THE ORBITAL PERIOD OF SCORPIUS X-1

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ABSTRACT

The orbital period of Sco X-1 was first identified by Gottlieb et al. While this has been confirmed on multiple occasions, this work, based on nearly a century of photographic data, has remained the reference in defining the system ephemeris ever since. It was, however, called into question when Vanderlinde et al. claimed to find the one-year alias of the historical period in RXTE/All-Sky Monitor data and suggested that this was the true period rather than that of Gottlieb et al. We examine data from the All Sky Automated Survey (ASAS) spanning 2001–2009. We confirm that the period of Gottlieb et al. is in fact the correct one, at least in the optical, with the one-year alias strongly rejected by these data. We also provide a modern time of minimum light based on the ASAS data.

Key words: binaries: close – stars: individual (Sco X-1) – X-rays: binaries

1. INTRODUCTION

The first extrasolar X-ray source discovered was the low-mass X-ray binary Sco X-1 (Giacconi et al. 1962). Its optical counterpart, V818 Sco, was discovered by Sandage et al. (1966), paving the way for many subsequent multiwavelength studies. The binary period is widely accepted to be 18.9 hr based on the discovery of a photometric modulation by Gottlieb et al. (1975) and spectroscopic confirmation by Cowley & Crampton (1975). We now know that Sco X-1 contains a low-mass late-type donor transferring mass onto a neutron star at a rather high rate. The modulation arises from X-ray heating of the donor star, which also manifests as narrow emission lines of N III and C III moving in phase with the donor star (Steeghs & Casares 2002).

Gottlieb et al. (1975) obtained the period of 0.787313 ± 0.000001 days quite remarkably by examining archival photographic plates from 1889 to 1974. A sinusoidal modulation of full amplitude around 0.2–0.3 mag was found in several independent data sets, with considerable scatter around the mean curve (Gottlieb et al. 1975; Wright et al. 1975). While the long baseline of photographic observations defined the period to incredible precision, the sparse sampling left a plethora of aliases, and Gottlieb et al. (1975) identified strong signals at one-day, one-month, and one-year aliases of their favored period. Of these, the one-year alias has been by far the hardest to reject. Several subsequent photometric studies reproduced the modulation, but none improved the ephemeris, or resolved the one-year alias issue (van Genderen 1977; Augusteijn 1992).

Spectroscopic confirmation of this period was suggested by Gottlieb et al. (1975) and Wright et al. (1975), and demonstrated conclusively by Cowley & Crampton (1975), who found a period of 0.787 ± 0.006 days, and again by LaSala & Thorstensen (1985). Both of these works performed a period search on the data, but in both cases the frequency resolution was limited by only observing over a baseline of a week. Other spectroscopic analyses of these and other data have also found variations at this period (Crampton et al. 1976; Bord et al. 1976; Steeghs & Casares 2002), but no other groups have performed a rigorous independent period search.

Several groups also searched for the orbital period in X-ray data, with initially no success (Holt et al. 1976; Coe et al. 1980; Priedhorsky & Holt 1987; Priedhorsky et al. 1995). The only positive detection of an orbital period in X-rays came from Vanderlinde et al. (2003) based on a multi-year RXTE/All-Sky Monitor (ASM) data set. They did not find exactly the Gottlieb et al. (1975) period, but instead the one-year alias (0.78893 days) with a modulation around 1%. Given the intensive multi-year coverage of RXTE, this is surprising, since this data set should not be susceptible to the one-year alias problem. Vanderlinde et al. (2003) therefore claimed that their period was the true orbital period and that Gottlieb et al. (1975) had misidentified the alias. While this result was tantalizing, Levine et al. (2011) could not reproduce this period using a larger RXTE data set. They did, however, not use as sophisticated an analysis as Vanderlinde et al. (2003), leaving open the possibility that the X-ray period could be real.

Surprisingly, then, 50 years after discovery of the prototypical LMXB Sco X-1, there remain doubts about its most fundamental parameter, the orbital period. While the original optical ephemeris of Gottlieb et al. (1975) has remained the standard reference for the 37 years since its publication, it remains to be resolved whether this, or the X-ray period of Vanderlinde et al. (2003), is the true orbital period. To attempt to resolve these questions, and update the ephemeris of Sco X-1 with modern data, we examine here archival photometry from the All Sky Automated Survey (ASAS). This nine-year data set has both the long baseline to determine a precise period and coverage of a large enough fraction of a year to finally break the one-year alias problem using optical data.

2. OBSERVATIONS

ASAS monitored Sco X-1 from 2001 to 2009 (Pojmanski 2002). We note that while Sco X-1 was not included in the ASAS Catalog of Variable Stars (ACVS), its photometry is in the ASAS-3 Photometric V Band Catalog in two data sets, 161955–1538.4 and 161955–1538.5. The Sco X-1 data sets include 640 observations from 2001 January 22 to 2009 October 5. With multi-year coverage spanning typically about 270 days of the year, it is ideally suited for obtaining an updated ephemeris and breaking the one-year alias.

We performed our analysis for a range of choices of data grades and apertures to optimize our filter criteria. For final analysis, we retained the 567 grade A or B observations, and used the smallest ASAS aperture. Inclusion of grade C or worse data, or use of larger aperture data, significantly reduced the quality of the fits.
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3. EPHEMERIS

To determine the orbital period we performed a sinusoidal fit to the data points. Since the scatter around the model is dominated by intrinsic flickering rather than photometric uncertainties, we assigned a mean uncertainty of 0.30 mag to each point to represent the flickering. This was chosen to produce a minimum \( \chi^2 \) equal to the number of degrees of freedom. We then evaluated sinusoidal fits over a range of trial periods. For each period the best-fitting mean magnitude, amplitude, and phasing were determined using the downhill simplex algorithm (Nelder & Mead 1965). We show the results in the vicinity of the disputed periods in Figure 1.

We see that the Gottlieb et al. (1975) period is reproduced exactly to within the limits of our frequency resolution. Our formal best period is 0.787313 ± 0.000015 days. The uncertainty quoted is a formal 1σ error determined from the \( \Delta \chi^2 = 1 \) confidence range in period. We verified the uncertainty using the bootstrap method with 30 resamplings of the data. This gave a consistent 1σ uncertainty (1.6 \( \times 10^{-5} \)). We also show the period of Vanderlinde et al. (2003), and the one-year aliases with which they associated it. We find that none of these alternatives are consistent with the ASAS data, and all can be rejected at better than 5σ confidence. We therefore cannot directly improve on the period of Gottlieb et al. (1975) using the ASAS data.

We have established that in optical photometry the 0.787313 day period produces a stable modulation over 120 years of observation. The ephemeris of Gottlieb et al. (1975) reliably and precisely predicts the time of minimum in the ASAS data, over 17,000 intervening cycles. It is hard to imagine any clock other than the orbital period providing this stability. This has to be the true orbital period.

The question then arises as to what, if anything, Vanderlinde et al. (2003) detected. We of course should allow that it was a spurious detection, until it can be reproduced with data from the remainder of the RXTE mission. Levine et al. (2011) failed to reproduce it, but also did not use all the techniques that Vanderlinde et al. (2003) used. Associating it with an alias of the true orbital period seems unlikely, as RXTE/ASM data on Sco X-1 are rather well sampled through the year (just as ASAS data are).

One possible explanation might be if the X-ray signal came at the beat frequency between the orbital period and a super-orbital period of around a year. Many X-ray binaries have indeed shown super-orbital periods of tens to hundreds of days (see, e.g., Charles et al. 2008), although typically all are shorter than a year. The only claim of such a long period in Sco X-1 came from early RXTE/ASM data, from which Peele & White (1996) suggested a 37 day period. This detection has not been sustained in subsequent data, and no super-orbital period was found by Farrell et al. (2009) in Swift/BAT data. On longer timescales, Durant et al. (2010) and Kotze & Charles (2010) both independently suggested that a ~9 year X-ray modulation is present in RXTE/ASM data, although this is too long to account for the Vanderlinde et al. (2003) period. This explanation therefore seems unlikely, and it remains to be seen if the X-ray period can be reproduced from the full RXTE mission-long data set.
5. CONCLUSIONS

We have analyzed ASAS data of Sco X-1 spanning nine years. We can confirm the period of Gottlieb et al. (1975), while rejecting its one-year aliases, and also the putative X-ray period of Vanderlinde et al. (2003). Our updated ephemeris is \( T_{\text{min}}(\text{HJD}) = 2453510.329(17) + 0.787313(1)E \).

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Facility: ASAS

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