Stellar wind accretion in GX 301−2: evidence for a high-density stream

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ABSTRACT

The X-ray binary system GX 301−2 consists of a neutron star in an eccentric orbit accreting from the massive early-type star Wray 977. It has previously been shown that the X-ray orbital light curve is consistent with the existence of a gas stream flowing out from Wray 977 in addition to its strong stellar wind. Here, X-ray monitoring observations by the Rossi X-ray Timing Explorer (RXTE)/All-Sky Monitor and pointed observations by the RXTE/Proportional Counter Array over the past decade are analysed. We analyse both the flux and column density dependence on orbital phase. The wind and stream dynamics are calculated for various system inclinations, companion rotation rates and wind velocities, as well as parametrized by the stream width and density. These calculations are used as inputs to determine both the expected accretion luminosity and the column density along the line-of-sight to the neutron star. The model luminosity and column density are compared to observed flux and column density versus orbital phase, to constrain the properties of the stellar wind and the gas stream. We find that the change between bright and medium intensity levels is primarily due to decreased mass loss in the stellar wind, but the change between medium and dim intensity levels is primarily due to decreased stream density. The mass-loss rate in the stream exceeds that in the stellar wind by a factor of ~2.5. The quality of the model fits is better for lower inclinations, favouring a higher mass for Wray 977 in its allowed range of 40–60 M☉.

Key words: stars: emission-line, Be – stars: individual: GX 301−2 – stars: neutron – X-rays: stars.

1 INTRODUCTION

GX 301−2 (also known as 4U 1223−62) is a pulsar with a 680 s rotation period, in a 41.5-d eccentric orbit (Sato et al. 1986). The mass function is 31.8 M☉, making the minimum companion mass 35 M☉ for a 1.4-M☉ neutron star. The measurement of optical radial velocity amplitude by Kaper, van der Meer & Najarro (2006) further limits the mass, M, of Wray 977 to 39 < M < 53 (68) M☉ with the upper limit given for a neutron star mass of 2.5 (3.2) M☉. The companion Wray 977 has a B1 Ia+ spectral classification (Kaper et al. 1995), determined via comparison with the hypergiant ζ 1 Sco. This classification was confirmed by Kaper et al. (2006), using Very Large Telescope/Ultraviolet and Visual Echelle Spectrograph spectra. Model atmosphere fits by Kaper et al. (2006) yielded a radius for Wray 977 of 62 R☉, an effective temperature of 18 100 K and a luminosity of 500 000 L☉. The latter corresponds to a distance of 3 kpc, consistent with its distance determined from interstellar absorption (Kaper et al. 2006).

The neutron star flares regularly in X-rays approximately 1–2 d before periastron passage, and several stellar wind accretion models have been proposed to explain the magnitude of the flares and their orbital phase dependence (e.g. Haberl 1991; Leahy 1991; Koh et al. 1997). The modelling by Leahy (1991) and Haberl (1991) was done using TENMA and EXOSAT observations, respectively, which cover many short data sets spaced irregularly over orbital phase. More recently, better orbital phase coverage has been obtained by CGRO/BATSE (Koh et al. 1997) which, however, has much lower sensitivity than the previous studies.

The broad-band X-ray spectrum of GX 301−2 has been studied by TENMA (Leahy & Matsuoka 1990; Leahy et al. 1989a,b) and ASCA measurements (Saraswat et al. 1996). The latter study illustrates the complexity of the GX 301−2 spectrum. Four components are necessary: (i) an absorbed power law with high column density; (ii) a scattered power law with much lower column density; (iii) a thermal component with a temperature of 0.8 keV; and (iv) a set of six emission lines (including the iron line at 6.4 keV). Out of the above, components (ii) and (iv) are due to reprocessing in the gas in the stellar wind from Wray 977 which surrounds the X-ray source. Reprocessed spectra were calculated for a centrally illuminated cloud by Leahy & Creighton (1993) and for an externally illuminated cloud by Leahy (1999), including the Comptonized iron line shapes. Later, the Comptonized iron line was detected in GX 301−2 using the Chandra High Energy Transmission Grating (Watanabe et al. 2003), confirming the high column density (of the order of 1024 cm−2) and yielding an upper limit on electron temperature of ~3 eV. The orbital phase dependence of the X-ray spectrum of...
GX 301−2 was observed by the Proportional Counter Array (PCA) onboard the Rossi X-ray Timing Explorer (RXTE) (Mukherjee & Paul 2004). It was concluded that clumpiness in the matter surrounding the neutron star caused large variability in column density measurements.

Long-term monitoring of GX 301−2 has been carried out by the All-Sky Monitor (ASM) onboard RXTE. An analysis of these observations for the 5.5 yr time period MJD 500 87.2 to MJD 522 84.5 was done by Leahy (2002, hereafter L02). In this paper, the light curve based on the significantly longer 10 yr RXTE/ASM data base is analysed. In addition, we study the flux and column density measurements made by the RXTE/PCA, as well as column densities derived from the RXTE/ASM softness ratios. Improved modelling methods are introduced: accurate analytic description of the stream and inclusion of simultaneous flux and column density calculations. The inclusion of this much more extensive data and the more realistic modelling results in significant improvement in constraints on the system properties of GX 301−2 and allows new conclusions to be drawn.

2 RXTE/ASM AND RXTE/PCA OBSERVATIONS

The ASM onboard RXTE (Levine et al. 1996) consists of three scanning shadow cameras (SSCs), each with a field of view of 6° × 90° full width at half-maximum. The SSCs are rotated in a sequence of ‘dwells’ with an exposure typically of 90 s, so that most of the sky can be covered in one day. The dwell data are also averaged for each day to yield a daily-average. The RXTE/ASM dwell data and daily-average data were obtained from the ASM website. The data reduction to obtain the count rates and errors from the satellite observations was carried out by the RXTE/ASM team, and the procedures are described in the website. The ASM count rates used here include the full energy range band as well as the three subbands 1.3–3.0, 3.0–5.0 and 5.0–12.1 keV. The data covered the time period MJD 501 72.6 to MJD 539 78.6. The regular outbursts every 41.5 d orbital cycle are seen in the 5–12 keV count rates, as well as the variability from cycle to cycle.

The orbital parameters of GX 301−2, updated with the BATSE observations (Koh et al. 1997) and used for this study are as follows. \( P_{\text{orb}} = 41.498 \) d, \( a_i \sin(i) = 368.3 \) lt-s, eccentricity \( e = 0.462 \), longitude of periastron \( \omega = 310^\circ \), and time of periastron passage \( T_0 = \text{MJD 488 02.79} \).

The dwell data are used in the analysis that follows. The three RXTE/ASM subbands and full energy range band were epoch-folded. The orbital light curves for these bands and the full energy range band are shown in Fig. 1 with orbital phase zero defined by the time of periastron passage, \( T_0 \). The low-energy bands (1–3 and 3–5 keV) are dominated by scattered X-rays: very little direct X-rays from the neutron star reach the observer. This is caused by the high column density in the stellar wind and results in almost no orbital modulation in these energy bands.

GX 301−2 shows a significant variability above statistical uncertainties in intensity from orbit to orbit. This is illustrated in Fig. 2 which shows the RXTE/ASM data over the entire observation period with time-bins equal to one orbital period. The rms variability is 0.33 ASM counts s⁻¹ compared to a mean error of 0.044 ASM counts s⁻¹: the variability is real at greater than 7σ significance. There is a secular decrease in the mean flux in the amount of \(-0.07\) ASM counts s⁻¹ yr⁻¹. However, the length of the data set is not long enough to establish a long-term trend, and the flux is also consistent with no secular decrease after \( \sim\text{MJD 512 00} \). The high time-resolution data were tested for long-term periodicities by examining \( \chi^2 \) versus period for epoch-folding over periods up to 500 d. This showed peaks at \( N \) times the orbital period (with \( N = 1, 2, 3, 4 \ldots \)):
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Figure 2. Long-term variability: RXTE/ASM data for the entire observation period with time-bins equal to one orbital period (41.498 d).

this is due to aliasing of the orbital light curve. To negate the effect of aliasing, one bin per orbital period was used as input to the epoch-folding. This then yielded peaks at four and eight times the orbital period. A visual inspection of Fig. 2 verifies that this long-term period is real: there are prominent oscillations around MJD 52000 which have a period of approximately four times the orbital period.

Fig. 3 shows the 5–12.1 keV orbital light curves when the total time period is divided into three different intensity levels based on the average count rate per orbit: bright (average count rate per orbit greater than 2 counts s$^{-1}$); medium (average count rate per orbit in range 1.5–2 counts s$^{-1}$) and dim (average count rate per orbit less than 1.5 counts s$^{-1}$). The variability in the shape of the light curve for GX 301−2 between bright, medium and dim levels is primarily due to variability in the outburst peak near orbital phase 0.9. The medium- and dim-level folded light curves are consistent with each other between orbital phases 0.1 to 0.8, and the bright-level light curve is different from medium and dim between orbital phases 0.3 and 0.55.

Column densities were extracted from the RXTE/PCA spectral fits of Mukherjee & Paul (2004). The values used were the column densities of the absorbed component, since that measures the column density to the neutron star, whereas the column densities of the scattered component are complicated to interpret and represent mean values to the scattering region. The orbital phase coverage of the RXTE/PCA column densities is not very uniform, and all column densities are from a single orbit observation of GX 301−2. To obtain better orbital coverage and to cover the same multiyear time-span as the ASM light curve observations, an estimate of column density versus orbital phase was created based on the 3–5 to 5–12 keV softness ratio of the ASM observations. Conversion coefficients from the softness ratio to column density were determined using NASA’s WEBPIMMS software assuming a power-law spectrum with photon index −1.0. Fig. 4 shows the derived ASM column densities compared to the observed PCA column densities. The main approximation in calculation of column densities from ASM softness ratio is the use of a single power-law spectrum, which is the equivalent of ignoring the scattering contribution to the spectrum.

3 MODEL

3.1 Wind model

The stellar wind velocity and density profiles are considered first. Both radial and azimuthal velocity components of the wind were included in this analysis. The radial wind velocity follows a power law and is taken to be of the form

$$v_w(r) = v_\infty (1 - R_s / r)^\beta + c_s$$

with $\beta = 1$, $c_s$ the speed of sound and $v_\infty$ the terminal velocity of the wind (Castor, Abbott & Klein 1975). Conservation of angular momentum dictates that the azimuthal component of the wind velocity drops off as $1/r$. The constant stellar angular speed $\omega$ of Wray 977 is expressed using the parameter $f$:

$$\omega(f) = f \omega_{ob} + (1 - f) \omega_{per},$$

where $\omega_{ob}$ is the average orbital angular velocity $(2\pi / P_{orb})$ and $\omega_{per} = \omega_{ob}(1 + e)^{0.5}/(1 - e)^{0.5} = 3.06 \omega_{ob}$ is the periastron angular velocity. Thus, the primary is taken to be rotating at some angular velocity between $\omega_{ob}$ and $\omega_{per}$. The large difference in $\omega_{ob}$ and $\omega_{per}$ is due to the high eccentricity of the orbit. Fits of a wind-driven accretion model for GX 301−2 were studied by L02 and found to be unable to fit the ‘double-bump’ nature of the light curve. L02 as well tested a wind and disc model of accretion for GX 301−2 which could not fit the observations. The conclusion drawn by L02 was that a wind and stream model (Stevens 1988) is the best-supported model for GX 301−2.
Figure 3. 5–12.1 keV orbital light curves for bright (average count rate per orbit greater than 2 counts s\(^{-1}\)); medium (average count rate per orbit in range 1.5–2 counts s\(^{-1}\)) and dim (average count rate per orbit less than 1.5 counts s\(^{-1}\)).

Figure 4. Column densities derived from ASM 3–5 to 5–12 keV softness ratio for bright level data, compared to the observed PCA column densities.
to be free parameters, the stream position was interpolated in \( f \) at the point on the surface of Wray 977 that is nearest to \( \frac{\sigma f}{\sigma f(0)} \approx 0.93 \). GX 301–2 is nearing its peak speed to overtake the stream, but the stream is near its highest density and lowest radial velocity resulting in a large increase in luminosity. The second stream crossing is at orbital phase \( \sim 0.55 \). As GX 301–2 approaches apastron, it slows to its most-leisurely pace, so the stream is able to overtake the neutron star. Since the radial wind speed is highest and stream density lowest at apastron, a significantly lower peak in luminosity occurs. Physically, one expects the stream width to increase with radial distance from the companion star, due to expansion of the higher density, overpressured stream in the lower density surrounding stellar wind. Here, we use a Gaussian density profile with variable width. The angular width (\( \sigma \)) is taken as a power-law function of distance from the centre of the companion star: \( \sigma(r) = \sigma_0 (r/r_{\text{per}})^{-\kappa} \), with \( \sigma_0 \) the width normalized at periastron distance \( r_{\text{per}} \). \( \kappa < 0 \) corresponds to a stream with increasing physical width as the stream propagates outwards. We ensure mass conservation by employing the continuity equation, so the density of the stream varies with \( r \) depending on the value of \( \kappa \). The angular width of the stream (viewed from the companion star) depends on \( (r/r_{\text{per}})^{-\kappa+1} \), so \( \kappa > -1 \) corresponds to a stream with decreasing angular width as the stream propagates outwards.

### 3.2 Wind plus stream model

Simplified models describing a simultaneous wind and stream accretion process were first used by Haberl (1991) (straight line stream) and Leahy (1991) (spiral stream) to fit the less-complete data from EXOSAT and TENMA. In the model (Stevens 1988), a stream originates at the point on the surface of Wray 977 that is nearest to GX 301–2. The stream then bends backwards (with respect to the direction of orbital velocity of GX 301–2) as it travels radially outwards from the primary star. A progression of the binary system through its orbit is shown in Fig. 5.

Here, we calculate the stream position at any given orbital phase by integrating the radial and azimuthal equations of motion. Roughly speaking, the stream is like an Archimedes spiral corotating at the orbital angular velocity. However, since the point of origin of the stream follows the neutron star, it has a greatly varying angular velocity, by a factor of \((1 + e)/(1 - e)^2 \approx 7.4 \) for GX 301–2. The result is a stream that changes shape considerably with orbital phase, similar to a garden sprinkler with an uneven rotational speed. Animations of the stream can be found at www.iras.ucalgary.ca/~leahy/. The stream shape depends on the terminal wind velocity (\( v_\infty \)), the angular speed \( \omega f(0) \) of Wray 977, the system inclination, and on companion radius (through the wind law). The model light curve depends also on the stream width and density and the speed of sound. In order to calculate the full stream shape, we started with a set of terminal wind velocities and stellar angular velocities (\( f \)) and then created a stream for each combination of \( v_\infty \) and \( f \). To allow \( v_\infty \) and \( f \) to be free parameters, the stream position was interpolated in \( f \) and \( v_\infty \).

An analysis done by L02 suggests that two crossing points (with orbital phases \( \gamma_1 \) and \( \gamma_2 \)) between GX 301–2 and the stream exist. While L02 allowed \( \gamma_1 \) and \( \gamma_2 \) to be free parameters, here we constrain them to be governed by the computed stream shape. The relative velocity of GX 301–2 with respect to the stream and the stream density both play a large role in the intensity of the X-ray flux. One stream crossing occurs just before periastron (orbital phase \( \sim 0.93 \)). GX 301–2 is nearing its peak speed to overtake the stream, but the stream is near its highest density and lowest radial velocity resulting in a large increase in luminosity. The second stream crossing is at orbital phase \( \sim 0.55 \). As GX 301–2 approaches apastron, it slows to its most-leisurely pace, so the stream is able to overtake the neutron star. Since the radial wind speed is highest and stream density lowest at apastron, a significantly lower peak in luminosity occurs. Physically, one expects the stream width to increase with radial distance from the companion star, due to expansion of the higher density, overpressured stream in the lower density surrounding stellar wind. Here, we use a Gaussian density profile with variable width. The angular width (\( \sigma \)) is taken as a power-law function of distance from the centre of the companion star: \( \sigma(r) = \sigma_0 (r/r_{\text{per}})^{-\kappa} \), with \( \sigma_0 \) the width normalized at periastron distance \( r_{\text{per}} \). \( \kappa < 0 \) corresponds to a stream with increasing physical width as the stream propagates outwards. We ensure mass conservation by employing the continuity equation, so the density of the stream varies with \( r \) depending on the value of \( \kappa \). The angular width of the stream (viewed from the companion star) depends on \( (r/r_{\text{per}})^{-\kappa+1} \), so \( \kappa > -1 \) corresponds to a stream with decreasing angular width as the stream propagates outwards.

### 3.3 Comparison to data

GX 301–2 has a significant absorption by its stellar wind in soft X-rays with column densities several times \( 10^{23} \) cm\(^{-2} \). This shows up well in Fig. 1 above: Band 1 and Band 2 data are affected significantly by absorption but Band 3 (5–12.1 keV) is mostly free of absorption effects since the photoelectric cross-section is very small above 3–4 keV. This is also confirmed by the consistency in the shape of the Band 3 light curve with the BATSE light curve (Koh et al. 1997), although the RXTE/ASM light curve here is of significantly better statistical quality. Thus, the 5–12.1 keV band flux is taken here to be proportional to the X-ray luminosity of the pulsar.

The comparison of our wind plus stream models to the RXTE/ASM orbital light curve is made by \( \chi^2 \)-minimization using the non-linear conjugate gradient method. For each minimization (i.e., fitting), some parameters were taken as fixed parameters (stellar radius and system inclination) and the remaining parameters were taken as free parameters.

The mass–radius constraints on Wray 977 were discussed in detail in L02. There a mass–luminosity relation was used (Shaller, Schaerer & Maeder 1992) in addition to the no-eclipse constraint, mean Roche lobe constraint and tidal radius constraint. Kaper et al. (2006) also give an updated mass–radius constraint diagram incorporating their new results on allowable mass ratio of the system and
omitted the last five points in the column densities derived from the ASM softness ratio (see Fig. 4) since they did not agree with the RXTE/PCA column densities, which are more reliable. The parameters for these joint fits are given in Table 1. The parameters are very nearly the same as for the case when fits to the light curve and the column density done sequentially. The largest change was for the mass-loss rates, which were systematically smaller in the joint fits by about 30 per cent. This is likely caused by omitting the values of ASM column densities which did not agree with the PCA column densities, which are more reliable. The parameters for these joint fits are given in Table 1. The parameters are very nearly the same as for the case when fits to the light curve and the column density done sequentially. The largest change was for the mass-loss rates, which were systematically smaller in the joint fits by about 30 per cent. This is likely caused by omitting the values of ASM column densities which did not agree with the PCA column densities: the discordant ASM values were all high (see Fig. 4).

### 4 RESULTS

For each set of fixed parameters (radius, $R$, and inclination $i$ in Table 1), the best-fitting parameters for fitting to the ASM light curve and column density data are listed in Table 1. B, M and D refer to bright, medium and dim intensity levels. The fit parameters for the light curve fits are base wind velocity ($v_{\infty}$), stellar angular velocity parameter ($\Omega$), stream width and width variation parameters ($\sigma_\ell$ and $\kappa$), and stream central density enhancement at periastron ($\chi$). The $\chi^2$-values are listed in column 8. They are large compared to the number of degrees of freedom (73), showing that the model does not number of degrees of freedom (73), showing that the model does not number of degrees of freedom (73), showing that the model does not number of degrees of freedom (73), showing that the model does not number of degrees of freedom (73), showing that the model does not number of degrees of freedom (73), showing that the model does not.

| $(R, i)$ | Data | $v_{\infty}$ (km s$^{-1}$) | $f_1$ | $\sigma_\ell$ | $\kappa$ | $d_\ell$ | $\chi^2$ | $\dot{m}_{\text{wind}}$ (M$_\odot$ yr$^{-1}$) | $\dot{m}_{\text{stream}}$ (M$_\odot$ yr$^{-1}$) |
|---------|------|-----------------|------|--------------|--------|------|--------|-----------------|-----------------|
| (75 R$_\odot$, 55°) | B | 620 | 0.44 | 0.44 | -0.40 | 25 | 481 | 2.8 $\times$ 10$^{-5}$ | 6.8 $\times$ 10$^{-5}$ |
| (68 R$_\odot$, 60°) | B | 570 | 0.38 | 0.43 | -0.32 | 22 | 510 | 2.5 $\times$ 10$^{-5}$ | 5.1 $\times$ 10$^{-5}$ |
| (62 R$_\odot$, 70°) | B | 500 | 0.35 | 0.43 | -0.29 | 22 | 660 | 7.9 $\times$ 10$^{-6}$ | 1.6 $\times$ 10$^{-5}$ |
| (55 R$_\odot$, 70°) | B | 510 | 0.32 | 0.42 | -0.24 | 21 | 600 | 1.8 $\times$ 10$^{-5}$ | 3.3 $\times$ 10$^{-5}$ |
| (51 R$_\odot$, 70°) | B | 450 | 0.39 | 0.44 | -0.16 | 23 | 300 | 1.3 $\times$ 10$^{-5}$ | 2.9 $\times$ 10$^{-5}$ |
| (48 R$_\odot$, 75°) | B | 450 | 0.22 | 0.41 | -0.13 | 22 | 300 | 1.7 $\times$ 10$^{-5}$ | 3.8 $\times$ 10$^{-5}$ |

### Table 2. Mass and inclination.

| $\dot{M}_{\text{ne}}$ | $\dot{M}_{\text{e}}$ | $\dot{M}_{\text{e}}$ | $\dot{M}_{\text{e}}$ |
|--------------------------|--------------------------|--------------------------|--------------------------|
| $i$ | 55° | 60° | 65° | 70° | 75° |
| $M_{\text{ne}} = 1.4 M_\odot$ | $M_{\text{e}} = 62.5 M_\odot$ | $M_{\text{e}} = 53.3 M_\odot$ | $M_{\text{e}} = 46.9 M_\odot$ | $M_{\text{e}} = 42.3 M_\odot$ | $M_{\text{e}} = 39.2 M_\odot$ |
| $M_{\text{ne}} = 2.5 M_\odot$ | $M_{\text{e}} = 64.6 M_\odot$ | $M_{\text{e}} = 55.3 M_\odot$ | $M_{\text{e}} = 48.8 M_\odot$ | $M_{\text{e}} = 44.3 M_\odot$ | $M_{\text{e}} = 41.1 M_\odot$ |

on the surface gravity of Wray 977. We choose a sample set of input inclinations and radii for our models which sample approximately the range of possible radii and masses for Wray 977. These are listed in the first two columns of Table 1. Table 2 gives the conversion between inclination and mass for two different sample neutron star radii (1.4 and 2.5 M$_\odot$): the dependence of mass of Wray 977 on neutron star mass is weak. For each case of the two fixed parameters, $R$, and inclination, the stream model was fitted to the ASM data. The free parameters in the model were terminal wind velocity ($v_{\infty}$), stream density contrast ($d_\ell$), stream width variation parameter ($\kappa$), mass-loss rate ($\dot{m}$), a normalization factor, and the stellar angular velocity factor ($\Omega$) that determined the rate of rotation of Wray 977. Initial fits were done on the light curves and column densities from the full ASM data set, and then fits were carried out on the three subsets of light curve and column density data for the different intensity levels (bright, medium and dim). Since the light curves for the three different intensity levels were significantly different, we present results for separately fitting the different intensity levels. We carried fits to light curve data to determine all model light curve parameters, followed by fits to column density to determine wind mass-loss rate. This has the advantage of faster computer run-time. We followed this by joint fits to both the light curve and column density. When doing the joint fits, we
column densities (at all orbital phases). The fluctuations are likely due to clumps in the stellar wind and stream that we cannot model currently: Mukherjee & Paul (2004) also noted large fluctuations in their RXTE/PCA observations which they attributed to clumps in the stellar wind.

There are several trends in the fit results. As one goes to smaller $R_c$ and larger inclination, the best-fitting wind velocity decreases: from $\sim$600 to $\sim$300 km s$^{-1}$. The derived wind speeds are in reasonable agreement with the values estimated from the optical spectrum of Wray 977 (Kaper et al. 2006). In all cases, for a given $R_c$ and inclination, the wind velocity is highest for bright and lowest for dim. Also in all cases the best-fitting mass-loss rate is highest for bright and similar for medium and dim, whereas the density enhancement ratio, $ds$, is smallest for bright and highest for medium. Instead, one can consider the central density of the stream (proportional to density-enhancement ratio, column 7, times mass-loss rate, column 9). This shows that the central density of the stream is essentially unchanged between bright and medium levels, so the main change between bright and medium is the stellar wind mass-loss rate. However, the central density of the stream drops from medium to dim, whereas the wind mass-loss rate does not change significantly. Thus, the main change between medium and dim is that the stream density is lower for dim.

The angular rotation rate parameter $f_1$ systematically decreases with $R_c$. From the stream model, this is just due to the requirement of having the neutron star–stream crossings at the correct observed orbital phases as the position of the base of the wind (at $R_c$) changes. From equation (1), a value of $f_1 = 1$ is for the companion rotation synchronous with the mean orbital rotation and a value of 0 is for the companion rotation synchronous with periastron angular velocity. Tidal torques in the eccentric orbit would yield an intermediate value, consistent with the best-fitting values in Table 1.

Values of $\kappa$ are in the range $-0.4$ to 0, thus the stream physical width grows with $r$, as expected, and the stream angular width decreases with $r$ ($-1 < \kappa < 0$). The stream density enhancement over that of the spherical component of the stellar wind is typically 25 (with a range of 20–30), and the stream angular width at periastron is in the range of $22^\circ$–$26^\circ$.

The column density model gives two gradual peaks (see Fig. 6): one near periastron and the other near orbital phase 0.25. The stream is seen to dominate over the wind component for the periastron peak but both wind and stream contribute roughly equally for the peak near phase 0.25. The system inclination can be such that the neutron star is nearly eclipsed by the companion. In this case, the wind contribution to the column density becomes large near orbital phase 0.25, when the line-of-sight passes near the companion’s surface.
and $\chi^2_B$ for the column density fit becomes large. An example of this is the (48 R$_\odot$, 75°) case in Table 1.

Finally, we have calculated the mass-loss rate in the stream and added this as column 10 in Table 1. It is seen that the stream mass-loss rate is about a factor of 2–2.5 times higher than the mass-loss rate in the wind. This is a dramatic confirmation of the importance of the stream in the total mass-loss rate from Wray 977. It is also consistent with Wray 977 being close to filling its Roche lobe.

5 CONCLUSION

Long-term (10-yr) monitoring of GX 301−2 with the RXTE/ASM has revealed some new properties of this high-mass X-ray binary. Secular changes in flux (Fig. 2) are also accompanied by flux oscillations with a period of four 41.5-d binary orbits. The orbital light curve is seen to be significantly different between bright, medium and dim flux levels (Fig. 3). We do not understand this long-term periodicity in X-ray flux. However, we think it may be due to feedback from the neutron star on to the tidal stream, since that is locked to the orbital period, thus forcing the variability to occur at some multiple of the orbital period. One possible mechanism which could affect the trajectory and density of the stream is the X-ray radiation from the accreting neutron star. This is analogous to 35-d cycle of Her X−1, where radiation from the neutron star drives a 35-d precession of the disc (Wijers & Pringle 1999). However, here there is no disc but a tidal stream instead which is affected by irradiation.

We have constructed an improved stellar wind and stream model for the GX 301−2/Wray 977 binary system, extending the work of L02. The model is compared to long-term light curve observations from the RXTE/ASM and to column densities derived from the RXTE/ASM 3–5 to 5–12 keV softness ratios. We have validated the necessity of including a stream in the mass flow from Wray 977 in addition to a spherically symmetric wind in order to explain the observed light curves and column densities. The timings and amplitudes of the two peaks in the light curve, near orbital phases 0.92 and 0.5, are naturally explained by accretion on to the neutron star from an Archimedes spiral-type stream. The quality of the column density data is low due to statistical uncertainties. Yet the column density data provide the primary constraint on the stellar wind mass-loss rate.

We have found best-fitting parameters for a range of radii for Wray 977 and a range of system inclinations which are consistent with the physical constraints such as no-eclipse. The model fits at higher inclinations are worse than those at lower inclinations. The total $\chi^2_{BMD}$ can be obtained by summing the $\chi^2$ in Table 1 for the three intensity levels B, M and D. For the eight rows of Table 1, one finds $\chi^2_{BMD} = 1480, 1600, 1980, 1820, 2250, 2460$ and 2970, respectively. However, since the difference between our models and the data is dominated by fluctuations in the data, this is only a weak indicator that lower inclinations are preferred.

From the model fits, we find the change between bright- and medium-intensity levels is primarily due to decreased mass loss in the stellar wind, but the change between medium- and dim-intensity levels is primarily due to decreased stream density. For any intensity level, the total mass-loss rate in the stream exceeds that in the wind by a factor of ~2–5, indicating the crucial role of the stream in this binary system.

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