Black–Hole Transients and the Eddington Limit

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ABSTRACT

I show that the Eddington limit implies a critical orbital period $P_{\text{crit}}(\text{BH}) \approx 2$ d beyond which black-hole LMXBs cannot appear as persistent systems. The unusual behaviour of GRO J1655-40 may result from its location close to this critical period.

1 INTRODUCTION

It is now well understood that the accretion discs in low-mass X-ray binaries (LMXBs) are strongly irradiated by the central X-rays, and that this has a decisive effect on their thermal stability (van Paradijs, 1996; King, Kolb & Burderi, 1996). Irradiation stabilizes LMXB discs compared with the otherwise similar ones in cataclysmic variables (CVs) by removing their hydrogen ionization zones. In CVs this instability causes dwarf nova outbursts, and in LMXBs it produces transient outbursts rather than persistent accretion. The irradiation effect appears to be weaker if the accretor is a black hole rather than a neutron star, possibly because of the lack of a hard surface (King, Kolb & Szuszkiewicz, 1997). The result is that neutron–star LMXBs with short (≈ hours) orbital periods tend to be persistent, while similar black-hole binaries are largely transient. Both types of LMXBs must be transient at sufficiently long orbital periods, since a long period implies a large disc, so that a large X-ray luminosity would be needed to keep the disc edge ionized and thus suppress outbursts. We can write this stability requirement as

$$M_{\text{crit}}^{\text{irr}} \sim R_3 \sim P^{4/3},$$

where $M_{\text{crit}}^{\text{irr}}$ is the minimum central accretion rate required to keep the disc stable, $R_3$ is the outer disc radius, and $P$ is the orbital period, and we have used Kepler’s law. Thus for large $P$, $M_{\text{crit}}^{\text{irr}}$ will rise above any likely steady accretion rate, making long–period systems transient. This simple prediction (King, Frank, Kolb & Ritter, 1997) seems to be borne out by the available evidence.

2 THE CRITICAL ACCRETION RATE

The precise coefficient in (1) depends on uncertainties in the vertical disc structure (see the discussion in Dubus, Lasota, Hameury & Charles, 1999). Here I adopt the form derived by King, Kolb & Szuszkiewicz (1997). They argued that for a steady black-hole accretor, the central irradiating source is likely to be the inner disc rather than a solid spherical surface, as for a steady neutron–star accretor. (Note that during an outburst of a transient black-hole system such a spherical source may be present, as the central accretor may develop a corona.) For a small source at the centre of the disc and lying in its plane, the irradiation temperature $T_{\text{irr}}(R)$ is given by

$$T_{\text{irr}}(R) = \frac{\eta M c^2 (1 - \beta)}{4 \pi \sigma R^2} \left( \frac{H}{R} \right)^2 \left( \frac{d \ln H}{d \ln R} - 1 \right)$$

(Fukue, 1992). Here $\eta$ is the efficiency of rest–mass energy conversion into X-ray heating, $\beta$ is the X-ray albedo, and $H(R)$ is the local disc scale height. The minimum accretion rate required to keep the disc in the high state is given by setting $T_{\text{irr}}(R) = T_H$, where $T_H$ is the hydrogen ionization temperature. Since $T$ always decreases with $R$, the global minimum value $M_{\text{crit}}^{\text{irr}}$ is given by conditions at the outer edge $R_3$ of the disc. For the parametrization adopted by King, Kolb & Szuszkiewicz (1997), and $g = 0.2$, this leads to

$$M_{\text{crit}}^{\text{irr}}(R) = 2.86 \times 10^{-11} m_1^{5/6} m_2^{-1/2} f_{0.7}^2 f_h^{4/3} M_\odot \text{ yr}^{-1},$$

where $f_{0.7}$ is the disc filling fraction $f$ (the ratio of $R_3$ to the accretor’s Roche lobe) in units of 0.7; $m_1, m_2$ are the accretor and companion star mass in $M_\odot$; and

$$g = \left( \frac{1 - \beta}{0.1} \right)^{-1} \left( \frac{H}{0.2 R} \right)^{-2} \left( \frac{2/7}{d \ln H/d \ln R - 1} \right) \left( \frac{T_H}{6500 \text{ K}} \right)^4$$

Equation (3) is the same as eqn (12) of King, Kolb & Szuszkiewicz (1997) apart from the factors $f_{0.7}^2 f_h^{4/3}$; there taken as unity. All of the uncertainties over disc thickness, warping, albedo etc are lumped into the quantity $g$. With $g \approx f_{0.7} \approx 1$, equation (3) appears to be largely successful in predicting that systems with reasonably massive ($5 - 7 M_\odot$) black holes and main–sequence companions should be transient. By contrast, neutron star systems with main–sequence companions should be persistent, as the index of the ratio $H/R$ in (2) is unity, implying more efficient disc irradiation. (Equation (3) also implies that lower–mass black hole systems might be persistent.) These results suggest that the quantity $g$ appearing in (3) cannot be too far from unity.

3 THE EDDINGTON LIMIT

Here I concentrate on another aspect of eq. (3) which does not seem to have received much attention. Namely, for large enough $P$, $M_{\text{crit}}^{\text{irr}}$ must exceed the Eddington accretion rate
$\dot{M}_{\text{Edd}} \simeq 1 \times 10^{-8} m_1 M_\odot \text{ yr}^{-1}$. \hfill (5)

The obvious consequence of eqs. (3, 5) is that for sufficiently long orbital periods irradiation will be unable to suppress outbursts, as the required central luminosity exceeds the Eddington limit, and the system presumably cannot be both super-Eddington and persistent. Note that this conclusion holds whatever the actual value of the mass transfer rate in the particular binary happens to be. Thus we should expect to find no persistent LMXBs above a certain critical orbital period $P_{\text{crit}}$. For the neutron–star case this was recognised by Li & Wang (1998), who found $P_{\text{crit}}(\text{NS}) \simeq 20 \text{ d}$, in agreement with observation. For the black–hole case, combining (3, 5) gives

$$P_{\text{crit}}(\text{BH}) \simeq 2.0 f_0^{1.5} g^{-0.75} \left( \frac{\dot{M}}{0.5 \dot{M}_{\text{Edd}}} \right)^{0.75} m_1^{1/8} m_2^{1/8} \text{ d}, \quad (6)$$

where we have included a factor $(\dot{M}/0.5\dot{M}_{\text{Edd}})$ to allow for the fact that the radiation pressure limit for the accretion rate $\dot{M}$ may in practice be below $\dot{M}_{\text{Edd}}$. We thus expect to find no persistent black–hole LMXBs above this period. This is indeed supported by the available data, but hardly surprising in view of the difficulty in identifying black holes in persistent systems. Note that in high–mass black–hole systems such as Cygnus X–1, the powerful UV luminosity of the companion star, as well as the small disc size expected in a wind–fed system, are both likely to keep the disc hot and therefore give a persistent system.

4 GRO J1655–40

With $g \sim 1$ as argued above, the value of $P_{\text{crit}}(\text{BH})$ found above is close to the observed period $P = 2.62 \text{ d}$ of the black–hole soft X–ray transient GRO J1655–40 (the nearest periods among alternative black–hole systems are $P = 6.47 \text{ d}$ for V404 Cyg and $P = 1.23 \text{ d}$ for 4U 1543–47). Indeed Kolb et al (1997) pointed out the system’s proximity to the Eddington limit during outburst, and Hynes et al. (1998) explicitly suggested that no globally steady disc solution might be possible for this system with $\dot{M} < \dot{M}_{\text{Edd}}$. GRO J1655–40 is unusual in at least two respects:\n
1. The companion star has spectral type F3 – F6IV and mass $M_2 \simeq 2.3 M_\odot$. On a conventional view, this places it in the Hertzsprung gap. The companion star should therefore be expanding on a thermal timescale and thus driving a mass transfer rate $M_2 \sim 10^{-7} M_\odot \text{ yr}^{-1}$ (Kolb et al., 1997). This is well above the appropriate value of $M_{\text{crit}}(\text{BH})$, making it puzzling that the system is nevertheless transient, and far above the mean mass accretion rate of $M_{\text{obs}} = 1.26 \times 10^{-10} M_\odot \text{ yr}^{-1}$ deduced by van Paradijs (1996) from observation. Regös, Tout & Wickramasinghe (1998) appeal to convective overshooting to increase the main–sequence radius of stars of $\sim 2 M_\odot$. The companion might then be on the main sequence rather than in the Hertzsprung gap. This implies a slower evolutionary radius expansion, bringing the predicted mass transfer rate below $M_{\text{crit}}(\text{BH})$. However $-M_2$ is still predicted to lie uncomfortably far above $M_{\text{obs}}$.

2. The system was first detected in an outburst in 1994, and had probably been quiescent for at least 30 yr before that. Yet two more outbursts followed in the next two years.

The considerations given here offer explanations for both of these unusual features. First, if $P > P_{\text{crit}}(\text{BH})$, the system must be transient in some sense, regardless of the actual mass transfer rate (cf Hynes et al., 1998). It would therefore not be necessary to appeal to convective overshooting. Further, since the system is close to $P_{\text{crit}}(\text{BH})$, it is evidently accreting at a value close to the Eddington rate during its quasi–steady states (see below), making it natural that $M_{\text{obs}}$ is much smaller than the predicted mass transfer rate $-M_2$.

Second, assuming that the quantity $g$ has a relatively constant value close to unity, as argued above, we see from (6) that the value of $P_{\text{crit}}(\text{BH})$ is most sensitive to the filling factor $f$ (I consider the effect of dropping the assumption $g \sim \text{ constant below}$). Thus if $f$ decreases, $P_{\text{crit}}(\text{BH})$ can increase above the actual orbital period, allowing irradiation to keep the disc in the high state (prolong an outburst) for as long as $f$ remains sufficiently small. Hence the unusual outburst behaviour of GRO J1655-40 may be explicable in terms of the time evolution of the disc size. Encouragingly there is some observational evidence (see the discussion in Orosz & Bailyn, 1997) that the grazing eclipses seen in the optical are time–dependent, just as expected if the disc size varies. Moreover Soria, Wu & Hunstead (1999) find evidence from the rotational velocities of double–peaked emission lines that the disc is at some epochs slightly larger than its tidal limit. The large resultant torques on the disc suggest that this state cannot persist and the disc must eventually shrink.

In fact we do expect $f$ to evolve systematically: in the early part of an outburst, the central accretion of low angular–momentum material will raise the average disc angular momentum and thus cause $f$ to increase, hence lowering $P_{\text{crit}}(\text{BH})$ and making the system more vulnerable to a return to quiescence. However at some stage matter transferred from the companion will tend to reduce the angular momentum of the outer disc, thus decreasing $f$, raising $P_{\text{crit}}(\text{BH})$ and allowing irradiation to stabilize the disc in the high state. But eventually the disc must grow towards its tidal limit, increasing $f$ and thus lowering $P_{\text{crit}}(\text{BH})$ again, finally enforcing a return to quiescence. Obviously a full disc code is required to follow this sequence in detail and to check if it can account qualitatively for the unusual outburst behaviour of GRO J1655–40.

Clearly, systematic evolution of one or more of the quantities appearing in $g$ during the outburst could have a similar effect in making $P_{\text{crit}}(\text{BH})$ oscillate around the actual orbital period $P$. The most likely alternative candidate is the disc aspect ratio $H/R$, which would appear explicitly with the power 1.5 if we substitute for $g$ in (6). The aspect ratio could evolve systematically on a viscous timescale because the disc may warp under radiative torques (Pringle, 1996). A warp presenting more of the disc surface to the central source would tend to stabilize it against a return to quiescence even though the central luminosity was below the Eddington limit. Again considerably more work is required to check this possibility.

5 CONCLUSIONS

I have shown that the Eddington limit implies a critical orbital period $P_{\text{crit}}(\text{BH})$ beyond which black–hole LMXBs cannot appear as persistent systems. The precise value of
$P_{\text{crit}}(\text{BH})$ is subject to uncertainties expressed by the quantity $g$ in (3). I have argued that $g$ cannot be very far from unity if we are to understand the difference in the stability properties of discs in neutron–star and black–hole systems. In this case GRO J1655-40 lies much closer to $P_{\text{crit}}(\text{BH})$ than any other black–hole system.

The unusual behaviour of GRO J1655-40 may result from its location very close to $P_{\text{crit}}(\text{BH})$; evolution of the disc size or possible radiative warping may move the system across the boundary where a sub–Eddington luminosity can keep the disc stably in the high state. This system, and those at longer orbital periods, probably have central accretion rates which are highly super–Eddington during outbursts. Since observed radiative luminosities are mildly sub–Eddington, most of this mass must be expelled. Strong support for this comes from the observation of P Cygni profiles in GRO J1655–40 (Hynes et al., 1998). The superluminal jets observed (Hjellming & Rupen, 1995) in an outburst of this system may therefore simply represent the most dramatic part of this outflow.

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REFERENCES

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