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The X-ray Intensity-Hardness Ratio Relation in LMXRB

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Abstract. It is sometimes suggested that the change from the horizontal to the normal branch in the X-ray intensity-hardness ratio diagram of low mass X-ray binaries, is due to a change from a thin to a thick disk. It is shown here that wind from the hot thick disk depletes the amount of matter reaching the neutron star, thus causing the observed reduction of X-ray intensity as hardness ratio decreases in the normal branch.

Key words: X-rays—binary system—accretion disk

1. Introduction

One of the intriguing results of observations of the low mass X-ray binaries (LMXRB) by the EXOSAT satellite is the behaviour of the hardness ratio (defined as the ratio of X-ray intensity in a given energy band to that in a lower energy band) with respect to X-ray intensity (Hasinger 1987 and references therein). In a diagram of these two quantities, the locus of the hardness ratio variation forms a Z-pattern in general. In the top portion of the Z, the ratio is nearly constant and is termed the horizontal branch (HB). The ratio then decreases forming the cross-line and is termed the normal branch (NB). The ratio again picks up and increases and this branch is termed the flaring branch (FB).

It is generally believed that the accretion rate of matter ($\dot{M}$) that enters the disk around the neutron star increases continuously as one goes from HB to NB to FB (Hasinger 1987). This then leads to the consequence that in the NB, the X-ray emission decreases, even while $\dot{M}$ into the disc increases. Priedhorsky (1986) suggested that the emitted X-ray energy is derived from a combination of energy due to accretion of matter and dissipation of energy of rotation of the neutron star; this has a minimum during the transition from HB and FB leading to the inverse relation between the hardness ratio and X-ray intensity in the NB. By comparing the time spent by a system in each of the branches, Hasinger, Priedhorsky & Middleditch (1989) find that the above suggestion “may no longer be tenable”. Apparao & Tarafdar (1992) take note of the formation of a hot corona above the inner regions of the accretion disk; they then suggested that as $\dot{M}$ increases the region of the disk over which a corona forms increases. They suggested that a wind emanates from the corona, thus depleting the gas reaching the neutron star, leading at some $\dot{M}$ to the inverse relation referred above. However, their calculation of the amount of wind was based on an empirical model of the corona, as no theoretical calculation of the structure of the corona as a function of height above the disk exists at various distances from the neutron star.

It was suggested (Hasinger, Priedhorsky & Middleditch 1989) that the change from the HB to NB can occur when the accretion disk changes from a thin to a thick disc. As $\dot{M}$ increases, the thin disk indents the magnetic field lines near the boundary until at some $\dot{M}$, instabilities force the disk to become thick in the inner regions. The structure of this two temperature thick disk was studied by Shapiro, Lightman & Eardley (1976). This thick disk has a high temperature. We suggest that due to the high temperature, a wind emanates from the surface of the thick disk which depletes the gas accreting on to the neutron star ($\dot{M}_{NS}$). This results in the decrease of the intensity of emitted X-rays in the normal branch even as M increases.

In section 2, using the results of Shapiro, Lightman & Eardley (1976), we calculate the value of the wind ($\dot{M}_W$) at the value of $\dot{M}$ at which the thick disk forms. In section 3, we discuss the result.

2. Wind from a thick disk

Thorne & Price (1975) argued that the instability present in the inner regions of an accretion disk (Lightman & Eardley 1974) can blow it up to form a thick disk. Shapiro, Lightman & Eardley (1976) found that this leads to a two temperature thick disk in the inner regions. By assuming that the gas pressure dominates in this hot region and that the gas is optically thin to radiation absorption, they worked out the structure of the thick disk. The solutions of the various equations considered lead to the following expressions for the density ρ, height of the disk h, gas pressure P, T_e the electron temperature and T_i the ion temperature:

$$\rho = (5 \times 10^{-5}\,\mathrm{g\,cm^{-3}}) M_*^{-3/4} \dot{M}_*^{-1/4} I^{-1/4} r_*^{-9/8} \alpha^{3/4} \tag{1}$$

$$h = (1 \times 10^{5}\,\mathrm{cm}) M_*^{7/12} \dot{M}_*^{5/12} I^{5/12} r_*^{7/8} \alpha^{-7/12} \tag{2}$$

$$P = (2 \times 10^{15}\,\mathrm{dyn\,cm^{-2}}) M_*^{-19/12} \dot{M}_*^{7/12} I^{7/12} r_*^{-19/8} \alpha^{-5/12} \tag{3}$$

$$T_e = (7 \times 10^{8}\,\mathrm{K}) (M_* \dot{M}_*^{-1} I^{-1} \alpha^{-1})^{1/6} r_*^{1/4} \tag{4}$$

$$T_i = (5 \times 10^{11}\,\mathrm{K}) M_*^{-5/6} \dot{M}_*^{5/6} I^{5/6} r_*^{-5/4} \alpha^{-7/6} \tag{5}$$

Here $M_* = M/3M_\odot$, $\dot{M}_* = \dot{M}/10^{17} gs^{-1}$ $r_* = r/(GM/c^2)$, and $I = 1-(6GM/\ rc^2)^{1/2}$, with r the distance from the centre and M the mass of the central object. G is the gravitational constant and c the velocity of light. α is the factor corresponding to the viscosity law in the accretion disk (see Shapiro, Lightman & Eardley 1976). We have taken the mass of the neutron star as $1M_\odot$ to give $(GM/c^2) = 1.49 \times 10^5$ cm.

In the case of a neutron star with a magnetic field, the accretion disk is stopped by the field at a distance r_* given by

$$r_* = 2 \times 10^3 \dot{M}_*^{-2/7} \mu_{30}^{4/7} \tag{6}$$

where μ_{30} is the magnetic moment of the neutron star in units of 10^{30} gauss cm^3. Neutron stars in low mass X-ray binaries are thought to have substantially lower values of the magnetic field canonical than the value of 10^{12} gauss.

The condition for the instability to blow the thin cool disk into a thick disk is (Shapiro, Lightman & Eardley 1976),

$$r_*^{21/8} I^{-2} \approx 10^4 M_*^{-7/4} \dot{M}_*^2 \alpha^{1/4} \tag{7}$$

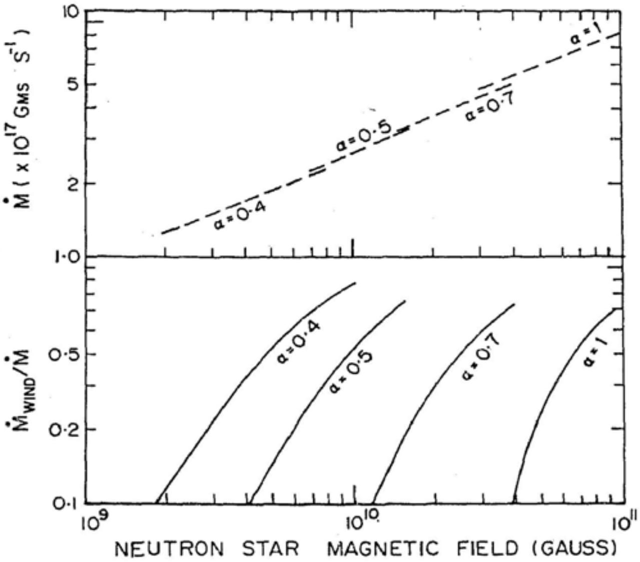

Figure 1. The top panel shows the accretion rate for a given magnetic field of the neutron star for different values of the viscosity parameter α. The bottom panel shows the ratio of wind from the thick disk to the accretion rate M for a given α and magnetic field.

Expressions (6) and (7) can be used to obtain $\dot{M}_*$ and r_* for a given μ_{30} and α; the dependence on α is very weak. The value of M for different values of α and magnetic field corresponding to different values of μ_{30} are plotted in Fig. 1.

The expression for mass loss by wind from a sphere of hot gas without rotation was given by Tarafdar (1988) and is

$$\dot{M}_{\mathrm{NR}} = \pi \frac{e^{3/2}(GM)^2(1-\Gamma)^2}{C_s^3} \rho \exp\left[-\frac{GM(1-\Gamma)}{rC_s^3} \right] \tag{8}$$

where ρ and C_s are the density and sound speed respectively at the surface from which wind is emanating. This value is for a spherical surface of radius r. Γ is given by

$$\Gamma = \frac{\kappa L}{4\pi c GM} \tag{9}$$

when k is the absorption cross-section in cm^2 g^{-1}, L is the luminosity of the underlying star and c the velocity of light. For the value of L we will use the X-ray luminosity implied by the accretion rate. The wind from the disc is

$$\dot{M}^{\mathrm{D}}_{\mathrm{NR}} = \beta \dot{M}_{\mathrm{NR}} \tag{10}$$

where β is the fraction of the spherical surface of radius r which the disk occupies. β can be obtained by calculating h from (2) and using M_* and r_* for a given μ_{30}.

The value for the wind from the disc (10) was however obtained for the non-rotation case. In fact the gas in the disc is rotating at the Keplerian rate. The case of wind from rotating gas was considered by Marlborough & Zamir (1984), Friend & Abbott (1986) and Poe & Friend (1986). In all the cases they find that the wind in the rotation

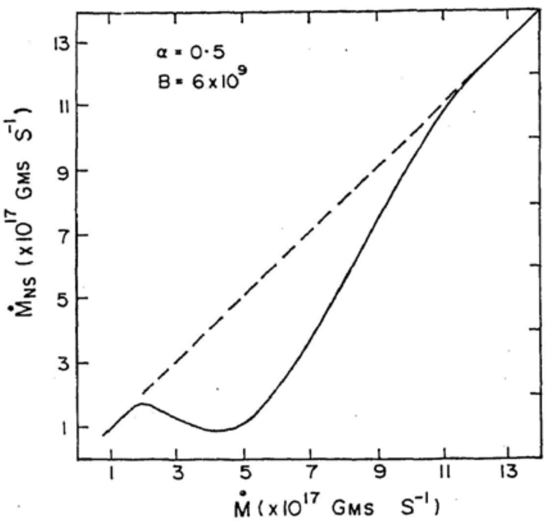

Figure 2. The amount of matter $\dot{M}_{NS}$ reaching the neutron star as a function of the accretion rate-shown as the solid line. The dashed line shows the same if there were no wind from the accretion disk.

case ($\dot{M}_R$) is higher than the non-rotating case by a factor δ of the order of unity. Therefore the wind from the disc in the rotating case is $\dot{M}_R^D \sim \delta\, \dot{M}_{NR}^D$.

The ratio of the wind from the disk to the accretion rate $R = \dot{M}_R^D / \dot{M}$. We have calculated the ratio R for various values of the magnetic field with $\delta = 1$ and using the above equations. The ratio R is shown in Fig. 1, as a function of the magnetic field.

3. Discussion

A perusal of Fig. 1 shows that the wind from a two temperature disk can be an appreciable fraction of the accretion rate. As an application, we may take the X-ray source Sco X – 1, when the changeover from HB to NB occurs at an $\dot{M} \sim 3 \times 10^{17}$ g s^{-1}, and the reduction in X-ray intensity from the top end to the bottom end of NB is ~ 30% (Hasinger, Priedhorsky & Middleditch 1989). These two match with $\alpha \sim 0.5$ and B~ 6×10^{10} gauss as can be seen from Fig. 1. If these values for α and B are now fixed and $\dot{M}$ is changed from 2×10^{17} gs^{-1} to 13×10^{17} gs^{-1}, the equations in section 2 can be used to obtain the amount of matter reaching the neutron star ($\dot{M}_{NS} = \dot{M} - \dot{M}_R^D$) and this is shown in Fig. 2 as the solid line; the dashed line shows the accretion onto the neutron star if there were no wind.

It is seen from Fig. 2 that at $\dot{M} \sim 3 \times 10^{17}$ gs^{-1}, the matter reaching the neutron star reduces and therefore the X-ray emission decreases, even as $\dot{M}$ is increasing, as is observed. The magnetic field of the neutron star implied here is slightly higher than a value in the range $10^9 - 10^{10}$ gauss considered for LMXRB by several authors, but is still small compared to the canonical value of 10^{12} gauss.

Thus it seems that the reduction in X-ray emission as an LMXRB changes its state from HB to NB, can be explained as due to a wind from a low temperature disk formed at the changeover time, which takes away matter accreting on to the neutron star.

References

Apparao, K. M. V., Tarafdar, S. P. 1992, *Astrophys. Space Sci*, **189**, 89.
Friend, D. B., Abbott, M. J. 1986, *Astrophys. J.*, **311**, 701.
Hasinger, G.1987,*The Origin and Evolution of Neutron stars*, *IAU Symp.*,**125**, Eds D. Helfand & J. H. Huang, p. 333.
Hasinger, G., Priedhorsky, W., Middleditch, J. 1989, *Astrophys. J.*, **337**, 843.
Lightman, A. P., Eardley, D. H. 1974, *Astrophys. J.*, **187**, L1.
Marlborough, J. H., Zamir, M. 1984, *Astrophys. J.*, **276**, 706.
Priedhorsky, W.1986, *Astrophys. J.*, **306**, 297.
Shapiro, S. L., Lightman, A. P., Eardley, D. M. 1976, *Astrophys. J.*, **204**, 187.
Tarafdar, S.P.1988, *Astrophys. J.*, **331**, 932.
Thorne, K. S., Price, P. H. 1975, *Astrophys. J. Lett.*, **195**, L101.