Structure and Stability of X-Ray Irradiated Accretion Disk

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Abstract:

We present here the mathematical approach in calculating the structural changes which take place in the outer regions of the accretion disk due to X-ray irradiation. It is shown here that an X-ray source powered by accretion, modifies the outer disc structure. Our calculations for the transition radius and Circularization Radius in case of various low mass X-ray binaries show that the X-ray irradiation becomes dominant after transition radius only in some binary systems.

Introduction:

In a Binary System, the compact objects gravitationally capture the ambient matter by the process called as Accretion. The captured matter before accreting on to the compact star forms a disk like structure around the compact star called as Accretion disk. Depending upon the radius, the accretion disk is divided into three distinct regions, i) the Inner region , at a very small r, in which the radiation pressure dominates the gas pressure and the opacity is controlled by electron scattering, ii) the Middle region, at a smaller r, in which the gas pressure dominates the radiation pressure but again the opacity is controlled by electron scattering and iii) the outer region, at large r, in which gas pressure dominates the radiation pressure but the opacity is mainly controlled by free-free absorption. This distinction is according to the Standard Disk Model. Now, when the mass accretes on to the compact star, the x-rays emitted hit and change the behavior of the outer region of the Accretion Disk. We are concerned here with finding the structural changes that occur in the outer region due to X-ray irradiation and also study the stability of such a disk.

1. Structure of the X-ray Irradiated Accretion Disk:

The general Radiative Transport equation is given by

$$\frac{acT^4}{\tau} \approx \frac{acT^4}{\kappa\Sigma} \approx F(r), \quad \tau(r) > 1 \qquad (1)$$

where $F(r)$ is the flux of the heat generated internally by viscosity,
τ represents optical depth,
κ represents opacity,
Σ is the Surface Density.

or, The above equation can be written as

$$\sigma T^4 = F_0(r)\,[\tau] \qquad (2)$$

Now taking X-ray Irradiation into consideration, the above equation modifies to (Dubus et.al. 1999)

$$\sigma T^4 = F_0(r)\,[\tau] + F_{ir}(r,h) \qquad (3)$$

Where Fir(r,h) measures the flux due to X-ray Irradiation and is given by (Vrtelik et.al 1989)

$$F_{ir}(r,h) = \frac{f_2 L_X}{4\pi r}\frac{\partial h/r}{\partial r} \qquad (4)$$

Taking into account both the opacities, equation (3) can be written as :

$$\sigma T^4 = F_0(r)\left[\Sigma\left(\bar{\kappa}_{ff} + \bar{\kappa}_{es}\right)\right] + F_{ir}(r,h) \qquad (5)$$

Solving the above equation with other Standard Model Equations, we get a differential equation given as:

$$\frac{\partial y}{\partial x} = \frac{y}{x} + A_p x^{-10} y^8 - B_p x^{\frac{25}{2}} y^{-12} - C_p x^{\frac{1}{2}} y^{-2} \qquad (6)$$

Where

$$x = \frac{r}{r_g} \qquad y = \frac{h}{r_g}$$

$$A_p = \frac{4\pi\sigma r_g^2 c^6}{f_2 \eta \dot{M}_{in}}\left(\frac{\mu m_H}{k f_1}\right)^4 \qquad B_p = \frac{12 \times 0.64 \times 10^{23}}{128}\left(\frac{\dot{M}_{out}^3}{\dot{M}_{in} r_g^3 c^9}\right)\left(\frac{1}{\pi^2 \alpha^2 f_2 \eta}\right)\left(\frac{k f_1}{\mu m_H}\right)^{\frac{7}{2}}$$

$$C_p = \frac{12}{32}\left(\frac{\dot{M}_{ou}^2}{\dot{M}_{in} r_g c}\right)\left(\frac{\bar{\kappa}_{es}}{\pi \alpha f_2 \eta}\right)$$

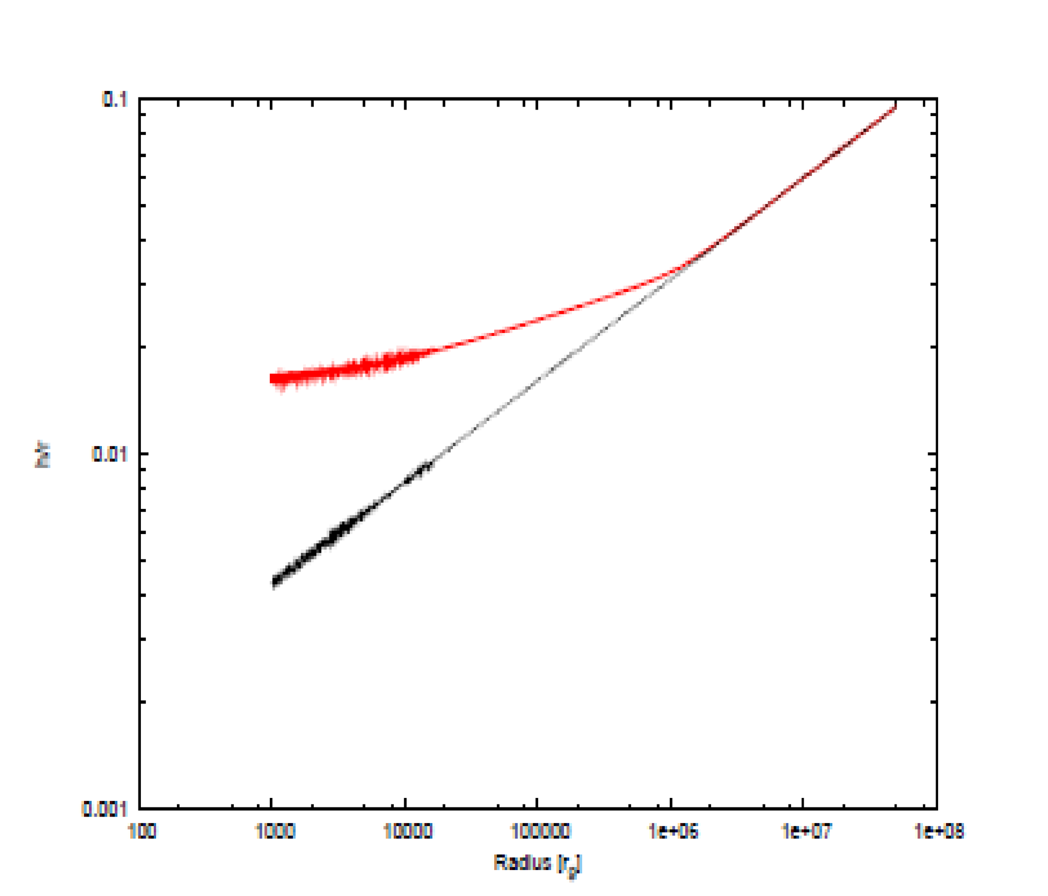
Solving equation (6) for fixed values of M, $\dot{M}$, α, and η, We get the plots as shown .

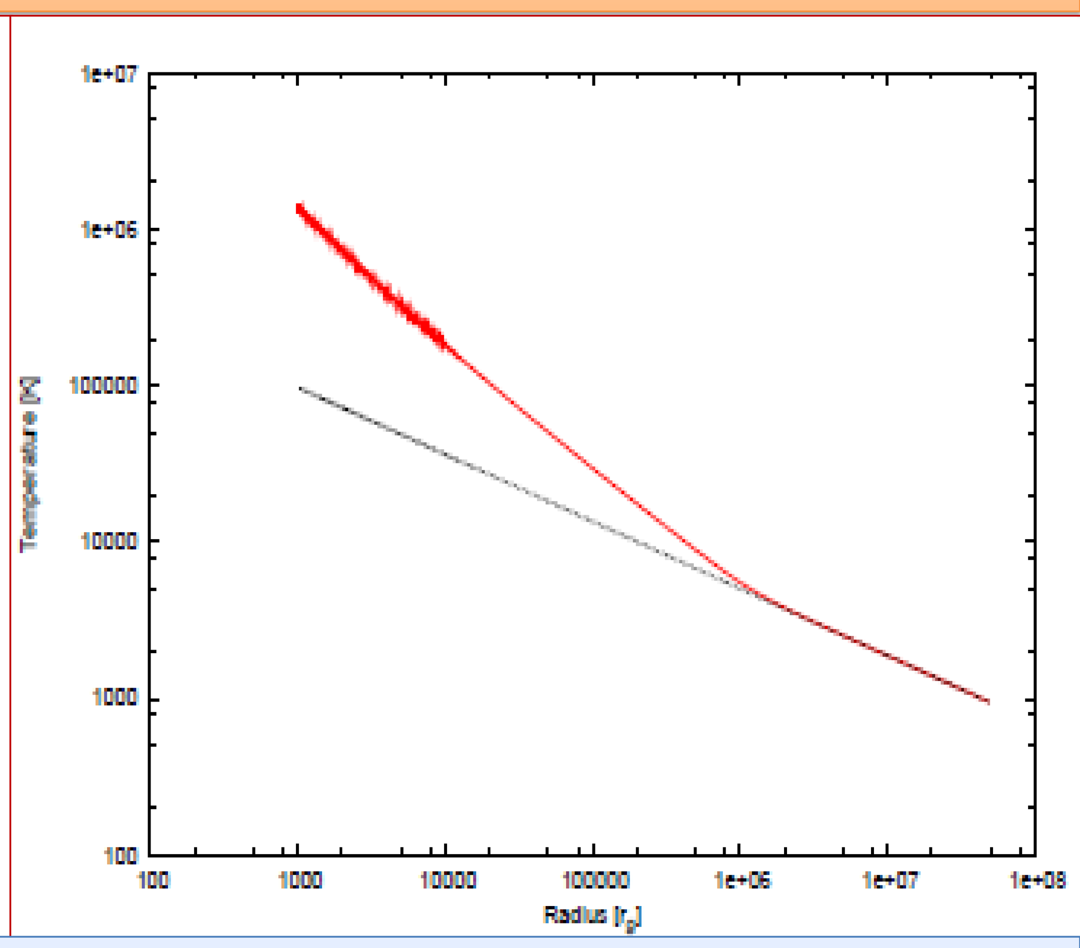
Viscous Time scale

It is the timescale on which matter diffuses through the disk under the effect of viscous torques and is given by:

$$t_{visc} = \frac{1}{2}\left(\frac{12 \times 0.64 \times 10^{23}}{128}\right)^{13/45}\left(\frac{7}{2\eta f_2}\right)^{10/9}\left[\frac{(4\sigma)^{37/45}}{(\alpha)^{71/45}}\right]\left(\frac{\dot{M}_{out}^{13/15}}{\dot{M}_{in}^{10/9}}\right) r_g^{16/9}\, c^{4/3}\left(\frac{\mu m_H}{k f_1}\right)^{41/18} \qquad (7)$$

For a Neutron star of mass 1.4 solar *masses* and uniform accretion rate of 10^{17}, the viscous timescale comes out to be 3.82×10^{17} secs.





Circularization Radius and Transition Radius:

As is clear from the figure 2, that there is a sharp transition as, we go from the X-ray Irradiated region to the region where X-Ray Irradiation is not important. We have developed an expression for calculating this transition point, called as '*Transition Radius*,'given by

$$r_{tr} = \left[\frac{(4\alpha)^{26/45}}{\pi^{2/45}}\right]\left(\frac{12 \times 0.64 \times 10^{23}}{128\alpha^2}\right)^{14/45}\left(\frac{7}{2f_2\eta}\right)^{8/9} (\dot{M})^{2/45}\left(\frac{m_H}{k}\right)^{11/9} c^{2/3}\, r_g^{11/9}\left(\frac{\mu}{f_1}\right)^{104/45}$$

Or,

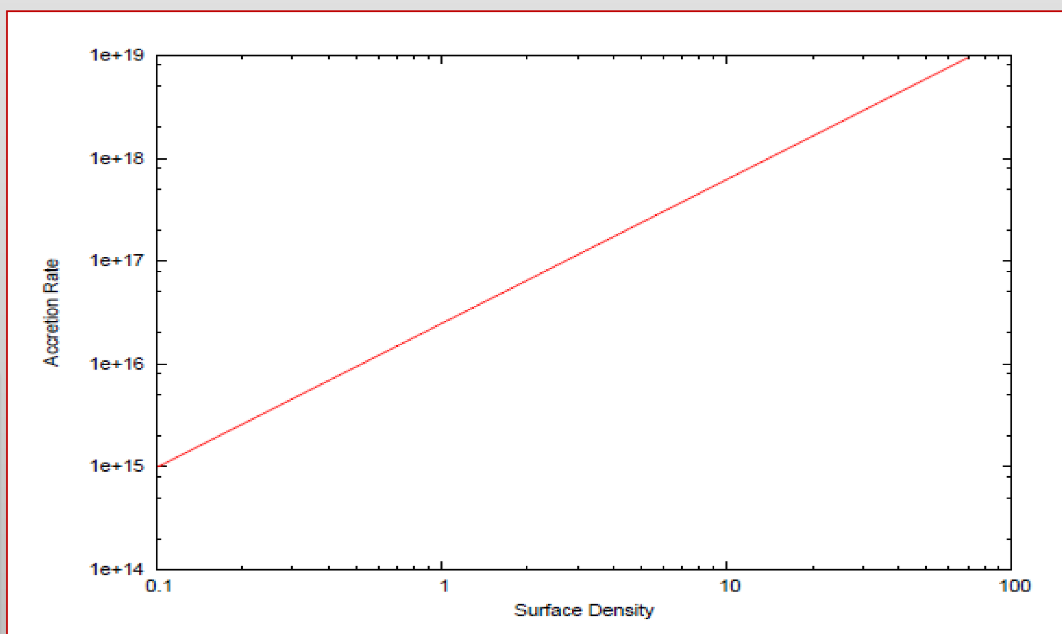
$$r_{tr} = 1.4815 \times 10^{11} \times \left(\frac{\dot{M}}{10^{17}}\right)^{2/45}\left(\frac{r_g}{1.5 \times 10^5}\right)^{11/9}\left(\frac{\alpha}{0.1}\right)^{-28/45} \qquad (8)$$

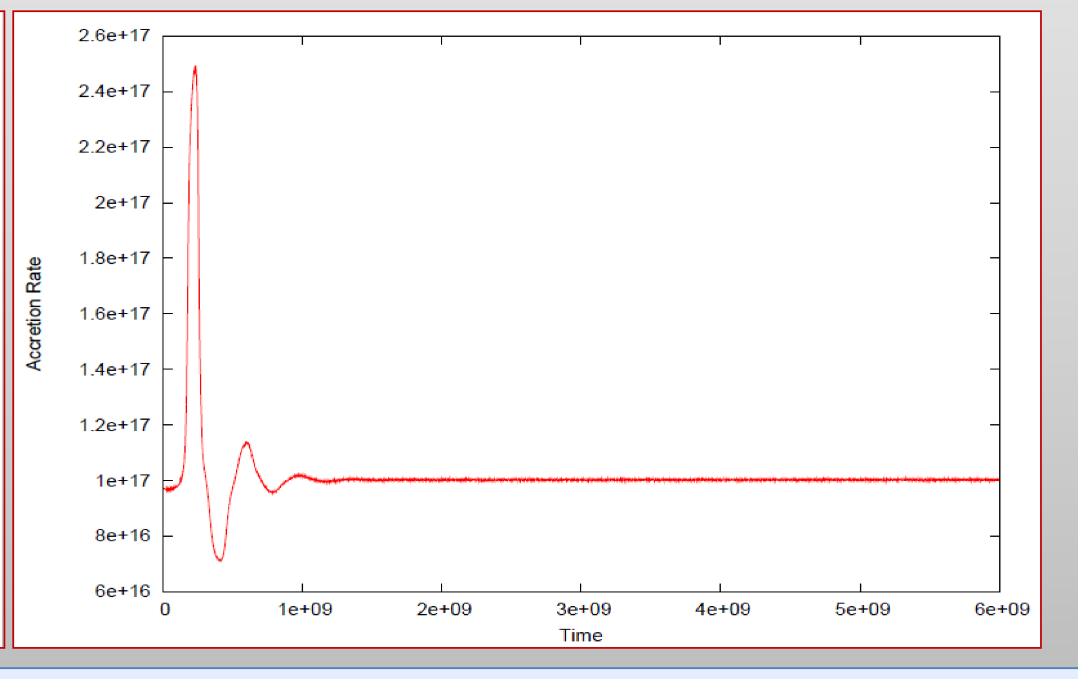
Table 1. Comparison between the Circularization radius, Tidal Radius and Transition Radius in case of Low Mass X Ray Binaries.

System	Type	P_{orb} (d)	$M_{1\odot}$	R_c ($10^{11} cm$)	R_T ($10^{11} cm$)	R_{tr} ($10^{11} cm$)	T (K)
3A1516-569*	NS	16.60	1.4	6.5	13.0	2.2	4900
1E1740-7-2942*	BHC	12.73	10	10	20	27.38	1400
GRS-1758-258*	BHC	18.45	10	14	28	27.38	1400
401811-17*	NS	24.0667	1.4	8.3	16.6	2.2	4900
GRS 1915 +105*	BHC	33.500	14	59	118	41.3	1100
GS2023 + 338*	BHC	6.4750	12	7.1	14.2	34.2	1200
CygX-2**	NS	9.84	1.780	3.2	6.4	3.0	4200
V395 CAR**	NS	9.02	1.44	3.1	6.2	2.3	4900
XTE J2123-058**	NS	0.25	1.415	.25	0.5	2.3	4900
2A 1822-371**	NS	0.23	0.97	0.2	0.4	1.47	6300

2. Stability:

For studying the stability of the such a disk, we plot a graph (Fig 3a) between the Accretion rate $\dot{M}$ and Surface density, Σ for a given value of radius and also considering That the inner accretion rate is same as the outer accretion rate. However , if the inner Accretion rate changes, the effect of the same on the outer Accretion rate on viscous timescale is depicted in the fig 3b.





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