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Optical photometry of Sco X-2^{*}

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Abstract. We present optical photometry of the galactic bulge low-mass X-ray binary GX 349+2 (Sco X-2) obtained in July 1993 and March 1996. Short-term variations up to one magnitude are present on time scales of a few hours, which are related to the known X-ray behaviour of the source.

We find (equally strong) evidence for a periodicity at either 22.3 hours or at 14.9 days. These periodicities are close to the 22 hour reported by Wachter & Margon (1996) and the 14 day period reported by Southwell et al. (1996). The two periods are related to each other through aliasing with the frequency of observations, which is approximately one day. We therefore suggest that one of the periods reported is the true (orbital) period, whereas the other is the ~ 1 day alias. This confirms that both reported periods are present in the data. Independent of which is the real one, we conclude that the orbital period of Sco X-2 is relatively long.

Key words: stars: binaries: eclipsing – stars: imaging – stars: individual

1. Introduction

During the last decade, studies of the X-ray spectral behaviour and X-ray fast-timing variability of bright persistent low-mass X-ray binaries (LMXBs) has led to the classification into ‘Z’ sources and ‘atoll’ sources (Hasinger & Van der Klis 1989). All Z sources have luminosities close to the Eddington limit, while the atoll sources have systematically lower luminosities. A difference in mass accretion rate alone seems insufficient to explain the differences in the observed variability behaviour (see e.g. Van der Klis 1995, Oosterbroek et al. 1995). Hasinger & Van der Klis (1989), therefore, suggested that the neutron stars

in Z sources have stronger magnetic fields (of order 10^{10} G) than those in atoll sources (10^9 G). Such a difference might have an origin in different evolutionary histories of these two groups of LMXBs. The fact that the two Z sources with known orbital periods (Sco X-1 and Cyg X-2) both have relatively long orbital periods (19 hour and 9.8 days, respectively) and therefore an evolved mass donor, and that most atoll sources have orbital periods below 10 hours (4U 2129+12 in the globular cluster M15 with an orbital period of 17.1 hour is an exception), has been taken as support for this evolutionary idea (Hasinger & Van der Klis 1989). Clearly, to substantiate this idea it is important to obtain orbital periods for as many Z and atoll sources as possible.

The X-ray light curves of LMXBs usually do not contain a periodic component at the orbital period. Most orbital periods of LMXBs have been derived from optical observations (see Van Paradijs & McClintock 1995). The optical identification of Sco X-2 (Penninx & Augusteijn 1991) with an 18.5 magnitude (in V) star provides an opportunity to derive the orbital period for a third Z source. Attempts to measure its orbital period have been made by Wachter & Margon (1996) and Southwell et al. (1996), who reported periods of 22 hours and 14 days from photometric and radial-velocity variations, respectively.

We here report on the results of optical photometry of Sco X-2 obtained between June 1991 and March 1996. From a period search we find that the periodicities found by Wachter & Margon (1996) and Southwell et al. (1996) are both present in our data, one of them being the ~ 1 -day alias of the other. This indicates that, independent of which of the two periods is the correct choice, the orbital period of Sco X-2 is relatively long, adding some support to the idea that the evolutionary histories of Z and atoll sources are different.

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^{*} Based on observations made at the European Southern Observatory.

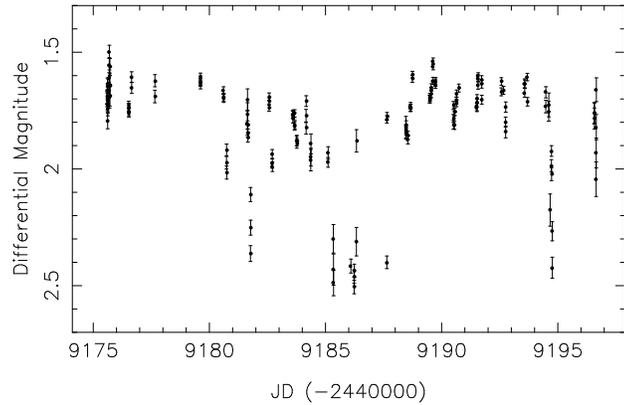


Fig. 1. Light curve of Sco X-2 (V band) observed between July 3rd and August 2nd 1993 with the Dutch 90cm telescope at ESO.

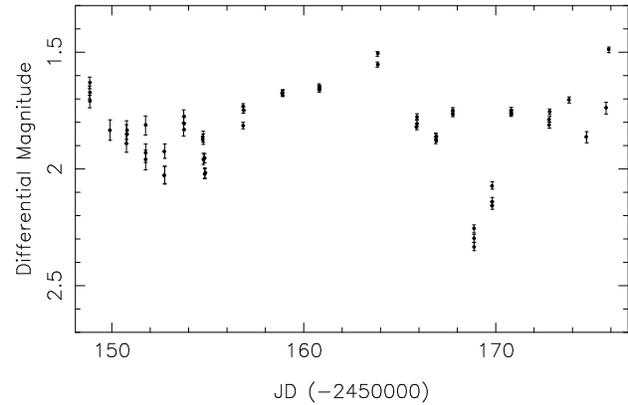


Fig. 2. Light curve of Sco X-2 (V band) observed between 5th of March and 2nd of April 1996 with the Dutch 90cm telescope at ESO.

Table 1. Number of observations

Date	Telescope	Observations in V ($\lambda_{peak}=5442$)
July 1993	Dutch 90cm	167
March 1996	Dutch 90cm	67

2. Observations and data reduction

We report here on observations of Sco X-2 (= GX 349+2) made during 20 nights in July 1993 and 28 nights in March 1996, with the Dutch 90cm telescope at ESO (see Table 1). The observations were made with CCD #33, which has 512×512 pixels, each $27\mu m$, giving a field of view of 3.8 arcmin^2 . All observations were made in the V band, with exposure times between 240 and 900 seconds.

We analysed the data using DAPHOT, a package for differential aperture photometry (de Jong 1995), which allows the selection of optimal sizes of circular apertures centered on the star and of annuli for background determination for which the dispersion in the relative fluxes of comparison stars (tested for constancy) is minimized. We used the same set of eight comparison stars for all two observing runs. The differential magnitudes of Sco X-2 were calculated with respect to the average flux of all comparison stars.

3. Results

3.1. Optical light curves

In Figs. 1 and 2 we show the differential V band light curve of Sco X-2 of the July 1993 and March 1996 data set, respectively. From these figures it appears that during both July 1993 and March 1996 the optical brightness of Sco X-2 was variable, on short time scales (few hours) within one night, and on longer, night-to-night time scales, with a total range in brightness of about one magnitude.

By comparing the average differential V magnitude of the source from year to year we find that its average brightness

level did not change by more than 0.03 magnitudes, which is well below the amplitude of its short-term variations. From a photometric calibration of the V band data, using a CCD frame of the Rubin 149 standard field (Landolt 1992) taken in the first night of March 1996, we find that the V magnitude of Sco X-2 is 18.5 (in Fig. 1 differential magnitude 2 corresponds to calibrated magnitude 18.8), in agreement with the value found by Penninx & Augusteijn (1991).

3.2. Period search

We searched for a period in the July 1993 and the March 1996 V band data sets, using various algorithms. Both the power spectrum from the Fourier transform and the periodogram from the Lomb-Scargle method (Lomb 1976, Scargle 1982) show two strong peaks close to 1 day and close to 15 days, respectively. The Phase Dispersion Method (Marraco & Muzzio 1980) and the Entropy Minimization Method (Cincotta et al. 1995) gave a sharp minimum close to one day and a wide minimum between 10 and 16 days.

We calculated the window function of the data set which is shown in Fig. 3 (lower panel). We then deconvolved the window function from the “dirty” power spectrum (Fig. 3, middle panel) by using an iterative, one-dimensional, Hoegbom CLEAN algorithm (Roberts et al. 1987). The cleaned power spectrum (200 iterations, gain 0.3) shows only a 15-day peak (Fig. 3, top panel).

The two highest peaks in the Fourier spectrum, i.e. $P_1=22.33$ hour and $P_2=14.93$ days may be 1-day aliases of one another, i.e. $(1/P_1) - (1/P_2) \approx 1\text{day}^{-1}$. The same applies for the peaks at $\sim 2 \text{ day}^{-1}$ and $\sim 3 \text{ day}^{-1}$. The 15-day peak which appears in the cleaned spectrum, cannot be considered more significant than the 1-day peak since the strength of the two peaks in the Fourier spectrum is almost equal. Also, the folded data on the two periods (Figs. 4 and 5, lower panels) do not give a clear indication of which of the two periods is to be preferred.

To check whether one of the above mentioned frequencies is indeed an alias of the other, we determined two periodic functions with the two periods mentioned above, which included

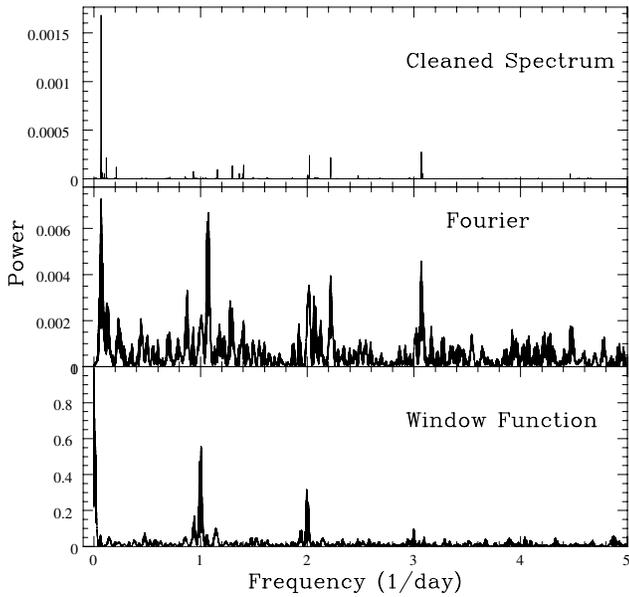


Fig. 3. Window function of the data sets from 1993 and 1996; Fourier transform and cleaned spectrum (200 iterations, gain 0.3).

the first five harmonics; the amplitudes were determined by a fit to the initial light curve (see Figs. 4 and 5, lower panels). Both functions were, in turn, subtracted from the original data. If there is an alias relation between the two frequencies, one would expect that subtracting one of them from the data would cause the other one to disappear as well.

We see from Figs. 4 and 5 (middle panel) that subtracting either of the two frequencies from the data, causes indeed the other peaks to disappear from the power spectrum. This confirms our suspicion that the ~ 1 -day period is an alias of the 15-day period.

From the available data it is not possible to distinguish the real orbital period from its one-day alias, but it becomes clear that the periods suggested by Wachter (22 hours) and Southwell (14 days) arise from the same periodic variability present in Sco X-2, and are related to each other through the window function of the observations which is about one day, i.e. they both arise from the same periodical signal.

3.3. Optical versus X-ray behaviour

Since the beginning of 1996 the All Sky Monitor onboard the Rossi XTE provides long-term monitoring of the intensity of many X-ray sources in the sky (see Levine et al. 1996). We therefore investigated possible correlations between our March 1996 data set and the ASM data which coincided with our observations. In Fig. 6 we show the optical brightness (the optical flux is derived from the differential magnitudes and multiplied by an arbitrary number) and the ASM count rate from JD 2 450 148 to JD 2 450 177. Both light curves show changes in brightness on time scales of less than an hour. In the ASM light curves these flares are clearly visible during the end of our observing run,

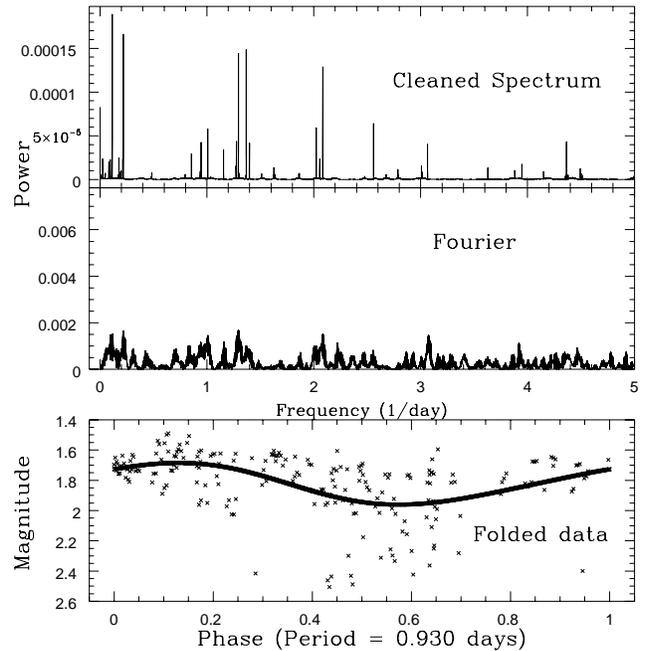


Fig. 4. *Upper panel:* Cleaned power spectrum, *Middle panel:* Power spectrum of the data from which a sinusoidal function with a 0.93 day period plus five harmonics have been subtracted, *Lower panel:* The 1993 and 1996 data folded on a period of 22.3 hour ($=0.93$ days) and the sinus curve which was fitted and subtracted from it.

where a better time coverage is available. On longer time scales (>1 day) the mean X-ray brightness level does not change much ($\lesssim 15\%$), whereas the mean optical brightness seems to vary by $\sim 40\%$. No clear correlation between optical and X-ray can be seen.

The ASM collects typically 5–10 points per day (Levine et al. 1996); these are usually not simultaneous with our optical observations. Only on two occasions were our optical observations very close (<40 minutes) in time with the ASM measurements. We conclude however that these observations are too limited to test the idea that the optical flux varies in the same way as the X-rays.

4. Discussion

From our period search from optical observations of Sco X-2 we found two approximately equally strong peaks in the power spectrum, at 14.9 days and 22.3 hours. These periods are close to the 14 day period reported by Southwell et al. (1996) and the 22 hour period reported by Wachter & Margon (1996), respectively.

Our analysis shows that these two periodicities are one-day aliases of each other. Thus, the combined evidence is strong that one of the two is the real period, but we cannot, on the basis of our data, conclude which of the two it is. To be able to rule out either the 14.9 day or the 22.3 hour period, one would need a substantially longer and more densely sampled data set. We note that although Southwell et al. (1996) reported a ~ 14 day

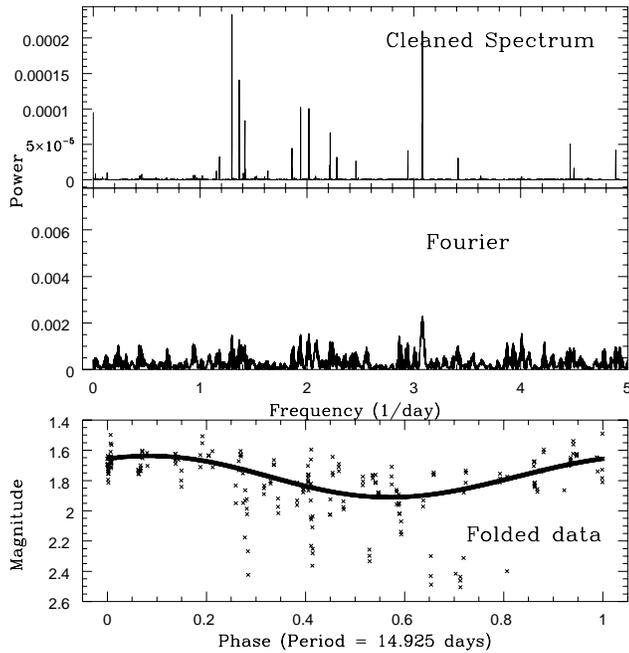


Fig. 5. Similar to Fig. 4 but now for the 14.9 day period.

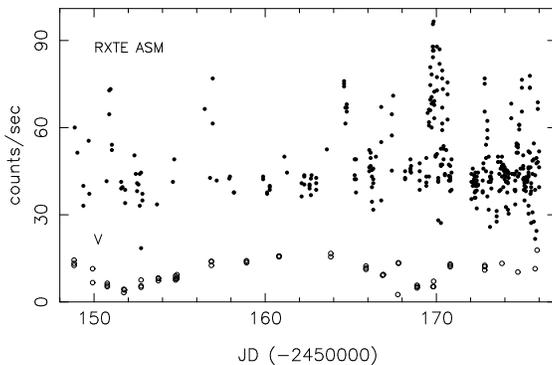


Fig. 6. Optical and RXTE-ASM X-ray flux of Sco X-2 versus Julian Date (the optical flux is derived from the differential magnitudes and multiplied by an arbitrary number).

period in their radial velocity data, a ~ 22 hour period fit their data equally well (K. Southwell, 1997, private communication). The photometric data set of Wachter & Margon (1996) is far too short (6 days) to allow detection of the the 14-day period, so this is probably the reason why they only find the 1-day alias.

Independent of which of the two periods is the correct one, we conclude that the orbital period of Sco X-2 is long enough to give support to the idea that the evolutionary histories of Z and atoll sources are different.

We compared our March 1996 dataset with the publicly available RXTE ASM X-ray light curve of Sco X-2. On time scales $\lesssim 1$ hr both curves show fast brightness changes, which reflect the flaring behaviour known to occur in Sco X-2 (e.g. Ponman et al. 1988).

Similar variability in the optical as well as in X-rays is present in the well-known Z source Sco X-1 (Augusteijn et al. 1992). For this source several coordinated X-ray and optical campaigns have been organized (see Augusteijn et al. 1992, and references therein) and it was found that the optical brightness increases as Sco X-1 moves from the normal to the flaring branch. Similar behaviour was observed in the Z source Cyg X-2 (Hasinger et al. 1990, Vrtilik et al. 1990). A correlation of optical and X-ray brightness is expected since the optical brightness is dominated by X-ray irradiation of the accretion disc (e.g. Van Paradijs & McClintock 1995). We suspect that the short time-scale variability which appears in the optical light curve of Sco X-2 is caused by the same effect. However, since the optical observations were not obtained simultaneously with the X-ray data they do not allow a meaningful study of the X-ray/optical brightness relation.

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