The Influence of Reprocessing in the Column on the Light Curves of Accretion Powered Neutron Stars

Miljenko Čemeljić and Tomasz Bulik
Nicolaus Copernicus Astronomical Center, Bartycka 18, 00-716 Warszawa, Poland

ABSTRACT

Flow of matter onto strongly magnetized neutron stars in X-ray binaries proceeds through accretion funnels that roughly follow geometry of the magnetic field. X-rays originate near surface of the neutron star, and it may happen that the accretion flow passes through the line of sight as the star rotates. We consider the effects of such accretion flow eclipses on the X-ray light curves of accretion powered pulsars, and present a set of X-ray light-curves measured by BATSE for A0535+262 for which this phenomenon is very likely to take place.

1. Introduction

X-ray binary systems have been observed and analyzed since early 1970. They are powered by accretion from a companion star onto a compact object: neutron star or black hole. In this paper we concentrate on a subclass of these sources, namely high mass X-ray binaries. Here, the spin period of a neutron star is in the range from about less than one second to a couple hundred seconds [White, Nagase & Parmar 1995]. Neutron stars are believed to have strong magnetic fields, in the range of $10^{12}$ Gauss for a number of reasons. First, lines have been discovered in the spectra of some objects at the energies of 5 to 60 keV (one object, A0535+262, even has a possible line feature at 110 keV) and interpreted as cyclotron scattering lines. Second, the existence of a short pulse period indicates anisotropy on the surface of the star, which is most likely due to strong magnetic field. Since spin periods of these objects are rather long, typically from ten to even hundreds seconds, the magnetospheric radius must be large and therefore field is quite strong, or else the star would have been spun up to much shorter pulse period. The distribution of magnetic field strength measured by cyclotron lines overlaps with that of the radio pulsars magnetic fields measured by the spindown [Mihara 1995].

In these systems matter is transferred from the companion star either through the stellar wind, or also possibly in some systems through the Roche lobe overflow. An accretion disc may be formed around a neutron star, however
inside the magnetospheric radius, flow of matter is guided by the magnetic field. As matter hits the surface of the neutron star, the kinetic energy in the flow is transformed into radiation and X-rays are produced. Radiation from the neutron star surface have been modeled by a number of authors using different approaches to solve the radiative transfer in a strongly magnetized medium. Nagel and Mészáros (1985) have used the finite difference method, and their approach was later improved by Alexander and Mészáros (1991) who included the effects of higher harmonics. Bulik et al. (1995) used a similar technique and solved for the hydrostatic equilibrium with the inclusion of the effects of radiation pressure, as well as some temperature corrections in the atmosphere. Another method of solving the radiative transfer - the Monte Carlo simulations - has been used in by Wang, Wasserman and Lamb (1993), Araya & Harding (1996), however these approaches have only been able to treat very small optical depths for computational reasons. Recently this difficulty has been overcome by Isenberg, Wang and Lamb (1997) who calculated a number of cases with optical depth $\tau_T$ up to a few. This model atmospheres have been used as an input in modeling of the light curves of rotating accretion powered pulsars. The free parameters in these models are the geometry of the rotation, magnetic field, and the position of the observer with respect to the system (Bulik et al. 1992, Bulik et al. 1993).

Most of the models of the light curves of accretion powered pulsars have neglected the interaction with the accretion column. However the typical density in the column is $\approx 10^{19}$ cm$^{-3}$ at its base and the direction to the observer may happen to be close to the direction along the column. Thus, for some objects interaction with the matter in the accretion column may be important for the formation of the light curves. In section 2 we present a model of emission from a neutron star and calculate the effects of the accretion column. In section 3 we calculate some representative light curves and compare them observations of light curves of A0535+262 in a giant outburst in 1994. Finally, we summarize and discuss our results in section 4.

## 2. Radiative Transfer in the Column

Our model of emission from a neutron star follows the models described elsewhere e.g. Bulik (1995). The geometry of emission is shown in Figure 1. The angle between the direction to the observer and the neutron star rotation axis is $\Theta$, and the angle between the magnetic axis and the rotation axis is denoted by $\beta$. It should be noted that in general the two polar caps do not have
to lie opposite one another, as has been already shown (Bulik et al. 1992, Bulik et al. 1995). However, in this work we will consider only a simplified model with a single value of $\beta$. The angular sizes of the accretion caps are denoted by $\delta$. In this paper we ignore the general relativistic effects (gravitational light deflection in strong gravitational field) which affect the shape of the light curves. Observationally little is known about the shape of the accretion column. It depends on the exact mechanism of how matter latches onto the magnetic field lines on the edge of the magnetosphere and also on the geometry of the magnetic field in the neighborhood of the neutron star. The accretion flow may have a geometry of a hollow column, or a fraction of such (Basko and Sunyaev 1977), or a filled column. Regardless of the details, we can say that there must exist a range of lines of sight for which the observer will look close to the direction along the accretion column. If the column is bent then there are directions in which the column passes through the line of sight to the observer, for some observing directions. In these directions a significant reprocessing of the underlying radiation will be very likely to occur and dips in the light curve, similar to eclipses, will take place.

We use a detailed model of the X-ray emission from accretion-powered pulsars (Bulik et al. 1992, Bulik et al. 1995). The radiative transfer equation is solved using a first order difference scheme and we impose the condition of hydrostatic equilibrium on the model atmosphere. Calculation of the radiation pressure includes the effects of resonant scattering and is coupled to the radiative transfer equation. The code can incorporate various energy release profiles in the atmosphere and the final solution satisfies the condition of radiative equilibrium. We will not go into further details of the code, and we will denote the intensity at the surface of the radiating cap as $I(\omega, \mu)$, ($\omega$ is the frequency and $\mu$ is the cosine of the angle of propagation with respect to the magnetic field).

In order to evaluate the relevant radiative processes for the radiative transfer in the column we need to determine the physical conditions that prevail there. The density can be estimated as the free fall density of matter

$$n = 1.3 \times 10^{19} L_{37} R_{6}^{1/2} A_{10}^{-1} \left( \frac{M_{\odot}}{M} \right) f^{-1} \text{cm}^{-3}$$

(1)

where $L = 10^{37} \text{ erg s}^{-1}$ is the luminosity, $R = 10^{6} R_{6} \text{ cm}$ is the radius of the neutron star, $A = 10^{10} A_{10} \text{ cm}^{2}$ is the area of the accreting cap, $M$ is the mass of the neutron star and $f$ is the radiative efficiency. The density will changes as the matter moves along the column. Two effects play a role here: on one hand as the matter accelerates its density decreases. On the other hand as matter
approaches a neutron star the field lines are increasingly squeezed and this also increases the density in the flow.

The accreting material consists primarily of hydrogen which will be ionized. We assume that the magnetic field is dipolar, which should hold pretty well in the region above the neutron star up to the edge of the magnetosphere. Thus the value of the field falls down as $B \approx B_{\text{surf}} \times (R_{*}/R)^3$, where $R_*$ is the stellar radius. Note that near the surface the field geometry may well be modified. Since we consider a region only a fraction of the star radius above the surface, the magnetic field in the column is a small factor smaller than that at the surface. The ratio of the free-free absorption cross section is \cite[e.g.][]{Bulik1997}

$$\frac{\sigma_{\text{abs}}}{\sigma_{\text{scat}}} \approx 5.7 \times 10^{-7} n_{19} T_6 \omega^{-3}_{10}$$

where $n = 10^{19} n_{19}$ cm$^{-3}$ is the density, $T = 10^6 T_6$ K is the temperature, and $\omega = 10 \omega_{10}$ keV is the photon energy. Thus in the range of interest the opacity will be dominated by the scattering. The scattering cross section depends on the polarization of a photon and the direction of propagation with respect to the magnetic field. Since most of the emission from a magnetic cap is in the extraordinary mode, we will only consider the E-mode cross section, which can be approximated by

$$\frac{\sigma_E}{\sigma_T} \approx \left( \frac{\omega}{\omega + \omega_c} \right)^2,$$

where $\omega_c = eB/mc$ is the electron cyclotron frequency. The optical depth through the column in the E-mode is

$$\tau = 1.09 L_{37} R_{6}^{1/2} A_{10}^{-1/2} f^{-1} \left( \frac{\omega}{\omega + \omega_c} \right)^2.$$  

Here we do not consider the details of the cross sections in the neighborhood of the electron cyclotron resonance as far as the reprocessing is concerned. It must be stressed, however, that the cyclotron resonance is included in the calculation of the underlying radiation from the accretion cap. Thus the column is optically thin for most of the parameter space, especially for strongly magnetized sources.

As a neutron star rotates we see the accretion caps at an angle $\Theta$ which changes as

$$\cos \theta(\varphi) = \cos \Theta \cos \beta + \sin \Theta \sin \beta \cos \varphi$$

where $\varphi$ is the phase of the rotation. The light curves is thus described by

$I(\omega, \varphi) = I(\omega, \mu_1(\varphi)) + I(\omega, \mu_2(\varphi))$, where $\mu(\varphi)$ are the cosines of viewing angles for the two accretion caps, and are given by equation \cite[5]. In order to calculate
the effects of the column eclipses we must know how the optical depth through
the column depends on the observed phase, i.e. the function \( \tau(\varphi) \). The observed
light curves with the inclusion of the effects of reprocessing in the column will
be given by

\[
I(\omega, \varphi) = I(\omega, \mu_1(\phi)) \times \exp[-\tau_1(\varphi)] + I(\omega, \mu_2(\varphi)) \exp[-\tau_2(\varphi)]
\]

and we ignore the scattered radiation. We approximate the unknown functions
\( \tau(\varphi) \) by Gaussian

\[
\tau(\varphi) \propto \exp\left[-\left(\frac{\varphi - \varphi_0}{\sigma}\right)^2\right].
\]

Thus the model for the observed light curves is as follows. Accreted matter
is funneled from the disc onto the surface of the neutron star by the strong
magnetic field. We model the emission from the magnetic polar cap using the
radiative transfer code described elsewhere (Bulik et al. 1995). The geometry
allows us to see either one or two polar caps. However, the funnel of the accreted
matter crosses our line of sight once every rotational period, and causes the
additional strong dip in the light curve. The parameters of the model are the
angles that describe the geometry and those describing the physical conditions
of the emitting region: the angle between the rotation axis and the line of sight, the
angle between the rotation axis and the position of the magnetic polar cap,
the phase at which the absorption by the accretion funnel occurs.

3. The Light Curves

In order to visualize the effects of the reprocessing in the column we calculate
a couple of representative light curves. We assume that the underlying emission
from the accretion cap is characterized by the temperature \( kT = 8.1 \) keV,
and the surface magnetic field with cyclotron energy \( h\omega_C = 55 \) keV. Energy
considered in this model is of the 20-30 keV band. In the simulations we ignore
the extent of the accretion caps and also neglect the general relativistic effects.
Such an approach provides only simplified light curves that should not be used
for detailed fits, however here we concentrate on the reprocessing of radiation in
the column.

The shape of the light curve depends strongly on the geometry of viewing
with respect to the system. As a first example we consider the case when the
accretion flow is curved toward the rotation axis, see Figure 2. We assume
that the angle between both magnetic and rotation axis is \( \beta = 45^\circ \), and we
present the light-curves for three different viewing angles \( \Theta = 15^\circ, 30^\circ, \) and
65°. In the first case only one accretion cap is seen, and no reprocessing in
the accretion column occurs since the accretion flow does not cross the line of
sight. In the second case we still see only one accretion cap, however, the line
of sight is crossed by the accretion flow. These results in the dips in the light
curves that produces a double peaked profile. For clarity we also show with a
dashed line a profile that would be obtained if the accretion flow was ignored.
Here we assumed that the column density of the accretion flow is $3 \times 10^{24} \text{cm}^{-2}$,
the phase at which the absorption by the accretion funnel occurs $\phi = 330^\circ$. It
has to be stressed that the depth of the dips is a very sensitive function of the
column depth. Finally, we show the case when the observing direction is such
that two accretion caps are visible, and the accretion flow does not cross the
line of sight. The light curve has two broad symmetric peaks corresponding to
seeing two accretion caps.

The second example set of light curves is shown in Figure 3 where we present
the case when the accretion flow is bent towards the equatorial plane. Here we
also show three light curves for three different viewing angles $\Theta = 25^\circ$, $60^\circ$, and
$85^\circ$. In the first case the light curve is similar to the top panel in Figure 2.
In the second case, we observe two accretion caps, however the accretion flow
interferes with the radiation from one of them. This results in a triple peaked
profile, where the larger peak is split because of the scattering of radiation when
the accretion flow passes through the line of sight. The last case, when the
observer is located nearly perpendicular to the rotation axis, leads to a double
peaked profile, and there are no effects of reprocessing in the light curve. The
position of the ”accretion flow eclipse” dip with respect to the pulse center is
a measure of bending of the accretion flow. The larger the difference in phase
between the pulse center and the dip, the more the flow is bent.

It has to be stressed that the sharp drops in a number of light curves
presented here are not physical. In reality they will be smoothed because of the
gravitational light bending, as well as the finite extent of the emission regions
on the surface of a neutron star.

3.1. Light Curves of A0535+262

As a very tempting example of a possible application of the formalism we
present the BATSE observations of a binary pulsar A0535+262. The binary
pulsar A0535+262 has been discovered by Ariel V satellite (Rosenberg et al.
1975, Coe et al. 1975), and the companion star has been identified as a Be star
(Liller 1975). The binary period has been estimated to be $\approx 111$ days from the
frequency of X-ray outbursts (Nagase et al. 1982). This result was later refined to 111.38 ± 0.11 days (Motch et al. 1991), and the full orbit was found using the BATSE observations (Finger et al. 1994). The rotational period of the neutron star is 103.54 s (Coe et al. 1990). The intensity of the X-ray outbursts varies and has been classified based on the flux in the 2-10 keV band. It is denoted as ”giant”, when these flux reaches above 1 Crab, ”normal” when it is below 1 Crab, and ”missing” when only the quiescent flux, 5-10 mCrab is measured. Only four ”giant” outbursts have been observed so far: in 1975, 1980, 1984, (Giovannelli & Graziati 1992), and in 1994.

The X-ray spectrum is thermal and has been modeled as an exponential with $kT \approx 17$ keV (Hameury et al. 1983), or a blackbody or Wien with $kT \approx 8 - 9$ keV (Frontera et al. 1985, Dal Fiume et al. 1988). Analysis of the HEXE observation showed a presence of two harmonically spaced lines (Kendziorra et al. 1992, Kendziorra et al. 1994) at 55 keV (with low significance) and a highly significant line at 110 keV which were interpreted as cyclotron scattering lines. Recently, OSSE observed A0535+262 (Grove et al. 1995) and confirmed the existence of a line at 110 keV, at the same time finding no evidence of the line at 55 keV. A further analysis of the data showed that the model with 110 keV line as the fundamental is preferred by the data (Araya & Harding 1996). Thus, the value of the field can either be $\approx 5 \times 10^{12}$ Gauss or $\approx 10^{13}$ Gauss.

BATSE detected a giant outburst from A0535+262 in February and March 1994 (Finger et al. 1996), and triggered a target of opportunity observation by OSSE (Grove et al. 1995). The outbursts was detectable by BATSE over an interval of 52 days. We should note that BATSE provides a unique opportunity of almost constant monitoring of an outburst over a time of next to two months. Over this time the source changed the flux by a factor of more than 30. The BATSE experiment can monitor the intensity of the source using the occultation technique, and also the light curves folded with the pulse period using the pulsar mode. A number of such observations have been performed during the outburst.

The pulse shapes of A0535+262 in different X-ray bands for four luminosity states are presented in Figure 4. The light curves are double peaked except for the lowest luminosity state, where the light curve is very noisy. The two peaks are divided by a rather narrow dip with the depth and width varying depending both on the luminosity and on the spectral band. The light curves vary substantially from one spectral band to another as expected for radiation from a rotating, strongly magnetized source.

We present a set of simulated light curves for this set of observations. In
this particular calculations we assumed that the angle between the rotation axis and the line of sight is \( \theta = 25^\circ \), the angle between the rotation axis and the magnetic axis is \( \beta = 15^\circ \). The temperature of the magnetic cap is estimated assuming a blackbody radiation from the area of \( 10^{10} \text{cm}^2 \). We obtain \( T = 4.5, 6.3, 8.1 \) and \( 9.5 \) keV for the luminosities of \( L = 0.4 \times 10^{37}, 1.6 \times 10^{37}, 4.5 \times 10^{37} \) and \( 9.1 \times 10^{37} \) erg s\(^{-1} \) respectively. We alter the temperature of the underlying continuum radiation with the increasing luminosity and we also change the density in the column as the luminosity (and consequently the accretion rate) changes. The results of this qualitative comparison are shown in Figure 4. The detailed fits of the model to the data are currently under way, here we want to stress a qualitative similarity of the simulated and observed light curves for a wide range of luminosities and spectral ranges.

4. Summary

We have analyzed the influence of reprocessing of radiation when the accretion flow crosses the line of sight in the accretion powered pulsars. Some simulated light curves for different positions of the observer and the source geometry are presented. We find that in some cases, perhaps about 10% of the sources, reprocessing of the radiation in the accretion column may play a significant role. There are a few dozen currently known high mass X-ray binaries so we expect a few sources where such an effect can be seen.

This opens a very exciting possibility for studying such sources; the radiation from the accretion cap can serve as a beacon that shines through the accretion column and allows to probe the conditions there. Objects that can be observed for different accretion rates are the best case for such a study. As the accretion rate changes the conditions in the accretion column change and they can be probed through analysis of the light curves. Observations of the underlying continuum, especially if a cyclotron line is present in their spectrum, provide very strong constraints on the geometry of the system, e.g. the inclination of the magnetic axis, and the position of the observer (Bulik et al. 1992, Bulik et al. 1995). The spectral analysis of the pulse resolved spectra may yield the density, temperature, and possibly the strength of the magnetic field in the column. One can also learn about the geometry of the column by combining the information of the pulse resolved fits of the underlying emission from the cap with the analysis of the accretion flow dips in the pulses.

A good candidate for such analysis is presented here. A transient pulsar A0535+262 has been observed by many satellites. It undergoes outbursts of
different strength, and its pulse shape has a dip that is consistent with the interpretation as "accretion flow eclipses".

This work has been funded by the KBN grant 2P03D00911.

REFERENCES

Alexander, S., Mészáros, P., 1991, ApJ, 372, 545
Araya, R. A. and Harding, A. K., 1996, ApJ, 463, L33
Basko, M. M., Sunyaev, R. A., 1975, MNRAS, 175, 395
Bildsten, L. et al., 1997, ApJ. Supp., submitted
Bulik, T., Meszaros, P., Woo, J. W., Nagase, F., and Makishima, K., 1992, ApJ, 395, 564
Bulik, T., Riffert, H., Meszaros, P., Makishima, K., Mihara, T., and Thomas, B., 1995, ApJ, 444, 405
Bulik, T., Miller, M. C., 1997, MNRAS, 288, 596
Coe, M. J., Carpenter, G. F., Engel, A. R., and Quenby, J. J., 1975, Nature, 256, 630
Coe, M. J., Carstairs, I. R., Court, A. J., Davies, S. R., Dean, A. J., Dipper, N. A., Lewis, R. A., Perotti, F., Quadrini, E., Bazzano, A., Ubertini, P., and Stephen, J. B., 1990, MNRAS 243, 475
Dal Fiume, D., Frontera, F., and Morelli, E., 1988, ApJ, 331, 313
Finger, M. H., Cominsky, L. R., Wilson, R. B., Harmon, B. A., and Fishman, G. J., 1994, in AIP Proc. 308, The Evolution of X-ray Binaries, p. 459
Finger, M. H., Wilson, R. B., and Harmon, B. A., 1996, ApJ, 459, 288
Frontera, F., Dal Fiume, D., Morelli, E., and Spada, G., 1985, ApJ, 298, 585
Giovannelli, F. and Graziati, L. S., 1992, Space Science Reviews 59, 1
Grove, J. E., Strickman, M. S., Johnson, W. N., Kurfess, J. D., Kinzer, R. L., Starr, C. H., Jung, G. V., Kendziorra, E., Kretschmar, P., Maisack, M., and Staubert, R., 1995, ApJ, 438, L25
Hameury, J. M., Boclet, D., Durouchoux, P., Cline, T. L., Teegarden, B. J., Tueller, J., Paciesas, W. S., and Haymes, R. C., 1983, ApJ, 270, 144
Isenberg, M., Wang, J. C., Lamb, D. Q., 1997, ApJ, in press.
Kendziorra, E., Kretschmar, P., Pan, H. C., Kunz, M., Maisack, M., Staubert, R., Pietsch, W., Truemper, J., Efremov, V., and Sunyaev, R., 1994, A&A, 291, L31

Kendziorra, E., Mony, B., Kretschmar, P., Maisack, M., Staubert, R., Doebereiner, S., Englhauser, J., Pietsch, W., Reppin, C., and Truemper, J., 1992, in NASA. Goddard Space Flight Center, The Compton Observatory Science Workshop, p. 217

Liller, W., 1975, IAU Circ. 2784

Mihara, T., 1995, PhD thesis, University of Tokyo

Mészáros, P., Nagel, W., 1985, ApJ, 298, 147.

Motch, C., Stella, L., Janot-Pacheco, E., and Mouchet, M., 1991, ApJ 369, 490

Nagase, F., Hayakawa, S., Kunieda, H., Makino, F., Masai, K., Tawara, Y., Inoue, H., Kawai, N., Koyama, K., Makishima, K., Matsumoto, M., Murakami, T., Oda, M., Ogawara, Y., Ohashi, T., Shibazaki, N., Tanaka, Y., Miyamoto, S., Tsunemi, H., Yamashita, K., and Kondo, I., 1982, ApJ, 263, 814

Rosenberg, F. D., Eyles, C. J., Skinner, G. K., and Willmore, A. P., 1975, Nature 256, 628

Wang, J. C. L., Wasserman, I. Lamb, D. Q. 1993, ApJ, 414, 815

White, N. E., Nagase, F., Parmar, A. M., 1995, in ”X-Ray Binaries”, eds. Lewin, W. H. G., van Paradijs, J., van den Heuvel, E. P.J., Cambridge University Press.

---

This preprint was prepared with the AAS Li\TeX\ macros v4.0.
Fig. 1.— Geometry of emission from a rotating neutron star.
Fig. 2.— The upper left panel shows a sketch of the neutron star and the accretion flow bending toward the rotation axis. The panels show light curves for three orientations of the observer in relation to the system, $\Theta = 15^\circ$ (upper right panel), $\Theta = 30^\circ$ (lower left panel), and $\Theta = 65^\circ$ (lower right panel).
Fig. 3.— The upper left panel shows a sketch of the neutron star and the accretion flow bending toward the equatorial plane. Three panels show light curves for three orientations of the observer in relation to the system, $\Theta = 25^\circ$ (upper right panel), $\Theta = 60^\circ$ (lower left panel), and $\Theta = 85^\circ$ (lower right panel).
Fig. 4.— The top panel shows light curves of A0535+262 obtained by BATSE (Bildsten et al. 1997) folded with the pulse period. Columns correspond to four luminosity states when A0535+262 was observed and are labeled accordingly. Rows show light curves in three hard X-ray bands. The light curves are plotted relative to the mean rate. The bottom panel shows simulated light curves of A0535+262. Geometry of emission is identical in the simulations for all four luminosity states, while the accretion rate (or temperature of the emitting region) is varied. The surface magnetic field is $\hbar \omega_B = 110$ keV. Dashed lines show the light curves when no absorption by the accretion funnel is taken into account, and solid lines show the light curves with absorption included.