Relativistic effects on radiative ejection of coronae in variable X-ray sources

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We discuss coronal ejection in a general relativistic calculation of the motion of a test particle in a spherically symmetric radiation field. At every radial distance from the star larger than that of the ISCO, and any initial luminosity of the star, there exists a luminosity change which leads to coronal ejection. Mildly fluctuating luminosity will lead to dissipation in the plasma and may explain the observed X-ray temperatures of coronae in low mass X-ray binaries (LMXBs). At large radial distances from the star ($3 \cdot 10^3 R_G$ or more) the results do not depend on whether or not Poynting-Robertson drag is included in the calculation.

1 Introduction

Most LMXBs vary in luminosity on many timescales. Particularly rapid and luminous variations are exhibited by the numerous X-ray bursters, which are thought to be neutron stars undergoing a thermonuclear explosion on their surface, yielding an Eddington luminosity at maximum. Sometimes the maximum flux corresponds to super-Eddington luminosities, as in the pulsating neutron star "LMC transient" A0535-668 (at a firm distance of 50 Kpc), which is thought to attain an isotropic flux $L_\infty = 1.2 \times 10^{39}\mathrm{erg/s} = 6.9\, L_{\mathrm{Edd}}$ for a $1.4\, M_\odot$ star (Bradt & McClintock, 1983). The observed LMXBs are thought to be powered by accretion occurring through an optically thick disk. We are attempting to understand luminosity effects on the corona by modelling test-particle motion around the star. The dynamics are described by equations of motion of a particle moving in a spherically symmetric radiation field in the Schwarzschild metric, while interaction with the radiation by momentum absorption with a cross-section whose numerical value will correspond to the Thomson cross-section times the mass of the particle expressed in units of proton mass. This assures that the conventional Eddington luminosity, k_{Edd}, will balance gravity exactly for hydrogen plasma at infinity (i.e., in the Newtonian limit). The calculation can be carried over to other compositions, and other cross-sections for photon absorption, by suitably redefining the Eddington luminosity.

2 Coronal ejection

If a particle is moving in a circular orbit, it can become unbound under a sudden increase of luminosity. For a test particle in Newtonian dynamics, moving initially in a Keplerian circular orbit under initial luminosity k_1, the minimum *luminosity change* required to unbind the particle is $(k_{\mathrm{Edd}} - k_1)/2$. Thus, in the Newtonian limit the minimum luminosity required to eject a test particle is $L_{\mathrm{NL}} = (1 + k_1)L_{\mathrm{Edd}}/2$. An

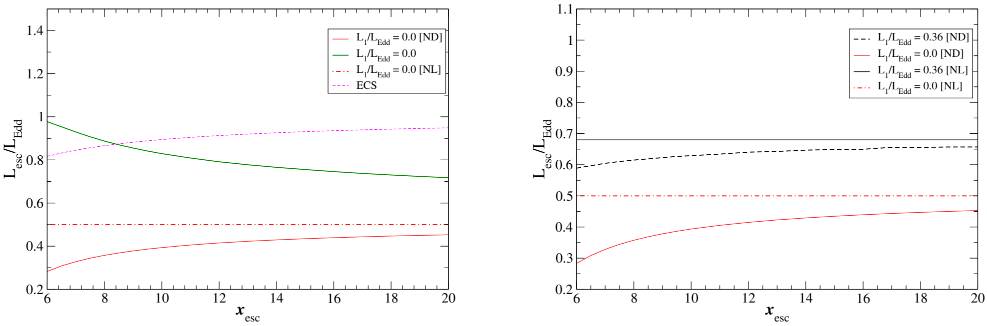

Fig. 1: Left panel shows minimum luminosity that will eject to infinity a particle initially in circular orbit at $x_{\rm esc}$. Initial luminosity is $k_1 = L_1/L_{\rm Edd} = 0$, stellar radius $X = 5$. The Newtonian limit is also shown ([NL], dot-dashed line), as well as the radius of the Eddington capture sphere (ECS). Right panel shows radius of escape sphere without drag.

impulsive change of luminosity to this value will also lead to coronal ejection if the radiation drag is neglected Kluźniak (2013).

We will be contrasting conditions under which particles escape to infinity with those in which the particles remain in the system (Mishra & Kluźniak, 2014). To isolate the effects of drag from gravitational effects in GR we shall discuss two cases, in the first case we shall omit effects of radiation drag, and in the second case we shall also include the radiation drag. Interestingly, radiation drag dominates GR corrections, and already at a radius of about $10^2 R_G$ the non-drag GR corrections appear to be negligible.

2.1 GR effects without drag

We consider an initial luminosity, k_1 which at some point in the evolution of the system will be changed impulsively to a different value k_2. To contrast the effects of the Schwarzschild space-time with the Newtonian case, in this subsection we assume the absence of radiation drag. We investigate for what luminosity change $(k_2 - k_1)$ the particle will become unbound (neglecting radiation drag). The initial conditions correspond to a circular orbit, at a particular radius around the star of luminosity k_1. Since the effective radiative force diminishes more rapidly with increasing distance from the center of a variable X-ray source than the gravitational attraction, in the absence of drag a smaller luminosity change is required to eject the particle from a circular orbit close to the ISCO ($x = 6$ for a non-rotating neutron star) than from a more distant one.

2.2 GR effects with drag

Now we shall include effect of radiation drag on test particle motion. Radiation drag is automatically included in the formalism, and the angular momentum and energy of the test particle are no longer constants of motion. We find that at any particular radius, x, there is a minimum luminosity $k_2 = k_{\rm esc}$ that will cause a particle satisfying the initial conditions to escape to infinity. A final luminosity value larger than $k_{\rm esc}$ will also lead to the expulsion of the particle. The $k_{\rm esc}(x)$ curve is monotonically decreasing. The inverse function, $x_{\rm esc}(k_2) = x(k_{\rm esc})$ is the minimum radius of circular

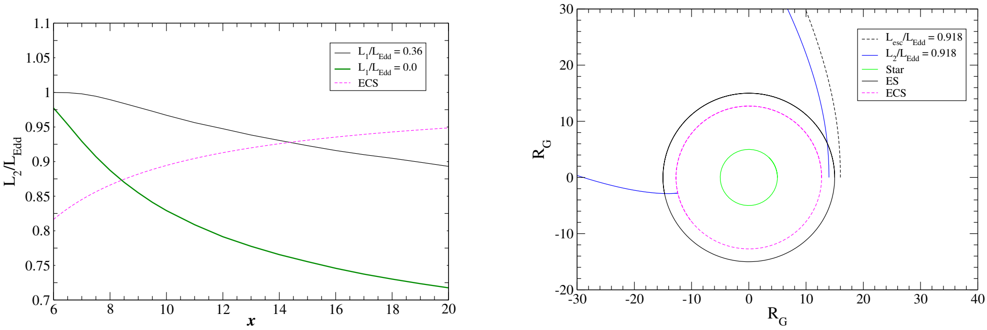

Fig. 2: Left panel shows the variation of escape radius with the final luminosity, $x = x_{\rm esc}(k_2)$, after a sudden change from $k_1 = 0$ or 0.36 to k_2 and dashed curve shows radius of ECS. Right panel shows the particle trajectories and escape sphere.

orbits from which the particles escape (*minimum escape radius*), for a given value of k_2. Clearly, radiation drag is responsible for capturing all particles that are initially within the sphere of escape radius $x_{\rm esc}$. At lower luminosities, the particles will actually be accreted onto the central star. However, at about Eddington luminosities they will lose all their momentum before settling on the star, and will levitate above the surface of the star in a state of equilibrium on a spherical surface concentric with the star, the so called *Eddington capture sphere* (ECS) (Stahl et al., 2012, 2013).

3 Discussion and Conclusion

Radiation increases so strongly towards the source in general relativity that at first sight it seems easy to unbind matter orbiting a compact luminous star. For instance, a modest increase in luminosity would be sufficient to expel matter from the ISCO *if there were no radiation drag*, e.g., a change from 0 to $0.283\,L_{\rm Edd}$, or from $0.360\,L_{\rm Edd}$ to $0.589\,L_{\rm Edd}$ would suffice, as can be seen in right panel of Fig.1. However, the same radiation very strongly impedes the motion of matter moving in the optically thin regions illuminated by the star by exerting a drag that reduces the angular momentum and energy inherent in the motion (Fig.2). When this effect is properly taken into account, the conclusion is reversed: it is, in fact, very difficult to expel matter orbiting at the ISCO, typically this is only possible when super-Eddington luminosities are attained. However, the effects of drag fall off very quickly with distance to the radiation source, so that an Eddington outburst of a lower luminosity source, such as an atoll source is sufficient to clear out all test particles orbiting in the optically thin region at $r \gtrsim 10R_G$ (Fig.1)

The numerical results obtained here apply to the motion of test particles. However, they should be also applicable, at least qualitatively, to optically thin plasma, e.g., the coronae of accretion disks. The radiation front following an outburst of the source moves at the speed of light appropriate for the medium, which is always larger than both the sound speed and the speed of the orbiting particles along any trajectory they may follow. All parts of the optically thin plasma will feel the influence of radiation before any significant hydrodynamic interaction occurs between the different regions at various radial distance from the source. We expect that similar conclusions will also hold for the motion of plasma, or hot gas, and we intend to verify these expectations in future work with a hydro code.

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