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A New Asymmetric Emission Model for Accreting X-ray Pulsars

D.A. Leahy[1]
[1]Dept. of Physics and Astronomy, University of Calgary, Calgary, Alberta T2N 1N4, Canada

Abstract

A new model for pulsed emission from rotating accreting neutron stars is presented. This model considers asymmetrically-filled accretion columns extending above the neutron star polar caps. The particular geometry which is modelled is expected to result from an accretion flow from a disk onto the magnetosphere of the pulsar, and is described by a few basic parameters. The model uses the local emission derived from published magnetic-radiative transfer calculations as input. The output is the x-ray pulse shape at various energies, as a function of the parameters of the polar accretion flow geometry. The emission is generally of a fan-beam type, which results from emission by the sides of the accretion column.

1 Introduction:

A binary X-ray pulsar is a rotating magnetic neutron star, which emits x-rays from a bright region on or near its surface. The energy is derived from gravitational potential energy release of matter accreted from the companion star onto the surface of the neutron star. The presence of a magnetic field around a neutron star strongly influences the accretion flow near the neutron star, and for the strong fields typical of pulsars ($B \sim 10^{12} Gauss$), the inflowing material will follow the field lines to the neutron star surface. The region which is bright in x-rays may be a thin layer, called the polar cap, near the surface, defined by the base of the field lines along which matter accretes. There are generally two polar caps: one for each magnetic pole. Or the bright region may be a significantly tall layer, called the accretion column. Since the bright region is generally optically thick, the emission from a polar cap is roughly perpendicular to the neutron star surface and is called a pencil beam, whereas the accretion column emission is roughly perpendicular to the column or parallel to the neutron star surface and is called a fan beam. However the latter will only be fan shaped if the accretion column is sufficiently similar to a cylinder normal to the neutron star surface.

For polar cap emission from the neutron star surface various calculations have been done. Meszaros & Nagel (1985) perform a radiative transfer calculation for emission by a slab of magnetized plasma, which can be used to estimate the emission from a polar cap (for the case magnetic field perpendicular to the slab) or from an accretion column (for the case magnetic field parallel to the slab). However in either case, the geometry of a flat slab does not represent the actual shape of the polar cap or the accretion column. Leahy (1990) used the results of Meszaros & Nagel (1985) for the local emission of a slab, by means of an analytic approximation, in a more complex geometry. A model for filled or annular polar caps was constructed on the surface of the neutron star, including correct viewing geometry, such as self-occultation of the emission region by the neutron star surface. The model was then fitted to the observed pulse profiles of 15 x-ray pulsars. The results required rather large polar caps compared to previous estimates. A second study (Leahy, 1991) generalized the model to two different size filled or annular polar caps which were offset from an axis passing through the center of the star and fit the model to 20 observed pulse profiles. The new model considerably improved the fits of the model pulse profiles to the observed pulse profiles. Bulik et al. (1992) used a radiative transfer calculation, instead of the analytic approximation, for the case of filled polar caps and applied it to 4U1538-52. Their results agreed with the findings of Leahy (1990) and Leahy (1991): they required rather large polar caps and significant differences between the two caps.

Riffert et al. (1993) used a similar geometry model as Leahy (1991), but simplified by assuming the two emission regions to have identical shape and size. An important new factor is that they took into account corrections from the relativistic light bending near the neutron star. They chose some specific set of cap and ring sizes to do the calculations. Their best fits to observed pulse profiles occurred with smaller sizes compared to the best fits of the nonrelativistic model of Leahy (1991). Based on these calculations, they concluded that the relativistic model is more consistent with the theoretical estimates. Leahy and Li (1995) generalized the model of Leahy (1991) to include relativistic light bending, thus giving the most physically comprehensive model to date for emission from polar caps. Fits to pulse profiles from 7 observed pulsars were carried out, and in most cases (5 of 7) the polar cap size decreased from the fits without including light bending. In addition, the pulsar EXO2030+375, which has been observed to have a pulse profile which depends on luminosity, was studied. The pulse profile changes could not be explained using the polar cap model, thus it was concluded a different pulse shape model was required, such as an accretion column model. This paper describes such an accretion column model.

2 The Accretion Column Model

A new model is described here for pulse profiles produced by accretion columns. The model includes a realistic geometry for the accretion column. The model also includes dependence of the emission spectrum on local magnetic field, and thus on position above the neutron star surface.

The general cause for the origin of the pulse shape from a rotating neutron star is as follows. Accretion results in (nearly) constant emission regions at the magnetic poles of the neutron star. The emission regions rotate in and out of the field-of-view of the observer over one rotation period of the neutron star. The geometry is illustrated in Figure 1. The model parameters for the overall geometry are: R_o - radius of neutron star; d - distance of neutron star from observer (this is important only in determining the flux level of the pulsed emission); θ_m- angle between rotation and magnetic axes; θ_r- angle between rotation axis and line-of-sight. Note that the angle θ_1 is determined by the other parameters and the rotation phase.

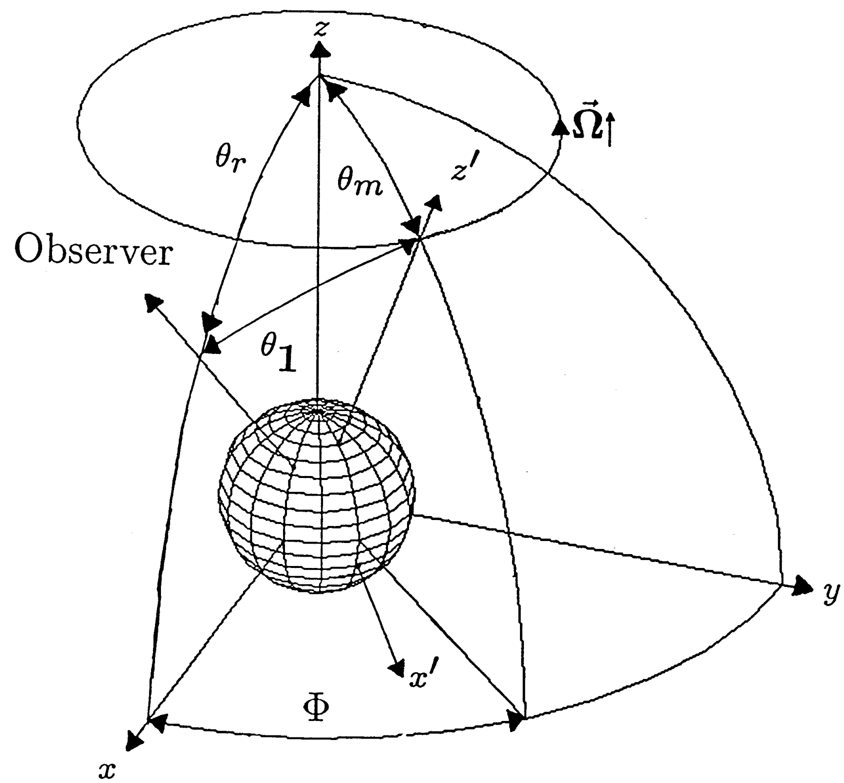

Figure 1: The orientation geometry illustrated. The magnetic field axis is the z' axis, the rotation axis is the z axis, θ_1 is the angle between the observer and the magnetic axis, θ_r is the angle between the observer and the rotation axis, θ_m is the angle between the rotation axis and the magnetic axis, and Φ is the rotation phase angle. The accretion column is centered on the magnetic axis.

The accretion flow in the magnetosphere of an accreting strongly magnetic neutron star is along magnetic field lines. These are taken to be dipolar in form here. Since the matter should be nearly in free-fall (with velocity of order 10%

of the speed of light) prior to its entry into the accretion column, it will be of very low density. When it reaches the accretion column the matter is slowed suddenly by the accretion shock and settles slowly onto the neutron star at high density. Thus matter inside the accretion column is generally optically thick and the top of the accretion column is a sharp boundary. We make the approximation that the top of the accretion column is at a constant height over the full column. The sides of the accretion column will be bounded by the magnetic field lines which separate the field lines which receive a significant amount of matter from the accretion disk from those field lines which do not. We make the simplifying assumption that these bounding field lines join the neutron star surface at a constant polar angle with respect to the magnetic axis.

The matter is channeled onto the field lines from the accretion disk but since the magnetic field for a pulsar is misaligned with the rotation axis, the matter is most likely to become attached to magnetic field line nonuniformly with respect to magnetic azimuth. In the model here, this effect is approximated by having an accretion column which covers only a finite range of azimuth about the magnetic axis. The asymmetry in observed pulse profiles indicates that the field is not a pure magnetic dipole or that the dipole axis is offset from the center of the neutron star. Thus the model here allows for the magnetic pole for the second accretion column to be offset from the line through the first magnetic pole and the center of the neutron star.

Figure 2 illustrates the resulting accretion column geometry. The two accretion columns have the following parameters: θ_o - polar angle of the base of the accretion column (at surface of neutron star); θ_{off} - polar angle offset of the axis of the second accretion column; ϕ_{off} - azimuthal angle offset for the axis of the second emission region; $\varphi_o^{(1)}$ lower limit of azimuthal angle for the first emission region; $\varphi_o^{(2)}$ - lower limit of azimuthal angle for the second (offset) emission region; $\varphi_L^{(1)}$ - angular extent of the first emission region in azimuth; $\varphi_L^{(2)}$ - angular extent of the second emission region in the azimuth; $R_L^{(1)}$ - radial height of the first emission region; $R_L^{(2)}$ - radial height of the second emission region.

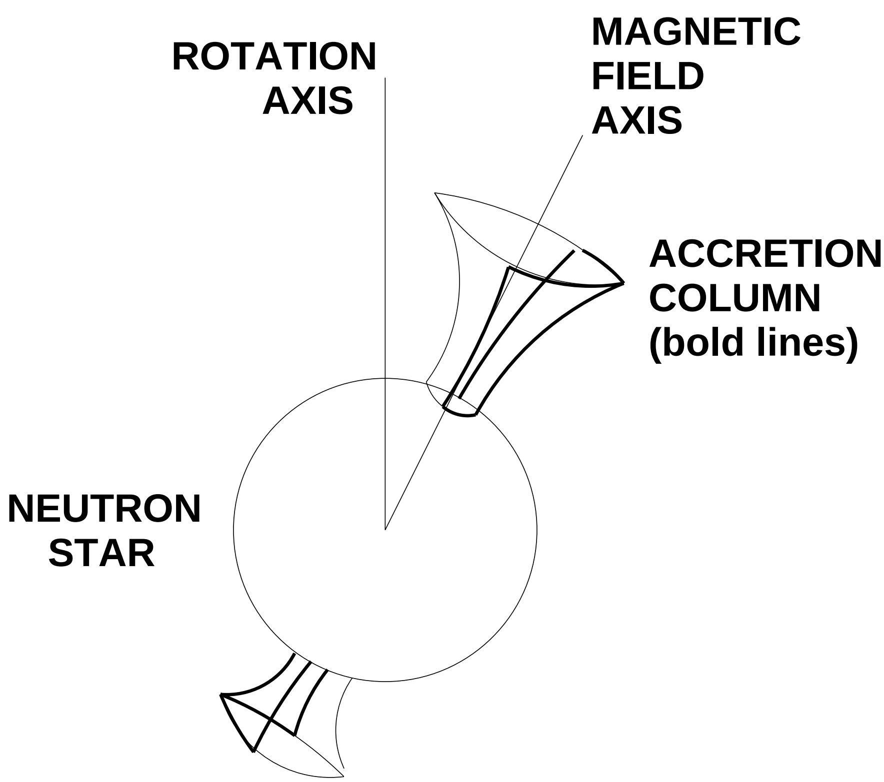

Figure 2: The accretion column geometry illustrated. The boundaries of the column are dipole field lines, the surface of the neutron star and a maximum altitude above the surface. There is an accretion column at each magnetic pole, and the sizes of the two columns can be different.

The model here calculates the angle and frequency (i.e. energy) dependence of the radiation from any given surface element of the accretion column. Meszaros & Nagel (1985) have performed numerical calculations of radiation transfer in magnetized plasmas for slab geometry with magnetic field parallel to the surface, which is used to approximate the emission from the side of an accretion column. They calculated the angle and frequency dependence of emission from an optically-thick slab of density ρ=0.50 g cm^{-3}, temperature kT=8.0 keV, and optical depth $5 \cdot 10^4$ g cm^{-2}. For the model here, their intensity distribution was cubic-spline fitted in two dimensions (angle and frequency). Their emission calculation scales with magnetic field. The scaling is incorporated here, in order to account for the changing spectrum and angular dependence of the emission with magnetic field. This translates into a change of emission with height, due to the decreasing magnetic field of the magnetic dipole field.

The above describes briefly the geometry of the emission surface, and also what is needed to calculate the emission from any surface element of the accretion column. For each rotation phase angle of the neutron star one can integrate over the entire surface of the emission region, including for each surface element only those light rays that reach the observer. In this way effects due to occultation of parts of the emission region either by the neutron star or other parts of the emission region can be correctly taken into account. Finally, one would like to be able to take a model pulse profile, which depends on a number of parameters, and vary the parameters in order to fit the model to an observed pulse profile. The current model includes a non-linear least-squares fitting routine and allows this to be done. The model has also been tested for a number of test cases and verified to yield the correct results.

3 Discussion

A model for accretion column emission has been developed which incorporates realistic geometry and emission physics. This includes: correct calculation of ray paths from emission region to observer; partially filled accretion columns which are bounded on the sides by dipole magnetic field lines; accretion columns at the "north" and "south" magnetic poles which have different boundaries in height and different boundaries in magnetic azimuth (due to different accretion rates onto the two poles and different threading of the matter onto the magnetic field out in the accretion disk); a dipole axis which is offset from the center of the neutron star; a variable emission spectrum depending on the local value of magnetic field.

Currently the numerical implementation of the model has been tested for correctness. The next phase is applying the model to observed pulse shapes. Due to lack of space the preliminary results are not presented here. However, this model does appear promising. A key test of this model (and any pulse shape model) is whether it can provide a simple explanation for pulse shape changes observed for a single pulsar, such as those associated with luminosity changes.

References

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