X-RAY BEAMING IN THE HIGH MAGNETIC FIELD PULSAR GX 1+4

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ABSTRACT   Pulse profiles from X-ray pulsars often exhibit strong energy dependence and both periodic and aperiodic variations with time. The great variety of profiles observed in various sources, and even from individual sources, makes it difficult to separate the numerous factors influencing the phase-dependence of the X-ray emission. These factors include the system geometry and particularly the photon energy and angle dependence of emission about the neutron star poles.

Comptonisation may play an important role in determining beam patterns and hence pulse profiles in X-ray pulsars. A Monte Carlo simulation is used to investigate the beaming due to Comptonisation in a simple accretion column geometry. We apply the model to the extremely variable pulse profiles of the high-magnetic field pulsar GX 1+4.

KEYWORDS: scattering – X-rays: stars – pulsars: general – pulsars: individual (GX 1+4)

1. INTRODUCTION

To date essentially all the approaches which have been used to model the emission region in X-ray pulsars have limitations. Past efforts have typically adopted a geometry suitable for a particular accretion rate ($\dot{M}$) regime and then predict the emission properties by a range of techniques. Radiative transfer calculations (e.g. Burnard, Arons & Klein 1991) are necessarily restricted to symmetric, homogeneous emission regions, where in reality the accretion column may be hollow and even incomplete (an 'accretion curtain'). The geometric fitting approach, where a beam pattern is assumed and then the geometry is varied (e.g. Leahy 1991) cannot reproduce sharper features observed in several sources. Neither method can generate asymmetric pulse profiles without resorting to an off-center magnetic axis, for which there is no other observational evidence. Recent observations of the X-ray pulsar GX 1+4 suggest a rather different scenario.

The X-ray continuum spectrum of GX 1+4 is rather flat (with photon index ≈ 1.0) up to a cutoff around 10-20 keV, above which the decay is steeper; it is one of the hardest known amongst the X-ray pulsars. Analysis of recent Rossi X-ray Timing Explorer ($RXTE$) data shows that the spectrum is generally consistent

1

with those predicted by unsaturated Comptonisation models (e.g. Galloway et al. 1999). Pulse profiles are extremely variable and typically asymmetric, often with a sharp dip forming the primary minimum (Greenhill, Galloway & Storey 1998). During a low flux episode in July 1996, the pulse profiles were found to shift in asymmetry from 'leading-edge bright' (with the maximum closely following the sharp primary minimum) to 'trailing-edge bright'. The entire observation which captured the change spanned only 34 hours, and occurred just 10 days before a short-lived transition from rather constant spin-down to spin-up and back again (Giles et al. 1999). We propose a model which seeks to explain the sharp primary minima seen in this and other sources (A 0535+262, Cemeljic & Bulik 1998; and RX J0812.4-3114, Reig & Roche 1999) and ultimately the change in the pulse profiles.

2. MODEL DESCRIPTION AND PRELIMINARY RESULTS

A Monte-Carlo code is used to generate the spectra and pulse profiles emitted by two semi-infinite homogeneous cyclindrical accretion columns of radius R_C, diametrically located on the surface of a 'canonical' neutron star of radius $R_* = 10$ km (Figure 1a).

The algorithms of Pozdnyakov, Sobol' & Syunyaev (1983) are used to draw the photon energy and direction, electron energies, and to calculate the fully relativistic (non-magnetic) cross-section for Compton scattering. Outside the accretion column, the redshift and bending of photon trajectories by the neutron star's gravity is calculated by assuming a Schwarzschild metric. We simulate a single column for both poles of the star, and generate pulse profiles for a range of geometries simultaneously.

The beam pattern and pulse profiles over a range of geometries are shown in Figure 1 b) and c). We note that when ($|i - \beta| \lesssim 45°$) the emission exhibits a strong modulation at the stars rotation period, with the primary minimum corresponding to the closest passage of the line of sight with one of the magnetic polar axes. As i and β increase the primary minimum becomes progressively narrower. When $i \approx \beta \gtrsim 50°$, a secondary minimum (from the passage of the second axis through the line of sight) is observed. The emission is beamed at an angle $> 90°$ with respect to the column axis; this corresponds to a 'fan' type beam. Emission at smaller angles is supressed as a consequence of the decreased escape probability for photons propagating along the column axis. That emission is beamed at $> 90°$ is a consequence of the gravitational light bending; this is also affected by the size of the column R_C.

Our simulations indicate that the mean spectra also depend strongly on the density of the column and the viewing geometry.

3. DISCUSSION AND APPLICATION TO X-RAY PULSARS

Since we assume a constant infall velocity v_C and neglect effects due to radiation pressure on the infalling electrons, the results described are only applicable to systems with low $\dot{M}$. Previous low-$\dot{M}$ models predict a 'pencil' rather than 'fan' beam,
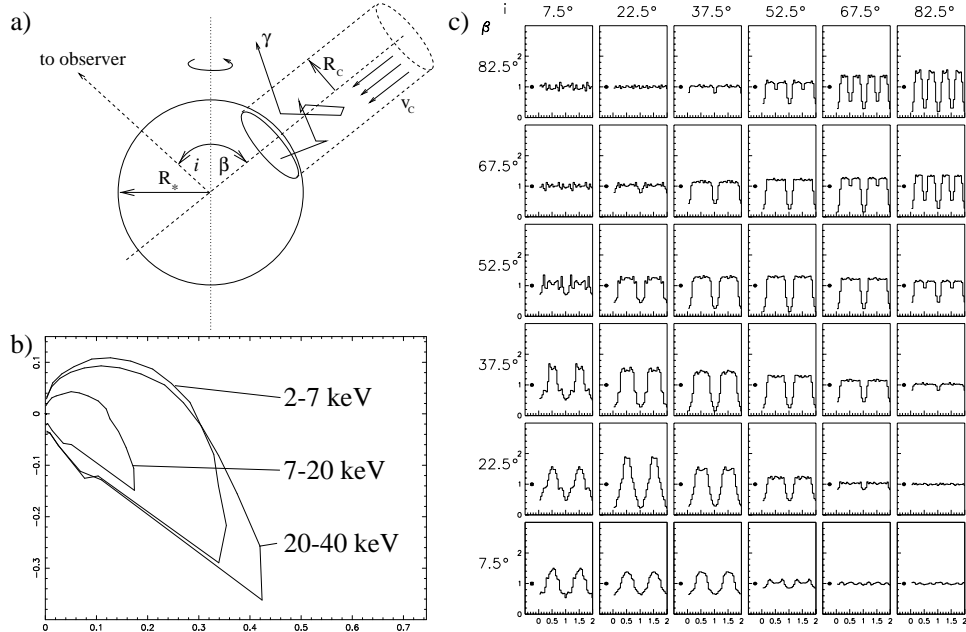
FIGURE 1. a) Model geometry (only one column shown for clarity). The magnetic axis of the star is aligned relative to the rotational axis by an angle β, with i the inclination angle of the system with respect to the observer. Photons are emitted isotropically from each (circular) polar cap, and are then Compton scattered by the column plasma before escaping towards the observer. The plasma is flowing towards the pole with speed v_C. The temperature of the polar cap T_0, temperature T_e and optical depth τ of the column plasma, and column diameter R_C are all free parameters in the model. Note that $\tau = \sigma_{\mathrm{T}} R_C N_e$ where N_e is the electron density in the column; that is, τ corresponds to photon paths from the centre of the column radially outwards. Clearly the optical depth experienced by individual photons will depend on the trajectory, and in particular with the angle relative to the column axis.

b) X-ray beam pattern within several energy bands. The model parameters are $kT_0 = 1$ keV, $kT_e = 8$ keV, $\tau = 3$, $R_C = 1$ km, and $v_C = 0.5c$; these conditions are such as to approximately correspond to those expected for a low-luminosity X-ray pulsar. The origin corresponds to the base of the accretion column, which is aligned along the (positive) y-axis. The normalisation is arbitrary.

c) Predicted pulse profiles using the same model parameters over a range of geometries. Each profile shown corresponds to a particular choice of i and β, which vary between $7.5°$ and $82.5°$ along the x- and y-axes respectively. Profiles are normalised to the mean and plotted over two cycles; a typical error bar is shown at the left of each panel.

3

with emission reaching a maximum at small angles relative to the accretion column. This is probably because of the assumed 'slab' or 'mound' shaped emission region. Interactions between photons and the inflowing material in the accretion column, which is neglected by these models, is crucial for the formation of sharp primary minima in the pulse profiles as observed in GX 1+4 and several X-ray pulsars. The persistence of the sharp feature in GX 1+4 as X-ray flux drops almost to zero points to the continued importance of this effect, even at extremely low $\dot{M}$ (Giles et al. 1999).

A significant approximation is the use of the nonmagnetic Compton scattering cross-section. For GX 1+4 - with an estimated magnetic field strength of $2 - 3 \times 10^{13}$ G (Cui et al. 1997) - deviations from the nonmagnetic cross section will be significant within typical observational bands for X-ray astronomy. However we suspect that magnetic effects may only play a minor role in shaping the pulse profile, principally narrowing the primary minimum and possibly giving rise to the local maxima ('shoulders') immediately prior to and following the minimum (Giles et al. 1999).

Finally we note that the model-predicted pulse profiles are in general quite symmetric. A possible cause of asymmetry in the observed profiles is a variation in density across the accretion column, which could potentially develop in the region where the disc plasma becomes entrained onto the magnetic field lines and persist to the neutron star surface. This effect further suggests a mechanism for the rapid changes in profile asymmetry observed in GX 1+4 (Giles et al. 1999); that is, the sense of asymmetry in the column changes and consequently so does the pulse profile. The detailed structure of the entrainment region is rather poorly understood, and we feel it is not possible to rule out such a phenomenon.

We have described a model with homogeneous, axisymmetric, cyclindrical emission regions. To explain other qualitative features of observed pulse profiles, our model needs to be modified to take into account effects due to inhomogeneities and more complicated geometry of the emission regions.

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