δ SCORPII: VISUAL PHOTOMETRIC VARIABILITY IN 2000-2002

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δ Scorpii is a previously unremarkable early-B star that underwent a sudden, large visual outburst and transitioned to a strong Be-state in mid-2000. Otero, Fraser, and Lloyd (2001) described their post-eruption photometry and briefly discussed the *Hipparcos* photometry and some spectroscopic aspects of the star. Miroshnichenko et al (2001), hereafter METAL, published an extensive study of their post-outburst spectroscopy, and they correlated the Otero, Fraser, and Lloyd photometry with their observations. δ Sco is also a long-period visual binary star, whose orbit was interferometrically determined by Hartkopf, Mason, and McAlister (1996) and spectroscopically by METAL; the period is 10.58 years, and the eccentricity is extremely high.

This paper describes δ Sco's visual photometric behavior from the outburst's discovery in 2000 through 11 October 2002 and correlates it with some aspects of METAL's observations. Our observations show that a quasi-periodic and transient variation of very close to 71 days in length existed during most of the outburst, through approximately 1 June 2002. That quasi-periodic variation is superposed upon a long-term trend of so far indeterminate length. We also identify three main phases of the outburst and determine estimated dates for the outburst's start and for the long-term trend maximum.

Our light curve shows that the amplitude of the 71-day variability has generally decreased with time, and that there are time intervals, of approximately the same length as the 71-day quasi-periodic variability, during which the amplitude appears to have been statistically zero (i.e., "lulls"). During the last ∼75 days of our data, only the long-term variability has been apparent. A fuller discussion of our data is in preparation.

The existence of a putative periodicity of 78 days in published radial velocity data (dating from 1903 through 1975) and in the early outburst photometry was suggested by Gandet (2001a); the period was later estimated to fall between 68 and 78 days (Gandet, 2000b). A ∼70-day-long variability is consistent with the time scale of the variations in the Hα EW and relative intensity reported in METAL during ∼50 days on either side of periastron. We note, without bias, the intriguing similarities between the putative spectroscopic period and the photometric mid-term-length variation reported here, and of their transient nature.

Our observations consist of previously published (Otero et al. 2001) visual (v) and photoelectric photometry (V); and from more recent visual (Otero), photoelectric (Fraser)

Table 1.
Comparison Star Magnitudes and Colors

Site*	Star	HR	V	$B-V$	$U-B$	Sp. Type
1	λ Sco	6527	1.62	−0.23	−0.89	B2IV+B[1]
1	ϵ Sgr	6879	1.84	−0.03	−0.13	B9.5III
1	α Pav	7790	1.93	−0.20	−0.71	B2IV
1	σ Sgr	7121	2.09	−0.21	−0.75	B2.5V
1	γ Cen	4819	2.16	−0.02	−0.01	A0IV+A1IV
1	α Lup	5469	2.30	−0.22	−0.89	B1.5III[1]
1,3	$\beta^{1,2}$ Sco[2]	5984	2.50	−0.07	−0.87	B1V
1,2,3	ω^1 Sco	5993	3.95	−0.04	−0.81	B1V
3	λ Lib	5902	5.03	−0.03	−0.56	B2.5V
2	HD 142315	——	6.86	+0.04	−0.21	B8V

Notes: [1] Low amplitude ($\leq$0.05 mag) β Cep variables. Their use does not affect the visual data meaningfully; there are no other suitable comparison stars when δ Sco is near this magnitude.
[2] Unresolved visually. The V magnitude is the combined magnitude; the colors and spectral type of only the primary component are given. The two components are virtually identical in color and spectral type.

* Site codes: (1) Buenos Aires, Argentina (Otero); (2) Sunninghill Observatory, South Africa (Fraser); (3) Lizard Hollow Observatory, Arizona USA (Gandet).

and CCD V photometry (Gandet). A qualitative comparison of the visual observations with the PEP and CCD data (see Figure 1) beautifully demonstrates the notable precision of which visual observations are capable using the observing techniques developed by SO (described in Stefl et al 2002). The individual observations are available in electronic tabular form, at the IBVS website as 5352-t2.txt.

Fraser used a .20-m SCT with an Optec SSP-3 photometer. He used the comparison and check stars given in Otero et al (2001). Otero used a set of comparison stars from which the two closest to δ Sco in magnitude at any one time were chosen. Gandet used a .28-m SCT, stopped to a 1-inch aperture, with an SBIG ST7-E CCD photometer and V (Bessell) filter. Table 1 lists the comparison and check stars, and their adopted Johnson magnitudes and colors, used at each site.

Fraser adopted the differential photoelectric photometry reduction techniques used in the AAVSO PEP observing program, which results in magnitudes on the Johnson system. No corrections for color or extinction were applied to Otero's visual observations (Stefl et al., 2002).

Gandet used aperture photometry to determine differential V and $B-V$ with respect to ω^1 Sco on two nights and $\beta^{1,2}$ Sco on one night; both components of β Sco were included within the aperture. Mean extinction and seasonal transforms measured previously at the LHO site were used to place the observations on the Johnson system; the V-band extinction coefficient at the LHO site is quite consistent between nights of photometric quality within a particular season. The nominal $B-V$ difference, δ Sco *minus* ω^1 Sco, of −0.08, was adopted for the transforms, and the resulting corrections were no larger than 0.015 mag in V.

We have therefore assumed that all of our observations are on the Johnson system. Our B-band data are too few to confidently reach a conclusion about color variations, but there is some indication that the star may have reddened by up to ∼0.1 in $B-V$ since the outburst began.

Otero's visual magnitudes (filled circles), Fraser's (open circles), and Gandet's CCD *V* magnitudes (crosses) are shown in Figure 1, plotted against Geocentric JD. The estimated maximum internal uncertainty of the PEP and CCD observations is ±0.02 mag and ±0.05 mag for the visual observations.
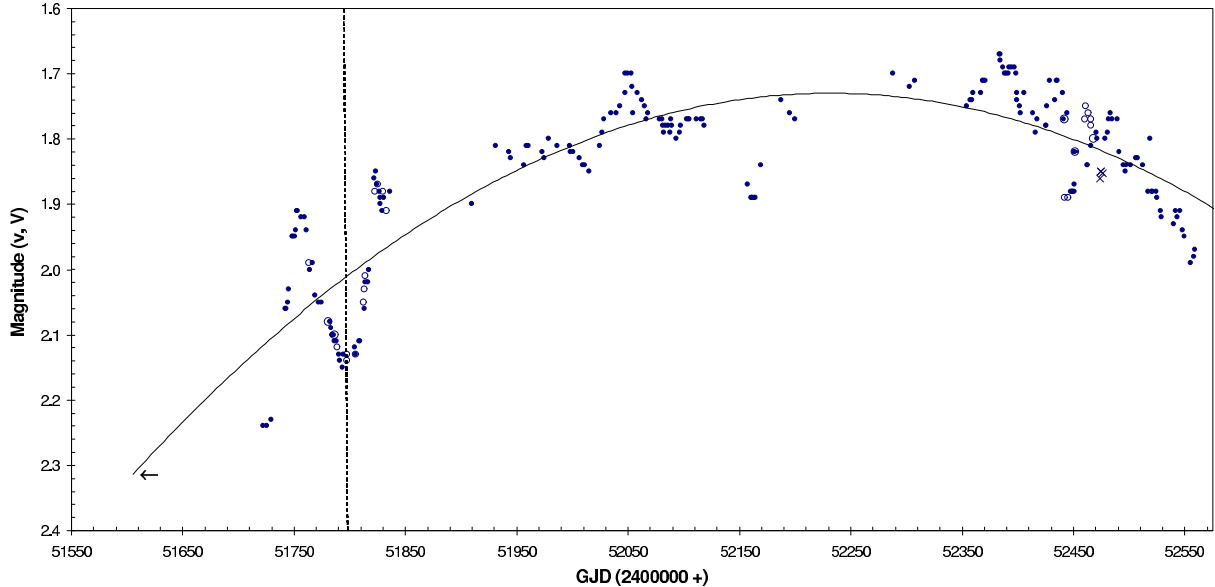
Figure 1. Visual, PEP *V*, and CCD *V* observations, through 11 October 2002, of δ Scorpii. See text for an explanation of the symbols.

We used Scargle's periodogram algorithm, as implemented in the AVE software (Barberá, 2000), to search the entire data set of our raw magnitudes for peaks in the power spectrum. The range of inverse frequencies tested was from .1 to 400 days. The power spectrum shows strong peaks near 180, 251, and 400 days. Possible alias periods due to seasonal gaps in the observations are related to the true period by $1/\mathrm{P}_{alias} = (1/\mathrm{P}_{true})$ ± n/365.25 days (see, e.g., Percy and Kastrukoff 2001). If a truly periodic variability of 71 days in length is present in our data, then the three strong peaks are closely related by that relation to the ∼800-day time interval covered by the observations and to the approximate length of the observing season; the 180-day peak corresponds to an "observing gap" of ∼71 days. The magnitude range of the long-term trend has so far been ∼0.6 mag while the amplitude of the mid-term variation, when it is visible, has averaged ∼0.2 mag, so the long-term variation would therefore be expected to dominate the power spectrum. We concluded, as a result, that two of the strong peaks are aliases, and the 180-day peak is a signature of variability of ∼71-days.

The next strongest peaks in the power spectrum are at 68 and 88 days, but the peaks at inverse frequencies larger than about 70-75 days could be ruled out by the first two season's photometry. There were no significant peaks near one day in the power spectrum. Variability greater than 0.01 mag on a time scale ≤3.0 hours was not seen in observations made by Fraser and Gandet on three separate nights; those observations, and the large difference in longitude between their sites, virtually rule out any variations on a time scale near one day on those nights.

To determine probable dates for the outburst's start and long-term maximum light, we performed a least squares, quadratic fit to our raw magnitude data; the solid curve

in Figure 1 represents the resulting fit. Assuming a nominal pre-outburst magnitude of $V=2^m32$ (Hoffleit and Jaschek, 1982), our admittedly crude approximation indicates that the outburst began on about JD 2451600, shown in Figure 1 by the left-facing arrow. That date qualitatively agrees with METAL's estimate. The long-term trend's maximum, as predicted by our quadratic, occurred on approximately JD 2452240; that date is close to two 71-day cycles after the decrease in disk density found by METAL and is within 4% of six 71-day cycle lengths after periastron. The vertical dotted line in Figure 1 represents the time of periastron passage determined by METAL.

There are at least three possible lulls visible in the Figure 1 and 2 light curves, each of approximately 70-75 days in length, during which the magnitude residuals are essentially constant. The average standard deviation of the mean magnitude during a lull is ~±0.02 mag, while the same quantity for ex-lull intervals is ~±0.10 mag, calculated using the residuals from the quadratic fit to the entire data set.

The first two (sequential) lulls begin on approximately JDs 2451940 and 2452100; they occur before the long-term trend maximum and could not have begun less than ~145 days apart. The first lull begins ~140 days after periastron, which is very close to the time METAL finds that the disk density decreased suddenly; that interval is within 1.5% of two 71-day cycles long. Because of gaps in the data, we do not know if the lulls reoccur with a characteristic frequency or if each lull's duration is the same. The third putative lull begins by JD 2452287, at the latest, and lasts through approximately JD 2452355, an interval of ~65 days; however, because of a gap in the observations, the duration of this lull could be as long as ~71 days.

The last recognizable 71-day cycle begins on about JD 2452355, following the end of the putative third lull, and ends on about JD 2452420. We can only say that it is a minimum of ~65 days in length; its time-of-onset may not have been observed; a longer duration is not be ruled out by our observations.

Figure 2 is an expanded time scale of our data after long-term maximum. A quadratic fit made to only these data (dotted line) clearly shows a departure from the quadratic fit to the entire data set (solid line). The descending branch is steeper than the ascending branch, whereas the descending branch of the 71-day variation is shallower than the ascending branch. The magnitude residuals, from the post-maximum quadratic fit, of the most recent ~65 days of our data set are essentially zero.

While fitting separate quadratics to subsets of the data may apparently represent the long-term brightness variation's behavior more closely, that process could be extended to increasingly shorter time intervals without gaining necessarily meaningful physical insight, and potentially useful information on the gross behavior of the brightness variations could be lost. We therefore adopt the "one-quadratic-fits-all" approach we have used here as being adequate for our purposes, but note that there are no *a priori* reasons to expect the light curve to be either symmetrical or unsymmetrical about maximum.

Onset of what we characterize as the chaotic state occurs on about JD 2452455, although the date is somewhat arbitrary, as can be seen from Figure 2. A transition to the chaotic phase may involve a sudden decrease in what we have called the quasi-periodic variability to ~35 days, on about JD 2452420 that lasts approximately one cycle-length; the stability of the light curve appears increasingly degraded after that. The quasi-periodic variability's length may decrease further until the start of the chaotic state. We cannot say either that the quasi-regular photometric variability of δ Sco presented here has had the same length, character, or that it has existed at all, at previous epochs.

The outburst so far may be divided into three phases, or states. The first phase is a post-outburst, pre-chaotic interval, during which the 71-day quasi-periodic variation was
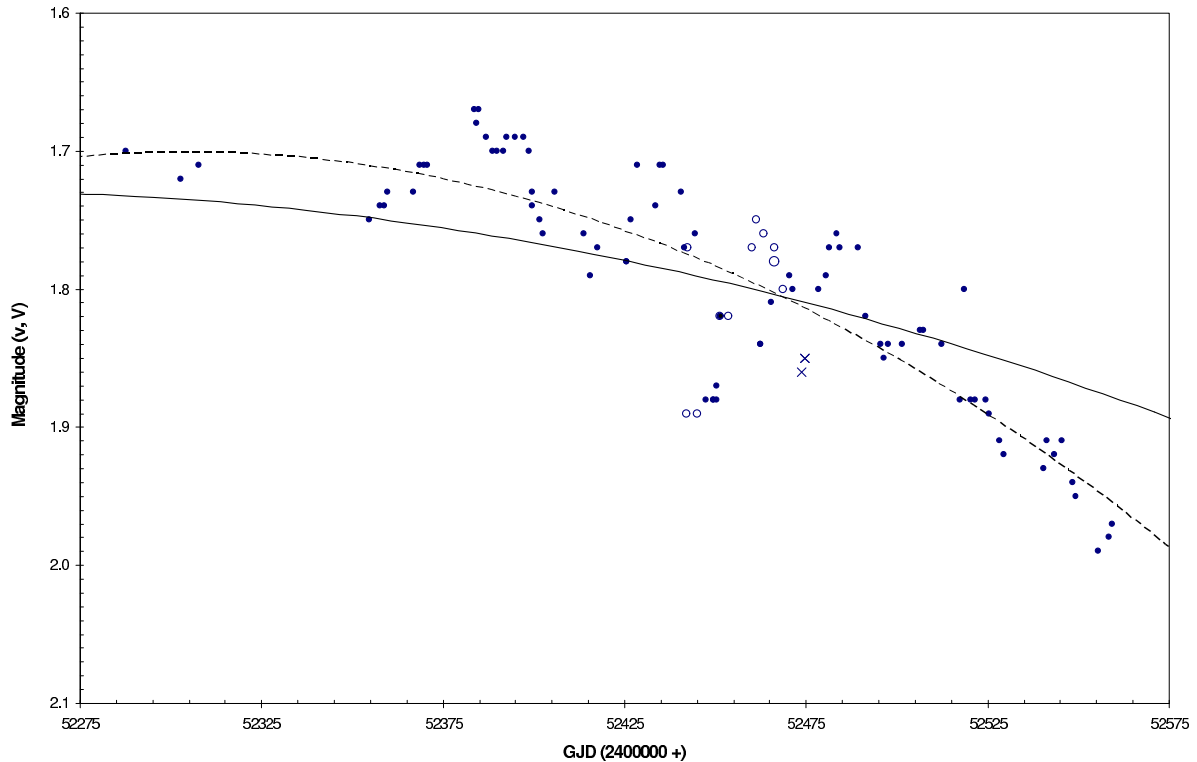
Figure 2. δ Scorpii raw magnitudes after long-term maximum. The solid and dashed lines are quadratic fits to the entire data set and to only the post-maximum data, respectively. The symbols are the same as in Figure 1.

apparent. Soon after the long-term trend's maximum, a second phase began in which the 71-day variability initially decreased in length and the light curve gradually entered a chaotic state of behavior. The third, post-chaotic state, of the outburst was in progress at the cut-off date of our observations (11 October 2002) and is primarily characterized by the presence of only the long-term trend variability. If mid-term-length photometric variability resumes soon after our cut-off data and the length of the lulls remains essentially constant, this third phase can be considered a lull.

We stress the importance of the extremely high eccentricity of the binary orbit. As METAL has pointed out in connection with the eruption's origins, strong interactions between the components and the circumstellar envelope near periastron passage occur. Considered as a binary star, δ Sco thus presents a virtually unique opportunity to explore questions of binary- and Be-star evolution taking place in a highly eccentric, perhaps relatively rapidly evolving, binary system.

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