The Orbit and Position of the X-ray Pulsar XTE J1855-026 - an Eclipsing Supergiant System

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ABSTRACT

A pulse timing orbit has been obtained for the X-ray binary XTE J1855-026 using observations made with the Proportional Counter Array on board the Rossi X-ray Timing Explorer. The mass function obtained of $\sim16M_\odot$ together with the detection of an extended near-total eclipse confirm that the primary star is a supergiant as predicted. The orbital eccentricity is found to be very low with a best fit value of 0.04 ± 0.02. The orbital period is also refined to be 6.0724 ± 0.0009 days using an improved and extended light curve obtained with RXTE's All Sky Monitor. Observations with the ASCA satellite provide an improved source location of R.A. = 18^h 55^m 31.3^s, decl. = -02° 36′ 24.0″ (2000) with an estimated systematic uncertainty of less than 12″. A serendipitous new source, AX J1855.4-0232, was also discovered during the ASCA observations.

Subject headings: stars: individual (XTE J1855-026) — stars: neutron — X-rays: stars

1. Introduction

The X-ray source, XTE J1855-026, was discovered during Rossi X-ray Timing Explorer (RXTE) scans along the galactic plane (Corbet et al. 1999; hereafter Paper I) . The source showed pulsations at a period of 361 s and a light curve obtained with RXTE's All Sky Monitor (ASM) showed modulation at a period of 6.067 ± 0.004 days which was interpreted as the orbital period of the system. The X-ray spectrum above ~3 keV could be fitted with an absorbed power law model with a high-energy cut-off, and an iron emission line at

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approximately 6.4 keV. These results, in particular the location of the source in the orbital period/spin period diagram (Corbet 1986), were interpreted as indicating that XTE J1855-026 is likely to consist of a neutron star accreting from the wind of an O or B supergiant primary. A less likely interpretation was that XTE J1855-026 is instead a Be/neutron star binary, in which case it would have an unusually short orbital period for such a system.

Here we present the results of observations made with the RXTE Proportional Counter Array (PCA) that were performed over the course of one complete orbital cycle. The observations were performed with the aims of (i) measuring the orbital parameters to determine the X-ray mass function and thus the nature of the primary star, and (ii) determining whether a eclipse is present in the light curve. A system containing a supergiant primary rather than a main-sequence Be star would be much more likely to exhibit an eclipse due to the much greater size of the primary star. We also report on observations made with the imaging detectors onboard the ASCA satellite which enable the source position to be refined. RXTE ASM observations utilizing this improved position and extending over six years allow further refinement of the orbital period. Spectroscopic results from both satellites are not discussed here and will be presented elsewhere.

2. Observations

2.1. RXTE Observations

In this paper we present the results of observations of XTE J1855-026 that have been made with two of the instruments on board RXTE (Bradt, Rothschild, & Swank 1983): the All Sky-Monitor (ASM) and the Proportional Counter Array (PCA).

The ASM (Levine et al. 1996) consists of three similar Scanning Shadow Cameras, sensitive to X-rays in an energy band of approximately 2-12 keV, which perform sets of 90 second pointed observations ("dwells") so as to cover ~80% of the sky every ~90 minutes. The Crab produces approximately 75 counts/s in the ASM over the entire energy range. Observations of blank field regions away from the Galactic center suggest that background subtraction may produce a systematic uncertainty of about 0.1 counts/s (Remillard & Levine 1997). The ASM light curve of XTE J1855-026 considered here now covers approximately 6 years compared to the less than 3 years reported in Paper I. In addition, the light curve is improved because a new ASM light curve was generated using the improved source position that we determine with ASCA (Section 3.2). Because ASM fluxes are determined using a model fitting procedure which uses cataloged source locations, uncertainties in a source's position can lead to larger uncertainties in the measured X-ray fluxes. The ASM data were

further filtered by excluding all dwells where the modeled background in the lowest energy band was greater than 10 counts/s. This procedure helps to exclude points where the data are contaminated by solar X-rays.

The PCA is described in detail by Jahoda et al. (1996). This detector consists of five, nearly identical, Proportional Counter Units (PCUs) sensitive to X-rays with energies between 2 - 60 keV with a total effective area of $\sim$6500 cm^2. The PCUs each have a multi-anode xenon-filled volume, with a front propane volume which is primarily used for background rejection. The Crab produces 13,000 counts/s for the entire PCA across the complete energy band. The PCA spectral resolution at 6 keV is approximately 18% and the field of view is 1° full width half maximum (FWHM). PCA observations of XTE J1855-026 were obtained over the course of one complete binary orbit in November 1999. Observations were not continuous due to both interruptions because of instrumental constraints such as Earth occultations of the source and passages through the South Atlantic Anomaly when the instruments are not operated, and because observations of other sources were also undertaken during this time. The resulting total exposure time was 150 ks. Due to instrumental problems not all of the PCUs are always operated during an observation and the typical number of PCUs turned on at any one time was three. To give consistency in the analysis presented here we make use of data collected by the two PCUs (numbers 0 and 2) which were always operated. Data extraction, including background subtraction, followed standard procedures. The light curve used in the analysis presented here includes photons in the energy range of approximately 2.5 to 24 keV.

In addition to the ASM and PCA, RXTE also carries the HEXTE experiment (Rothschild et al. 1998) which is sensitive to high energy X-rays in the range of 15 to 250 keV. However, results from this experiment are not presented here as its smaller collecting area, together with the lower source photon flux at higher energies, make HEXTE less useful for pulse timing. HEXTE data will instead be presented together the with PCA and ASCA spectral results.

2.2. ASCA Observations

Observations of XTE J1855-026 were made with the ASCA X-ray astronomy satellite (Tanaka, Inoue, & Holt 1994) on 1999 October 14 from 00:21:38 to 11:52:43 and from October 15 15:34:01 to October 15 03:42:01. These observations had durations of 40.3 and 41.5 ks respectively and were timed to coincide with the predicted times of orbital minimum and maximum X-ray flux. ASCA carried four sets of X-ray telescopes, two of which were equipped with solid-state SIS detectors (Burke et al. 1993) and two with Gas Imaging Spectrometer

detectors (GIS, Makishima et al. 1996, Ohashi et al. 1996). The intrinsic point spread function of the ASCA mirrors themselves had a core of FWHM 50″ (Jalota, Gotthelf, & Zoonematkermani 1993). This was greatly oversampled by the SISs but the GISs' own spatial resolution is comparable to the mirror point spread function. For bright sources, positions can be determined to an accuracy of 12″ radius when temperature dependent errors in the attitude solution are compensated for (Gotthelf et al. 2000).

3. Results

3.1. RXTE

The additional data obtained from the ASM over the more than three years period since the results presented in Corbet et al. (1999) and the improved flux measurement accuracies were used to determine a more precise value for the orbital period. From fitting a sine wave to the orbital modulation a period of 6.0724 ± 0.0009 days is obtained. While this 0.001 day error is the statistical 1σ error from the χ^2 fitting, it is possible that systematic effects may make the measurement somewhat less accurate than this if, for example, there are systematic effects such as changes in the orbital modulation that are not independent from cycle to cycle. The ASM light curve folded on this period is shown in Figure 1.

The light curve obtained with the PCA is shown in Fig. 2. A clear feature of this light curve is a near total eclipse. During this period the X-ray flux is 1.03 ± 0.01 (statistical) counts/s/PCU. Although eclipse ingress and egress were not observed we can use our light curve to derive limits on the length of the eclipse of 1.63 > T > 0.42 days. Examination of shorter stretches of the data shows that pulsations are present at all times except during the eclipse. Bright flares can be seen at approximately 3.5×10^5 s after the start of the observation. When these flares are examined in detail (Fig. 3) the flaring maxima appear to occur at the maximum of the pulse profile.

In order to determine the orbital parameters from the pulse arrival times a reiterative procedure was used. An initial pulse template was constructed by folding the PCA light curve on a value for the pulse period obtained from a power spectrum of the entire light curve. The profile was binned into 720 bins thus giving approximately 0.5s time resolution. The light curve was then divided into sections using individual "good time intervals" (i.e. continuous data stretches between Earth occultations, passages through the high particle background regions where the detectors were turned off, and observations of other sources). For each of these intervals a pulse profile was constructed by folding on the estimated period and the relative phase compared to the template was calculated by cross-correlation. An

initial circular orbit was then calculated from the relative phase changes. The light curve was then corrected for this orbit and a new sharper pulse template derived. This procedure was performed several times until no significant change in orbital parameters occurred on the next iteration. The resulting mean pulse profile is shown in Fig. 4. This shows that, in addition to an overall quasi-sinusoidal modulation, there are also sharp features in the pulse profile. As long as they are always present, such features aid in obtaining greater precision in the pulse delay curve.

The pulse delay curve is shown in Fig. 5 together with a circular orbit fit. It can be seen that a small number of the pulse delay values (three) show much larger deviations from the orbital fit than do the other points. These points were investigated in more detail but do not show any large difference from the other data points. They have maximum values of the cross-correlation function that are not especially small, and the X-ray flux is not significantly lower or higher than for neighboring data stretches. It is possible that some type of small flare occurred that was not modulated with the usual pulse profile. However, the very large flares that can clearly be seen in the light curve were *not* accompanied by any anomalous pulse arrival time effects and, for those flares, the usual pulse modulation continued throughout the flares. In Fig. 6 we show all the individual profiles. While pulse profile changes can be seen, the discrepant points do not appear to show obvious peculiarities. Performing orbital fits both with and without these discrepant points does not greatly change the best fit values. However, it does result in much larger errors on the parameters if error bars on individual points are scaled so as to give a reduced χ^2 of 1. The results from fits using both edited and unedited data sets and employing both circular and eccentric orbit models are given in Table 1. As there is no significant detection of an orbital eccentricity ($e = 0.04 \pm 0.02$ for the edited data set) in Figures 1, 2 and 5 where orbital phase is marked we use the circular orbit together with T0 defined as the predicted eclipse center. The resulting pulse period of 360.741 ± 0.002 s is consistent with the value of 361.1 ± 0.4 s found in Paper I. In order to determine the limits on pulse period changes a two step process was necessary because the data only span a single orbit. For all four cases the fits were initially done with $\dot{P}$ fixed at zero. Next, $a \sin i$ was fixed at the value found from the first fit, and $\dot{P}$ was allowed to vary. This process is similar to that used by Clark (2000). Using the circular orbit ephemeris we find the PCA limits on the times of eclipse ingress and egress to be: $-0.138 < \phi_{ingress} < -0.033$, and $0.036 < \phi_{egress} < 0.131$.

3.2. ASCA

From the ASCA observations at orbital maximum a position is found of R.A.= $18^h55^m31.3^s$, decl.= $-02°$ $36'$ $24.0''$ (2000) in SIS-0 and SIS-1, after correcting for the temperature-dependent attitude solution error (Gotthelf et al. 2000) present in the current (revision 2) processing. These coordinates are statistically accurate to about 2.5 SIS pixels ($4''$). The dominant error, however, is the residual systematic uncertainty in the attitude reconstruction, estimated to be $12''$ (90% confidence; Gotthelf et al. 2000). The source position as determined from the GIS-2 data, although subject to a larger uncertainty, is consistent with the SIS position. The GIS-3 data are unsuitable for this purpose, as the source was observed very near a window support mesh on this instrument. A finding chart based on this position is shown in Fig. 7 using a red Space Telescope Science Institute Digitized Sky Survey image. While there is no obvious bright candidate within the error circle we note the presence of an object at the NW of the region.

Our new orbital ephemeris shows that the two ASCA observations were obtained during orbital phase ranges of 0.020 - 0.099 (orbital minimum) and 0.288 - 0.372 (orbital maximum). There is no sign of an eclipse egress in the ASCA observations at orbital minimum thus extending the limit on eclipse egress beyond the PCA limit of $\phi_{egress} > 0.036$ to give combined limits of $0.099 < \phi_{egress} < 0.131$. The combined PCA and ASCA limits on eclipse ingress and egress are marked on the folded ASM light curve in Figure 1.

In addition to XTE J1855-026, another faint source is detected in the ASCA observations and is most prominent in the observations obtained during the eclipse of XTE J1855-026. The coordinates of this new source are found to be R.A. = $18^h55^m28.0^s$, decl. = $-02°$ $32'$ $33''$ (2000) and the flux is $4 \pm 1 \times 10^{-13}$ ergs cm^{-2} s^{-1} (1 - 5 keV). Due to the faintness of this new source (AX J1855.4-0232) the position uncertainty is greater at approximately $1'$.

4. Discussion

The small residual flux seen by the ASM during the eclipse of XTE J1855-026 (Figure 1) may be interpreted as a systematic measurement error. The residual PCA flux of approximately 1 count/s/PCU corresponds to only $\sim$0.03 ASM counts/s. This indicates that there is a systematic offset in the ASM fluxes for XTE J1855-026 of about 0.15 ASM counts/s which is consistent with the expected accuracy. A contribution to the PCA and ASM fluxes during eclipse will also occur from AX J1855.4-0232 which is only $\sim$4$'$ from XTE J1855-026 and thus not far from the peak of the 1° FWHM PCA collimator response. Evidence for the presence of the eclipse can also be seen in the folded ASM curve but it is difficult to extract

eclipse constraints from this because of the low source count rate in the ASM.

The discrepant points in the pulse delay curve may perhaps be caused by brief changes in the pulse profile. However, if this occurred it might be expected to be related to overall flux which does not appear to be the case. We note the presence of a flare at an orbital phase of about 0.5. Although there appears to be no known reason to expect flares at this phase in particular we note that two other supergiant systems have light curves that have exhibited flaring near this orbital phase. These are 2S 0114+650 (Hall et al. 2000) and X 1538-522 (Corbet et al. 1993). However, this small number of examples does not yet give definite evidence that this is a real phase related effect.

If we assume that the eclipse is symmetric around phase 0 for the circular orbit fit then we can obtain somewhat stricter limits on the duration of the eclipse. With this assumption, and the combined ASCA and PCA results, we thus find that the total phase duration of the eclipse is in the range of 0.198 to 0.262, and the corresponding angular half width is $36° < \theta_e < 47°$. The lower limit on the eclipse duration implies a minimum radius of the mass donating star of approximately 50 lt-s or 20 $R_\odot$. This radius is consistent with that of a B0I star, comparable with the primaries in other wind-accretion driven high-mass X-ray binaries (Liu, van Paradijs & van den Heuvel 2000). While the orbital period and pulse period are also comparable with parameters measured for similar systems the low orbital eccentricity we find is apparently the lowest known for this class (Bildsten et al. 1997, Clark 2000).

5. Conclusion

The light curve and pulse timing orbit clearly show XTE J1855-026 to be a supergiant X-ray binary as predicted in Paper I. With the detection of the eclipse and timing measurements over an entire orbit the system parameters can now be determined. Future pulse timing observations would enable a search for orbital period changes as seen in some other high mass X-ray binaries (e.g. Clark 2000, Levine, Rappaport, & Zojcheski 2000, and references therein).

If an optical or IR counterpart could be found and its radial velocity orbit measured this would be valuable as the system would then be a "double-lined" eclipsing binary and the neutron star mass could be directly determined. While the optical reddening to this object implied by the measured X-ray absorption is high ($N_H = 15 \times 10^{22}$ cm^{-2} $\Rightarrow$ E(B-V) = 24, Paper I) at least some of this absorption may be local to the X-ray source rather than genuinely interstellar. Tighter constraints on the eclipse duration will also be valuable in

obtaining precise measurements of the system parameters.

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Figure Captions

Fig. 1.— The RXTE ASM light curve of XTE J1855-026 folded on the orbital period. The solid and dashed vertical lines indicate the lower and upper limits on the eclipse duration respectively as derived from the PCA and ASCA observations.

Fig. 2.— The background subtracted light curve of XTE J1855-026 obtained with the RXTE PCA. Time is relative to the start of the observation at MJD 51488.066

Fig. 3.— Detail of the background subtracted light curve of XTE J1855-026 showing the two flares.

Fig. 4.— The mean background subtracted pulse profile of XTE J1855-026 obtained with the RXTE PCA

Fig. 5.— The pulse delay curve for XTE J1855-026. The dashed line indicates the best fit circular orbit. Three data points with values very discrepant from the curve, marked as open circles in the plot, were excluded from the fit.

Fig. 6.— The pulse profiles of XTE J1855-026 used in the pulse arrival time analysis. Pulses numbers 2, 19, and 32 have exceptionally large discrepancies from the fitted orbit.

Fig. 7.— A Space Telescope Science Institute Digitized Sky Survey (red, second generation) image centered on the position of XTE J1855-026 found from the ASCA observations. North is at the top and East at the left. Image size is 2.5′× 2.5′.

Table 1: Orbital Parameters of XTE J1855-026

Parameter	All Data Eccentric	All Data Circular	Edited Data Eccentric	Edited Data Circular
P_{pulse} (s)	360.733 ± 0.006	360.734 ± 0.005	360.739 ± 0.002	360.741 ± 0.002
$\dot{P}_{pulse}$ (s s^{-1} $\times$ 10^{-8})	3.7 ± 12	2.1 ± 11	1.7 ± 4.4	1.5 ± 3.6
a sin i (lt s)	81.8 ± 4.2	82.4 ± 2.4	80.5 ± 1.4	82.8 ± 0.8
T0 (MJD - 51400))	Undefined	95.25 ± 0.02	91.4 ± 0.3	95.276 ± 0.007
e	0.0 ± 0.06	–	0.04 ± 0.02	–
ω (degrees)	Undefined	–	226 ± 15	–
χ^2_ν (d.o.f.)	11.5 (34)	10.8 (36)	1.0 (31)	1.06 (33)
Orbital period (days)	6.0724 ± 0.0009	–	–	–
Mass function (M$_\odot$)	15.9 ± 2.5	16.3 ± 1.4	15.2 ± 0.8	16.5 ± 0.5

All parameter errors are 1σ single-parameter confidence levels. Errors on individual pulse timing measurements were scaled to make $\chi^2_\nu = 1$ for the edited data set eccentric orbit fit. The edited data set excludes the points plotted as open circles in the figure which have large deviations from the best fit curve. The orbital period is derived from the ASM light curve rather than pulse timing. T0 corresponds to periastron passage for the eccentric orbit fits and the phase of mid-eclipse for the circular fits.

Count Rate

0.0 0.2 0.4 0.6 0.8

Pulse Phase