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Modeling the dependence of the X-ray emission of 4U1907+09 on orbital phase

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Abstract. 4U1907+09 is an x-ray binary which has a 437.5 s pulsation period and a 8.38 day orbital period. The mass function is 9 solar masses, implying a B-type or more massive companion to the neutron star. Over an orbital period, 4U1907 exhibits a main peak and a smaller peak in x-ray emission, though both are variable. The neutron star is believed to accrete matter from the stellar wind with the variability due to variations in physical conditions around an eccentric orbit. Long term monitoring of 4U1907 has been done by the RXTE/All-Sky-Monitor. Here, modeling of the 4U1907 system, including the stellar wind, is carried out to explain the x-ray intensity variations with orbital phase.

1 Introduction

The properties of 4U1907+09 are reviewed in Roberts et al. (2001). Here a brief overview is given. 4U1907+09 is a variable X-ray source which was identified (Schwartz et al. (1980)) with a heavily reddened $m_v \simeq 16.4$ star with broad H_α emission. Analysis of Ariel V x-ray observations revealed a period of 8.4 days (Marshall and Rickets, 1980). The folded period profile shows a large primary peak as well as a smaller secondary maximum ~half a cycle later. The orbital elements of the system were established by TENMA observations (Makishima et al. (1984)): an 8.38 day orbital period; eccentricity $e \sim 0.22$ but not inconsistent with 0; and mass function of $\sim 9M_{sun}$. 437.5 s x-ray pulsations were discovered which allowed the orbital element analysis. The companion star has been studied most recently by van Kerkwijk, van Oijen, van den Heuvel (1989), who find that the evidence is most consistent that the companion is a supergiant star in agreement with Schwartz et al. (1980), rather than a Be star as suggested by the study by Iye (1986). A recent study using RXTE and TENMA data (in't Zand, Baykal, Strohmayer (1998)) gave improved orbital parameters: orbital period of 8.3753 ± 0.0003 days; eccentricity with a 68% confidence region of 0.14-0.38.

Long-term monitoring of 4U1907+09 has been carried out by the All-Sky-Monitor (ASM) on board RXTE. This provides the best measurement of the orbital light curve of 4U 1907+09 yet. Here are presented the results of the analysis of the x-ray orbital time variability of 4U1907+09 from the RXTE/ASM data.

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2 Data Analysis

The RXTE/ASM dwell data and dayly-average data were obtained from the ASM web site. The data reduction to obtain the count rates and errors from the satellite observations was carried out by ASM/RXTE team, and the procedures are described at the web site. The ASM count rates used here include the full energy range band. The data covered the time period MJD50088.3 to MJD52039.1. Fig. 1 shows the light curve for the whole time period using the dayly-average full energy band data. The regular outbursts every 8.37 day orbital are present but not easily identified on the plotted timescale. However, the long-term variability is easily seen.

An epoch folding analysis was carried out on the full energy range band data, with the chisquared statistic used to assess the reality of variability at any given trial period. The dayly-average and dwell data were folded into a variety of numbers of bins per period for periods in a range around 8.4 days. The dwell data gives a much more significant lightcurve, due to the 1 day averaging in the dayly-average data causing a smoothing effect. Thus we analyze the dwell data lightcurve here. The epoch folding gives a maximum statistical significance for a number of bins of about 24. Larger numbers of bins increases the statistical error per bin, whereas smaller numbers of bins averages over real structure. Both effects reduce the significance compared to the optimum number of bins. The chisquared vs. period from epoch folding for 24 bins is shown in Fig. 2. The maximum chisquared with 24 bins was 828 for a period of 8.3746 days. This is equal to

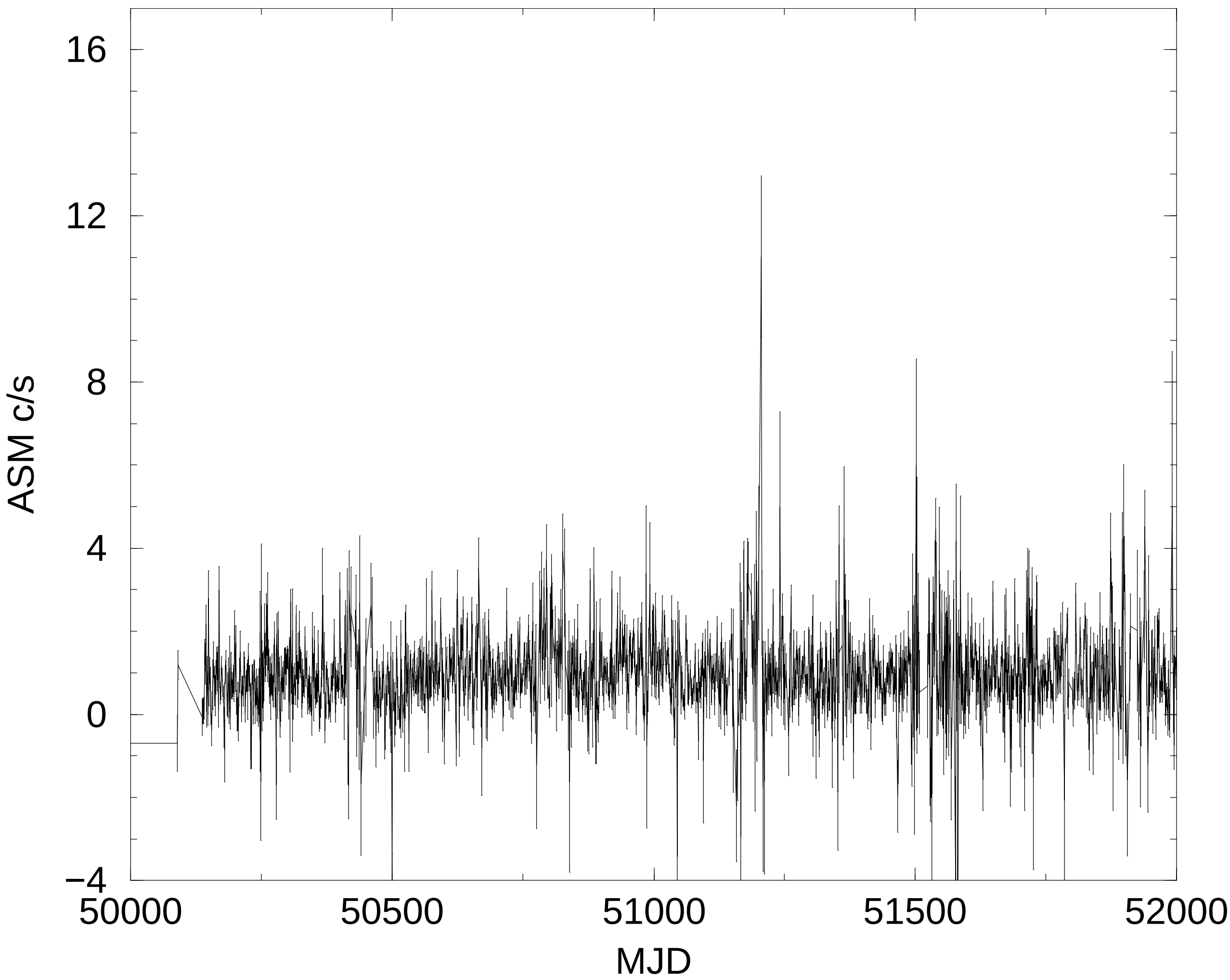

Fig. 1. 4U1907+09 RXTE ASM light curve using dayly-average data.

the known orbital period of 8.3753 days, within errors. The period error from epoch folding is $\simeq 0.002$ day, significantly greater than the error of 0.0002 day from x-ray timing analysis. The orbital light curve for the RXTE/ASM data is shown in Fig. 3 below.

3 Comparing models to the data

The current work involves comparing various models to the RXTE/ASM orbital light curve. Work in progress includes fitting to previous data on column densities, which is incomplete over orbital phase.

Least squares fits of the models to the RXTE/ASM light curve were carried out. The orbital parameters of the 4U 1907+09 system have signficant uncertainties. The two main ones are: the eccentricity, e, has a 68% range 0.14 to 0.38; and longitude of periastron, ω has a 68% range $310°$ to $350°$. $T_{\pi/2}$ is known fairly well, but the uncertainty in e and ω imply a significant uncertainty in the time of periastron passage. The time of periastron passage has an important effect in the models. For the plots below phase 0 is taken to be $T_{\pi/2}$, but periastron passage varies depending on the values of e and ω. Here, the result of van Kerkwijk, van Oijen, van den Heuvel (1989) is adopted, that is a companion mass of $\simeq 24 M_{sun}$ but e and ω are varied within the range of their uncertainties.

3.1 Pure wind model

A spherically symmetric wind has been shown to be able to reproduce the main flux peak prior to periastron but not the secondary peak (Roberts et al. (2001)). The wind velocity law here is taken to be that of Castor, Abbott, Klein (1975) with $\beta = 1.0$:

$$v_w(r) = v_o(1 - R_s/r)^{\beta} \quad (1)$$

The wind has an additional azimuthal component due to stellar rotation. The accretion rate is taken to be the Bondi-Hoyle accretion rate (e.g. see Leahy (1991)). The best-fit models for the three cases of ω = 310, 330 and 350 are shown in Fig. 4 and are labelled by $2\pi + (90 - \omega)$, which is the angle that periastron preceeds $T_{\pi/2}$. These fits show that the wind

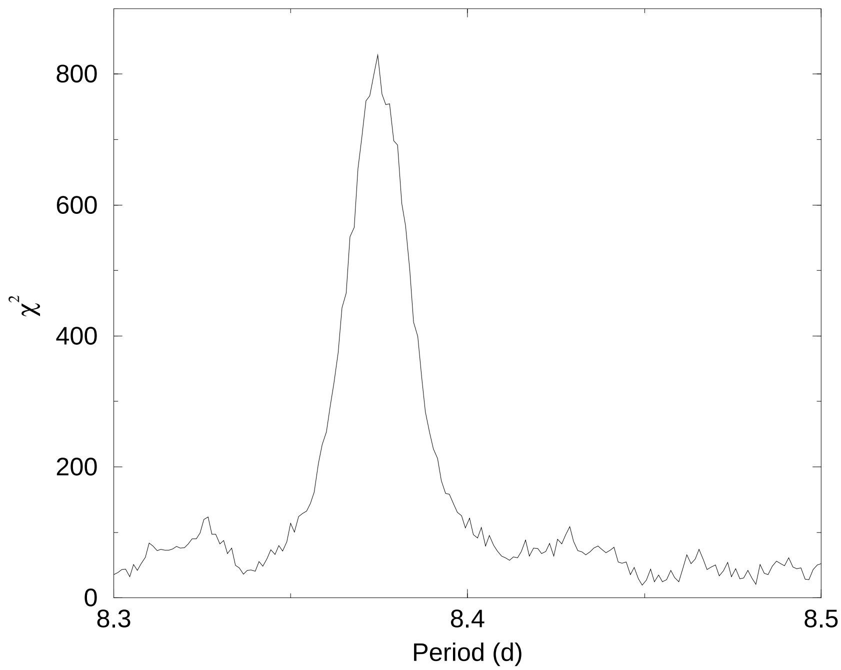

Fig. 2. Chisquared vs. period for the RXTE/ASM dwell data for 4U1907+09.

only model peaks at the wrong time for $\omega = 330$ and 350. Even for $\omega = 310$, the fit is poor: chisquared of 161 for 21 d.o.f., with the minimum occuring for e=0.27 and wind velocity at infinity, $v_o = 260$ km/s. The $\omega = 310$ wind only model (long-dashed line) is a poor fit to the shape of the light curve for phase 0 to 0.6, and does not give at all the observed broad secondary flux peak around phase 0.1-0.3.

3.2 Wind plus disk model

An additional dense, slowly expanding circumstellar disk is a possible explanation of the secondary flux peak: the neutron star could pass through the disk twice per orbit, once near periastron to contribute to the main flux peak and once near apastron to give the secondary flux peak. From Fig. 3 here, the RXTE/ASM data shows the apastron flux peak is very broad covering phase $\simeq$ 0.1-0.3. A circumstellar disk is crossed by the pulsar twice per orbital period at positions $180°$ apart, which translates to a phase difference which will be different than 0.5 depending on the position of the first crossing. This is due to the eccentric orbit. To test whether a disk could explain the two peaks seen in the RXTE/ASM light curve, the disk model was fitted to the data. The disk was gaussian in density in the θ direction, with θ the co-polar angle in coordinates with equatorial plane equal to the disk plane. The disk was taken to be tilted at $45°$ to the orbital plane, since the tilt angle is a near degenerate fit parameter with the disk σ_d. The normalization of the disk density to the stellar wind density and the line of intersection of orbital and disk planes were also fit parameters. The resulting best-fit disk model for $\omega = 330$ (labelled 120 disk) is shown in Fig.3 by the dot-dash line. The disk gives a reasonable fit to both the pre-periastron and apastron flux peaks: chisquared of 64.6 for 18 d.o.f., with the minimum occuring for e=0.14 (the limit allowed in the fit), wind velocity at infinity $v_o = 430$ km/s, disk to wind density at center of disk of 1.38, disk thickness of $\sigma_d = 22.9°$. The disk statistically is not a good fit to the data: the main discrepancy is that the secondary flux peak in the model occurs too early compared to the observations.

3.3 Wind plus stream model

This type of model has been used previously to fit the x-ray light curve of the supergiant x-ray binary system GX301-2 by Haberl (1991) and Leahy (1991) and by Leahy (2001). The basic idea is that the pulsar causes a denser stream of gas to leave the primary star, along with the rest of the wind, from the point on the primary facing the neutron star, as proposed by Stevens (1988). The motion of the stream as it flows out from the primary can be calculated from the rotation of the primary assuming it flows at the same speed as the rest of the wind. However the initial acceleration of the stream from the surface is quite uncertain, yet has a major effect on the position of the stream. Here, the stream is hypothesized to be a spiral stream which is crossed twice by the pulsar during its orbit. The light curve depends only on the stream density where it is crossed by the pulsar. Thus the model only specifies the over-density and the Gaussian width of the stream where it crosses the orbit of the pulsar. The density and position of the stream at other locations than where it crosses the pulsar orbit is important for the column density as a function of orbital phase.

The best fit stream model is shown in Fig. 3 by the solid line. Due to the large number of parameters for the wind and the two stream crossings, only the case $\omega = 330$ was

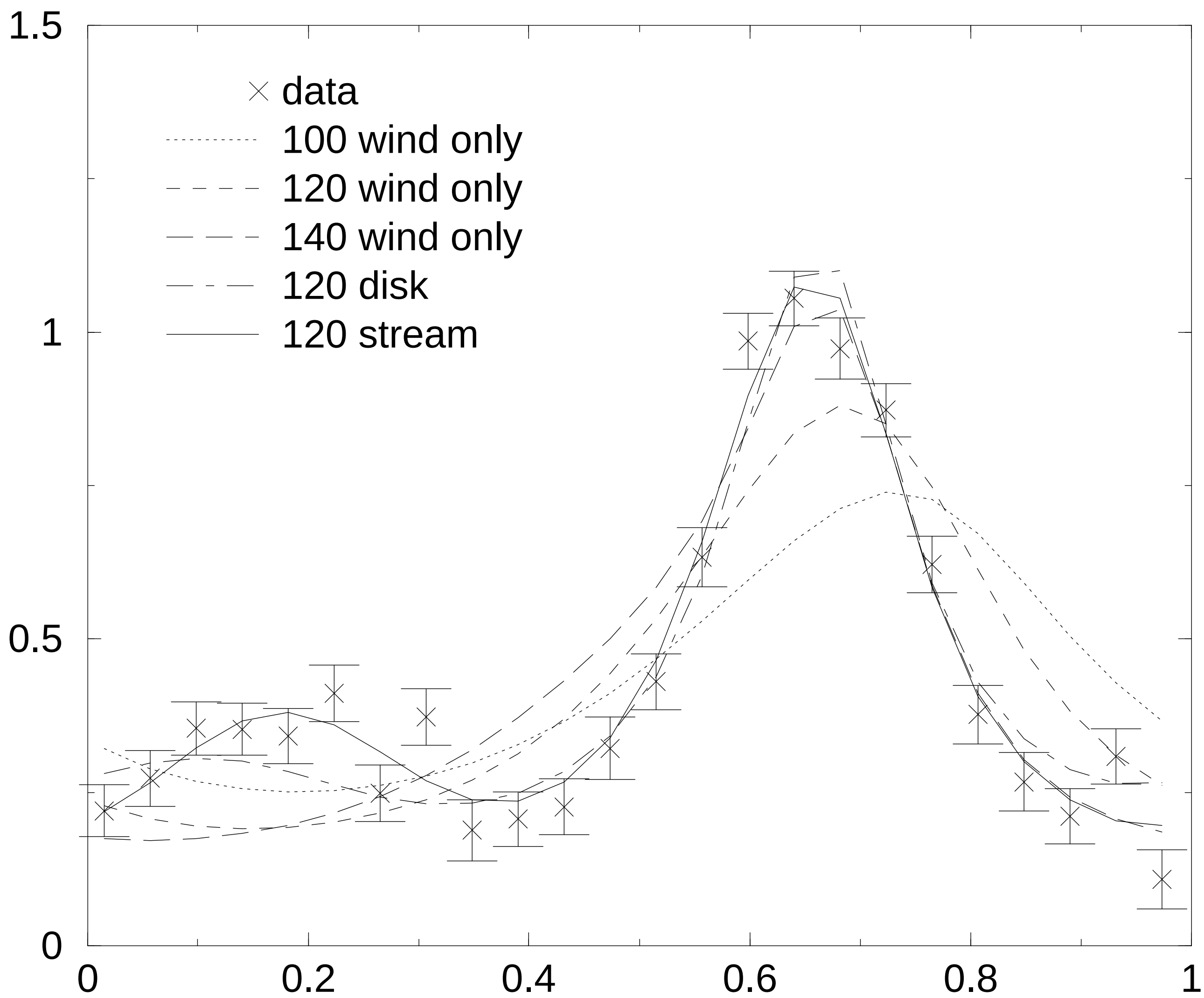

Fig. 3. Light curve of 4U1907+09 compared to the models (see text).

studied. The stream model does produce the best fit of any of the models to the data: chisquared of 31.2 for 15 d.o.f.

4 Conclusion

The RXTE/ ASM lightcurve is the best measurement yet of the orbital lightcurve of 4U1907+09. It shows the main flux peak near periastron and also a broad near-apastron flux peak. Model fitting shows that a wind-only cannot fit the observations. A wind plus disk model is better but still not statistically acceptable. The wind plus two stream model is a significant improvement over the wind plus disk model. Work in progress includes fitting of the measured column densities. This should provide an even stronger discriminator between various models for the distribution of gas in this system.

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