A&A 380, L13–L16 (2001)
DOI: 10.1051/0004-6361:20011508

Astronomy & Astrophysics

Letter to the Editor

Near infra-red and optical spectroscopy of Delta Scorpii

D. P. K. Banerjee, P. Janardhan, and N. M. Ashok

Physical Research Laboratory, Navrangpura, Ahmedabad – 380 009, India
e-mail: orion, jerry, ashok@prl.ernet.in

Received 26 September 2001 / Accepted 14 October 2001

Abstract. Spectroscopic observations of δ Sco in the near IR and optical wavelengths, obtained shortly after its recent periastron passage are reported. The IR spectra are dominated by the HI Paschen and Brackett lines. An IR excess is seen which can be attributed to free-free emission from a circumstellar shell. The observed Paschen and Brackett line intensities deviate significantly from Case B predictions and indicate optical depth effects. These effects are modeled. The overall spectral behaviour of δ Sco at present is that of a typical Be star.

Key words. stars: emission–line, Be – infrared: stars – techniques: spectroscopic – stars: individual: δ Sco

1. Introduction

The star δ Sco (HD 143275; HR 5953; 7 Sco) has been considered to be a typical B0.3IV star ($V = 2.3$) for many years. Previous high resolution spectra obtained by Heasley & Wolfe (1983) and by Grigsby et al. (1992) did not show any emission in the Hα profiles. However, Coté & van Kerkwijk (1993) in a survey for unidentified Be stars found a weak double-peaked emission component in the Hα profile of δ Sco.

Observations using speckle interferometric techniques showed that δ Sco is in a binary system with a highly eccentric orbit with a period of ∼10.6 years (Bedding 1993; Hartkopf et al. 1996). The last periastron passage of δ Sco occured in 1990. During its present periastron passage in June 2000, S. Otero discovered an approximate 0.4 mag brightening in δ Sco. First spectroscopic observations taken during this phase by Fabregat et al. (2000) showed the star to be strongly emitting in Hα and showing all the characteristics of a typical Be star. Since then the star has been regularly monitored photometrically and the light curve is available in the VSNET data bank (http://www.kusastro.kyoto-u.ac.jp.vsnet).

Spectroscopic observations of δ Sco during its recent periastron passage were done extensively by Miroshnichenko et al. (2001) between July 2000 and March 2001. These authors have used their spectroscopic data to refine the orbital elements of δ Sco and also discuss possible mechanisms for the mass loss and line emission from the star. We describe here our spectroscopic observations of δ Sco which were carried out just after its recent periastron passage.

Send offprint requests to: D. P. K. Banerjee,
e-mail: orion@prl.ernet.in

2. Observations

Near IR JHK spectra were obtained at the Mt. Abu 1.2 m telescope on 6 May 2001 using a Near Infrared Imager/Spectrometer with a 256×256 HgCdTe NICMOS3 array. The resolution of the spectrometer is ∼1000. The spectra in different bands are obtained by rotating the grating. For each position of the grating two spectra were taken with the star offset to two different position of the slit (slit width = 2 arcsec). Exposure times of 10 s in J and H and 15 s in K were used for the observations.

High resolution Hα, Hβ and He 5876 Å line profiles were acquired on different epochs viz. 4 May 2001 and 4, 5 June 2001 using a high resolution fiber linked spectrograph (FLAGS, Banerjee et al. 1999) with exposure times of 10 minutes. The resolution of FLAGS is ∼11 000 at Hα. Low resolution spectra in the 8000–9000 Å range, with exposure times of 2 min each, to cover the Paschen (Pa) series, were also obtained using FLAGS but with a 100 lines/mm grating which gives a resolution of ∼600 in this spectral region. The near IR spectra were all reduced using IRAF. The preliminary reduction of the optical CCD spectra from FLAGS was done using PMIS software, subsequent to which IRAF was used to derive the final spectra and line profile parameters.

Much as we would have liked, observations during June–October 2000 were not possible due to the strong Indian monsoon in this period which necessitates the closure of the observatory. Further, the accessibility of δ Sco

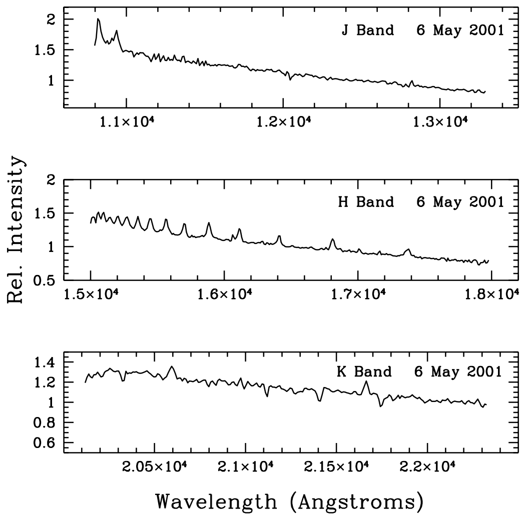

Fig. 1. JHK Spectra of δ Sco. The description of the various features seen may be found in the text.

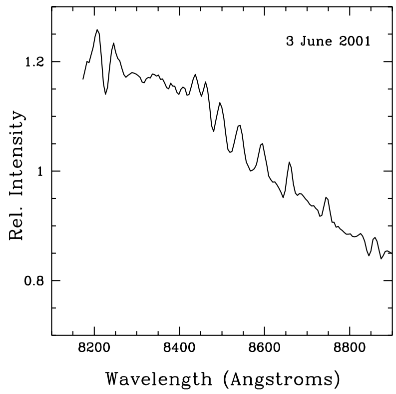

Fig. 2. The Paschen 11–20 emission lines in δ Sco. The H_2O band absorption head at 8227 Å can be seen.

at Mt. Abu (24.6533° N; 72.7794° E) permitted us to begin our observations only in May 2001.

3. Results and discussion

Figure 1 presents the J, H and K spectra of δ Sco. The prominent features of the J band spectrum are the HeI 1.0831 and Paγ 1.0930 μm lines which may be marginally blended at the wings due to inadequate resolution. Paβ, at 1.2818 μm, is present but weak. The H band spectrum is dominated by the HI Brackett series lines (Br10 to 20). A weak HeI feature at 1.7003 μm is seen and also a weak unidentified feature at 1.7159 μm. The K band spectrum shows emission lines of HeI at 2.0583 μm and Brγ at 2.1657 μm. There are a few absorption features at 2.0323, 2.1114, 2.14 and 2.174 μm. Although the 2.1114 μm feature may be identified with HeI at 2.113 μm, the other absorption lines are unidentified. The near IR spectra are rather similar to that we have found in a survey of classical Be stars, some of the results of which are presented in Ashok & Banerjee (2000). The 8000–9000 Å spectrum is presented in Fig. 2. This figure shows the Pa11–20 lines in emission and below 8400 Å one can see the Z absorption band of H_2O with its head at 8227 Å.

In the case of δ Sco we have first used the J, H and K data to check for an excess of IR flux which is a standard property of Be stars. The flux calibration of the J, H and K spectra was done by comparing the spectra of δ Sco and the comparison star ω^1 Sco (HR 5993) at similar airmass. The ratio of the intensities of their spectra was converted into a flux scale by using the following parameters for ω^1 Sco viz. $V = 3.96$, spectral class B1V, intrinsic colours $B - V = -0.26$, $V - K = -0.76$, $J - K = -0.14$, $H - K = -0.04$. Koornneef's (1983) data for zero magnitude fluxes in the JHK bands was used. Interstellar extinction was corrected using a value of $E(B - V) = 0.14$ $A_J = 0.265\ A_V$, $A_H = 0.155\ A_V$ and $A_K = 0.090\ A_V$ (Koornneef 1983).

The IR excess in δ Sco may be seen from Fig. 3. In this figure the JHK spectra are shown in bold wavy lines. Assuming a $T_{\rm eff} = 27\,000$ K for δ Sco (Grigsby et al. 1992; Heasley & Wolfe 1983) the corresponding blackbody distribution, indicated by the dashed line, is seen to fall below the observed flux. The blackbody flux has been normalized to coincide with the center of the observed J band flux. This assumption may be reasonable since the work of Gehrz et al. (1974) on a sample of 33 Be stars shows that at 1.25 μm most of the observed flux from the stars can be accounted by a blackbody component. The excess IR flux is generally seen to build up beyond 2 μm (Gehrz et al. 1974). The excess flux can be explained by assuming an additional input from free-free emission from a hot circumstellar plasma shell. The free-free volume emission coefficient is given by (e.g. Tucker 1975)

$$j_{\lambda\rm ff} = 2.05 \times 10^{-30}\ \lambda^{-2} z^2 g T^{-1/2} n_{\rm e} \times n_{\rm i} {\rm e}^{(-c_2/\lambda T)}\ {\rm W\,cm^{-3}}\mu{\rm m}^{-1}$$

where λ is the wavelength of emission in μm, z is the charge, g is the Gaunt factor, T is the temperature, $n_{\rm e}$ and $n_{\rm i}$ are the electron and ion densities respectively and $c_2 = 1.438$ cm K. The free-free contribution from the circumstellar shell can be got by multiplying the above equation by the envelope volume, $V_{\rm s}$, calculated using a disc geometry $V_{\rm s} = \pi {R_{\rm s}}^2\ H_{\rm s}$ cm^3 where $R_{\rm s}$ and $H_{\rm s}$ are the disc radius and thickness respectively. We have taken a typical value of $H_{\rm s} = R_{\rm s}/5$ (Gehrz et al. 1974; Ashok et al. 1984). The observed flux (in units of W μm^{-1} cm^{-2}) will be given by $F_{\lambda\rm ff} = j_{\lambda\rm ff} \times V_{\rm s}/4\pi D^2$ where D is the distance to δ Sco. In the above calculations we take $g = 1$. We assume a pure hydrogen shell and therefore take $n_{\rm e} = n_{\rm i}$ and $z = 1$. From the work of Gehrz et al. (1974) we adopt representative values of $R_{\rm shell} \sim 5\ R_{\rm star}$, $R_{\rm star} = 4.5 \times 10^{11}$ cm, $n_{\rm e} = 4 \times 10^{11}$ cm^{-3}, $T_{\rm shell} = 13\,000$ K. A value of $D = 123$ pc has been taken based on the 8.12 milliarcsec parallax of the star as measured by Hipparcos (ESA 1997).

The free-free contribution, calculated from above is shown in Fig. 3 by the dashed-dotted line. Small changes

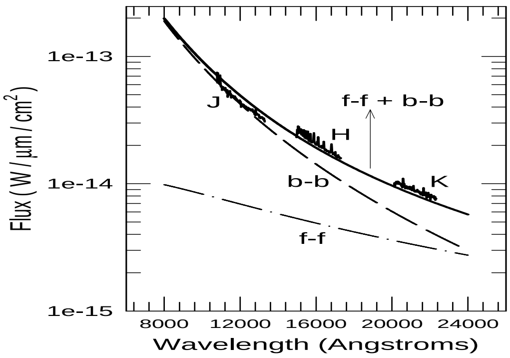

Fig. 3. Flux distribution of δ Sco showing the IR excess. The bold wavy line is the observed JHK spectra, the dashed line is the black body (b-b) distribution and the dashed-dotted line is the free-free (f-f) emission. The total flux (b-b + f-f) is shown by the bold line which fits the observed flux fairly well.

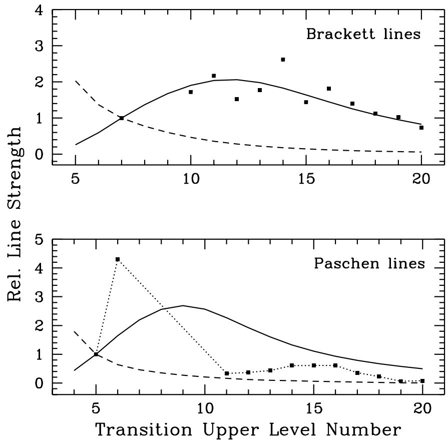

Fig. 4. The observed Br line strengths are shown by filled squares (upper panel). Case B line strengths are indicated by the dashed line and the model fit from Lynch et al. (2000) is shown by the bold line. The same is shown for the Paschen lines (bottom panel). A fuller description is given in the text.

in the parameters do not change the model results unduly. The total flux, which is a sum of the free-free and black-body components, is shown by the continuous line. As can be seen it provides a much better fit to the observed flux. It can therefore be concluded that δ Sco shows an excess IR radiation which is well fitted by free-free emission from a circumstellar shell which has parameters very typical of a classical Be star.

Another point of interest is the observed ratio of the line strengths of the Br and Pa series lines. Our data covers Brγ and Br10 to 20 in the Br lines and Paβ, Paγ and Pa11–20. In Fig. 4 (upper panel) we have plotted the observed line strengths of the Br lines (relative to Brγ) by filled squares. The Case B line strengths, shown by the dashed line, are seen to deviate significantly from the observed values indicating optical depth effects. Lynch et al. (2000) have developed a model to explain such deviations and have shown that the relatively larger intensities of the higher members of the Pa and Br series are because of emission from high-density or optically thick emission-line gas. Increased strength in the higher lines occurs when the level populations become thermalized at high densities ($n_{\rm e} \geq 10 \times 10^{10}$ cm^{-3}) or at large optical depths. In such cases radiative decays become less important relative to electron collisions in determining level populations.

Using the results from their model, we have plotted the expected line strengths by the bold line. The model values are the expected line strengths for a gas having $n_{\rm e} = 6 \times 10^{11}$ cm^{-3}, $T = 1.5 \times 10^4$ K and an optical depth $\tau = 1000$ (τ has been given at the Paα line-center). We tried model fits for other combinations of the parameters $n_{\rm e}$, T and τ. Lynch et al. (2000) give data for combinations of $n_{\rm e} = 6\times10^{10}$ and 6×10^{11} cm^{-3}; $T = 5\times10^3$, 1.0×10^4, 1.5×10^4 K; and $\tau = 10$, 100 and 1000. However, we found that the excessive strength of the higher lines vis-à-vis the lower lines like Brγ (just the opposite of Case B predictions) can only be explained by invoking large optical depth values for the parameter τ. The model fit to the data is remarkably good in the case of the Br lines. For the Pa lines (lower panel of Fig. 4), the Case B values again deviate a lot from the observed values (dotted line through filled squares). All line strengths in this figure panel are normalized to Paβ. The model fit from Lynch et al. (2000), using the same parameters for the gas as described above, do not however give as good a fit as before. The ratio of Paγ to Paβ is depressed in the model vis-à-vis the observed value. This could be partly due to the over estimation of the observed strength of Paγ (1.09 μm) line because of its blending with the wings of HeI 1.08 μm line. Some of the other likely possibilities of Pa line blending are due to Pa13 (8665.02 Å), 15 (8545.38 Å) and 16 (8502.49 Å) blending with Ca II lines at λ = 8662.14 Å, 8542.09 Å and 8498.02 Å respectively and also some OI and NI lines in this spectral region (Andrillat et al. 1990). However, the effects of such blending if present and accounted for, will only move the observed data points farther away from the model fit. This discrepancy in the model results can be explained if the geometry of the emitting regions is rather more complex than assumed by Lynch et al. (2000). Further as stated by them, their model is meant to be simple and illustrative rather than an accurate model of the formation of lines in a realistic emission-line region. On the whole, it may be concluded that the observed line intensities deviate from Case B and that the Lynch model is fairly successful in showing the effects of high densities and optical depths on line strengths. It may be noted that optical depth effects in the Br lines have also been seen in other Be stars (Ashok & Banerjee 2000).

High resolution Hα, Hβ and He 5876 Å line profiles are shown in Figs. 5 and 6. The He 5876 Å line is very weak but this is similar to the findings of Miroshnichenko et al. (2001). Hβ emission was also found to be rather weak. Hα was observed on 3 epochs. The Hα profiles show double peaked structures, typical of Be stars, and are rather similar to profiles reported by others

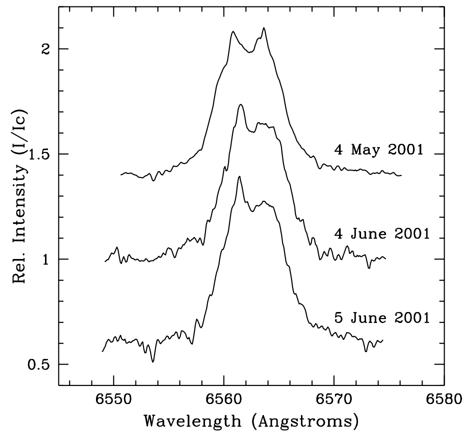

Fig. 5. The Hα line profiles in δ Sco at different epochs normalized to the continuum intensity I_c. The profiles are offset from each other along the y-axis, by 0.4 units, for clarity.

since the periastron passage of δ Sco. However we note changes in the V/R ratio between the profiles at different epochs. Small changes in the central wavelength of the Hα profiles are possibly due to changes in emission line structure. Radial velocities were used effectively by Miroshnichenko et al. (2001) to model and refine the orbital parameters of δ Sco. Although we were constrained to limited observations, the V/R and radial velocity data at these epochs may usefully supplement observations (finished or ongoing) of δ Sco taken by others and thereby help in studying the system's evolution. The line parameters for profiles of 4 May 2001, 4 June 2001 and 5 June 2001 are as follows – Equivalent widths: −4.7, −4.8, −5.0 Å (typical error 10%); V/R ratio: 0.98, 1.06, 1.09; line center wavelength: 6562.40 Å, 6562.74 Å and 6562.68 Å respectively (accurate to ±0.1 Å). Line center wavelengths are w. r. t rest Hα wavelengths obtained using a hydrogen spectral lamp. To test for other Be star characteristics in δ Sco we checked for correlations between H alpha line parameters like $v \sin i$ vs. fullwidth, $v \sin i$ vs. halfwidth, peak to continuum intensity ratio vs. equivalent width etc. (Andrillat & Fehrenbach 1982; Banerjee et al. 2000; Dachs et al. 1986) and found it to exhibit standard Be star behaviour.

We therefore conclude that the spectral behaviour of δ Sco at present, both from IR and optical data is similar to a classical Be star. It may be noted that even as late as April 1998, the lines were in pure absorption (Miroshnichenko et al. 2001). Since the appearance of emission lines coincide with the close periastron passage of δ Sco around its companion, it shows that binarity could be an alternative mechanism in producing the mass loss that leads to Be star envelopes. This is vis-à-vis the conventional picture of equatorial mass loss due to fast rotation. Further observations, till the next periastron passage, should give a clearer picture on the evolution of Be stars born in binary systems. δ Sco provides a good opportunity for doing so.

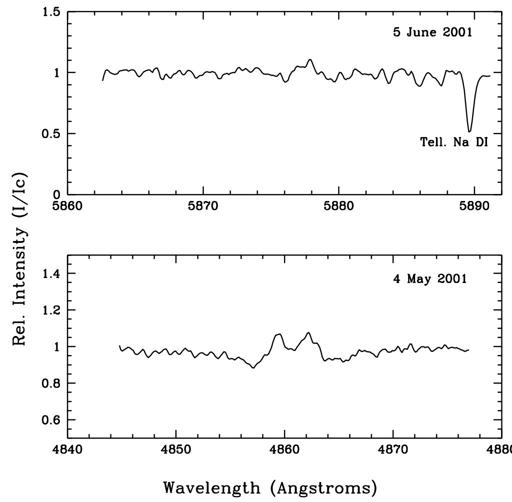

Fig. 6. Hβ and HeI 5876 Å line profiles in δ Sco normalized to the continuum intensity I_c.

Acknowledgements. The research work at PRL is funded by the Department of Space, Government of India.

References

Andrillat, Y., & Fehrenbach, C. 1982, A&A, 48, 93
Andrillat, A., Jaschek, M., & Jaschek, C. 1990, A&AS, 84, 11
Ashok, N. M., & Banerjee, D. P. K. 2000, in The Be Phenomenon in Early Type Stars, ed. M. A. Smith, H. F. Henrichs, & J. Fabregat, ASP Conf. Ser., 214, 468
Ashok, N. M., Bhatt, H. C., Kulkarni, P. V., & Joshi, S. C. 1984, MNRAS, 211, 471
Banerjee, D. P. K., Rawat, S. D., Pathan, F. M., & Anandarao, B. G. 1999, Bull. Astr. Soc. India, 27, 425
Banerjee, D. P. K., Rawat, S. D., & Janardhan, P. 2000, A&AS, 147, 229
Bedding, T. R. 1993, AJ, 106, 678
Coté, J., & van Kerkwijk, M. H. 1993, A&A, 274, 870
Dachs, J., Hanuschik, R. W., Kaiser, D., et al. 1986, A&AS, 63, 87
Fabregat, J., Reig, P., & Otero, S. 2000, IAUC 7461.
Gehrz, R. D., Hackwell, J. A., & Jones, T. W. 1974, ApJ, 191, 675
Grigsby, J. A., Morrison, N. D., & Anderson, L. S. 1992, ApJS, 78, 205
Hartkopf, W. L., Mason, B. D., & McAlister, H. A. 1996, AJ, 111, 370
Heasley, J. N., & Wolfe, S. C. 1983, ApJ, 269, 634
The Hipparcos and Tycho Catalogues ESA SP-1200 1997.
Koornneef, J. 1983, A&A, 128, 84
Lynch, D. K., Rudy, R. J., Mazuk, S., & Puetter, R. C. 2000, ApJ, 541, 791
Miroshnichenko, A. S., Fabregat, J., Bjorkman, K. S., et al. 2001, A&A, 377, 485
Tucker, W. H. 1975, Radiation Processes in Astrophysics, (MIT Press)