The Orbit of the Binary Star Delta Scorpii

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Received: 18 February 1993; Accepted: 26 April 1993

Abstract

Although δ Sco is a bright and well-studied star, the details of its multiplicity have remained unclear. Here we present the first diffraction-limited image of this 0′.12 binary star, made using optical interferometry, and resolve the confusion that has existed in the literature over its multiplicity.

Examining published speckle measurements, together with the present result, reveals a periodicity of 10.5 yr and allows calculation of the orbital parameters. The orbit has a high eccentricity (e = 0.82) and large inclination (i = 70°), making it a favourable target for radial velocity measurements during the next periastron (in 2000).

1 Introduction

The star δ Sco (HR 5953) is known to be a multiple system, although there has been some confusion in the literature over the exact degree of multiplicity. Its entry in the Bright Star Catalogue (Hoffleit 1982) indicates that the primary has companions at separations of 0′.1 and 0′.18. Close triple stars are rare and make excellent targets for optical interferometry. An observation of δ Sco made with MAPPT, an optical interferometer at the Anglo-Australian Telescope, is presented in Section 2. The resulting image reveals only two components, which prompted me to search the literature for clarification. The origin of the confusion makes an interesting tale and appears in Section 3.1.

In addition, inspection of published speckle observations (together with the MAPPT measurement) reveals a periodicity of 10.5 yr and allows determination

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Figure 1: Restored image of δ Sco. Contour levels are at −2, 2, 5, 10, 20, 30, 50, 70 and 90% of the peak; the dynamic range is about 50:1. North is to the top and east to the left.

of the orbital elements of the system. As shown in Section 4, radial velocity variations should be measurable near periastron, making δ Sco one of the brightest in a growing list of stars which are both visual and spectroscopic binaries.

2 Observations

MAPPIT (Masked APerture-Plane Interference Telescope) is an optical interferometer located at the coude focus of the 3.9-m Anglo-Australian Telescope (Bedding et al. 1992; Bedding 1992). The instrument uses the technique of non-redundant masking (Haniff et al. 1987; Nakajima et al. 1989), in which short-exposure images are recorded through an aperture mask containing a small number of holes. The images are analysed to determine the power spectrum and closure phases of the object, which can be used to reconstruct a true diffraction-limited image.

One advantage of using a non-redundant aperture mask is that it increases the signal-to-noise ratios of the power spectrum and closure phase measurements relative to observations with an unobstructed aperture. This is despite the fact that much of the light is blocked by the mask. Another advantage is that it improves the accuracy with which one can correct for variations in atmospheric seeing, something which is often the limiting factor in high-resolution imaging. The main drawback of non-redundant masking is a less efficient coverage of spatial frequencies. However, for simple objects such as multiple and barely resolved stars, adequate spatial frequency coverage can be obtained by combining observations made with different masks and with the masks rotated to several different position angles on the sky.

The observations reported here were made on the nights of 31 May 1991 and 1 June 1991. The detector was the Image Photon Counting System (IPCS; Boksenberg 1990), operated in high-speed mode with a video frame time of 6.5 ms. Two aperture masks were used, each with five 5-cm holes in a linear non-redundant array. The longest baselines on these masks were 2.2 m and 3.3 m, respectively. We took seven sets of data, each containing ~15000 frames and each made with the mask array set to a different position angle on the sky. Three of the data sets used the 3.3-m mask and four used the 2.2-m mask. The reconstructed image of δ Sco shown in Figure 1 was produced using standard radio-astronomical methods (CLEAN and self-calibration). More details of the observations and the data processing methods may be found in Marson et al. (1992) and Bedding (1992).

We find δ Sco to be a double source with a separation of $0^\prime.116 \pm 0^\prime.005$ at
position angle $345^\circ \pm 5^\circ$. The use of closure phases allows us to determine the orientation without the $180^\circ$ ambiguity inherent in conventional autocorrelation processing. The magnitude difference is best extracted by fitting directly to the power spectrum measurements, and we find a value of $\Delta m = 1.5 \pm 0.3$. There is no evidence for a third component, either in the power spectra or in the reconstructed image.

3 Previous Studies of $\delta$ Sco

$\delta$ Sco has a combined spectral type of B0.3 IV and a V magnitude of 2.32 (Hoffleit 1982). It has been studied several times, both in its own right and as a probe of the interstellar medium, and its multiplicity therefore deserves clarification. The following is a summary of some previous observations of $\delta$ Sco, including a discussion in Section 3.1 of the multiple nature of the star.

$\delta$ Sco has no record of photometric variability and so is not classified as a $\beta$ Cephei star, although it does show line-profile variability with a period of several hours. This was discovered by Smith (1986), whose observations suggested a total of six non-radial modes of oscillation and of ‘mode switching’ on time scales of months.

The $\delta$ Sco system lies in the $\rho$ Ophiuchi cloud, which is itself part of the Upper Scorpius region of the Scorpio-Centaurus association. The $\rho$ Ophiuchi cloud is of interest as an area of high-density interstellar dust, high depletions and low ultraviolet extinction (Carrasco et al. 1973; Snow & Jenkins 1980). $\delta$ Sco itself is surrounded by a roughly circular patch of Hα emission about 3° in diameter (Sivan 1974). This emission appears to be associated with an expanding shell of neutral hydrogen, possibly the remnants of a supernova explosion (Sancisi 1974).

The ultraviolet spectrum of $\delta$ Sco is unusual in that it shows no evidence for a strong wind (Snow & Morton 1976). The star does have a high-velocity outflow, but the mass-loss rate ($3 \times 10^{-11} M_\odot \text{yr}^{-1}$) is lower than for other stars of similar spectral class and luminosity (Snow 1981). In the infrared, a 60 $\mu$m IRAS image presented by van Buren & McCray (1988) shows an arc-like feature around $\delta$ Sco, which these authors interpret as thermal dust emission arising from a bow shock. They suggest that such bow shocks are formed by the interaction between the interstellar medium and the stellar wind of a rapidly moving star. In the case of $\delta$ Sco, it seems that such a mechanism is inconsistent with the low mass-loss rate inferred from the ultra-violet spectra. This may indicate that the stellar wind has varied significantly.

Because of its brightness, particularly in the ultraviolet, $\delta$ Sco has been used in several studies of the interstellar medium. Absorption-line observations towards the star have been made in the sodium D-lines by Hobbs (1969) and in the lines of Mg I and Mg II near 280 nm using a balloon-borne spectrograph (Bates et al. 1976). These observations revealed low-velocity absorption clouds
comprising gas with Mg/H and Na/H abundances approximately a factor of ten below solar. There was also a report by Hicks et al. (1975) of two components of high-velocity gas, at $-47$ and $-63$ km s$^{-1}$, observed in the Na(D$_2$) line. However, subsequent observations by Hobbs (1976) failed to detect these features and they were also absent in the ultraviolet Mg lines (Boksenberg et al. 1976). The consensus appears to be that the high-velocity components seen by Hicks et al. were not interstellar sodium, and were probably due to telluric absorption features.

More recently, δ Sco was one of several stars used to determine extinction in the far-ultraviolet caused by interstellar dust grains (Snow et al. 1990). The extinction curves, based on data from the two Voyager spacecraft, were found to be consistent with theoretical predictions. Snow et al. (1988) made high-resolution sounding rocket observations of interstellar H$_2$ lines towards δ Sco. They deduced that the ultraviolet radiation field in the ρ Oph region is about six times more intense than in the solar neighbourhood. Lower resolution spectra towards similar stars have shown systematic velocity separations between lines arising from different rotational levels (Spitzer & Morton 1976). These results implied that the high-$J$ lines arose in material being expelled from the background O or B star. For δ Sco, Snow et al. (1988) found no such systematic velocity separations, indicating that H$_2$ towards this star does not have a significant component arising in an expanding circumstellar shell or bubble. This is consistent with δ Sco having an unusually low mass-loss rate.

### 3.1 The Multiplicity of δ Sco

There is some evidence that δ Sco is a single-lined spectroscopic binary with a period of about a month and an amplitude of $\sim 7$ km/s (van Hoof et al. 1963; Levato et al. 1987). However, the inferred separation is unresolvable with a 4 m telescope and we therefore would not expect our MAPPIT observation to detect the secondary, if it exists.

We now turn to the more distant component of the δ Sco system, detected in the MAPPIT image at a separation of 0′′12. The ‘discovery’ of this component was published in 1974 in three independent papers:

1. In the *Occultation Newsletter*, Dunham (1974) listed an observation of a lunar occultation of δ Sco made in April 1974 by R. Nolthenius. The observation revealed a companion star at separation 0′′1 and position angle 335°.

2. Labeyrie et al. (1974) used speckle interferometry to find a ‘previously unknown companion to δ Sco.’ From observations made in February and May 1973, they measured a separation of 0′′18 at position angle 170° with $\Delta m = 2$. 
3. Describing measurements made using the Intensity Interferometer, Hanbury Brown et al. (1974) wrote: ‘δ Sco has not been listed previously as a multiple star but the observed value of [the zero-baseline correlation] \( C_N \) (0.75 ± 0.07) is consistent with a binary star with \( \Delta m \simeq 1.9 \) [±0.5].’ These observations, which were made in April 1971, did not provide information about the separation or position angle of the components.

There is a large discrepancy in position angles between the speckle and occultation measurements. We can account for this by recalling that the speckle observations have a 180° ambiguity. This now explains the entry in the Bright Star Catalogue: the speckle and occultation measurements are listed separately, although they actually describe the same component. From observations of a grazing occultation of δ Sco, Rattley & Dunham (1988) confirmed that 180° needs to be added to the speckle position angles (by that time, the star had been observed several times using speckle interferometry). The correct orientation is also confirmed by the MAPPIT image.

Interestingly, it turns out that all three 1974 papers were wrong in their claims to have discovered the companion to δ Sco. As Rattley & Dunham (ibid) point out, the star’s duplicity was actually discovered during a lunar occultation at the turn of the century when Innes (1901) observed that the star took several tenths of a second to disappear and realized it was a double.

The Bright Star Catalogue also mentions an occultation companion at a separation of 0′′00001, which must be an error. It is certainly too close to have been measured by lunar occultation techniques. In any case, the distance of δ Sco (~135 pc; de Geus et al. 1989) would imply a separation of only 0.3 R☉, whereas the radius of the primary star is expected to be many times this.

4 The Orbit of δ Sco

Although δ Sco has now been observed many times using speckle interferometry, I have found no discussion in the literature of the orbit. Indeed, it generally appears to be believed that the binary has shown no relative motion since its discovery. However, when we plot the published speckle measurements as a function of time, both separation and position angle exhibit a periodicity of about a decade.

Figure 2 shows the separation and position angle of the δ Sco system from catalogued speckle observations, together with the MAPPIT result. We see that the binary has just begun the third orbital cycle since its discovery (or, rather, re-discovery). The motion of the secondary relative to the primary is shown in Figure 3.

The solid lines in these diagrams show an orbit with the elements given in Table 1. I calculated these values using trial-and-error, combined with single-parameter least-squares fitting to four of the elements (\( T \), \( P \), \( e \) and \( a \)). The
Figure 2: Separation and position angle measurements from published interferometric observations of δ Sco (McAlister & Hartkopf 1988; McAlister et al. 1990), together with the MAPPIT result. The solid curves show the orbit described in the text. A different symbol is used for each of the three orbital cycles covered by the data. Open circles indicate measurements belonging to Orbit 1 and asterisks indicate Orbit 2. The single measurement on Orbit 3 is from MAPPIT (□).

Figure 3: The orbital motion of δ Sco relative to the primary (+). The data and symbols are the same as for Figure 2. The calculated orbit is superimposed, with tick marks showing the position at intervals of six months during the cycle we have referred to as Orbit 2.

agreement with the observations is quite good and there is no need at this stage to refine the fitting procedure.

Finally, we note that the orbit of δ Sco is highly elliptical. It is possible that radial velocity changes will become measurable at the turn of the century during the next periastron, which would provide information about the masses in the system. We can estimate the expected radial-velocity signature as follows.

Suppose the primary and secondary have masses $M_1$ and $M_2$. The velocity curve of the primary star will have a semi-amplitude of (Heintz 1978):

$$K_1 = \frac{2\pi a' \sin i}{P \sqrt{1 - e^2 (1 + M_1/M_2)}}.$$  

Here, $a'$ is the semi-major axis of the orbit, which we can estimate from its angular size ($a = 0''11$) and the assumed distance of the star (135 pc), giving $a' = 2.2 \times 10^9$ km.

Based on the magnitude difference, the mass ratio for the system should be 1.5–2, depending on the spectral type of the secondary (Lang 1992). Combining this with the orbital elements in Table 1 gives $K_1 = 23$–28 km s$^{-1}$. This amplitude is 3–4 times larger than the 20 day variation reported by van Hoof et al. (see Section 3.1) and so should be easily measurable during several months around periastron. If spectral lines from both components can be measured, both masses and the distance could be determined directly. The study of sys-

Table 1: Orbital elements for δ Sco

| $P$  | $T$   | $a$   | $e$  | $i$  | $\omega$ | $\Omega$ (2000) |
|------|-------|-------|------|------|-----------|-----------------|
| 10.5 yr | 1979.3 | $0''11$ | 0.82 | 70°  | 170°      | 0°              |
tems which are both visual and spectroscopic binaries is a powerful method of determining fundamental stellar quantities.

Note added in proof. Coté & van Kerkwijk (A&A, in press) have discovered δ Sco to be a Be star, with the Hα line showing emission on the flanks of an absorption core. This makes δ Sco one of the brightest known Be stars (the Bright Star Catalogue lists only four Be stars that are brighter). Previous observations in the literature have shown no indication of Be behaviour in δ Sco and, interestingly, the Coté & van Kerkwijk spectrum was taken only ten months after the last periastron of the system. It is tempting to speculate that the approach of the companion (about 600R⊙ ≃ 85 stellar radii) triggered the mechanism responsible for Be emission. I am grateful to Rens Waters for bringing this new result to my attention.

Acknowledgments

MAPPIT is supported by a grant under the CSIRO Collaborative Program in Information Technology. The observations and data reduction were made in collaboration with J. G. Robertson and R. G. Marson. I also thank J. G. Robertson for helpful comments on this manuscript. This research has made use of the Simbad database, operated at CDS, Strasbourg, France.

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