More and more amateurs nowadays have medium-resolution spectrographs mounted on their own private telescopes. This equipment is suited for many long-term studies that do not require an access to very big facilities.
- Amateurs with their own equipment are not constrained by the schedule of a professional observatory. They can observe whenever the weather permits and whenever they like.
- Amateur spectrocopists, by their nature, are very patient people. They are more willing to support long-term campaigns than are the time allocation committees of professional observatories…

The most obvious targets in the northern hemisphere for a collaboration between amateurs and professionals are HD108 ($V = 7.4$), HD45314 ($V = 6.6$) and HD60848 ($V = 6.9$). However, other objects such as λ Cep ($V = 5.1$), HD192639 ($V = 7.1$) or λ Ori ($V=3.3$) are also of interest. Ideally, the observations should focus on a specific wavelength domain (Hα is obviously an interesting line to monitor) and should be taken with the same set-up all the time. For professional astronomers studying massive stars, this can open up brand new avenues to obtain unique data on their favourite objects, and for amateurs, it can be great fun to contribute to the scientific research.

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