K2 and MAXI observations of Sco X-1 - Evidence for disc precession?

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ABSTRACT

Sco X-1 is the archetypal low mass X-ray binary (LMXB) and the brightest persistent extra-solar X-ray source in the sky. It was included in the K2 Campaign 2 field and was observed continuously for 71 days with 1 minute time resolution. In this paper we report these results and underline the potential of K2 for similar observations of other accreting compact binaries. We reconfirm that Sco X-1 shows a bimodal distribution of optical "high" and "low" states and rapid transitions between them on timescales less than 3 hours (or 0.15 orbits). We also find evidence that this behaviour has a typical systemic timescale of 4.8 days, which we interpret as a possible disc precession period in the system. Finally, we confirm the complex optical vs. X-ray correlation/anticorrelation behaviour for "high" and "low" optical states respectively.

Key words: accretion, accretion discs – X-ray binaries - X-rays: individual: Sco X-1

1 INTRODUCTION

Sco X-1 is the brightest persistent extra-solar X-ray source in the sky (Morrison 1967) and is a low mass X-ray binary (LMXB), where a Roche-lobe-filling secondary star is losing matter that is accreted by a neutron star via an accretion disc (Charles & Coe 2006). There are numerous studies on this 0.787 d orbital period system over the last fifty years covering almost the entire electromagnetic spectrum. It is also predicted to be a strong source of gravitational waves (e.g. Aasi et al. 2014).

As the prototype LMXB, Sco X-1 has been studied for decades at all wavelengths, but especially at optical and X-ray wavelengths. Ilovaisky et al. (1980) found that the optical and X-ray flux was well correlated, especially when in a bright state, whilst a longer series of optical observations showed that Sco X-1 changes from a high to low state on a timescale of a few hours (Hiltner & Mook, 1967). McNamara et al. (2003) presented a year-long optical study of Sco X-1 and concluded that the optical observations can be accounted for by variations in the mass accretion rate. Sco X-1 is unique amongst LMXBs, because to our knowledge, it is the only one showing clearly bimodal optical states (Hiltner & Mook, 1967).

The optical light curves of LMXBs are complex and changes are seen on short time-scales (see for instance Homer et al. 2001 and Hakala et al. 2009). The interpretation of these light curves is made more difficult because of data gaps, the limited duration and cadence of the observations. Much time and resources have been spent in this endeavour (e.g. Shih, Charles & Cornelisse 2011 to name but one). The possibility of uninterrupted photometric observations of sources by Kepler has therefore led to dramatic discoveries and results in the field of exo-planets, asteroseismology and accretion physics. Whilst the original Kepler field contained several dozen accreting cataclysmic variables (e.g. Howell et al 2013), it did not contain any known LMXB.

Since the loss of two of its reaction wheels, Kepler has been re-purposed into K2, and is now making a series of observations of fields along the ecliptic plane, where each field is observed for ~70 days (Howell et al. 2014). The fact that these fields go through the Galactic plane allows the study of types of objects which were not present in the Kepler field. In the Campaign 2 field, Sco X-1 was included as one of the target sources. This paper presents the K2 observations of Sco X-1 and also simultaneous X-ray data using MAXI. The unprecedented set of optical observations allows us to characterise the optical behaviour of Sco X-1 in a way not previously possible.
2 OBSERVATIONS

2.1 K2 observations

K2 observations were made of the Campaign field 2 between 2014 Aug 23 and 2014 Nov 10 (MJD = 56892–56971). Both Long Cadence (LC) data (30 min) and Short Cadence (SC) data (1 min) were obtained from a 14×12 pixel array centered on Sco X-1. Because of a pointing adjustment early on in the Campaign, data from the first 2.5 days were omitted, giving a timeline of 71 days. A light curve was made using PyKe software (Still & Barclay 2012) which was developed for the Kepler and K2 mission by the Guest Observer Office. Although the results shown in this work use 1 min time resolution data i.e. SC data, we find that the 30 min resolution data confirm these results.

Because the Kepler satellite lost two of its four reaction wheels, thrusters are used to periodically re-saturate the reaction wheels which can then be used to correct for the drift in the satellite pointing. This results in a significant movement in the targets position on the array on a timescale of 6 hr and ~2 days. Since these systematic effects apply to all of the extracted light curves in the K2 field they can be removed using the method outlined in Vanderburg & Johnson (2014). (See Fig 5 of this paper to see an example of removing this correlated noise from a light curve). The resulting optical (4370-8360˚A) light curve of Sco X-1 (Fig. 1) is unprecedented in the field of optical monitoring of X-ray binaries. Given the brightness of Sco X-1 ($R \sim 12.4$) the photometric error on each K2 point is negligible.

2.2 MAXI observations

The MAXI all-sky monitor on the International Space Station allows for the detection and monitoring of bright X-ray sources over the entire sky in the 2–20 keV band (Matsuoka et al. 2009). Data covering the time interval of the K2 observations was downloaded from the MAXI archive giving a total of 750 photometric points. Thus, on the average, we obtained one point approximately every 100 mins (Fig.1). The typical error on an individual MAXI point is less than 1%.

3 DATA ANALYSIS AND DISCUSSION

3.1 Optical light curve

The K2 light curve (Fig. 1) immediately reveals that the system has effectively a bimodal optical brightness distribu-
tion, which we refer to as "low" and "high" states. This is clearly demonstrated by the light curve, as well as by the histogram of optical fluxes (Fig. 2). Earlier studies of the optical flux distribution (eg. McNamara 2003 and the references therein) have yielded more varied results, which we believe, has been due to the uneven coverage of the variety of datasets employed. It is worth noting though, that the 89 h observing campaign of Hiltner & Mook (1967) produced an almost identical brightness histogram that presented here (Fig. 2).

K2, however, provides us with an unbiased view of the source behaviour over 71 days. We find that the source spends almost exactly equal amounts of time in both "low" and "high" states. If we adopt the mean flux (0.0) as the dividing line between the states, then the system spends 51 and 49 ±0.3% in "low" and "high" states respectively.

We have carried out the period analysis of the K2 data using the Lomb-Scargle power spectrum method (Scargle 1982) since there are some gaps in the data and the MAXI X-ray data is not equally spaced in time. The resulting power spectra are plotted in Fig 3. The optical power spectrum shows a clear signal at 0.787 d, which agrees with the reported orbital period of the system (Hynes & Britt, 2012). There are other peaks in the power spectrum worth commenting on. Firstly, there is another peak at about 4.8 d and a third one at around 20d. Since the length of the observation is 71 d, we find that the 20 d peak could easily be produced by red noise effects, even though there is some tentative evidence in the light curve (Fig 1.) that extended periods of "high" state might be separated by ~20 days (see the extended ~ 10d long periods of "high" state beginning approximately at times 5, 25 and 45d). However, the next extended "high" state which would have occurred at ~ 65d is missing. Although the signature of the 4.8 d quasi period is visible in the K2 light curve of Sco X-1 (Fig. 1) we have examined and derived power spectra of several dozen sources which were observed in the same module and chip as Sco X-1 and had a similar brightness. None show any indication of period around 4.8 d. We conclude that the 4.8 d quasi-period which we detect in the K2 photometry is intrinsic to Sco X-1.

Returning to the 4.8 d period, we can see evidence for transitions between the "low" and "high" states on this timescale all through the K2 observation. These transitions are fairly rapid, since they can take place in less than 3 h, considerably less than Sco X-1’s 18.9 h orbital period. We interpret the 4.8 d peak in the power spectrum as the main duty cycle for these state changes. If we fold the light curve on the orbital period of 0.787 d separately for the "low" and "high" state data (Fig 4.), it is clear that the shape of the orbital modulation changes. In "high" state the orbital light curve is almost sinusoidal, whilst in the "low" state it becomes distinctly non-sinusoidal in appearance. Furthermore, the amplitude of modulation is somewhat reduced in the "low" state. This would imply that the "high" state curve could be produced simply by the X-ray heating of the inner face of the secondary star. However, the "low" state light curve requires a variable contribution from an accretion disc, either by means of phase dependent absorption, emission or changing projected area of the disc. It is also possible that if the disc is warped out of the orbital plane, it could partly shield the secondary star from the X-ray irradiation, thereby diminishing and/or skewing the X-ray heating effects.

3.2 The Optical/X-ray correlation

McNamara et al. (2003, 2005) demonstrated that the optical and X-ray emission in Sco X-1 is anti-correlated when the system is in the "low" state and correlated when in the "high" state. They also showed that the accretion rate and B magnitude of Sco X-1 are closely related for most of the optical variability range. Our analysis of K2 and MAXI data confirms this. We have binned the optical and X-ray points into 200 common time bins and show our correlation results in Fig 5. Whilst the correlation behaviour does not appear...
to be strong, the rank correlation analysis reveals (carried out separately for the "low" and "high" state points) that the -0.304 anticorrelation (Kendall’s tau) for the "low" state points has a chance probability of $9.4 \times 10^{-6}$. Similarly, for the "high" state points, we obtain Kendall’s tau of 0.305 and a chance probability of $5.4 \times 10^{-6}$. We do not see any evidence for the optical and X-ray fluxes being correlated at the very lowest level of optical emission as suggested by McNamara et al. (2003).

It is clear from Fig. 1 that the X-ray emission is increased and more stable during most of the optical minima. In order to demonstrate this further, we have plotted the data from the last minimum on a larger scale in Fig. 6. Evidently the optical data also show much larger variability than the X-ray data during the minimum. For some reason, the level of X-ray emission seems to be the same during several optical minima (Fig. 1) and whenever the X-ray emission reaches a level higher than this, it becomes more unstable and starts flaring. It is therefore possible that the X-ray flux during the optical minima could represent the Eddington limit i.e. when the system passes from normal branch to the flaring branch in the X-ray colour-colour Z-diagram (van del Klis 1989). This is, however, not in agreement with McNamara et al. (2005), where they show that the accretion rate should be a linear function of B magnitude.

3.3 The Origin of the 4.8d cycle

There are several plausible explanations for the origin of the 4.8 d modulation, some of which we now discuss in detail. It has been shown (McNamara et al. 2003 and this work) that when the system is in the "high" state, the X-ray and optical flux correlate. This, together with the sinusoidal orbital modulation of the optical light curve, strongly suggests that in the "high" state the disc is flat and probably does not precess considerably. This would mean that the optical orbital modulation is due to the heated face of the secondary (with a constant emission component from the accretion disc). This is supported by the SPH simulations of accretion discs in intermediate mass ratio $q \sim 0.3$ systems (Murray et al. 2000). The mass ratio in Sco X-1 is estimated to be $\sim 0.3$ (Steegehs & Casares 2002), which should make the system stable against the 3:1 resonance when it is accreting steadily. However, if
the accretion rate at L1 drops, it is plausible that the disc might then start precessing (Murray et al. 2000).

It has been suggested that the state changes in Sco X-1 are accretion rate related (Vrtilek et al. 1991, McNamara et al. 2005), in which case, the appearance of the "low" state folded orbital light curves could be explained as a result of reduced accretion rate plus precession (either through changing disc area or changing shadowing of the secondary from the X-rays). However, this raises two serious complications. Firstly, what drives the accretion rate to change on a time-scale less than 3 hours, as shown by our data? Furthermore, the large scale disc structure should not be able to react dramatically to the accretion rate changes in less than ~1/6 of an orbital cycle. Secondly, echo mapping of Sco X-1 has revealed that the accretion disc itself, not the heated face of the secondary, is the prime source of optical continuum emission, while Bowen blend emission lines are reprocessed on the secondary (Muñoz-Darias et al. 2007).

In general, the optical and UV emission lines can be produced both in the disc and in the heated face of the secondary (Steeghs & Casares 2002, Boroson, Vrtilek & Raymond 2014). The cross-correlation analysis of HST UV data with RXTE data (Kallman et al. 1998) produced somewhat mixed results with the UV continuum and lines displaying inverse behaviour in relation to the X-ray data.

The second possibility for the 4.8 d period is disc precession. Assuming that 4.8 d is indeed the disc precession period, and given the known 0.787 d orbital period, then this would imply a beat/superhump period of 0.94 d, assuming prograde precession of the disc. This would further imply a superhump period excess \( \epsilon = 0.20 \) which, although rather large, is still broadly compatible with that obtained from the SPH simulations for \( q = 0.3 \) (\( \epsilon = 0.16 \), Murray et al. 2000). However, there is no clear sign of the expected 0.94 d period in the power spectrum. One explanation for this could be that the superhump period is thought to arise in CVs as a result of the changing free fall length/potential well depth of the stream and disc impact point (Whitehurst & King 1991). Whilst this is the case in CVs where the disc is viscously heated, the impact point might not be significantly hotter than the surrounding disc in a system like Sco X-1, where the disc is predominantly X-ray heated. If the 4.8 d period is indeed due to the disc precession, it is still not clear how this could drive the "low"/"high" state behaviour with such short transition times (less than 3h) from one state to another.

4 CONCLUSIONS

The K2 observations of Sco X-1 have given the X-ray binary community a virtually uninterrupted and unprecedented optical light curve of a LMXB covering more than 70 days. It shows the detailed investigation of the complex relationship between the optical and X-ray flux in a way not previously possible. Furthermore, K2 data has clearly demonstrated that Sco X-1 has bimodal optical states with rapid (<3 h) transitions from state to state. There is also evidence that these transitions possibly occur periodically with a period of 4.8 d. As earlier studies have linked the optical brightness strongly with the accretion rate (McNamara et al. 2005), we conclude that the accretion rate could vary with a period of 4.8 d. This, in turn, could be due to the precession of the accretion disc at such a period. Further observations of the accretion disc structure (e.g. Doppler mapping) over this 4.8 d cycle are encouraged to verify the possible periodic changes in the disc geometry.

5 ACKNOWLEDGMENTS

Funding for the K2 spacecraft is provided by the NASA Science Mission Directorate. The data presented in this paper were obtained from the Mikulski Archive for Space Telescopes (MAST). This research has made use of the MAXI data provided by RIKEN, JAXA and the MAXI team. Our work has made use of PyKE, a software package for the reduction and analysis of Kepler and K2 data. This open source software project is developed and distributed by the NASA Kepler Guest Observer Office. Armagh Observatory is supported by the Northern Ireland Government through the Dept Culture, Arts and Leisure. After the submission of this Letter, a paper by Scaringi et al. (2015) appeared in astro-PH. Apart from the 4.8d period (which they do not refer to), their analysis of the same dataset is broadly in agreement with our results.

REFERENCES

Aasi, J., et al., 2014, PhRvD, 90, id.062010.
Boroson B., Vrtilek S.D., Raymond J., 2014, ApJ, 793, 17.
Charles P.A., Coe M., 2006, in "Compact Stellar X-ray Sources" eds. Lewin & van der Klis, CUP, p215.
Hakala P., Hjalmarsdotter L., Hannikainen D.C., Muhli P., 2009, MNRAS, 394, 892.
Hiltner W., A., Mook D.E., 1967, ApJ, 150, 851.
Homer L., Charles P.A., Hakala P., Muhli P., Shih I.-C., Smale A.P., Ramsay G., 2001, MNRAS, 322, 827.
Howell, S. B., et al., 2013, AJ, 145, 109
Howell, S. B., et al., 2014, PASP, 126, 398
Hynes R.I., Britt C.T., 2012, ApJ, 755, 66.
Kallman T., Boroson B., Vrtilek S.D., 1998, ApJ, 502, 441.
Ilovaisky, S. A., Chevalier, C., White, N. E., Mason, K. O., Sanford, P. W., Delvaille, J. P., Schnopper, H. W., 1980, MNRAS, 191, 81
Matsuoka M., et al., 2009, PASJ, 61, 999.
McNamara B. J., et al., 2003, AJ, 125, 1437.
McNamara B. J., Norwood J., Harrison T. E., Holtzman J., 2005, ApJ, 623, 1070.
Morrison, P., 1967, ARAA, 5, 325
Muñoz-Darias T., Martínez-Pais I. G., Casares J., Dhillon V. S., Marsh T. R., Cornelisse R., Steeghs D., Charles P. A., 2007, MNRAS, 379, 1637.
Murray J.R., Warner B., Wickramasinghe D.T., 2000, MNRAS, 315, 707.
Scargle J.D., 1982, ApJ, 263, 835.
Scaringi S., Maccarone T.J., Hynes R.I., Körding E., Ponti G., Knigge C., Brit C.T., van Winckel H., 2015, arXiv:1505.07824
Shih, I. C., Charles, P. A., Cornelisse, R., 2011, MNRAS, 412, 120
Steeghs D., Casares J., 2002, ApJ, 568, 273.
Still, M., Barclay, T., 2012, Astrophysics Source Code Library, record ascl:1208.004, http://adsabs.harvard.edu/abs/2012ascl.soft08004S
Vanderburg, A., Johnson, J. A., 2014, PASP, 126, 948.
van der Klis M., 1989, in "ESA, The 23rd ESLAB Symposium on Two Topics in X Ray Astronomy. Volume 1: X Ray Binaries", p203.
Vrtilek S.D., Penninx W., Raymond J.C., Verbunt F., Hertz P., Wood K., Lewin W.H.G., Mitsuda K., 1991, ApJ, 376, 278.
Whitehurst R., King A.R., 1991, MNRAS, 249, 25.