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Investigating Pulse Morphology in GX 1+4

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Abstract: Observational and theoretical evidence points to the existence of an unusually high magnetic field on GX 1+4. The pulsar is thus an ideal laboratory for studying two-photon cyclotron emission, an important source of photons of frequency significantly less than the cyclotron frequency in X-ray pulsars. Low-frequency approximations to the two-photon cyclotron emission transition probabilities are derived. These are used to calculate the theoretical opening angle of the double-humped pulse shape predicted by the two-photon cyclotron emission model. The theoretical pulse shape, incorporating the effects of gravitational light bending, is compared with observations of GX 1+4. Observed light curves have opening angles consistent with the theoretically predicted maximum value.

Keywords: radiation mechanism: non-thermal — pulsars: individual(GX 1+4) — X-rays: stars

1 Introduction

The X-ray pulsar GX 1+4 has been identified with the symbiotic system V2116 Oph, which is believed to contain a neutron star accreting from an M giant companion (Davidsen, Malina & Bowyer 1977). The high-energy X-ray spectrum of GX 1+4 is the hardest of all known X-ray binary systems (Mony et al. 1991). GX 1+4 is remarkable in other ways as well. It has the fastest known rate of period change of any pulsar. In the early 1980s the pulsar entered a low-intensity state and this transition was associated with a change from spin-up to spin-down of the pulsar period. The subsequent rise in intensity since then has been accompanied by several changes from spin-up to spin-down and back again. Observations of GX 1+4 and theoretical considerations (Dotani et al. 1989; Mony et al. 1991; Greenhill et al. 1993) have provided strong evidence for an unusually strong magnetic field on GX 1+4, $B_{\rm surface} >\sim 2\cdot 2\times 10^9$ T. This value is very large for an object that is thought to be very old, if theories that magnetic fields in pulsars decay are correct. The high magnetic field derived implies a cyclotron energy $\Omega_e \sim 250$ keV near the stellar surface, where the plasma deceleration region and the pulsed X-ray emission region is located.

GX 1+4 was observed with the ASCA satellite in September 1994, a month before a transition of GX 1+4 from a spin-down phase to a spin-up phase (Kotani 1996). In this paper we compare the ASCA observations with model calculations of the beam shape from GX 1+4. In Section 2, we describe the model proposed for the emission from GX 1+4. We derive expressions for the X-ray emission probability valid at the low frequencies of the ASCA observations, and incorporate gravitational light bending into the calculation of the pulse shape. In Section 3 we compare model calculations of the pulse shape with the ASCA observations and other observations of GX 1+4, and our conclusions are presented in Sections 4 and 5.

2 An Emission Model for GX 1+4

It has been shown (Kirk, Melrose & Peters 1984; Melrose & Kirk 1986; Kirk & Melrose 1986; Bussard, Alexander & Meszaros 1986) that the most important source of continuum photons (i.e. photons not near the cyclotron frequency) in X-ray pulsars of low to moderate luminosity is from two-photon cyclotron emission and the associated double Compton scattering. In two-photon cyclotron emission an excited electron in an $n = 1$ quantum state returns to the ground state by emitting two photons, the sum of whose frequency roughly equals the cyclotron frequency. The rate of two-photon cyclotron emission is highest when one photon has a frequency close to the cyclotron frequency and the other photon frequency is much lower. Kirk,

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Nagel & Storey (1986) calculated the X-ray emission intensity and resulting beam shapes for two-photon cyclotron emission for conditions existing in typical X-ray pulsars. The model applies to pulsars for which the frequencies observed are significantly less than the cyclotron frequency.

The observational and theoretical evidence that GX 1+4 has an unusually high magnetic field (implying that existing observations are at frequencies well below the cyclotron frequency) means that GX 1+4 is an ideal object for studying two-photon cyclotron emission. The Kirk, Nagel & Storey (1986) model calculations were compared with balloon observations of GX 1+4 (Greenhill et al. 1993) and it was shown that the model is consistent with the observed pulse shape up to energies of order 75 keV. The observed pulse at high frequencies was narrower than predicted by the two-photon cyclotron emission model alone, possibly due to resonant Compton scattering of X-ray photons by the accretion plasma above the emission region, or increased non-resonant Compton scattering (Greenhill et al. 1993).

The ASCA satellite observed GX 1+4 at energies between 3 and 10 keV. Compton scattering is less significant at frequencies far below the cyclotron frequency (Pavlov, Shibanov & Meszaros 1989) and so for the ASCA observations the observed pulse should correspond more exactly to the theoretically predicted pulse shape.

2.1 Low-frequency Approximation to Transition Rates

In the highly magnetised emission region plasma the X-ray radiation is emitted in two natural modes and, in general, the natural modes are elliptically polarised. However, at frequencies well below the cyclotron frequency the modes can be approximated as having transverse linear polarisation (Melrose & Kirk 1986, hereafter MK86) with polarisation vectors, indicating the polarisation direction of the two natural modes of radiation, given by

$$\mathbf{t} = (\cos\theta\cos\psi,\ \cos\theta\sin\psi,\ -\sin\theta)\,,$$
$$\mathbf{a} = (-\sin\psi,\ \cos\psi,\ 0)\,. \tag{1}$$

The angle θ is the polar angle of emission of the photon with respect to the magnetic field and the angle ψ is the azimuthal angle of the photon with respect to the magnetic field. The magnetic field B is in the z direction. The derivation of the transition rates for two-photon cyclotron emission in such a plasma, averaged over polarisation and angle of emissions is given in MK86. For the densities present in accretion streams ($\sim 10^{16}$ m^{-3}), vacuum polarisation effects dominate plasma effects. An analysis of radiative transfer effects has been given in Kirk, Nagel & Storey (1986). The effect of radiative transfer through the emission region is not included in the calculation below.

The transverse polarisation approximation is valid at very low frequencies compared to the cyclotron frequency, and so applies to the ASCA observations of GX 1+4 if the pulsar has a cyclotron frequency $\sim$250 keV. For two-photon cyclotron emission the probability of a soft photon of frequency ω being emitted in polarisation mode $\sigma = t, a$, as a function of the frequencies and angles of emission of the two photons, and v_z, the velocity of the emitting electron along B, is given by

$$\begin{aligned} w^{\sigma}(\omega,\theta,\omega',\theta',v_z) = {}& \frac{e^4}{4\epsilon_0^2 \mid \omega\omega' \mid}(\mid M^{\sigma a'} \mid^2 + \mid M^{\sigma t'} \mid^2) \\ & \times 2\pi\delta(\omega+\omega'-\Omega_e-(k_z+k_z')v_z \\ & + (k_z+k_z')^2/2m)\,, \end{aligned} \tag{2}$$

where $\sigma = a, t$, the $M^{\sigma\sigma'}$ are matrix elements (MK86), k_z is the wavevector of the emitted low-frequency photon in the z direction and m is the mass of the electron. Units where $h = c = 1$ are used throughout except where explicitly stated otherwise. Variables ω', k_z', θ' and σ' refer to the second, higher-energy photon. The delta function approximation is discussed in Kirk, Nagel & Storey (1986) [see equation (3) of that paper].

In MK86 expressions (36a to d) are given for the squares of the projected matrix elements, averaged over the azimuthal angles of the photons, and also averaged over the forward and backward directions, with respect to the magnetic field, of polar angles of the photons.

The results for the projected matrix elements are used to construct the transition probabilities for emission of a low-frequency photon in either polarisation mode as a function of its frequency ω and θ, the angle of emission with respect to the magnetic field. This is done by integrating over the frequency of the second photon using the delta function, and averaging over the direction of emission with respect to the magnetic field of the second photon. In the low-frequency limit, only the leading terms in ω/Ω_e need to be considered. Then the rate of emission of a soft photon of frequency ω has an angular dependence given by (after correcting some errors in the equations for the matrix elements in MK86)

$$\begin{aligned} w^t \propto {}& \tfrac{16}{15}\sin^2\theta[4/y^3 - 2/y^2 + 2/y - 4] \\ & + \tfrac{16}{15}\cos^2\theta[3/y - 4]\,, \\ w^a \propto {}& \sin^2\theta[32/3y] + \tfrac{16}{15}[3/y - 4]\,, \end{aligned} \tag{3}$$

where $y = \omega/\Omega_e$, superscript t indicates emission in the t polarisation mode and superscript a indicates emission in the a polarisation mode. For soft photons with $y \ll 1$, emission in the t polarisation mode dominates and the angular pattern for $\theta \neq 0$ goes as $\sin^2\theta$. For $\theta \to 0$ terms in w^a become important, and thus the equations above indicate that a change in polarisation direction could be observed across a pulse. The sum of w^t and w^a leads to the total transition probability, independent of polarisation.

Two-photon emission has been shown to be the dominant source of emission for moderate-luminosity X-ray pulsars (Kirk & Melrose 1986). For such pulsars the deceleration region of the accretion plasma is thought to occur close to the surface of the star, and the emission region is modelled as a thin slab of plasma on the polar cap of the neutron star (Kirk 1985).

The flux from the emission region F has an angular dependence given by

$$F \propto (w^t + w^a)\cos\theta\,, \tag{4}$$

where the factor of $\cos\theta$ takes into account the projected area of the slab. If the slab were radiating isotropically the pulse profile would have the form $F \propto \cos\theta$.

3 Comparison with Observations

The factor of $\sin^2\theta$ in equation (3) means that at low frequencies the emission probability is reduced for emission nearly along the magnetic field. The results therefore indicate that at low frequencies the pulse has a central dip and thus a double-humped pulse is emitted, as has been observed for GX 1+4 (Greenhill et al. 1993). The opening angle of the central dip in the pulse, i.e. the angle at which the flux is a maximum, is given by the value of θ for which

$$\frac{dF}{d\theta} = 0\,. \tag{5}$$

Using equations (3), (4), and (5), and assuming a cyclotron energy of $\sim$250 keV and an observing energy of 5 keV, the opening angle ρ at the site of the emission of the double-humped pulse produced by two-photon cyclotron emission is $\rho \approx 54°$. This is as would be observed on the surface of the pulsar. However, gravitational light bending significantly affects the beam shape. Leahy & Li (1995) have derived simple analytic formulae that adequately describe the effect of gravitational light bending due to general relativity for most neutron stars. Assuming a typical neutron star radius for GX 1+4, then the opening angle ρ' after gravitational light bending is related to the opening angle ρ from the emission process alone by equation (4) from Leahy & Li (1995):

$$\cos\rho' = 1\cdot 678\cos\rho - 0\cdot 684\,. \tag{6}$$

For an input angle of 54°, this gives an opening angle including the effect of gravitational light bending of 72°.

3.1 ASCA Observations

The folded light curves for different photon energies obtained from the ASCA satellite observations have been presented in Kotani (1996). The light curve for energies <3 keV is likely to suffer from considerable contamination from galactic ridge emission, and the light curve around 6·4 keV is likely to be contaminated with unpulsed iron line emission.

Figure 1 presents summed data for energies from 3 keV to 10 keV excluding the data from around the iron line. The data in Figure 1 are thus the most likely to give information on the emission process as they are the most likely to represent just pulsed emission. The pulse has a deep dip in emission at phase $\sim$0·75 and there is also possibly a small dip at phase $\sim$0·25. It is not self-evident which dip represents the true edge of the pulse and which represents the central dip expected in the two-photon cyclotron emission model. The two-photon cyclotron emission model predicts a harder spectrum in the centre of the dip as the reduction in emission for small θ is greater for low-frequency photons. In Table 1 we show the flux ratio R, calculated as

$$R = [\text{Counts/s (Energy} = 7\text{–}10\text{ keV)}] \times [\text{Counts/s (Energy} = 3\text{–}5\text{ keV)}]^{-1}\,, \tag{7}$$

at phases 0·25 and 0·75, and the average value over all phases. There is slight evidence of spectral hardening at phase $\sim$0·25. However, the error bars are too large around the deep dip at phase $\sim$0·75 to draw any conclusions about the spectral hardening here. Therefore, we do not consider that spectral hardening results conclusively determine which dip represents the central dip predicted by the two-photon model.

Table 1. Flux ratio *R* as a function of phase (see equation 7)

Phase	R
0·25	1·14±0·06
0·75	1·00±0·13
Average	1·01±0·06

Another feature of the pulse shape is that it is significantly asymmetric, with the leading half of the pulse brighter than the trailing half. The same asymmetry was observed by Greenhill et al. (1993). A possible mechanism causing the observed asymmetries in X-ray pulsar beams was outlined in Padden & Storey (1986). It was shown that the presence of a magnetic field in the neutron star whose dipole axis does not pass through the centre

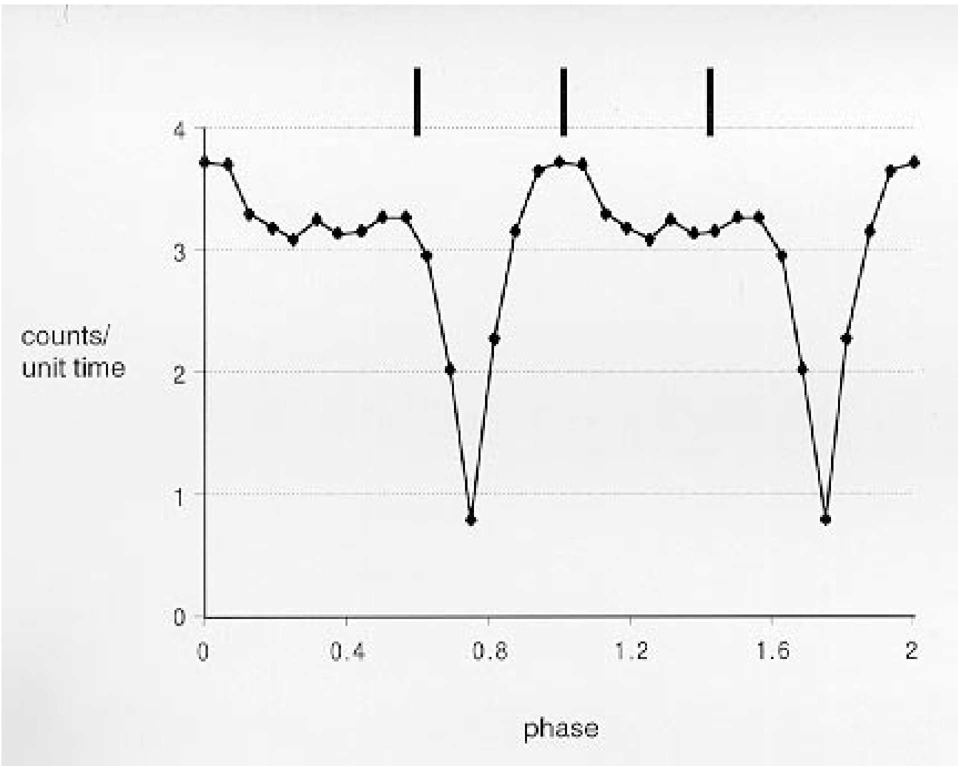

Figure 1—Folded light curve for GX 1+4 summed over energies from 3–10 keV, excluding the data from around the iron line. Galactic ridge emission is not subtracted. For details of the ASCA observations see Kotani (1996). The error bars in the above data are $\pm\sim 0\cdot 08$ counts/unit time. The vertical bars are separated by the theoretically predicted opening angle of the double-humped pulse.

of the star can cause asymmetric pulse shapes when an accretion disk is present. The asymmetry makes it harder to estimate the opening angle of either the deep or shallow dip. The vertical bars in Figure 1 are separated by 72°, the theoretical opening angle incorporating gravitational light bending. Taking the asymmetry of the pulse into account, the hypothesis that the dip at phase $\sim 0\cdot 25$ is the two-photon dip is consistent with the observations. However, it is also possible that the deep dip at phase $\sim 0\cdot 75$ is the two-photon dip and that there is another component in the beam. This possibility is discussed further in Section 4.

3.2 Other Observations

Pulse profiles observed after the low-intensity state in the 1980s tend to exhibit a double-humped profile and an asymmetry where the leading edge of the pulse is brighter than the trailing edge. The pulse peak separations on either side of the shallow dip in the pulse profiles from GX1+4 shown in Greenhill et al. (1993) at energies of 20–75 keV and Mony et al. (1991) at energies of 20–60 keV are consistent with the theoretically predicted maximum value of 72°.

However, the light curves observed during the high state of the the 1970s tend to exhibit an asymmetry where the trailing edge of the pulse is brighter than the leading edge. The beams are much broader, there is often no clear double-humped structure, and there is some evidence for additional components in the beam (e.g. White, Swank & Holt 1983; Doty, Hoffman & Lewin 1981). This implies that the emission geometry must have been significantly different during the high state.

4 Constraints on the Emission Geometry

It is important to note that the value of 72° derived above represents the expected upper limit to the opening angle of the double-humped pulse. At moderate frequencies with respect to the cyclotron frequency, one would expect scattering to decrease the opening angle to a value less than the theoretical maximum (Kirk, Nagel & Storey 1986), and yet the maximum value is consistent with observations up to energies of several tens of keV. This supports the arguments for a very high surface magnetic field on GX 1+4.

However, there are other possible causes for a wide opening angle. It is possible that a very wide polar cap is present, which would produce a wider pulse than is produced by the flat polar cap model assumed here.

Alternatively, the wide pulses may be evidence for the existence of column geometry, rather than slab geometry, in the emission region for GX1+4. Treatments of the radiation transfer in the strongly magnetised plasma of the emission region usually concentrate on two geometries of the emission region—usually termed slab and column geometries, depending on whether the deceleration region lies either close to the surface of the star (thought to occur in low to moderate luminosity pulsars), or on top of an accretion column at a distance from the surface that is not necessarily small compared to the diameter of the column. In this latter case, a significant fraction of the radiation from the emission region is emitted from the sides of the post-shocked region, effectively increasing the projected area of the emission region at large angles with respect to the magnetic axis. This results in wider pulses than in the low-luminosity case, when the shock is a flat slab sitting on the surface and most emission comes from the top of the slab, as modelled above. The existence of column-shaped emission region geometry for GX 1+4 is consistent with the existence of a high surface magnetic field for this system. A high magnetic field results in the inner edge of the accretion disk being further from the star than for an average X-ray binary, which means that matter is channelled down a smaller range of field lines onto a narrower-than-average region of the neutron star surface. Thus, for even moderate luminosities, the restriction of the accretion funnel to a small region may result in a higher shock height, and thus wider pulses, than would be expected from an X-ray pulsar with the same luminosity but a slab-shaped emission region geometry. If column-shaped emission region geometry is applicable in GX 1+4, then one would not expect the formulae above to solely determine the pulse shape.

Greenhill et al. (1993) reported observations of a much narrower high-frequency profile at energies from 75–114 keV. They postulated that scattering at moderate θ values was narrowing the pulse from the theoretically predicted shape. On the other hand, the high-frequency pulse observed could be an interpulse. If the deep minimum is really the pulse centre, then, as mentioned in Section 3·1, there is evidence for an extra component in the beam. In this case, the narrow high-frequency pulse is at the phase where one would expect to observe an interpulse from a slab-shaped emission region. Alternatively, the combined effect of gravitational light bending and a column-shaped emission region can produce a narrow interpulse at the phase of the main pulse (Nollert et al. 1989). A higher magnetic field strength on the magnetic pole producing the interpulse may lead to a slower decrease in emission from this pole with frequency, thus leading to greater prominence of the interpulse as the frequency increases. A more detailed analysis of the pulse morphology of GX 1+4 is in preparation, together with an analysis of XTE satellite data taken in 1996, which extend to higher frequencies than observations to date (Giles, Greenhill, Galloway, Storey & Swank, in preparation). The XTE satellite data should help to confirm the shape of the high-frequency profile.

5 Conclusion

The ASCA satellite observed the unusual X-ray pulsar GX 1+4 in September 1994. Assuming that two-photon cyclotron emission is the dominant emission mechanism in X-rays for this pulsar, we have calculated the opening angle of the double-humped pulse predicted by the two-photon emission model, including the effects of gravitational light bending on the pulse shape. Light profiles of GX 1+4 exhibit opening angles of the shallow dip in the pulse consistent with the theoretically predicted maximum opening angle, although it is not certain that this phase represents the closest passage of the line-of-sight to the magnetic pole. The results are consistent with GX 1+4 having an unusually high surface magnetic field, or the wide opening angles may be evidence for the existence of more complicated emission region geometry than the simple slab model usually adopted. Analysis currently under way of XTE satellite high-frequency observations, and more detailed analysis of pulse morphology, should help to give more information on the pulse morphology of GX 1+4.

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