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The Be Binary δ Scorpii and Its 2011 Periastron Passage

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Abstract. δ Scorpii is an unusual Be binary system. The binarity was discovered by interferometry in the 1970's and only confirmed by radial velocity measurements during the periastron passage in September 2000, when the primary component became a Be star. The components brightness and mass suggest that both are normal B-type stars. However, the large orbital eccentricity (e = 0.94) is highly uncommon, as most such Be binaries have circular orbits. The orbital period, only recently constrained by interferometry at 10.81 years, needed confirmation from spectroscopy during the last periastron passage in July 2011. The periastron observing campaign that involved professionals and amateurs resulted in obtaining several hundreds of spectra during the period of a large radial velocity change compared to only thirty obtained in 2000. Along with a determination of the orbital period accurate to 3–4 days, the radial velocity curve was found to be more complicated than one expected from just a binary system. I will briefly review the primary's disk development followed by a discussion of the recent observations. Implications for the system properties and ideas for future observations will be presented.

1. Introduction

δ Scorpii or Dschubba is one of the brightest stars in the sky (V = 2.3 mag before 2000) that was used as a standard of spectral classification (B0 IV) for the entire 20th century. It was resolved into two components by interferometry in the 1970's that indicated a very eccentric orbit with a period of ~ 10.6 years (Hartkopf et al. 1996). The system is not eclipsing with the secondary ΔV ~1.6–1.9 mag fainter than the primary.

First weak signs of emission in the Hα line were detected by Coté & van Kerkwijk (1993) close to a periastron time in 1990, but they only slightly varied throughout the next orbital cycle (Miroshnichenko et al. 2001; Koubský 2005).

In June 2000, near the time of a periastron, the system was found ~0.03 mag brighter than usual, while a spectrum taken shortly after revealed a noticeable Hα emission line (Fabregat et al. 2000). A follow up spectroscopic campaign of the summer and fall of 2000 resulted in detection of a growing line emission and a significant variation of the radial velocity (Miroshnichenko et al. 2001). These data allowed to constrain the periastron time (2000 September 9 ± 3) that was predicted from the interferometric data to occur a few months earlier. Since that time the circumstellar disk around the primary component of δ Sco grew larger, the system brightness varied between V ~ 1.6 and 2.3 mag, but the line emission never disappeared. The disk development has been documented in several papers (Miroshnichenko et al. 2003; Carciofi et al. 2006).

The erroneous predictions of the periastron time in 2000 reflected the accuracy of interferometric data of the 1990's. The orbital separation of the components that varies from 6 to 200 mas only allowed to resolve them during about half the cycle around apastron. Recent advances in this field made it possible to cover the entire orbit (e.g., Tycner et al. 2011, Štefl et al., these proceedings). The interferometric observations obtained since 2000 combined with the orbit derived from the radial velocity curve (Miroshnichenko et al. 2001) resulted in predicting the periastron time in 2011 with a high accuracy (2011 July 2–6, Tango et al. 2009; Tycner et al. 2011). Nevertheless, such observations are still sparse and require spectroscopic data to verify the predictions.

In order to get ready for the periastron 2011, a spectroscopic observing campaign was planned well in advance (e.g., Miroshnichenko 2009). Its important feature was a broad participation of amateur astronomers whose contribution to spectroscopy boomed over the last decade. Below I report some results of this campaign.

2. The 2011 δ Scorpii Spectroscopic Campaign

Frequent spectroscopic observations of δ Sco began shortly after its brightening discovery mentioned above and has been ongoing till now. Since the object is very bright, it has mostly been observed with small and medium size telescopes. The amateur community participation has been steadily growing towards the time of the 2011 periastron. While only a few spectra of δ Sco were obtained by amateurs in 2000, they took over 200 spectra in 83 nights in 2010 and over 300 spectra in 149 nights in 2011. This contribution in 2010–2011 is comparable with that of professional astronomers in the number of spectra and exceeds it in the time coverage.

The main goals of the 2011 periastron campaign were 1) to obtain a well-defined radial velocity curve to independently constrain the orbital period, and 2) to study line profile variations to search for effects of the tidal interaction on the disk and possibly get some information about the secondary component. Tidal interaction of the secondary component and the primary's disk was expected due to a very small distance between the components at periastron (~15 primary's radii, Miroshnichenko et al. 2001) and an expected comparable size of the disk (Carciofi et al. 2006).

Since not all the involved observers were able to cover a wide spectral range, it was suggested to focus on the two following regions. First, a region around the Hα whose profile is indicative of the tidal interaction due to a possible density restructuring of the disk. Second, a region around the photospheric He ii 4686 Å line whose profile seems to be the least affected by the disk material and is therefore the best tracer of the orbital motion of the primary component. The He i that are lines abundant in the object's spectrum were rejected because they are much weaker than the Hα line, and their profiles are subject to complicated distortions by the disk material.

The main instruments that contributed to the campaign from the professional side were the 3.6 m CFHT with the spectropolarimeter ESPaDOnS (Donati et al. 1997), which covers a region of ~3600–10 500 Å with a spectral resolving power $R \sim 70\,000$, and the 1.52 m ESO telescope with the FEROS spectrograph (Kaufer et al. 2000), which covers a region ~3600–9200 Å with $R = 48\,000$. Over 300 individual spectra of δ Sco were obtained at these facilities during 40 nights in 2011.

The amateur contribution to the campaign involved nearly twenty observers from France, Germany, Australia, Portugal, Spain, and the USA. They used 0.2 m to 0.4 m telescopes with either échelle or long-slit spectrographs with a range of R = 1000–22 000. Only the spectra with $R \geq 10\,000$ were used in our analysis.

An important feature of the amateur campaign was a ten night observing run at the 0.8 m telescope of the Instituto de Astrofísica de Canarias at the del Teide Observatory on the Tenerife Island. The run took place from 2011 June 28th till 2011 July 8th, was centered on the predicted periastron time, and accomplished by a team of five authors of this presentation (A. Miroshnichenko, J. Ribeiro, A. Fernando, T. Garrel, and J. Knapen). We used a Lhires iii spectrograph[1] with $R \sim 17\,000$ in the Hα region and $R \sim 21\,000$ in the He ii 4686 Å line region. All nights were clear, and we obtained over 100 individual exposures in the two mentioned regions as well as in a region near Hγ and He i 4471 Å line.

Data reduction was performed using Libre-ESpRIT data reduction package (Donati et al. 1997) for the ESPaDOnS data and ESO-MIDAS package for the FEROS

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[1] http://www.astrosurf.com/thizy/lhires3/index-en.html

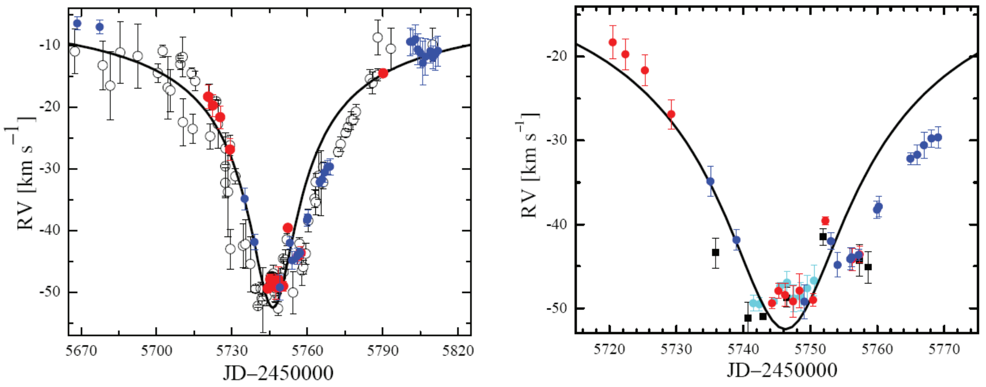

Figure 1. The radial velocity data for the Hα line in the spectrum of δ Sco. The left panel shows all data obtained in 2001, March–October. The right panel provides a close-up of the entire data set during a two-month period around the periastron. The heliocentric radial velocities in km s^{-1} are plotted against time in Julian dates. The solid line represents the best fit radial velocity curve to the data obtained during the 2000 periastron (Miroshnichenko et al. 2001). Symbols: red filled circles—CFHT/ESPaDoNs data, blue filled circles—ESO/FEROS data, black open circles—all amateurs data (only in the left panel), black filled squares—amateurs data averaged within 2–3 day period near the periastron (only right panel).

data. IRAF was used to reduce some of the Tenerife campaign data, while most amateurs data were reduced with software packages developed for amateur spectrographs, such as Audela[2] and IRIS[3]. Wavelength calibration was controlled by measuring positions of telluric and interstellar (e.g., Na I D$_{1,2}$) lines and contemporaneous observations of radial velocity standards (e.g., α Ser and δ Oph). Typical uncertainties of the radial velocities are less than 1 km s^{-1} in the ESPaDOnS and FEROS data and 2–4 km s^{-1} in the amateur data.

3. The Radial Velocity Curves

The radial velocity curve from the Hα data is shown in Fig. 1. The measurements were accomplished using the mirrored profile method (see, e.g., Nemravová et al. 2012). The curve shows a more complicated structure compared to the one observed in 2000 and expected from a binary system with no changes to the circumstellar matter. There are two turnover moments in addition to the one that marks the periastron. Both seem to be due to the readjusting disk structure which followed the motion of the secondary. This makes to curve broader than in 2000 and confirms that the tidal interaction had occurred.

The radial velocity curve derived for the He II 4686 Å line also seem to deviate from the one derived for the Hα line in 2000. It is a bit narrower and is shifted to the negative velocities by $\sim$ 4–5 km s^{-1}. Such a comparison is legitimate because the disk

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[2] http://www.audela.org/dokuwiki/doku.php/en/start

[3] http://www.astrosurf.com/buil/us/iris/iris.htm

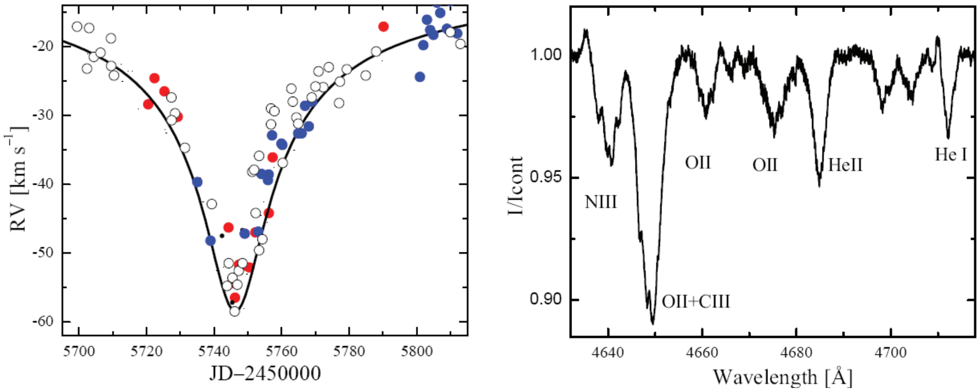

Figure 2. Left panel: The radial velocity data for the He II 4686 Å line in the spectrum of δ Sco. The radial velocities and time are in the same units as in Fig. 1. The solid line represents the same data as in Fig. 1. Right panel: Part of the 2011 July 4 CFHT spectrum near the He II 4686 Å line. Intensities are normalized to the underlying continuum, and heliocentric wavelengths are given in Å.

in 2000 was very small and not affected by the secondary's approach. The He II line profile kept stable and had a shape very close to Gaussian, but its weakness (~0.95 of the continuum at minimum) seems to be the source of scatter seen in Fig. 2. The radial velocity of this line was measured by fitting to a Gaussian that gives very similar results to the mirrored profile method for symmetric lines

Nevertheless, both curves indicate that the periastron has occurred on 2011 July 4 ± 2. This moment may still be better constrained when analysis of all possible errors is completed. In any case, the interferometric result for the orbital period has been confirmed spectroscopically.

4. Observed Spectral Variations

Variations of the line profiles in the spectrum of δ Sco in 2011 and particularly around the periastron time were mild. The Hα profile variations are discussed in the paper by Rivinius et al., these proceedings. Other lines mostly varied in radial velocity following the primary's orbital motion.

There was a hope to detect signs of the secondary component in the spectrum due to a relatively large radial velocity difference at periastron (~120 km s^{-1}) and its possible parameters deduced from the object's spectral energy distribution, orbital elements, and components brightness ratio (a mid-B dwarf, see discussion in Miroshnichenko et al. 2001; Miroshnichenko 2009). One of the expected signatures of the secondary is shown in the left panel of Fig. 3. This prediction may not be accurate, but a broadening of the He I 4471 Å line profile was detected on the periastron day (see the right panel of Fig. 3). This broadening is inconclusive of the secondary's parameters. However, it does not contradict the current view of this component.

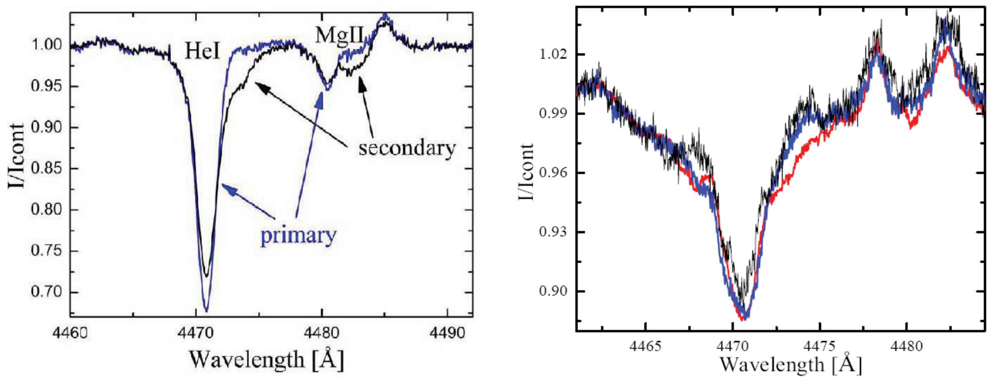

Figure 3. Possible effects of the secondary component on the spectrum of δ Sco at periastron. Left panel shows a sum of two spectra of a B0 V and a B3 V star with a projected rotational velocity $v \sin i \sim 150$ km s^{-1} each and a brightness difference of $\Delta V = 1.7$ mag. The components' radial velocity difference is 120 km s^{-1}. Right panel shows the CFHT spectra taken before (blue, 2011 June 8), at (red, 2011 July 4), and after the periastron (black, 2011 August 16). Intensities and wavelengths are in the same units as in Fig. 2b.

5. What is δ Sco?

Let me now discuss the 2011 periastron campaign results along with some recent findings about the system. There are several facts that make δ Sco unusual among Be binaries. First, the Bright Star Catalog (Hoffleit & Jaschek 1991) mentions a possible companion with a 20 day orbital period in the system. Second, most Be binaries have circular orbits, while most Be/X-ray binaries have eccentric orbits. Third, radial velocities of δ Sco measured in several papers throughout the 20th century show variations additional to those expected at periastra. Finally, the Wide-field Infrared Survey Explorer (WISE, Wright et al. 2010) images at $\lambda 12\,\mu$m and $\lambda 22\,\mu$m show that the system is surrounded by a bow shock-like structure, whose symmetry axis is parallel to the vector of the system's peculiar velocity.

Analysis of these facts allowed us to make the following conclusions. The presence of any inner additional component in such an eccentric binary is unlikely, because such a triple system is highly unstable. The 20 day orbital period is based on a very small data set and is most likely erroneous (see a brief discussion in Miroshnichenko et al. 2001). A noticeable motion of the system through the interstellar medium suggests that it was ejected from a young cluster long ago due to an encounter with another binary system. The observed deviation of the radial velocity curve derived for the He II 4686 Å line from the one of 2000 can be explained by the presence of an outer third component in the system. This idea is consistent with with a dynamical encounter, which could have resulted in ejection of a triple system (cf., Gvaramadze & Menten 2012). Additionally, periodogram analysis of the radial velocities published before 2000 indicates that the orbital period was probably shorter than the one between the two last periastra. This can also be due to the presence of a third component.

6. Conclusions

The spectroscopic campaign to observe the 2011 periastron passage in the δ Sco system was successful and resulted in a new measurement of the orbital period (10.8147 ± 0.0013 years or 3950 ± 5 days). It also detected signs of tidal interaction between the secondary component of the primary's circumstellar disk. Nevertheless, the campaign data did not clearly reveal properties of the secondary, but they are still consistent with an early- to mid-B spectral type for this component. The radial velocity curve for the He ɪɪ line slightly deviates from that derived in 2000 for the Hα line. This result suggests that δ Sco might have a third component, external to the interferometric binary, while the presence of the bow shock-like structure around the system implies that it was a runaway dynamically ejected from a parent cluster. Finally, the campaign revealed that amateur spectroscopy becomes an important factor in astronomy of emission-line stars.

It is very important to continue observing the system spectroscopically, photometrically, and interferometrically to search for more clues about the nature of this unusual stellar system.

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Discussion

Oudmajer: A comment: Given the magnitude difference of both components it may be possible to obtain the spectrum of the companion using spectroastrometry.

Groh: Is there X-ray emission from this system?

Miroshnichenko: As far as I know, there is detectable X-ray emission from the primary component, because it is a nearby hot star. There seems to be nothing unusual about it.

Damineli: Do you have a guess of what cluster ejected δ Sco?

Miroshnichenko: That cluster is most likely dispersed now. What we see is the Sco–Cen OB association.

Dietrich Baade: Is there any proper motion data, and can it be put into perspective with the shape of the nebula?

Miroshnichenko: The star moves through the interstellar medium with a peculiar velocity of $\sim 20\,\mathrm{km\,s^{-1}}$. The nebula seems to be consistent with a wind bubble created by the wind of the main component or with the result of a shock wave that arises from the motion of the hot star.

Martayan: Do you have any idea on how changed the spectral energy distribution at the moment of the periastron passage?

Miroshnichenko: I think the spectral energy distribution was not noticeably affected. The secondary component is much fainter than the primary, while the disk contribution depends on the amount of material in it. The latter did not seem to change significantly during the periastron. A weak change of the optical brightness at this time supports my speculation.

Ellenbroek: Why are there small absorption components present in one of the Hα profiles? If they are telluric lines, why are they not present in the other profiles?

Miroshnichenko: They are telluric lines whose strength highly depend on humidity. The profile with the absorption components seemed to be obtained on a very humid night.

de la Reza: If you know the spatial velocity of the center of mass of the binary, you can calculate its spatial orbit in the Galaxy. Maybe this can furnish an indication of the origin of this system in the Galaxy.

Miroshnichenko: It looks like features of the system, such as the presence of the nebula and the eccentric orbit, indicate that it was ejected from the young cluster that later became an OB association. We will use the direction of the system motion as well as the existing radial velocity data to address this issue in more detail.

Štefl: A comment on the 20 day photometric period of δ Sco. Photometric variations with a similar quasi-period can be observed also in some other Be stars. We followed the Be star 28 CMa for several years, particularly after the 2008 outburst, and it showed cycles of 20–30 days in the V-magnitude. Their appearance and amplitude may vary during the disk evolution after the outburst. Detailed radial velocity analysis (Štefl et al. 2003) shows no indication of binarity. It may be worth considering a physical mechanism, which would be common for Be star disks and which shows variations on a time scale of tens of days.