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Angular Momentum Transfer in the Binary X-ray Pulsar GX 1+4*

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Abstract: Optical and X-ray spectroscopy indicate that the X-ray pulsar GX 1+4 is seen through a cloud of gravitationally bound matter. We discuss an unstable negative feedback mechanism (originally proposed by Kotani et al. 1999), based on X-ray heating of this matter which controls the accretion rate when the source is in a low X-ray luminosity state. A deep minimum lasting ~ 6 hours occurred during observations with the RXTE satellite over 1996 July 19–21. The shape of the X-ray pulses changed remarkably from before to after the minimum. These changes may be related to the transition from neutron star spin-down to spin-up which occurred at about the same time. Smoothed particle hydrodynamic simulations of the effect of adding matter with opposite angular momentum to an existing disk, show that it is possible for a number of concentric rings with alternating senses of rotation to co-exist in a disk. This could provide an explanation for the step-like changes in $\dot{P}$ which are observed in GX 1+4. Changes at the inner boundary of the disk occur at the same timescale as that imposed at the outer boundary. Reversals of material torque on the neutron star occur at a minimum in L_X.

Keywords: accretion, accretion disks — pulsars: individual (GX 1+4) — stars: winds, outflows — X-rays: stars — radiation mechanisms: thermal — hydrodynamics

1 Introduction

The binary X-ray pulsar GX 1+4 is unique in several respects. It is the only known pulsar in a symbiotic system (V2116 Oph); $\dot{P}/P \sim 2\%$ per year is the largest measured for any pulsar and the neutron star magnetic field is believed to be $\sim 3 \times 10^{13}$ G—the strongest field in the known high mass or low mass X-ray binaries.

The optical spectrum is that of an M giant plus a variable blue continuum and a forest of strong emission lines from H, HeI, FeII, [FeVII], [OIII], etc. The emission lines are believed to arise from photo-electric interactions of accretion disk UV photons in circumstellar matter (Davidsen, Malina Bowyer 1977; Chakrabarty & Roche 1997). The blue continuum is generated by the disk.

The processes of angular momentum transfer in GX 1+4 are poorly understood. A long period of high luminosity and neutron star spin-up was followed by generally lower luminosity and spin-down interrupted by short episodes of spin-up. The average rates of spin-up and spin-down are similar but no clear correlation exists between $\dot{P}$ and X-ray luminosity L_X. The changes are not consistent with the standard accretion theory model (Ghosh & Lamb 1979).

Here we have investigated recent evidence relating to transitions between spin-up and spin-down in GX 1+4. In Section 2 we discuss evidence from X-ray and optical spectroscopy concerning the nature and distribution of the circumstellar matter in this system. In Section 3 we report sudden changes in X-ray pulse profiles associated with changes in L_X and probably associated with a brief transition to neutron star spin-up. In Section 4 we compare the observed relation between L_X and accretion torque with numerical simulations based on theoretical models of the accretion disk.

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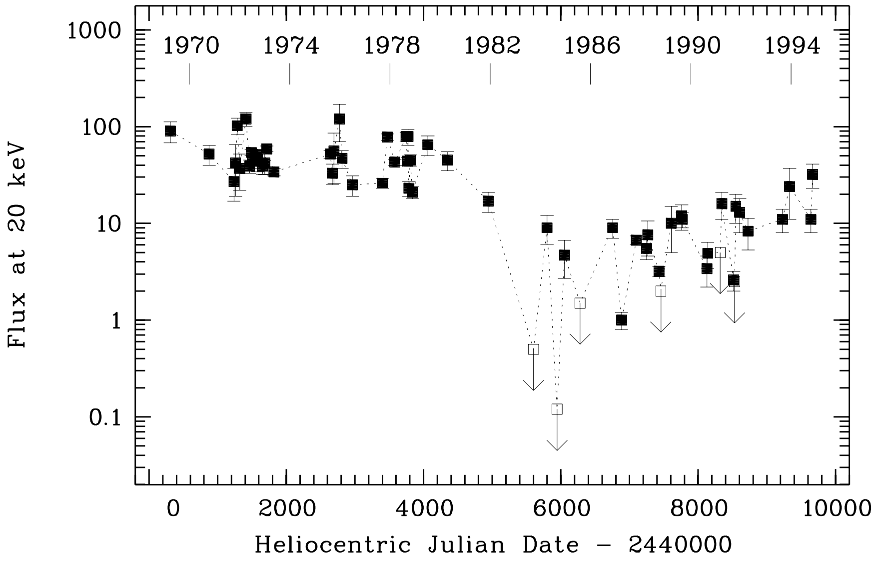

Figure 1—Time dependence of the 20 keV X-ray flux ($\times 10^{-4}$ cm^{-2}s^{-1}keV^{-1}) from 1970 to 1994. The data are from a compilation by Greenhill & Watson (unpublished report, 1994) of over 60 published and unpublished measurements. The filled squares represent positive detections and the open squares are 2σ upper limits.

2 Spectroscopic Evidence on the Nature of the Neutron Star Environment

GX 1+4 was observed with the ASCA X-ray satellite on 1994 September 14–15 and spectroscopy of the optical counterpart, V2116 Oph, was carried out at the Anglo-Australian Telescope using the RGO spectrograph on 1994 September 25–26. Photometry during 1994 August to October, using the Mt Canopus, Tasmania, and Mt John, New Zealand, 1 m telescopes showed little change in the source between the times of the X-ray and optical observations.

The X-ray spectroscopy showed considerable photo-electric absorption in the source region and strong iron line emisssion. The ionisation state of the iron (FeI–FeIV) shows that the ξ-parameter ($\equiv L_X/nr^2$ where n is the particle density of the circumstellar matter and r is the pathlength of the X-rays through this matter) is $\leq 30\,\mathrm{erg\,cm\,s^{-1}}$. Using the measured values of L_X and N_H ($\sim nr$) we estimate the characteristic scale of the attenuating matter distribution to be $r \geq 3\times 10^{12}$ cm and $n \leq 7\times 10^{10}\,\mathrm{cm^{-3}}$. The results of the optical spectroscopy were consistent with these conclusions. Using the Balmer line ratios and the calculations of Drake & Ulrich (1980) we estimate the electron density to be $n_e \sim 3\times 10^{10} - 10^{11}\,\mathrm{cm^{-3}}$ and the plasma temperature to be $\sim 20,000$ K in the emission line region. The absence of FeIII and the presence of FeII lines supports this temperature estimate.

Using this information, Kotani et al. (1999) propose a model in which the circumstellar matter is gravitationally bound to the neutron star during times of low L_X. This is consistent with the observed Hα line width (~2 AU) assuming Doppler broadening from bound hydrogen at $r \sim 3\times 10^{12}$ cm. The model provides an unstable negative feedback mechanism leading to large short term fluctuations in L_X when the system is in a low intensity state. Increased accretion raises L_X, heating the trapped matter until the thermal velocity exceeds the escape velocity driving off trapped matter and suppressing accretion from the stellar wind. This occurs only at large distances from the neutron star so there is a delay with timescale of the order of the orbital period (several months) before accretion begins to decrease. Hence the accretion rate $\dot{M}$ and L_X will be unstable and variable on timescales of months but relatively stable on longer timescales, while the mean L_X is low. If the ram pressure of the M giant wind (or matter transferred by Roche lobe overflow) becomes much higher than the thermal pressure in the trapped matter, it will not be blown off by X-ray heating and the feedback mechanism will not be active. Then L_X will be larger and dependent only on the rate of mass flow from the M giant. This mechanism requires very special conditions and is unlikely to operate in systems with supersonic winds, such as Cen X-3 or Vela X-1.

The Kotani et al. (1999) model provides a natural explanation for some aspects of the long term behaviour of GX 1+4. Greenhill & Watson (unpublished report, 1994) collated the results of over 60 published measurements of GX 1+4 between 1971 and 1994. Figure 1 is their estimate of the time dependence of the 20 keV X-ray flux during this period. Throughout the 1970s L_X was large and relatively stable as expected when the feedback mechanism is not active. Subsequently, the source was highly variable on timescales of order months and the mean value of L_X was much lower. We

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suggest that the feedback mechanism was active during this period. Another prediction is that large X-ray flares will be of shorter duration than smaller flares. Large flares will blow off matter closer to the neutron star and hence more rapidly affect accretion onto it. The pulsed flux history reported by Chakrabarty et al. (1997) is qualitatively consistent with this prediction.

The model does not provide an explanation for the transition between intensity states. This may be caused by some long term instability in the giant companion. Nor does it make any prediction concerning the direction of angular momentum transfer in this system. We note however that the negative feedback regime with a large diameter shell of low velocity trapped matter may be more conducive to the formation of a contra-rotating disk than the high luminosity regime when the ram pressure of the wind from the giant is higher and the wind extends much closer to the surface of the neutron star.

3 Spectral Characteristics of GX 1+4 throughout a Low Flux Episode

GX 1+4 was observed using the Rossi X-ray Timing Explorer (RXTE) satellite (Giles et al. 1995) over 1996 July 19–21 during a period of unusually low X-ray brightness for the source. For a detailed report see Galloway et al. (1999) and Giles et al. (1999). The count-rate from the proportional counter array (PCA) aboard RXTE indicates that the mean flux decreased smoothly from an initial level of $\approx 6\times10^{36}\,\mathrm{erg\,s^{-1}}$ to a minimum of $\approx 4\times10^{35}\,\mathrm{erg\,s^{-1}}$ (20–60 keV assuming a source distance of 10 kpc), before partially recovering towards the initial level at the end of the observation.

The pulse profiles (folded at the best-fit constant period) and the mean photon spectra before and after the flux minimum show significant variation. The observation is divided up into three distinct intervals based on the mean flux. Interval 1 includes the start of the observation to just before the flux minimum. Interval 2 spans ~ 6 hours including the flux minimum, while during interval 3 the mean flux is rising steadily towards the end of the observation.

The pulse profile is asymmetric and characterised by a narrow, deep primary minimum (Figure 2). During interval 1, the flux reaches a maximum closely following the primary minimum; this is referred to as a 'leading-edge bright' profile. Pulsations all but cease during interval 2, and in interval 3 the asymmetry is reversed, with the flux reaching a maximum just *before* the primary minimum ('trailing-edge bright' profile). This is the first observation of such dramatic pulse profile variations over timescales of <1 day.

Leading-edge bright profiles are generally associated with phases of spin-down in GX 1+4, while trailing-edge bright profiles are mostly observed during phases of spin-up (Greenhill, Galloway & Storey 1998). Re-analysed data from the regular monitoring of the source by the Burst and Transient Source Experiment (BATSE) aboard the Compton Gamma-ray Observatory (CGRO) indicate that the source switched from spin-down to spin-up ≈ 10 days after the RXTE observation. This suggests that the mechanism for the pulse profile variations may be related to that causing the poorly-understood spin period evolution in this source.

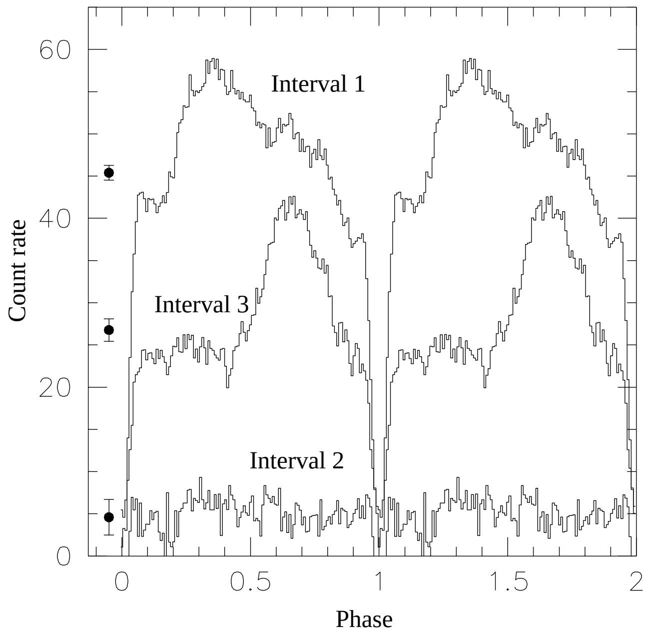

Figure 2—Pulse profiles for GX 1+4 during July 1996 folded on the best-fit constant barycentre corrected period of $P = 124{\cdot}36568 \pm 0{\cdot}00020$ s. The data are taken from the PCA on board RXTE and span the energy range 2–60 keV. Typical 1σ error-bars for each interval are shown at the left.

The best fitting spectral model (Galloway et al. 1999) is based on the work of Titarchuk (1994). The principal component is generated by Comptonisation of a thermal input spectrum at ≈ 1 keV by hot ($kT \approx 8$ keV) plasma close to the source with scattering optical depth $\tau_P \approx 3$. Additional components include a gaussian to fit Fe Kα line emission from the source and a multiplicative component representing photoelectric absorption by cold material in the line-of-sight. Variations in the mean spectrum over the course of the observation are associated with a dramatic increase in the column density n_H from 13×10^{22} to $28\times10^{22}\,\mathrm{cm^{-2}}$ between intervals 1 and 3, and also with significant energy-independent variations in the flux.

Similar spectral variations were seen in 4U 1626–67 before and after the spin rate transition in that source (Yi & Vishniac 1999). This strengthens the argument that the pulse profile and spectral changes reported here were associated with the torque reversal in GX1+4 reported by Giles et al. (1999).

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Pulse-phase spectral fitting indicates that variations in flux with phase can be accounted for by changes in the Comptonised model component, with variations in particular in the fitted optical depth τ_P and the component normalisation A_C accounting for the phase dependence. The spectral fits suggest that the soft input photons originate from the neutron star poles, and are subsequently Comptonised by matter in the accretion columns. The sharp dip in the pulse profiles is then tentatively identified with the closest passage of one of the magnetic axes to the line of sight. More details of the spectral analysis can be found in Galloway et al. (1999).

4 SPH Modelling of a Counter Rotating Disk

The new continuous monitoring data obtained by BATSE (Bildsten et al. 1997; Nelson et al. 1997; Chakrabarty et al. 1997) have yielded values for the mass accretion rate (X-ray luminosity) and the accretion torque (change in spin frequency) on a regular basis for a large number of X-ray pulsars. This data set has allowed a detailed comparison of the observed relation between accretion rate and torque, and that predicted by theoretical models.

The observations are not consistent with the standard Ghosh & Lamb (1979) model, since this predicts a clear correlation between spin-up and an increase in X-ray luminosity, whereas the observations show a variety of behaviour, with spin-up or spin-down occurring at the same apparent luminosity.

Numerical simulations (see Ruffert 1997, and references therein) have shown that it is possible to form temporary accretion disks with alternating senses of rotation in wind-accreting systems. Nelson et al. (1997) made the *ad hoc* suggestion that many observational features of some systems that are normally thought to contain disks (GX 1+4, 4U 1626–67) would be explained if they were accreting from disks with alternately prograde and retrograde senses of rotation. Previously, Makishima et al. (1988), Dotani et al. (1989) and Greenhill et al. (1993) had also sought to explain the rapid spin-down of GX 1+4 in terms of accretion from a retrograde disk.

If the secondary star is feeding the accretion disk via Roche lobe overflow, as is almost certainly the case in 4U 1626–67, it is hard to conceive how a retrograde disk could ever come about. However, in the case of GX 1+4, the suggestion is not unreasonable. This X-ray pulsar is unique in the sense that it is accreting from a red giant or AGB star wind (Chakrabarty & Roche 1997), and is in a very wide orbit. Estimating the timescale of disk reversal for accretion from such a wind, one obtains a timescale of the order of years, and the disk would form at a large radius ($\sim 10^{13}$ cm), so that the inner part of the accretion flow is expected to be like a normal accretion disk. A timescale of years corresponds well with the timescale on which the accretion behaviour in GX 1+4 is observed to change, with a negative correlation between accretion rate and spin-up in some phases while the disk would be retrograde, and a positive one at other times when it is prograde (Chakrabarty et al. 1997). Thus, this system is ideally suited to study the possibility of forming retrograde disks, since the timescale for disk reversal would be much longer than that of the torque fluctuations on a timescale of one day or less that are common in all types of X-ray pulsars. In the systems that accrete from a fast wind, the two timescales are comparable, and the effects will be difficult to separate.

Two-dimensional smoothed particle hydrodynamics (SPH) simulations were used to investigate the interactions of an existing accretion disk with material coming in with opposite angular momentum (see Murray, de Kool & Li 1999 for more details of the calculations). Ideally, we should like to simulate the entire accretion disk. However, for GX 1+4, this would require resolution over several decades in radius. Instead we completed two separate simulations: the first being of the inner, viscously dominated region which for GX 1+4 we expect to extend from the neutron star magnetosphere out to a radius $r \simeq 5 \times 10^{10}$ cm; and the second being of the outer disk in which the dynamical mixing of material with opposite angular momentum dominates.

We found that in the inner disk, once the sense of rotation of inflowing material was reversed (Figure 3), the existing disk was rapidly driven inside the circularisation radius of the new counter-rotating matter. Further evolution occurred on the viscous time scale, with the initial disk slowly being accreted at the same time as a second counter-rotating disk formed outside it. We found that the rate of angular-momentum accretion (i.e. the material torque shown in Figure 5) was proportional to the mass accretion rate. The material torque did not change sign until the initial disk had been entirely consumed. The change in sign of the torque was accompanied by a **minimum** in the accretion luminosity.

The second calculation (Figure 4) began with two counter-rotating rings with Gaussian density profiles. New material, with the same sense of rotation as the inner ring, was then added at a constant rate at the outer boundary. As with the first calculation we found the initial rings were rapidly driven in until they lay within the circularisation radius of the newly added material. We had anticipated a catastrophic cancellation of angular momentum followed by radial inflow once the rings interacted. This did not happen. Instead the rings remained cohesive with a well defined gap between them. The newly added material then formed a third, outer ring. We concluded that, if the external mass reversal timescale is significantly shorter than the

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viscous timescale at the circularisation radius, a number of concentric rings with alternating senses of rotation could be present between the circularisation radius and the radius at which the viscous timescale is comparable to the reversal timescale. These simulations neglected three-dimensional effects, and did not account for the unstable wind feeding non-coplanar material onto the system. However, we are confident that further work will not alter our main conclusion that changes at the inner boundary of the disk occur on the same timescale as that imposed at the outer boundary. Furthermore, we find that material torque reversals occurring as a result of a disk reversal would do so during an accretion luminosity minimum.

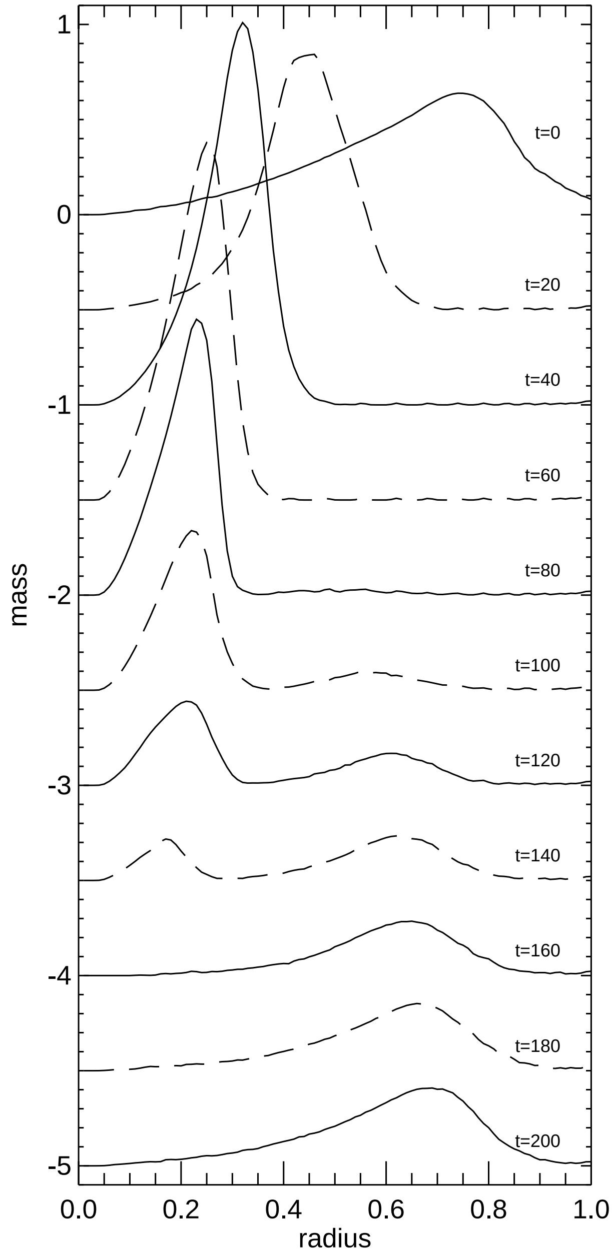

Figure 3—Evolution of the radial mass profile of a viscous ring that is subjected at its outer edge to the addition of material with opposite specific angular momentum.

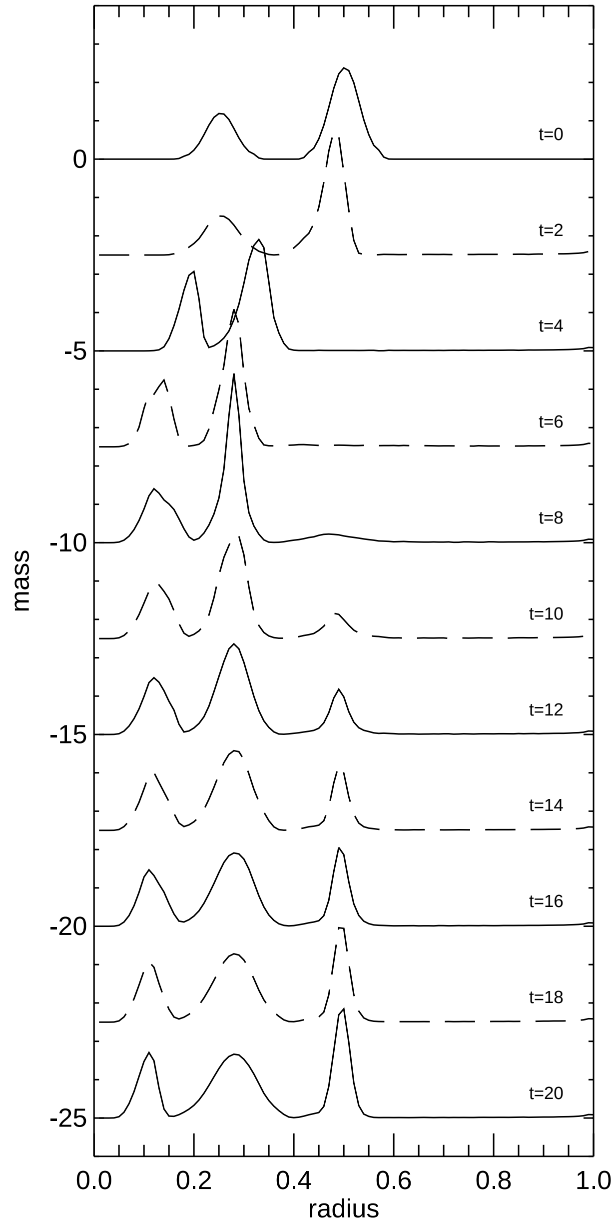

Figure 4—Evolution of two concentric counter-rotating rings that are subject to mass addition (rotating in the sense of the inner ring).

5 Discussion and Conclusions

Optical and X-ray spectroscopy indicate that a circumstellar cloud or thick disk extends to at least 3×10^{12} cm from the neutron star. This has a mean density $\sim 7 \times 10^{10}\,\mathrm{cm}^{-3}$ and temperature $\sim 20,000$ K in the emission line region. We describe a model, proposed by Kotani et al. (1999), in which, during the low intensity state, accretion is controlled by X-ray heating leading to an unstable negative feedback mechanism. This maintains L_X at relatively low levels but highly variable on timescales of the order of months. Physical conditions in the trapped matter region may be more conducive to formation of a contra-rotating disk and neutron star spin-down when this feedback mechanism is active.

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When the accretion rate is high, the mechanism fails and L_X is higher and more stable. The transition between states is presumably controlled by some instability in the giant companion.

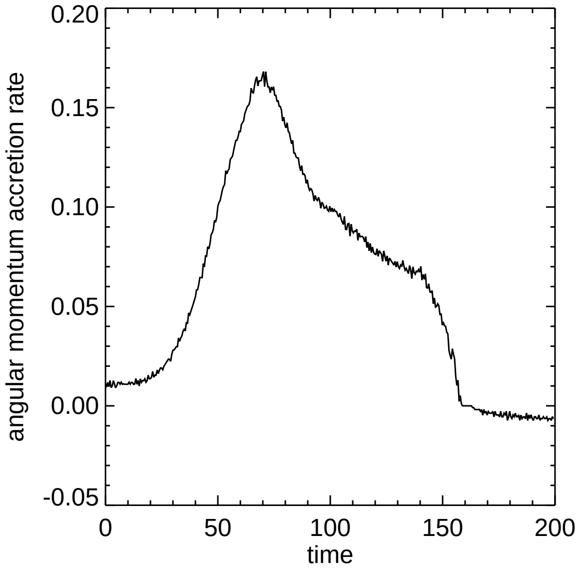

Figure 5—Angular momentum accretion rate (material torque) for the simulation of the viscous inner disk, as illustrated in Figure 3.

The X-ray pulse profiles from GX 1+4 changed remarkably during an observation by the RXTE satellite over 1996 July 19–21. The profiles were asymmetric and 'leading edge bright' during the early part of the observations when L_X (20–60 keV) was $\sim 6 \times 10^{36}$ ergs^{-1} (source distance 10 kpc). After an interval of ~ 6 hr, when L_X was ~ 10 times lower, the intensity increased towards the initial level but the profiles had changed to 'trailing edge bright'. The change in profile may be related to a transition from spin-down to spin-up which was detected by the BATSE experiment on CGRO at about the same time. According to Greenhill et al. (1998), leading edge bright/trailing edge bright profiles are normally associated with neutron star spin-down/spin-up respectively.

The X-ray spectrum during the RXTE observations was best characterised by Comptonised thermal emission with iron line emission and photo-electric absorption by cold matter in the source region. The column density n_H doubled between the early and late phases of the observation and showed significant variation on timescales as short as 2 hr. This change is too short to be associated with the feedback mechanism discussed above. The extra absorbing matter in the line of sight must be situated much closer to the neutron star.

Two-dimensional SPH simulations have been used to investigate the interactions of an existing accretion disk with incoming matter having opposite angular momentum. The simulations showed that a counter-rotating disk was formed outside the existing disk which quickly shrunk inside the circularisation radius of the outer disk. The inner disk was accreted on the viscous timescale. The torque did not change until this disk was fully consumed and torque reversal was accompanied by a minimum in L_X. If the external mass reversal timescale is significantly shorter than the viscous timescale at the circularisation radius, a number of concentric rings with alternating senses of rotation can co-exist. Changes at the inner boundary of the disk occur on the same timescale as that imposed at the outer boundary. Material torque reversals occur at a minimum in L_X.

The net torque on the neutron star depends also on magnetic torques due to linkage with disk matter both inside and outside the co-rotation radius (Ghosh & Lamb 1979; Li & Wickramasinghe 1997). The two transitions to spin-up reported by Chakrabarty et al. (1997) occurred when L_X was increasing by more than an order of magnitude from very low levels. Conversely the transition to spin-down was associated with a similar magnitude *decrease* to a very low level. Such transitions could be caused by a disk having alternate zones with prograde and retrograde motion. The BATSE record (Chakrabarty et al. 1997) shows that, during intervals of monotonic spin-up or monotonic spin-down, GX 1+4 and several other wind fed sources make step-like transitions from one value of $\dot{P}$ to another. Hence, if the disk velocity profile has abrupt changes switching the sense of rotation between different zones, as discussed in Section 4, step-like changes in the magnitude of $\dot{P}$ will occur as the matter is transported inwards. The analysis by Wang & Welter (1981) indicates that asymmetry in pulse profiles may be a consequence of an asymmetry in the accretion flow onto the polar cap region. Hence, the reversal in the asymmetry of the pulse profiles observed in the RXTE data could be a consequence of accretion flow changes as the direction of rotation of the inner edge of the disk reversed. This occurred at a minimum in L_X as predicted by the SPH modelling.

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References

Bildsten, L., et al. 1997, ApJS, 113, 367

Chakrabarty, D., & Roche, P. 1997, ApJ, 489, 254

Chakrabarty, D., Bildsten, L., Grunsfeld, J. M., Koh, D. T., Nelson, R. W., Prince, T. A., & Vaughan, B. A. 1997, ApJ, 481, L101

https://doi.org/10.1071/AS99240 Published online by Cambridge University Press

Davidsen, A., Malina, R., & Bowyer, S. 1977, ApJ, 211, 866
Dotani, T., Kii, T., Nagase, F., Makishima, K., Ohashi, T., Sahao, T., Koyama, K., & Tuohy, I. R. 1989, PASJ, 41, 427
Drake, S. A., & Ulrich, R. K. 1980, ApJS, 42, 351
Galloway, D. K., Giles, A. B., Greenhill, J. G., & Storey, M. C. 1999, MNRAS, accepted
Ghosh, P., & Lamb, F. K. 1979, ApJ, 234, 296
Giles, A. B., Galloway, D. K., Greenhill, J. G., Storey, M. C., & Wilson, C. A. 1999, ApJ, accepted
Giles, A. B., Jahoda, K., Swank, J. H., & Zhang, W. 1995, PASA, 12, 219
Greenhill, J. G., et al. 1993, MNRAS, 260, 21
Greenhill, J. G., Galloway, D. K., & Storey, M. C. 1998, PASA, 15, 254
Kotani, T., Dotani, T., Nagase, F., Greenhill, J., Pravdo, S. H., & Angelini, L. 1999, ApJ, 510, 369
Li, J., & Wickramasinghe, D. T. 1997, MNRAS, 286, L25
Makishima, K., et al. 1988, Nature, 333, 746
Murray, J. R., de Kool, M., & Li, J. 1999, ApJ, 515, 738
Nelson, R. W., et al. 1997, ApJ, 488, L117
Ruffert, M. 1997, A&A, 317, 793
Titarchuk, L. 1994, ApJ, 434, 570
Wang, Y. M., & Welter, G. L. 1981, A&A, 102, 97
Yi, I., & Vishniac, E. 1999, ApJ, 516, L87