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Long-Term Spectroscopic Monitoring and Surveys of Early-Type Stars with and without Circumstellar Envelopes

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Abstract: Ongoing studies of different groups of stars result in improving our knowledge of their fundamental parameters and evolutionary status. Also, they result in finding new phases of stellar evolution, which require theoretical explanation. At the same time, availability of large telescopes and sensitivity improvement of detectors shift the focus of many observational programs toward fainter and more distant objects. However, there are still many problems in our understanding of details of stellar evolution which can now be solved with small telescopes and observations of bright stars. Approaching these problems implies conducting surveys of large groups of stars and long-term monitoring of individual objects. In this talk, we present the results of recent international programs of photometric and spectral monitoring of several groups of early-type stars. In particular, we discuss the role of binarity in creation of the Be phenomenon and show examples of recently discovered binary systems as well as the problem of refining fundamental parameters of B and A type supergiants. Special attention will be paid to collaboration with the amateur community and use of échelle spectrographs mounted on small telescopes.

Keywords: early-type stars, spectroscopy, monitoring, emission-line stars, supergiants

1 Introduction

Astrophysics began in the second half of the nineteenth century with the advent of visual spectroscopy. It started from studies of the brightest stars whose properties have been re-investigated as more powerful telescopes and more sensitive detectors appeared and the spectral range available for observations grew. Large telescopes and orbital observatories equipped with modern sensitive instruments allow us to obtain high-quality data for individual stars and clusters in the Milky Way and other galaxies as well as for very distant galaxies. Such studies are exciting as they approach such problems as evolution of stars at various metallicities and early evolution of the Universe. At the same time, this knowledge rests on the results of previous studies of bright stars in our own galaxy. While

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currently the focus of stellar studies seems to be shifting toward fainter and more distant objects, some problems with bright stars remain unsolved.

In particular, this is due to recent discoveries of their new properties. Some examples include the presence of circumstellar disks surrounding such very bright stars as Vega (Aumann *et al.* 1984) and Fomalhaut from the results of the infrared (IR) sky survey accomplished by the IRAS satellite in 1989–1993, the detection of the secondary component of the first historically discovered Be star γ Cassiopeae (Harmanec *et al.* 2000; Miroshnichenko *et al.* 2002), and the discovery of a circumstellar disk around the brighter component of the eccentric binary δ Scorpii in 2000 (*e.g.*, Miroshnichenko *et al.* 2001). This object became a Be star and brightened by $\sim$70% in the optical region due to processing of the starlight in the circumstellar medium.

Analysis of the current state of such results reveals problems in our understanding of some processes and in the reliability of fundamental parameters of several groups of objects. We will focus on early-type stars only. The main goal of this talk is to present and discuss a few projects, which can be carried out with small telescopes and échelle spectrographs available for use on them. The following subjects will be discussed: brief history of the stellar spectral classification and its modern goals, current problems with fundamental parameters of B & A supergiants, and the problem of the role of binarity in the creation of the Be phenomenon.

2 Spectral classification

Classification is among the first tasks of any emerging science. In the case of astrophysics, spectral classification started developing with the first visual spectroscopic observations and went a long way from a few classes introduced by A. Secchi in the 1860-s to the familiar *OBAFGKM* temperature classes in the 1920-s suggested by the Harvard team. The luminosity classification was added by W. Morgan and Ph. Keenan in the 1940's (the MK process). However, it was still a qualitative description of the stellar fundamental parameters.

Development of model atmospheres (*e.g.*, Kurucz 1979) and techniques to determine the atmospheric chemical composition prompted transformation to a quantitative classification. Some classification criteria were suggested by Kopylov *et al.* (1982) based on high-resolution ($R = \lambda/\Delta\lambda \sim 20000$) spectra and by Gray and Corbally (2009) based on lower-resolution spectra ($R \sim 1300$). However, this process has been more successful for stars of spectral types *FGK* for which many pairs of temperature- and luminosity-sensitive spectral lines resulted in accurate calibration of these parameters have been found (*e.g.*, Kovtyukh *et al.* 2010).

Such procedures have been less successful for stars of earlier types, for which only a few temperature and luminosity criteria have been suggested (*e.g.*, Arellano Ferro *et al.* 2003). Also, it has recently been shown that stellar rotational velocity in early B–type stars is responsible for the variations of the CNO chemical abundances and thus needs to be taken into account in the fundamental parameters determination (*e.g.*, Lyubimkov 2016 and references therein). It seems desirable to critically review spectroscopic criteria proposed in the literature and combine them with photometric ones to improve quantitative classification. This process would benefit from obtaining observations of bright ($V \leq 8 - 9$ mag) stars, many of which have not been observed spectroscopically at a moderately high resolution (at least $R \sim 10000$). This is now possible with small telescopes. Enlarging the number of stars with measured spectral line parameters will make the classification more reliable.

3 BA supergiants

Large systematic surveys of Galactic supergiants located in clusters and associations were published by Humphreys (1978) and Garmany and Stencel (1992). These authors used MK classification, *UBV* photometry, and temperature and luminosity calibrations of MK classes available at that time. Studies of small groups of selected BA supergiants were published by Venn (1995, 22 A0–F0 Ia – II stars), Verdugo *et al.* (1999, 31 A0–A5 Ia – Ib stars), McErlean *et al.* (1999, 16 B4–A0 Ia – Ib stars), and Firnstein and Przybilla (2012, 35 B8–A2 Ia – Ib stars). Some other supergiants have been studied as part of various stellar groups or individually. Model atmospheres were used in these studies to constrain at least some fundamental parameters of the stars (*e.g.*, surface gravity).

Comparison of the results of these studies with each other and with adopted calibrations of MK types shows both luminosities and temperatures derived for the same stars in different studies vary significantly (*e.g.*, up to 1 mag in absolute magnitude and up to a few thousand K in temperature). At the same time, luminosity calibrations based on a large number of supergiants in a wide range of temperatures (*e.g.*, Arellano Ferro *et al.* 2003) are not very accurate (±0.3 dex) partly due to ignoring the temperature dependence of the chosen features, such as the equivalent width (EW) of the oxygen triplet at 7770–7775 Å. In particular, these uncertainties result in a mismatch between stellar masses derived from spectroscopic analysis, on the one hand, and from theoretical evolutionary tracks, on the other hand (see Miroshnichenko *et al.* 2013).

We obtained spectra of the majority of known Galactic B5–F0 supergiants and bright giants to the apparent visual magnitude of $\sim$10 with a moderate spectral resolving power ($R = 12000 - 20000$) in a spectral range between roughly Hγ and 7800 Å. Over 150 stars have been selected and observed mostly in the northern sky (typically down to $\sim -30^\circ$ Declination). The main goal was to find both the temperature and luminosity sensitive lines and their combinations (EW ratios) to improve determination of these parameters. The task is important because supergiants of this temperature range are the brightest sources in the visual part of the spectrum in galaxies and can be used as standard candles to determine distances toward nearby galaxies as part of the universal distance scale.

Nearly 400 spectra of 80 stars down to the V-magnitude of $\sim$ 8) were obtained with the 0.81 m telescope of the Three College Observatory (TCO, located near Greensboro, North Carolina, USA) with a commercial échelle spectrograph from Shelyak Instruments[1] and an ATIK 460EX CCD which allowed us to cover a spectral range between 4250 and 7800 Åin 24 apertures without gaps with $R \sim 12000$. Some, typically bright stars, were observed many times (10–50) to study possible variations of the spectral line parameters. An example of a spectrum taken with the TCO telescope is shown in Figure 1 (left panel).

Nearly 80 spectra of 70 $V = 6 - 10$ mag stars were taken at the 2.1 m telescope of the Observatorio Astronómico Nacional San Pedro Martir (OAN SPM, B.C., Mexico) with a REOSC échelle spectrograph in a range 4600–7800 Åwith $R \sim 18000$. Also, 15 spectra of 12 $V = 5 - 9$ mag southern stars were taken with a 2 m telescope of the Complejo Astronomico El Leoncito near San Juan (Argentina) also with a REOSC spectrograph with $R \sim 20000$ in a range of 3800–9000 Å.

All the spectra have been reduced using standard procedures typically with the *echelle* package in IRAF[2]. Parameters (EW, radial velocity, relative intensity) of nearly 50 spectral lines have been measured and are being analyzed. An example of the EW versus effective temperature for the He I 5876 Åline is shown in Figure 1 (right panel).

4 The Be Phenomenon

The Be phenomenon was observationally defined as the presence of emission lines in spectra of B–type dwarfs and giants (*e.g.*, Balona 2000). It is also associated with an IR excess due to free-free and free-bound radiation from a gaseous circumstellar disk, which surrounds a B–type star. Stars with the Be phenomenon are rotating near the critical (break-up) speed which is in part explains the disk's presence in the star's equatorial plane. The matter ejected from the B–type star is thought to be aided by non-radial pulsations (*e.g.*, Rivinius *et al.* 2013). Nearly a thousand Be stars are known at distances of ≤ 1 kpc from the Sun. Some of the brightest stars in the sky (*e.g.*, α Eridani, γ Cassiopeae, δ Scorpii, β Canis Minoris, ζ Tauri) are among them.

It is still unclear why Be stars rotate fast. They might have achieved high speeds during formation or were spun up by mass transfer from a secondary component in a binary system. The latter scenario was first suggested by Křiž and Harmanec (1975). However, it was shown that if a more massive component spins up the B–star, then only a small fraction of the latter will reach nearly critical speeds, and most of the evolved secondary components become helium-rich stars (Pols *et al.* 1991). Although some helium-rich secondaries have been discovered in binary systems with a Be–primary, most Be–binaries seem to be accompanied by not a very evolved low–mass secondary component, which may or may not be involved in the creation of the Be phenomenon. At the same time, there are many fast rotating B–type stars which have not been found to exhibit line emission. A systematic comparison between large samples of such Be stars and those without line emission, which can also be done with small telescopes, should provide more insights into the origin of Be stars.

Another problem with understanding the temporal behavior of Be stars is that their disks can suddenly appear and completely disappear on a timescale of years and decades. Not many such events have been well-documented. One of them is dissipation of the disk around π Aquarii (V up to 4.4 mag with the disk and $V \sim 4.8$ mag without the disk) that occurred in 1989–1995 (Bjorkman *et al.* 2002). Spectroscopic observations during the disk dissipation process allowed observers to detect the presence of the secondary component, which is $\sim$4 mag fainter than the B–primary in the V–band. The disk started

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[1] http://www.shelyak.com

[2] IRAF is distributed by the National Optical Astronomy Observatories, which are operated by the Association of Universities for Research in Astronomy, Inc., under cooperative agreement with the National Science Foundation.

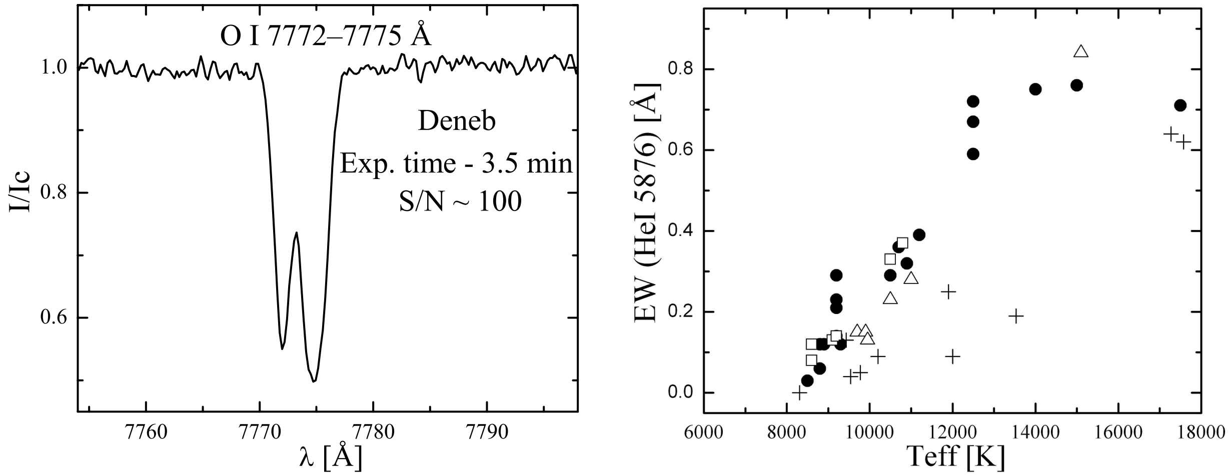

Fig. 1. Left panel: Example of a part of the longest wavelength order of a spectrum of *α* Cygni taken at TCO. This part contains the luminosity sensitive triplet of O I lines. Although two of the three lines are blended (the right line), their combined EW is usually used to measure the object's luminosity. **Right panel:** Relationship between the EW of the He I 5876 Å line and effective temperature for stars of various luminosity types: filled circles: – Ia, squares – Iab, triangles – Ib, pluses – III and V. Observational data were obtained at TCO, temperatures were taken from the literature.

Table 1. Some databases and archives that contain spectra of Be stars.

Observatory/ Database	Telescope size	R	Sp.range Å	Limit. V–mag	Number of spectra	Observ. period	Ref.
Ritter Obs.	1 m	26000	5280–6600	7.5	∼2000	1991–2007	1
BeSS	0.2–0.5 m	1000–22000	4200–7300	10	≥ 10000	since 1993	2
BeSOS	0.5 m	20000	3900–7300	9	∼1000	since 2011	3
TCO	0.81 m	12000	4250–7800	10	∼1000	since 2012	4

Column information: 1 – shows the name of the observatory or database, 2 – lists the telescope(s) primary mirror diameter, 3 – spectral resolving power(s), 4 – typical spectral range of the data, 5 – limiting V–magnitude, 6 – approximate number of spectra of Be stars contained in the database (keeps growing with time), 7 – lists timeframes when the data were taken, 8 – references to the database websites or contact are listed below.

1 – http://astro1.panet.utoledo.edu/∼wwritter/obs_home.html, more spectra have been taken at Ritter since 2007 in a wider wavelength range

2 – [a] (Neiner *et al.* 2011)

3 – [b] (Kanaan and Arcos 2017)

4 – not released yet, contact the first author of this paper

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[a] http://basebe.obspm.fr

[b] http://besos.ifa.uv.cl

re-appearing in 2001, but its radiation is not as strong as it was in 1980's when the H*α* line had a EW of ∼40 Å. It has also been noticed that the peak intensity ratio (V/R) in the H*α* emission line profile varies periodically with the system orbital period (84.3 days, Zharikov *et al.* 2013, see Figure 2, left panel).

Several other Be stars with relatively weak H*α* emission were found to show similar V/R variations that follow the orbital period, while in Be stars with stronger emission-line spectra periods of such variations are much longer than the orbital periods (*e.g.*, in *ζ* Tauri or 48 Librae). Therefore finding periodicity in the V/R variations of weak-lined Be stars may serve as a tool to detect their binarity. This task can also be accomplished with small telescopes and medium-resolution spectrographs ($R \sim 10000 - 20000$).

Several other bright Be stars have lost their disks recently. One of them is 66 Ophiuhi (Miroshnichenko *et al.* 2012). Its circumstellar emission disappeared around 2010, and no trace of its recovery has been detected until now (see Figure 2, right panel). Such diskless phases allow to determine the fundamental parameters of the B–type stars more reliably than during active phases and search for binarity using the radial velocity variations of strong lines (*e.g.*, Hα) undistorted by the presence of the disk. Contemporaneous photometric observations allow to measure the true B–star brightness and thus evaluate the strength of the circumstellar continuum during the active disk phase and correct the star position on the Hertzsprung-Russell diagram, hence refining its evolutionary status.

There is rich spectroscopic material on many other Be stars which is supplied by amateur astronomers along with professional teams. A list of some databases which contain many spectra of Be stars is given in Table 1. All these databases (perhaps except for BeSS) include some spectra of early-type supergiants. Many high-quality spectra of objects with the Be and B[e] (see the paper by Khokhlov et al. in this volume) phenomena used in our joint projects have been taken at the 2 m telescope of the Ondřejov Observatory (near Prague, Czech Republic, $R \sim 12000$), the 2.1 m telescope at OAN SPM ($R \sim 18000$), and the 3.6 m Canada-France-Hawaii Telescope at Mauna Kea (Hawaii, USA, $R \sim 65000$). These data become an invaluable resource for investigation of bright stars, constraining their nature and fundamental parameters.

With many spectroscopic observations that became available in the last two decades, it was possible to make statistical studies of various observational properties of Be stars. In particular, Miroshnichenko (2011, 2016) found that nearly 50% of Be stars brighter than $V = 4$ mag were recognized binaries. Known binaries are not that frequent among fainter Be stars which is probably a selection effect due to a smaller number of their observations. This result implies that the binary fraction in Be stars should be at least 50%. That calls for further studies of the role of binarity in creation of the Be phenomenon.

There is also a slight trend toward more binaries among Be stars with stronger line emission. Therefore, objects with the strongest emission-line spectra should be investigated for possible binarity. A list of such candidates was published by Miroshnichenko (2016).

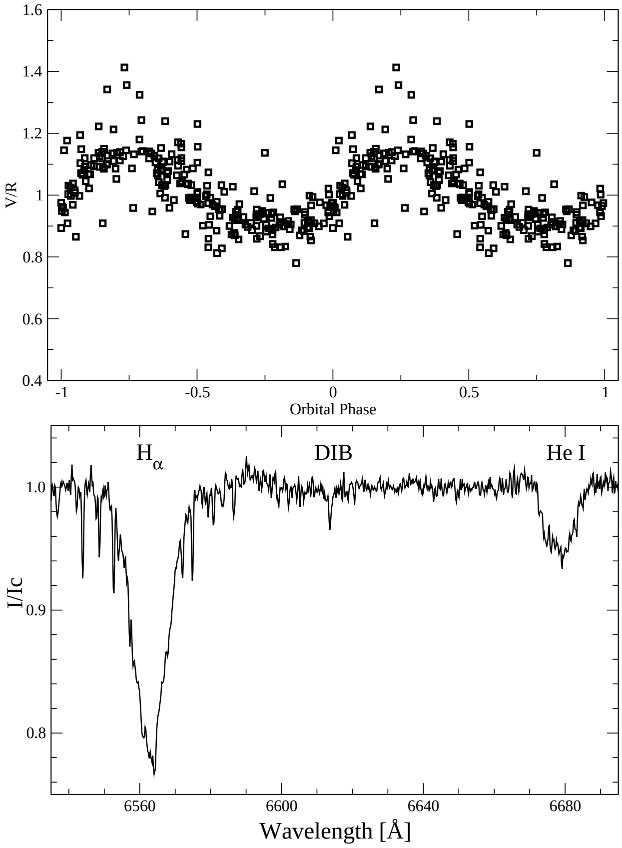

Fig. 2. Left panel: V/R variations of the double-peaked Hα profile in the spectrum of π Aquarii folded with an orbital period of 84.3 days that was found from analysis of the radial velocity variations (from Zharikov *et al.* 2013). **Right panel:** The Hα line profile of 66 Oph obtained at TCO in October 2016. Unmarked narrow features are telluric lines. The 6614 Ådiffuse interstellar band and the He I 6678 Åline are marked. Average signal-to-noise ratio in the continuum is $\sim$200.

5 Conclusions

Long-term monitoring of bright stars with small (≤ 1 m) telescopes in a collaboration of professional and amateur astronomers allows observers to achieve the following results:

- take reliable (in terms of signal-to-noise) spectra of stars brighter than $V \sim 10$ mag with a spectral resolution of $R = 10000 - 30000$ in a wide wavelength range with available commercial spectrographs, such as the Eshel from Shelyak Instruments (not the only model available from this company).
- improve our knowledge of the nature and fundamental parameters of stars with and without circumstellar envelopes. Such projects supported by photometry, which for bright stars is easier to take with smaller telescopes, get additional important information about properties of underlying stars allowing us to separate the effects of circumstellar matter.
- study processes of mass transfer and circumstellar matter evolution in stellar systems.

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University of North Carolina at Greensboro, which allowed him to summarize all the observations that have been taken at TCO so far.

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