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A variety of binary targets for small telescopes

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Abstract. Results are reviewed of a long-term program of binary systems observing since 2013 at the 0.81 m telescope of the Three College Observatory in North Carolina, USA, with an échelle spectrograph at a medium spectral resolution. The target list includes recognized and suspected binary systems with normal stars (no spectral lines in emission), classical Be stars, and objects with the B[e] phenomenon. The results include refinement of the orbital elements of bright binaries previously observed with photographic plates, further evidence for phased-locked peak intensity variations of double-peaked line profiles in Be binaries, and recent discoveries of binaries among objects with the B[e] phenomenon.

Key words: spectroscopy – emission-line stars – binary systems

1. Introduction

Many Galactic stars exist in binary systems, whose studies allow us to measure stellar masses and study the process and consequences of the mass exchange between the system components. It turns out that a noticeable fraction of bright (naked-eye or somewhat fainter) binaries have been observed during the epoch before the appearance of CCD detectors that resulted in determination of their orbital and physical properties with a relatively low accuracy. Revisiting these objects with higher quality detectors is necessary to better constrain their properties. This task is doable today with telescopes that are meter-class or smaller.

Binary systems that contain normal (not emission-line) stars can show spectral lines of either one (single-lined) or both (double-lined) components. Determining orbital properties, such as periods, radial velocity (RV) amplitudes, and eccentricities, from spectroscopic data of double-lined systems allows us to measure masses of the components directly. Dealing with single-lined binaries is more complicated, because in addition to the inclination angle of the system's orbital axis other orbital parameters need to be known for both components in order to determine their masses. If the inclination angle in a double-lined spectroscopic binary is unknown, one may determine the mass ratio of the pair from the inverse ratio of the RV amplitudes but it may not be possible to determine each individual mass. The latter is possible with the knowledge of the stellar fundamental parameters (temperature and luminosity).

Stars and stellar systems of all masses go through periods of being surrounded by large amounts of gaseous and dusty circumstellar (CS) material. The duration of these periods mostly depends on the objects' masses and orbital separations. Some reasons for the presence of the CS matter include formation of stars in molecular clouds, stellar winds, and mass transfer between components in binary systems. The CS matter processes starlight and becomes partially ionized; that results in the formation of emission lines, while CS dust can form in more distant and mostly neutral areas of the CS matter.

Although many phenomena due to the CS matter have been successfully explained by the theory of stellar evolution, some remain puzzling even with the currently available wealth of data and sophisticated modeling methods. Two of them, the Be and B[e] phenomenon, are still under investigation aimed at revealing their causes. The Be phenomenon is defined as the presence of permitted emission lines in the spectra of mostly B–type dwarf stars (effective temperatures, $T_{\rm eff}$ = 9,000–30,000 K), while the B[e] phenomenon also includes the presence of both forbidden emission lines and infrared (IR) excesses due to the radiation of CS dust. Explanations of both the phenomena went through periods of alternatively favoring or mostly ignoring the binary nature of the underlying stars. However, recent evidence that comes from traditional observing techniques (photometry and spectroscopy) and more advanced ones (e.g., interferometry, spectro-astrometry) shows that binary systems play an important role in formation of these objects.

Our observations are described in Sect. 2, examples of our results are shown in Sect. 3, and conclusions and future plans are presented in Sect. 4.

2. Observations

Our team uses the 0.81 m telescope of the Three College Observatory (TCO) located in the central North Carolina, USA, to monitor various binary systems in nearly the entire optical region with a fiber-fed échelle spectrograph. The Observatory was open in the early 1980's, and was used for public viewing and photometric observations until 2011, when the spectrograph eShel from Shelyk Instruments [1] was installed on the telescope. A focal reducer changes the original focal ratio of F/13.6 to F/9 that matches the input focal ratio of the fiber optics.

The spectrograph with an ATIK-460EX detector (2749×2199 pixels, pixel size 4.54 μm ×4.54 μm) provides a spectral resolving power of $R \sim 12,000$ in a spectral range from 3,800 Å to 7,900 Å without gaps between the spectral orders. The location latitude (35°56′ N) allow observations of the entire northern sky and a big portion of the southern sky (down to a declination of about −40°).

The signal gets low near the blue and red boundaries of the above spectral range due to a decreasing sensitivity of the detector. The maximum signal is achieved at wavelengths of ∼5800–6200 Å. The spectrograph is stored in a refrigerator at a stable temperature ∼10–15°C, one floor below the telescope and connected to it with a 10-meter long fiber. The one-stage Peltier cooler allows achieving working temperatures of −2°C to −20°C at the detector, which fortunately has a low temperature dependence of the quantum efficiency.

Final spectra typically consist of several individual exposures, which are summed up during the data reduction process. The latter uses the IRAF package *echelle* and includes bias subtraction, spectral order separation, and wavelength calibration using spectra from a ThAr lamp. The number of comparison lines identified in the calibration spectra range from ∼800 to over 1,000. A typical scatter of the comparison line positions from a polynomial solution is ∼0.03 Å which results in a potential RV accuracy of ∼300 $\mathrm{m\,s^{-1}}$.

Flat field images are not taken, because the detector has a pixel sensitivity difference of ≤ 1.5% and the flat field lamp does not cover the entire extracted spectral range. The spectra contained 24 orders between 4200 Å to 7900 Å during the first 7 years of observations. In the Fall of 2018 the number of orders increased to 31 after the installation of an optical fiber with better UV transmission. Since 2022 we also extract two additional spectral orders that extend the spectra to ∼8450 Å.

The location of TCO at a low elevation of ∼180 meters above the sea level has both advantages and disadvantages. The main advantage is that most cosmic rays get absorbed in the Earth's atmosphere before reaching the telescope. Another advantage is that the place has a relatively low humidity, which rarely

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

reaches 80–85% on clear nights. Typically there are ∼150 clear and semi-clear nights a year. One of the main disadvantages is that an average seeing is 2–3 arcseconds, but it can be better during nights with a high humidity. Another problem is high temperatures during summer time reaching 35°C.

The ATIK-460EX detector was installed in January 2013, while a Watec 120N TV camera has been used to view the observed targets since the very beginning of the spectroscopic program in October 2011. Observers (A.M. and S.D. and later A.A., who joined the team in 2018) were taking spectra on-site until 2020. TCO was automated in the Fall of 2019. Remote observations began in April 2020 and allowed us to increase the number of used nights from ∼80–85 to ∼150–160.

3. Results

Our observing projects target a variety of objects that include nearly 140 dwarfs and roughly the same number of supergiants of the spectral types B, A, and F for the purpose of calibration of fundamental parameters and studying spectral variations; ∼30 classical Be stars, ∼10 objects with the B[e] phenomenon, ∼10 pre-main-sequence Herbig Ae/Be stars, 5 horizontal branch stars, 5 post-AGB dusty binaries, and some other peculiar objects. In particular, we have been monitoring ∼20 binary systems of different kinds (with and without emission lines) and some stars suspected of binarity.

The total number of spectra taken since the beginning of spectroscopic observations during ∼ 1,150 nights approaches 12,000. Radial velocity (RV) standard stars of early and late spectral types from such lists as Stefanik et al. (1999) and Soubiran et al. (2018) are being observed every night. The fraction of RV standard observations in our entire set of data is nearly 12%. The latter allows us to constantly keep track of the wavelength calibration quality.

In this paper, we will present several results from our observing program mostly concerning very bright known binary systems undergoing different evolutionary stages. However, we first go over the observed features of binaries and difficulties of different kinds of object. The features include but are not limited to the following: the presence of two systems of spectral lines in the spectrum, periodic RV variations of spectral lines, periodic intensity variations in double-peaked line profiles (e.g., orbital phase-locked, found in Be stars), differing positions of the continuum and spectral lines on detectors (spectro-astrometry), and direct detection of secondary components by imaging or interferometry. The difficulties include the presence of broad spectral lines due to fast rotation of the underlying star (e.g., in Be stars), distortion of absorption lines by CS emission or replacement some absorption lines with emission lines (most often of hydrogen lines), and much fainter secondary components (≥2 mag in the visual part of the spectrum found in Be and B[e] stars) that hampers spectroscopic detection of the secondaries. The methods used for the data approximation, when periodic processes were found, are described in Andronov (2020).

A selection of recently published results on binary systems with a significant fraction of observations taken at TCO includes the following.

1. Refining orbital parameters of bright "normal" binaries Mizar B, 2 Lac, ϕ Aql (Miroshnichenko et al., 2023b)
2. A systematic study of the peak intensity variations of double-peaked line profiles in Be stars to detect faint secondary companion (Miroshnichenko et al., 2023a)
3. First reliable detection of the secondary companion in the brightest B[e] binary 3 Pup (Miroshnichenko et al., 2020)
4. Monitoring the pulsational period and surface temperature variations of Polaris A and refining its binary orbit (Usenko et al., 2020)

Examples of the results from some of the mentioned papers are given below.

3.1. Mizar B

Mizar B is the fainter among the two binary systems visible with the naked eye as one star, Mizar. Both systems are spectroscopic binaries easily resolved with a small telescope. Mizar B ($V = 3.9$ mag) is a single-lined binary. The RV variations in its spectrum were first announced by Frost (1908), while the first orbit determination attempt was made by Abt (1961) based on 24 photographic spectra taken in 1959 at the McDonald Observatory (Texas, USA) and found a wrong period of 361 days. Gutmann (1965) took 89 photographic spectra at the Dominion Astrophysical Observatory (DAO, Victoria, BC, Canada) between 1941 and 1963. These data covered several orbital cycles, but only 3 of them in detail. The latter is important due to a large orbital eccentricity. No new studies of Mizar B have been reported since that time to the best of our knowledge.

We took nearly 120 spectra of Mizar B in 2016–2021 and derived RVs by cross-correlation in a spectral region between ∼5100 and ∼5300 Å using the IRAF package *rvsao*. The cross-correlation template was obtained from averaging several exposures of the RV standard star δ03 Tau = HR 1389, heliocentric RV = 39.0±0.1 km s^{-1} (Stefanik et al., 1999; Soubiran et al., 2018).

Our data along with those from Gutmann (1965) are shown in Fig. 1. Both data sets are folded with the best-fit orbital period 175.11±0.10 days found from the TCO data, which exhibit a significantly lower scatter and a systemic RV of -14.34 ± 0.04 km s^{-1} that is 5 km s^{-1} more negative.

Based on the fundamental parameters of the primary component of Mizar B derived from published photometry and the Gaia distance (24.81±0.17 pc, Bailer-Jones et al., 2021), its evolutionary mass is 1.8 M$\odot$. From the mass function calculated from our orbital parameters and the absence of signs of the

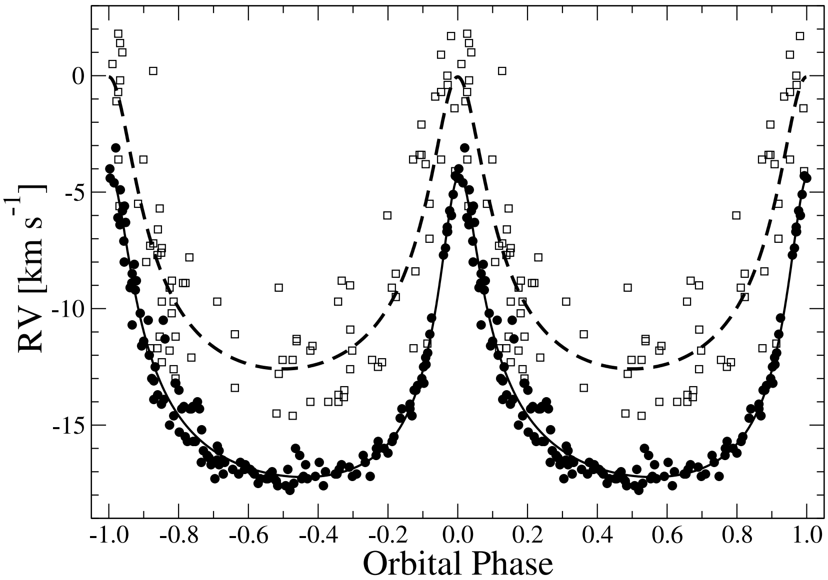

Figure 1. RV curves of Mizar B from Gutmann (1965) and from TCO data. The DAO data are shown by open squares, and the best fit to these data is shown by the dashed line. The TCO data are shown by filled circles, and the best fit is shown by the solid line. The RVs of both data sets are heliocentric.

secondary component, one can conclude that the secondary is a much lower mass star. It would be a K3 V star with a mass of 0.77±0.03 M⊙ at the orbital inclination angle of $i = 20°$ or an M3 V star with a mass of 0.37±0.02 M⊙ at $i = 40°$. The orbital parameters of the Mizar B binary system and more detailed conclusions from it are published in Miroshnichenko et al. (2023b).

3.2. Polaris A

Another bright interesting objects is Polaris A, a Cepheid that is the closest to our Solar system. A few facts about this object: it is a multiple system with three visual components (Polaris B = BD+88°9, C, and D) and a member of an anonymous open cluster; one of four Cepheids with a radius measured by optical interferometry (46±3 R⊙, Nordgren et al., 1999). On top of that, it has the largest number of RV measurements among Cepheids for over 120 years.

The pulsation period of Polaris A was found gradually increasing by 4.45±0.03 s yr^{-1} from 3.9669 to 3.9707 days in 1896-2004 (Turner et al., 2005). The pulsation amplitude dropped from ∼5 km s^{-1} before 1950 to ∼0.05 km s^{-1} in the 1980s, then increased from ∼1.5 km s^{-1} in 1987 to ∼2.4 km s^{-1} in 2007.

We started observing it at TCO in 2015 and took over 500 spectra to-date. Some of our results include measuring changes in the pulsation period and refining the orbit of the Polaris A binary. In particular, TCO data covered the most recent periastron passage of Polaris B. Figure 2 shows our RV data taken in 2015–2020 along with those from Anderson (2019). This is the only periastron passage in this system that has been covered with modern high-quality spectroscopy, as the orbital period of this binary system is 29.3 years. We plan to keep monitoring Polaris A to further constrain its pulsational properties and orbit.

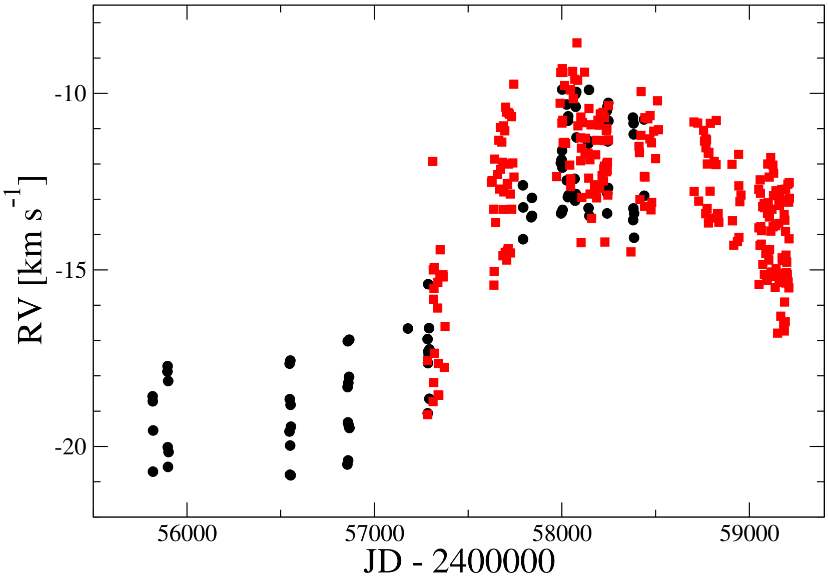

Figure 2. RV variations of Polaris over the last ten years. Red squares show TCO data, black circles show data from Anderson (2019).

3.3. Be stars

Our program studying classical Be stars includes $\sim$40 objects with a V–band brightness from $\sim$ 2.9 and $\sim$ 8.0 mag. It aims at long-term monitoring of various features, such as emission lines appearance/disappearance, variations of the emission peak intensities in double-peaked spectral lines ("V/R" variations), and absorption-line positional variations. It covers known and suspected binaries as well as those currently considered single. One of our goals is to verify previously published results and improve our knowledge of binarity by using different spectroscopic diagnostics based on large sets of homogeneous data.

The objects for this program were selected based of the following criteria: 1) sufficiently bright ($V \leq 6$ mag) to achieve high signal-to-noise ratios with the TCO telescope in a wide spectral region, and 2) the presence of double-peaked Balmer emission lines that are not very strong to avoid possible longer-term periodicities observed in some objects of this class (e.g., 48 Lib). We intended to study the V/R behavior in more detail than previously, test the V/R variations as an indicator of binarity, and put more constraints on the applicability of this method. Our data on some of the program stars were supplemented by other data either published or taken from public data archives, such as the BeSS database (Neiner et al., 2011).

The results of our Be star program include include confirmation of the orbital periods in ν Geminorum, ϵ Capricorni, κ Draconis, 60 Cygni, and V2119 Cygni, refinement of the orbital period of o Puppis, and suggestions of binarity in o Aquarii, BK Camelopardalis, and 10 Cassiopeae. Monitoring of the Hα line profile variations of β Canis Minoris for over the last 10 years gives further support to the existence of a 182.5–day period found earlier in a smaller set of data. A similar but still preliminary period (179.6 days) was found the Hα line profile variations of ψ Persei.

Perhaps the most important result of the TCO program concerns the 4th magnitude star ν Geminorum. History of studies of this multiple system was recently reviewed in Klement et al. (2021) and focused on the inner binary and the distant tertiary component. Following the first measurement of the inner binary orbital period (53.73 days) and the conclusion on the absence of phase-locked V/R variations of the double-peaked Hα line profile Rivinius et al. (2006), it was assumed that the Be star is the tertiary component, while the inner pair consists of two B-type stars of nearly equal masses. However, the latest long-baseline interferometry results (Gardner et al., 2021) revealed an inconsistency between the astrometric and the mentioned spectroscopic orbital solutions.

We have been monitoring ν Gem since 2014 at TCO, and our data always showed double-peaked Hα line profiles with small V/R variations. However, earlier observations published in Rivinius et al. (2006) as well as some others found in public archives showed a much larger range of the V/R ratios and a more complex structure the Hα line profile with three and even four emission peaks around the year 2000. The line profile returned back to a double-peaked in the beginning of 2003, but large V/R variations remained until mid–2006 matching the time period reported in Rivinius et al. (2006), when no regular V/R variations were detected.

Our spectra showed a V/R amplitude of $\sim$0.2 and a temporal trend toward smaller V/R. Also, the V/R ratio exhibited a strictly periodic phase-locked behavior, which became especially obvious after subtracting a linear trend. Therefore, the Be star takes part in the 53.78-day orbital period and cannot be identified with the tertiary component of the ν Gem system. The RVs derived by cross-correlation with in a spectral region near 4500 Å and a detrended V/R data are shown in Fig. 3.

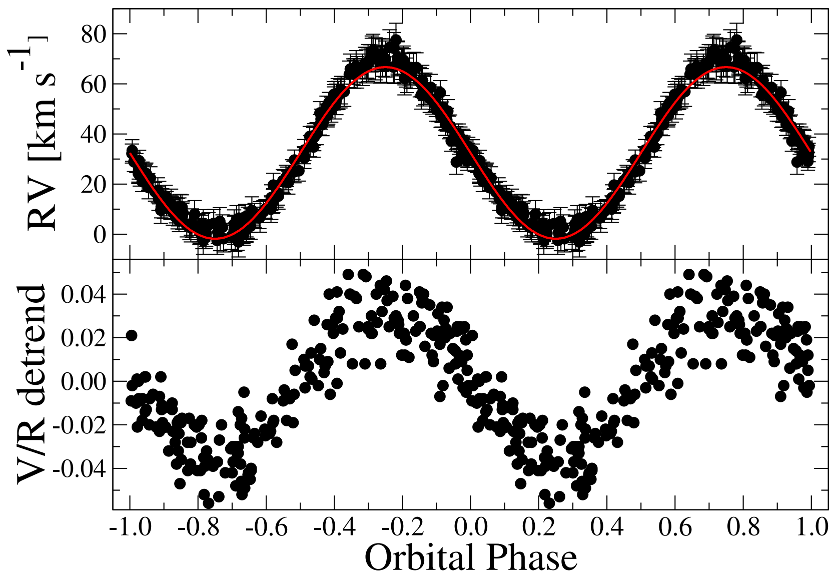

Figure 3. Top panel: RV variations of the absorption lines in the spectrum of ν Geminorum in a region 4450–4555 Å folded with the orbital period (53.73 days). Red line shows our circular solution. Bottom panel: V/R variations of the Hα line profile de-trended with a quadratic function and folded with the same period.

We also found the phase-locked V/R variations in ϵ Capricorni, κ Draconis, 60 Cygni, and V2119 Cygni, and o Puppis. Our results show that such variations are observed in more Be binary systems than previously known and can be used to search for binarity of Be stars when application of other methods is inconclusive. A detailed description of the results of our Be star program has been recently published in Miroshnichenko et al. (2023a).

4. Conclusions

Spectroscopy of binary systems is still important, because even very bright objects may not have well-constrained orbital and hence physical parameters. Spectral resolving powers of R $\geq$ 5,000 are needed to reliably search for RV and intensity variations. Observations needs to be taken as frequently as possible and for a period of at least several years. The V/R variation method successfully complements other methods of discovering binarity of Be stars.

These projects can be successfully performed with meter-class telescopes equipped with inexpensive échelle and long-slit spectrographs. Sensitivities of modern CCD detectors allow taking high-quality data of many stars and stellar systems down to V ~11 mag. at intermediate R ~ 10,000–20,000. Overall, performing these observations not only helps refining older results on binary systems but also discover new phenomena and contribute to a better understanding of stellar evolution.

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