Coronal ejection and heating in variable-luminosity X-ray sources

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Abstract. A sudden increase in stellar luminosity may lead to the ejection of a large part of any optically thin gas orbiting the star. Test particles in circular orbits will become unbound, and will escape to infinity (if radiation drag is neglected), when the luminosity changes from zero to at least one half the Eddington value, or more generally, from L to $(L_{\rm Edd} + L)/2$ or more. Conversely, a decrease in luminosity will lead to the tightening of orbits of optically thin fluid. Even a modest fluctuation of luminosity of accreting neutron stars or black holes is expected to lead to substantial coronal heating. Luminosity fluctuations may thus account for the high temperatures of the X-ray corona in accreting black hole and neutron star systems.

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1. Introduction

Low mass X-ray binaries (LMXBs) are bright X-ray sources whose luminosity is thought to be powered by accretion from a binary companion onto a neutron star or a black hole. Typically, each source can be found in one of two or more distinct spectral states, some of which include a hard X-ray power law component interpeted as radiation from a hot ($\sim 10^2\,$keV) corona. Each state has an associated characteristic variability on many timescales. Nearly all sources exhibit quasi-random excursions of luminosity. In this contribution, I examine some of the consequences of rapid variations of luminosity, particularly for optically thin Keplerian flow, which I identify with the X-ray corona.

Since the paper of Walker & Mészáros (1989) it is understood that high luminosity of an accreting neutron star will be associated with removal of angular momentum via the Poynting–Robertson drag. Further, it seems to be a part of the lore of neutron star astrophysics that the primary effect of high luminosity is to bring matter down from its nearly-circular orbits towards the inner parts of the accretion disk, and perhaps even onto the stellar surface. This is ideed true for optically thin flow in a steady radiation field. However, a rapid change in luminosity may have the opposite effect and, as I show below, under certain conditions may lead to ejection of the optically thin matter.

An even more important effect will occur when the luminosity undergoes a small but rapid change. The optically thin fluid will then continue its orbital motion in very nearly the same circular orbits, but will undergo strong heating, caused by dissipation of excess kinetic energy. This may explain the presence of hot X-ray coronae in some spectral states of LMXBs.

2. Keplerian orbits

In Newtonian physics, computing the response of an orbiting test particle to a sudden change in luminosity is a simple exercise in orbital mechanics. Consider orbits in a

spherically symmetric potential

$$V(r) = -\frac{GM}{r}. \tag{2.1}$$

As shown by Newton, these correspond to conic sections with eccentricity

$$e = \sqrt{1 + \frac{2El^2}{G^2 M^2}}, \tag{2.2}$$

where E and l are the specific (per unit mass) energy and angular momentum of the orbiting particle. The specific kinetic energy and angular momentum of a particle in circular orbit of radius r_0 are

$$K_0 = \frac{GM}{2r_0}, \quad l_0 = \sqrt{GMr_0}, \tag{2.3}$$

and the total specific energy is

$$E_0 = -\frac{GM}{2r_0}. \tag{2.4}$$

Suppose that the energy of the particle is changed to E, with no change in its angular momentum. The particle will now move in an orbit with eccentricity

$$e = \sqrt{1 + E/K_0}. \tag{2.5}$$

In particular, $E = E_0 \Rightarrow e = 0$, i.e., the original orbital energy corresponds to a circular orbit; while $E = 0 \Rightarrow e = 1$, i.e., a marginally unbound particle moves in a parabolic orbit. It is well known that $E > 0$ corresponds to an unbound hyperbolic orbit. As we will see, the effect of an impulsive change of luminosity on test particles in circular orbits is equivalent to a change of the particle energy.

3. Luminosity effects

Optically thin hydrogen plasma suffers radiation pressure forces proportional to the Thomson cross-section and the radiative flux. At Eddington luminosity, L_{Edd}, the radiative force balances gravity exactly at any radius—in Newtonian physics of a spherically symmetric source both the radiative flux $L/(4\pi r^2)$, and the force of gravity $-GM/r^2$ drop off inversely with the square of the radial distance. Hence, at lower luminosity the presence of radiation pressure is equivalent to a proportional reduction of the gravitational mass by irradiation: GM may simply be replaced by $GM(1-\lambda)$, with $\lambda \equiv L/L_{\mathrm{Edd}}$, so that eqs. (2.1), (2.2) become

$$V(r) = -\frac{GM(1-\lambda)}{r}, \tag{3.1}$$

$$e = \sqrt{1 + \frac{2El^2}{G^2 M^2 (1-\lambda)^2}}. \tag{3.2}$$

The specific kinetic energy in circular orbit at r_0 for a source with luminosity L and true gravitational mass M is

$$K_\lambda = \frac{GM(1-\lambda)}{2r_0}. \tag{3.3}$$

Upon an impulsive change of stellar luminosity from zero to L, a particle that has been travelling travelling in circular orbit at r_0 would conserve its kinetic energy and angular momentum, K_0, l_0 of Eq. (2.3), so that its new orbit would be described by the following specific energy and angular momentum:

$$E = \frac{GM}{2r_0} - \frac{GM(1-\lambda)}{r_0}, \quad l = l_0 = \sqrt{GMr_0}, \tag{3.4}$$

and because of the excess energy, $K_0 - K_\lambda = \lambda GM/(2r_0)$, this orbit would no longer be circular. The eccentricity of the orbit is, from Eq. (3.2),

$$e = \frac{\lambda}{1-\lambda}. \tag{3.5}$$

In particular, $\lambda \geqslant 1/2 \Rightarrow e \geqslant 1$, i.e., if the luminosity is now one half of the Eddington value, or greater, the particle is in an unbound orbit. If, on the other hand, the increase was from zero to less than one half of the Eddington luminosity, the particle remains in a bound elliptic orbit, $\lambda < 1/2 \Rightarrow e < 1$, with an increased semi-major axis $a = r_0(1-\lambda)/(1-2\lambda)$.

4. Coronal ejection

In reality, the fluctuations of luminosity in LMXBs do not occur between $L = 0$ and $L \neq 0$, but rather between some initial $L_1 \neq 0$ and some final value $L \neq 0$. Generalizing the derivation from the previous section, we start with circular orbits at luminosity L_1, with $\lambda_1 \equiv L_1/L_{\text{Edd}}$, the specific kinetic energy and angular momentum in circular orbits in the optically thin region being given by

$$K_1 = \frac{GM(1-\lambda_1)}{2r}, \quad l_1 = \sqrt{GM(1-\lambda_1)r}. \tag{4.1}$$

Following an impulsive change of luminosity to L, the new orbits are defined by a new potential and the same values of kinetic energy and angular momentum: $V(r) = -GM(1-\lambda)/r$, $K = K_1$, $l = l_1$, where, as before, $\lambda \equiv L/L_{\text{Edd}}$. The eccentricity of the new orbits is

$$e = \frac{|\lambda - \lambda_1|}{1-\lambda}. \tag{4.2}$$

Identifying the corona with the optically thin region, the condition for its ejection ($e \geqslant 1$) now becomes $1 - \lambda \leqslant (1-\lambda_1)/2$, i.e.,

$$L_{\text{Edd}} - L \leqslant (L_{\text{Edd}} - L_1)/2, \tag{4.3}$$

or

$$(L_{\text{Edd}} + L_1)/2 \leqslant L. \tag{4.4}$$

Thus, the condition for coronal ejection is that the luminosity reduces its distance to the Eddington value by at least a factor of two. E.g., an increase from $0.8L_{\text{Edd}}$ to $0.9L_{\text{Edd}}$ corresponds to a fluctuation of less than 13%, and this is sufficient to clear out the corona.

I would like to suggest that the evolution of spectral properties of black holes and neutron stars in outburst, see e.g., Fender *et al.* (2004), may be explained by such an ejection of the corona. Eventually, as the luminosity drops, the corona may reform, as suggested by the results of the next Section.

5. Coronal heating

If the luminosity has decreased, or increased (from L_1) by less than $(L_{\text{Edd}} - L_1)/2$, thus violating condition (4.4), the new test particle orbit is an ellipse with semi-major axis $r_0(1-\lambda)/|1 + \lambda_1 - 2\lambda|$, in the notation of the previous Sections. The periastron is

at radius r_0 for $\lambda > \lambda_1$, and at $r_- = r_0(1 - \lambda_1)/(1 + \lambda_1 - 2\lambda)$, for $\lambda < \lambda_1$. For a small decrease of luminosity, the latter value becomes $r_- \approx r_0[1 - 2(\lambda_1 - \lambda)/(1 - \lambda_1)]$.

Naturally, the state of the corona cannot be described by test particle orbits, as those of different particles would intersect. It is clear that some energy will be dissipated, and the fluid orbits will circularize. The ultimate outcome is difficult to predict, because redistribution of angular momentum may occur. However, it seems clear that the dissipated energy will be on the order of $(\lambda_1 - \lambda)^2$ times the virial energy of the corona.

Consider the evolution of a geometrically thin annulus, initially orbiting at r_0, under a small impulsive change of luminosity of the central star, $|\delta\lambda| \equiv |\lambda - \lambda_1| << 1$, and subsequent dissipation of energy. If the annulus conserves its angular momentum, it will settle down in a circular orbit at $r_1 = r_0(1 - \lambda_1)/(1 - \lambda)$ after dissipating an amount of energy equal to $[(\delta\lambda)^2/(1 - \lambda_1)] \cdot [(GM)/(2r_0)]$.

6. Discussion

The observed accreting neutron stars and black holes are usually quite luminous and are typically variable in time. It seems important to explore the consequences of rapid changes of luminosity, whose magnitude may be a large fraction of the Eddington value.

The relevance of Poynting-Robertson drag to neutron stars was first pointed out by Walker & Mészáros (1989). While there is no doubt that high luminosity is accompanied by radiation drag, which at least in the optically thin regime in a steady source will eventually remove kinetic energy and angular momentum of orbiting matter, this process takes time. If the luminosity undergoes a rapid change, the first and immediate response of orbiting matter is to change its trajectory.

By considering Newtonian orbital mechanics, I have shown that an impulsive increase of central luminosity of sufficiently high magnitude, $L - L_1 > (L_{Edd} - L_1)/2$, may lead to an ejection of the optically thin corona on a dynamical timescale. Qualitatively similar conclusions are obtained when the radiation drag is included in a fully general relativistic calculation (Stahl *et al.* 2012).

The coronal response to small changes in luminosity was considered in Section 5. It seems inevitable that relatively minor changes in the luminosity of the central source lead to substantial energy dissipation. This could be the as yet unexplained mechanism of coronal heating. The estimated magnitude of the effect is rather large. The dissipated energy at 50 Schwarzschild radii caused by a single excursion in luminosity of $0.1L_{Edd}$ (10% Eddington) is on the order of 10^{-4} of the coronal rest mass, i.e., it corresponds to a temperature of $\sim 100\,\text{keV}$. At 5 Schwarzschild radii the same result will be obtained by a fluctuation of only 3% Eddington luminosity.

The effects discussed here may be of some importance in X-ray bursts, and may explain the salient features of X-ray spectral-state changes of black holes and neutron stars, c.f., Fender *et al.* (2004).

In passing, we note that for a steady source of luminosity λ in Eddington units, the orbital frequency in the optically thin regime is modified by a factor of $\sqrt{1 - \lambda}$. Care must be taken to account for this effect when interpreting the redshift/blueshift of any spectral features in terms of orbital motion.

References

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