Optical observations of close binary systems with a compact component
Augusteijn, T.

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3

Coordinated X-ray and Optical observations of Sco X-1


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Abstract

We present the results of coordinated, partly simultaneous, optical and X-ray (Ginga) observations of the low-mass X-ray binary Sco X-1. We find that the division between the optically bright and faint state, at a blue magnitude $B = 12.8$, corresponds to the change from the normal to the flaring branch in the X-ray colour-colour diagram as proposed by Priedhorsky et al. (1986). From archival Walraven data we find that in both optical states the orbital light curve is approximately sinusoidal, and have similar amplitudes.

3.1 Introduction

In the decade after the optical identification of the low-mass X-ray binary Sco X-1 (Sandage et al. 1966) many optical studies were made of this source. In a number of cases these observations were coordinated with X-ray observations [detailed reports on campaigns of coordinated X-ray/optical observations have been given by Canizares et al. (1975), Bradt et al. (1975), Mook et al. (1975), White et al. (1976), Willis et al. (1980), Ilovaisky et al. (1980); for general reviews of optical observations of Sco X-1 we refer to Miyamoto and Matsuoka (1977) and Van Paradijs (1983)]. It was found that Sco X-1 is X-ray active, showing flares in X-ray intensity, when its blue magnitude $B \leq 12.8$, and inactive when optically fainter than this. In the active state the X-ray and optical brightness (averaged over a few minutes) often show a correlation, roughly according to $F_{\text{opt}} (\cdot) \sim F_X^{0.5}$. In the inactive state relatively large optical brightness variations occur without a corresponding change in X-rays. From the results presented by Canizares et al. (1975), Bradt et al. (1975) and Mook et al. (1975) it appears that also the radio behaviour is correlated with this optical threshold: radio flares appear only when Sco X-1 is in the optically faint state.

Following the discovery of QPO in the X-ray intensity variations of LMXB (Van der Klis et al. 1985, see Lewin et al. 1989, and Van der Klis 1990 for reviews) it has become clear that there are two groups of LMXB, each of which is characterized by its own type of correlation between the X-ray spectral behaviour and the fast-variability properties of the source (Hasinger and Van
Table 3.1 Log of observations

<table>
<thead>
<tr>
<th>Observatory</th>
<th>Start (UT)</th>
<th>Duration (hrs)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dodaira</td>
<td>8 March 17:45</td>
<td>2:03</td>
</tr>
<tr>
<td>&quot;</td>
<td>9 March 16:29</td>
<td>3:18</td>
</tr>
<tr>
<td>ESO</td>
<td>10 March 05:40</td>
<td>1:00</td>
</tr>
<tr>
<td>Dodaira</td>
<td>10 March 17:15</td>
<td>2:50</td>
</tr>
<tr>
<td>Wise</td>
<td>10 March 23:15</td>
<td>4:15</td>
</tr>
<tr>
<td>ESO</td>
<td>11 March 05:37</td>
<td>3:41</td>
</tr>
<tr>
<td>Dodaira</td>
<td>11 March 16:55</td>
<td>2:40</td>
</tr>
</tbody>
</table>

der Klis 1989). These groups are the Z sources and the atoll sources, so called after the shapes of the tracks which they trace out in X-ray colour-colour diagrams. Sco X-1 is classified as a Z source.

Priedhorsky et al. (1986) proposed that the optically faint and bright states of Sco X-1 are correlated with the normal and flaring branch, respectively, in the X-ray colour-colour diagram. Subsequent coordinated X-ray and optical (and UV) observations of Cyg X-2 show that also this Z-type source is brightest in the optical (and UV) when it is on the flaring branch (Hasinger et al. 1990; Vrtilek et al. 1990). X-ray/radio observations of most Z sources have shown that the radio brightness decreases along the Z track in the direction from the horizontal branch, via the normal branch to the flaring branch (Penninx et al. 1988; Hjellming et al. 1990a, 1990b; however, for GX 5-1 this appears not to be the case, Tan et al. 1991).

Here we report on coordinated X-ray and optical observations of Sco X-1 made during a multi-wavelength campaign in March 1989. We also report on a reanalysis of historical Walraven photometric data (Van Genderen et al. 1969; 1976), motivated by the new insights in the optical behaviour of Sco X-1. A preliminary description of the campaign has been given by Wood et al. (1989). A detailed spectral and temporal analysis of these X-ray data has been made by Hertz et al. (1991). Results of the coordinated radio/X-ray observations obtained during this campaign have been published by Hjellming et al. (1990b). The results of the UV observations obtained with IUE have been published by Vrtilek et al. (1991).

### 3.2 Observations

The Ginga X-ray observations were made between 1989 March 9, UT 20h and March 11, UT 8h. The Large Area Counters (Turner et al. 1987) were used in several instrumental configurations (the so-called MPC and PC modes), providing different combinations of spectral and time resolutions. For the purpose of the present paper it is important that except for the last six hours of the observation (when it was in the normal-branch state) Sco X-1 was in the flaring-branch state.

Coordinated optical photometric observations were made at ESO, Dodaira Observatory and Wise Observatory (see Table 3.1 for an observing log). At ESO the 90 cm Dutch telescope was used with the Walraven photometer, which provides simultaneous photometry in five passbands between 3250 and 6000 Å. A diaphragm of 16” diameter was used, the integration time was 16 seconds. At the Dodaira Observatory data were taken with the 91 cm telescope simultaneously in eight passbands between 3600 and 8800 Å. A diaphragm of 18” diameter was used, the integration time was 23.2 seconds. The observations were made continuously, with interruptions every ~20–30 minutes for measurements of the sky background and comparison stars. The
3.3 Results

Fig. 3.1. Optical light curve of Sco X-1 during the March 1989 campaign. Plotted as a function of time is the Johnson B magnitude of Sco X-1.

Data from ESO and the Dodaira Observatory were reduced differentially with respect to BD -15°4301, and transformed to the standard Johnson system using the transformation formulae given by Pel (1987), for the ESO data, and Kikuchi (1991, private communication), for the Dodaira observatory data. The visual magnitudes and colour indices B - V and U - B, in the standard Johnson UBV photometric system, for BD -15°4301 are V = 9.90, B - V = 0.324 and U - B = 0.255 (Van Genderen 1969, Pel 1987 and 1989 [private communication]).

At the Wise Observatory data were obtained in the Johnson UBVRI system. Unfortunately the observations were affected by poor weather conditions. Typical B magnitudes were comparable to those obtained shortly before at the Dodaira Observatory (see Table 3.1). However, the data showed a much larger scatter and quite different colours and were therefore not included in our analysis.

3.3 Results

In Fig. 3.1 we show the optical light curve (we have selected the B band since most of the previously published optical photometry of Sco X-1 was in this band). During one of the six nights the source was relatively faint (i.e., B > 12.8), during the remainder of the nights it was optically bright.

We have folded the data using the ephemeris of Gottlieb, Wright and Liller (1975), which is based on optical brightness variations during the interval 1890 - 1974 (in this ephemeris phase zero corresponds to minimum light). The folded light curve of the optically bright state is shown in Fig. 3.2, from which we see that an orbital light variation is present. The light curve seems to be slightly shifted with respect to the ephemeris of Gottlieb, Wright and Liller (1975). A sinusoidal fit to the data, excluding the "flares" occurring at orbital phase ~0.35 and ~0.75 (see also below), result in a minimum at orbital phase 0.87(1), and a full amplitude of 0.126(4) mag, somewhat smaller than that reported by Gottlieb, Wright and Liller (1975). As the phase coverage is not complete, and the light curve shows substantial irregularities (see Fig. 3.2), we do not consider this apparent phase-shift significant.

For the orbital U-B colour curve given in Fig. 3.2 we used only the data from the Dodaira Observatory as no proper transformation formula exist from the Walraven system to the Johnson U passband. This excludes a small part of the data between orbital phase ~0.6 and ~0.7 with respect to the B light curve. The colour curve shows two interesting features; (i) during the two "flares" (at phase ~0.35 and ~0.75) the source gets bluer (this is also marginally seen in the B - V indices); (ii) a clear orbital colour variation is present. A sinusoidal fit to the colour indices, excluding again the "flares", result in a maximum at orbital phase 0.42(1) (i.e. the source is redder at maximum light) and a full amplitude of 0.041(3) mag.
Coordinated X-ray and Optical observations of Sco X-1

Figure 3.2. Optical light and colour curve of Sco X-1. Plotted as a function of orbital phase is (left) the B Johnson magnitude, and (right) the U − B colour indices. U − B colour indices are averages of 10 consecutive points. The phases have been calculated according to the ephemeris of Gottlieb et al. (1975)

Radial-velocity studies of Sco X-1 (Crampton et al. 1976, LaSala and Thorstensen 1985) show that inferior conjunction of the emission line region occurs near photometric maximum. Assuming that the emission lines originate from the accretion disc this indicates that the photometric variations are due to the varying aspect of the X-ray heated side of the companion.

The inclination of the Sco X-1 system has been estimated to be fairly low (i~30° Crampton et al. 1976), so that the accretion disc is in full view during the entire orbital period. If the orbital brightness modulation is caused by the variable visibility of the heated side of the companion star, it follows that the emission from this heated side is redder than that from the accretion disk. From the orbital intensity and colour variations we derive a colour for the varying component of (U − B)_0 = −0.6(1) (we used E(B−V) = 0.35(5), see Willis et al. 1980). Interpreting this colour as that of a normal star one finds an effective temperature of ~19000 K (as the side of the companion pointing away from the X-ray source is not expected to contribute significantly to the total light from the system, this value can be considered as a [very rough] estimate for the temperature of the X-ray heated side of the companion).

To investigate the relation between the X-ray and optical properties we have (see Wood et al. 1989) characterized the X-ray state using a "soft" and a "hard" X-ray colour, which are defined as the ratios of the count rates in the photon energy bands (3.5 - 5.8) keV and (1.2 - 3.5) keV, and in the bands (9.2 - 18.4) keV and (5.6 - 9.2) keV, respectively. For data which have been taken simultaneously we have in Fig. 3.3 plotted the "hard" X-ray colour as a function of the B magnitude. We see that in the optically faint state (i.e., B≥12.8) these two quantities are anti-correlated. In the bright state the X-ray colour varies substantially, but the B magnitude is approximately constant at B~12.5.

This confirms that the separation between the two modes of the bi-modal X-ray behaviour is defined by an optical threshold at B~12.8 (Canizares et al. 1975, Bradt et al. 1975; see also Hiltner and Mook 1970).

To show the nature of the X-ray/optical bimodal behaviour more clearly we have plotted the optical data in an X-ray colour-colour diagram (Fig. 3.4); the size of the symbols is a measure of the B magnitude (ranging from B = 13.1 for the smallest symbol to B = 12.5 for the largest) and their location represents their X-ray spectral state (the distribution of the symbols in this plot shows the flaring branch and the normal branch, as earlier presented by Wood et al. 1989).

The two points located at the vertex of the flaring and normal branch in Fig. 3.4 both
correspond to magnitude $B = 12.80$. It is clear from the figure that the separation between
the optical bright and faint states correspond to the separation between the flaring and normal
branches in the X-ray colour-colour diagram, as previously suggested by Priedhorsky et al.
(1986).

Unfortunately no detailed comparison can be made of the optical data and the data from
IUE, as only very little data was taken simultaneously. However, the over-all shape of the light
curve in the optical (Fig. 3.1), and the UV (Vrtilek et al. 1991; their Fig. 1) is very similar.

3.4 Historical Walraven data

Histograms of the optical brightness of Sco X-1 have often shown a double peak, i.e., it appears
that not only are there optically bright and faint states but also preferred optical brightness
levels (see, e.g., Hiltner and Mook 1970). The distribution is not always bimodal, and if it is,
the two peak magnitudes are not always the same. E.g., the archival-plate photometric data
from which Gottlieb, Wright and Liller (1975) determined the orbital period of Sco X-1 show a
single-peaked magnitude distribution (Wright, Gottlieb and Liller 1976). The optical threshold
between the bright and faint state is consistently found to be in the range $B = 12.75 - 12.80$
(see Miyamoto and Matsuoka 1977).

The presence of "preferred" optical brightness levels makes it feasible to separate orbital and
secular brightness variations, and study the dependence of the orbital light curve on the optical
state. This we have attempted to do using already published Walraven data, comprising the
Figure 3.5. Optical light curves of Sco X-1. Plotted as a function of orbital phase is the Johnson B magnitude of Sco X-1. The orbital light curves are shown twice for clarity. The phases have been calculated according to the ephemeris of Gottlieb et al. (1975). (a) Data obtained during 23 nights in 1966, 1967, and 1968 (Van Genderen 1969). (b) Data obtained during approximately 150 nights in 1971, 1972, and 1973 (Van Genderen 1976). (c) Data obtained during seven nights in 1972 (Canizares et al. 1975)

following data sets.

(i) Photometry published Van Genderen (1969), comprising 380 data points obtained on 23 nights in 1966, 1966 and 1968; all data have been taken relative to BD -15°4300.

(ii) Data obtained in 1971, 1972, and 1973, used by Van Genderen (1976). Between one and five data points have been taken per night, during two weeks per month, and five months per year. The total data set consists of 476 individual data points. The comparison star is BD -15°4300.

(iii) Walraven photometry obtained as part of a multi-wavelength observing campaign conducted in 1972, covering seven nights (see Canizares et al. 1975) The data set contains 1654 points.

As these data were only available in printed form we limited ourselves to the Walraven V and B magnitudes, which were transformed to Johnson V and B magnitudes in the same way as before.

We have folded the data points in each of these data sets using the orbital ephemeris of Gotlieb, Wright and Liller (1975); the resulting B light curves are shown in Fig. 3.5.

From this Figure it is apparent that the light curve for data set (ii) shows a separation into high-state and low-state data points, each of which follows an average, approximately sinusoidal orbital light curve. Such a separation is not apparent for the folded light curves for data sets
(i) and (iii). This is likely caused by the fact that these are based on data obtained during a relatively small number of nights. As a result the folded light curves for these two data sets are strongly influenced by correlations between consecutive data points obtained during a single night.

In Fig. 3.6 we show the average B magnitude of data set (ii) as function of orbital phase for the optical bright and faint state, assuming an optical threshold flux corresponding to B = 12.80. From sinusoidal fits to the data we derive full amplitudes of 0.13(2) and 0.13(3) for the optically bright and faint state respectively. Photometric minimum occurs at phase 0.96(3) in the bright state, and 0.97(5) in the faint state. No significant variations of the B - V indices with orbital phase were found, and we derive average colour indices of B - V = 0.179(3) and 0.203(4) for the optically bright and faint state, respectively.

We performed similar fits to the data for threshold fluxes corresponding to B = 12.70, 12.75 and 12.85. No significant change in any of the above results was found.

Cyg X-2 is the only other Z-type source which is well studied in the optical (Cowley, Crampton and Hutchings 1979, Goranskii and Lyutyi 1988). The orbital light curve of this source consist of a double-peaked ellipsoidal curve (full amplitude ~0.25 mag in B; Goranskii and Lyutyi 1988), due to the gravitational distortion of the secondary star, with a variable contribution from the X-ray heating of the secondary, superposed on which are irregular variations. The total brightness variation of Cyg X-2 (~1 mag in Johnson B) is similar to that in Sco X-1. Cowley, Crampton and Hutchings 1979 found that during a period of relative high optical and X-ray brightness Cyg X-2 showed only a single-peaked orbital light curve in the Johnson U passband.

Cyg X-2 does not show any clear division between optically bright and faint states. However, the relatively strong ellipsoidal light modulation could mask the presence of a bimodal optical brightness distribution similar to that found for Sco X-1.

### 3.5 Conclusions

The division at B = 12.8 between the optically bright and faint states of Sco X-1 corresponds to the change from the normal to the flaring branches in the X-ray colour-colour diagram. This confirms the suggestion by Priedhorsky et al. (1986). In each of the two states the B magnitudes show an approximately sinusoidal variation with orbital phase, with similar amplitudes of 0.13 mag, superposed on which are substantial irregular variations (see Fig. 3.5).

We have found an orbital variation in the U - B indices in the optically bright state with
the source being bluer at photometric minimum. We interpret this as being due to the varying contribution of the X-ray heated companion which is slightly redder than the constant contribution from the accretion disc. No orbital variations were found in the B - V indices. The source is on average bluer in the optically bright state.

Acknowledgements

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