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The decline and fall of GRS1915+105: the end is nigh?

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ABSTRACT
The galactic microquasar GRS1915+105 has been in a continuous state of outburst since 1992, over 20 times longer than any other black hole X-ray transient. Assuming that the outburst is powered via accretion of an irradiated gaseous disc, we calculate how the predicted outburst duration varies according to the efficiency of the self-irradiation mechanism. At least one current model leads to the conclusion that the end of the outburst is imminent. The timing of the decline of GRS1915+105, whenever it arrives, will be an excellent discriminator of the self-irradiation mechanism in X-ray transients, allowing us to infer the fraction of the disc that is heated by the incident X-rays and the magnitude of the mass loss rate in the form of a wind.

Key words: accretion, accretion discs - binaries: close - stars: individual: GRS 1915+105.

1 INTRODUCTION

The galactic microquasar GRS1915+105 (V1487 Aql) lay undiscovered in quiescence until 1992, when it was identified as an extremely bright X-ray transient (Castro-Tirado, Brandt & Lundt 1992). The outburst that started in that year has continued to the present day, with no sign of an imminent decline. The binary comprises a $14 \pm 4.4\,\mathrm{M}_\odot$ black hole accreting from a companion of about a solar mass (Harlaftis & Greiner 2004), and remains the brightest accreting black hole in the galaxy, spending much of its time at a super-Eddington X-ray luminosity (Done, Wardzinski & Gierlinski 2004).

The unusually long outburst is over 20 times longer than any other black hole X-ray transient outburst. The duration is linked to the size of the accretion disc, which is very large: GRS1915+105 has an extremely long orbital period of 33.5 days, and as such the disc will have a radius of several 10^{12} cm. However, the reservoir of mass in the disc that is available to fuel an outburst is finite, and in this work we use a simple calculation to show how long the outburst is likely to continue if the current mean accretion rate is maintained. We present this calculation in Sections 2 and 3 below. In Sections 4 and 5, we discuss the implications for our understanding of the accretion process in X-ray transients.

2 FUELLING THE OUTBURST

Assuming that the outburst of GRS1915+105 is fuelled by the accretion of gas contained in a disc, an absolute upper limit for the outburst duration can be found by considering the time taken to accrete the entire reservoir of mass. Done, Wardzinski & Gierlinski (2004) made a simple estimate for the outburst duration of 10 years, based on an outer disc radius $R_{\rm disc} \sim 10^{12}\mathrm{cm}$. Clearly, this duration has been exceeded and this is the motivation for undertaking a more detailed calculation. We begin by considering the maximum available disc mass. The outburst duration will be given by

$$t_{\rm max} = \frac{M_{\rm disc}}{\langle \dot{M}_{\rm disc} \rangle}, \tag{1}$$

where $M_{\rm disc}$ is the mass of the accretion disc at the beginning of the outburst. We assume that the mass transfer rate from the donor star, $-\dot{M}_2$, remains constant throughout the outburst and consider a time-averaged central accretion rate onto the black hole, $\langle \dot{M}_1 \rangle$ and a time-averaged wind mass loss rate $\langle \dot{M}_{\rm wind} \rangle$. The time-averaged rate of mass loss from the accretion disc is then

$$\langle \dot{M}_{\rm disc} \rangle = \langle \dot{M}_1 \rangle + \langle \dot{M}_{\rm wind} \rangle - \dot{M}_2. \tag{2}$$

GRS1915+105 spends much of its time radiating with a super-Eddington luminosity (Done, Wardzinski & Gierlinski 2004), so we infer that the mass accretion rate is consistently very high. Assuming a distance $d = 12.5\,\mathrm{kpc}$ (Greiner, Cuby & McCaughrean (2001), see the discussion in Section 4), the mean luminosity is close to Eddington (Done, Wardzinski & Gierlinski 2004, Figure 5), implying a mass accretion rate at the black hole of order $\dot{M}_{\rm Edd} \sim 2 \times 10^{19}\,\mathrm{gs}^{-1}$. This is much larger than the estimate for the mass transfer rate from the companion, even taking into account its evolved nature. We use the formula for mass transfer driven by nuclear evolution given in equation 6 of King et al. (1997), which for the parameters of GRS1915+105 and a core mass of $0.28\,\mathrm{M}_\odot$ (Vilhu 2002) gives $-\dot{M}_2 \simeq 10^{-8}\,\mathrm{M}_\odot\mathrm{yr}^{-1} = 6.3 \times 10^{17}\,\mathrm{gs}^{-1}$.

We now wish to estimate the mass of the disc at the start of the outburst. Ideally, this would be determined from the duration of an interval of quiescence, but this is not possible with GRS1915+105. Only one outburst has ever been observed - the current one - and

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the quiescent interval for such a large disc is likely to be centuries. Therefore, we must assume an appropriate surface density profile for the disc, $\Sigma(R)$, at the onset of an outburst.

The mass of the disc is given by

$$M_{\rm disc} = \int_0^{R_{\rm disc}} 2\pi R\Sigma(R)\,{\rm d}R, \quad (3)$$

and we assume that the surface density at all radii in the disc is equal to the critical surface density required to trigger an outburst via the thermal-viscous instability:

$$\Sigma = \Sigma_{\rm max} = 11.4\alpha_{\rm c}^{-0.86}M_1^{-0.35}R_{10}^{1.05} \quad (4)$$

(Cannizzo, Shafter & Wheeler 1988), where R_{10} is the radius in units of 10^{10} cm. We take the masses $M_1 = 14\,{\rm M}_\odot$, $M_2 = 1\,{\rm M}_\odot$ and a cool state viscosity $\alpha_{\rm c} = 0.02$. We discuss the effects of taking different values for these parameters in Section 4. Integrating equation 3, we are left with

$$M_{\rm disc} = 3.4\times10^{28}\left(\frac{\alpha_{\rm c}}{0.02}\right)^{-0.86}\left(\frac{M_1}{14}\right)^{-0.35}R_{\rm disc,12}^{3.05}\quad {\rm g} \quad (5)$$

where the radius is now scaled to units of 10^{12} cm.

It is not immediately clear how to make a secure estimate for the maximum outer radius of the disc in quiescence. The maximum possible streamline radius in the three-body model of Paczyński (1977) is about $0.5a$. For $P_{\rm orb} = 33.5$ d and $M_1 + M_2 = 15\,M_\odot$, the binary separation $a = 7.5\times10^{12}$ cm so this estimate for the radius gives $R_{\rm disc} \simeq 3.7\times10^{12}$ cm. However, this is likely to be an overestimate. Taking a cue from low mass ratio cataclysmic variables, the radius of the disc in quiescence is always much less than the maximum streamline radius, only approaching it as the disc expands in the hot, highly eccentric outburst state. A more realistic estimate for the disc radius in a quiescent X-ray transient is given by Shahbaz, Charles & King (1998), who use angular momentum conservation arguments to show that in the case of negligible accretion onto the primary, $R_{\rm disc} = 1.36R_{\rm circ}$. An expression for the circularisation radius $R_{\rm circ}$ is given by

$$\frac{R_{\rm circ}}{a} = 0.0859q^{-0.426} \quad (6)$$

(Hessman & Hopp 1990), which is accurate for $0.05 \leqslant q < 1$. For $q = \frac{1}{14}$, we have $R_{\rm circ} = 0.26a$, giving us the refined estimate $R_{\rm disc} = 2.7\times10^{12}$ cm.

For $R_{\rm disc,12} = 2.7$, equation 5 gives an estimate for the disc mass $M_{\rm disc} = 7.0\times10^{29}$ g. It follows from equations 1 and 2 that the time taken to accrete the entire disc is in fact extremely long: $t_{\rm max} \sim 1150$ years if there is no mass loss due to a wind. The huge discrepancy between this estimate and that in Done, Wardzinski & Gierlinski (2004) is due to differences in our estimates of $R_{\rm disc}$ and $M_{\rm disc}$. Clearly, the outburst duration is sensitive to $R_{\rm disc}$ and the initial surface density profile $\Sigma(R)$: in the simple model described above, the disc mass scales as $R_{\rm disc}^{3.05}$. In the next section, we make a more detailed estimate of the outburst duration by considering a more realistic surface density profile and estimating the fraction of the total disc mass that is available to be accreted onto the black hole.

3 OUTBURST DURATION

The simple calculation described above makes two important assumptions. The first assumption is that the surface density profile follows $\Sigma(R) = \Sigma_{\rm max}$ at all radii at the onset of the outburst. This is not physically realistic, as the only requirement to trigger an outburst is that $\Sigma(R) > \Sigma_{\rm max}$ at a single radius. The second is that the entire disc mass is consumed in an outburst.

We begin by addressing the problem of the surface density profile at the onset of an outburst. Detailed models of outburst cycles in X-ray transients (Dubus, Hameury & Lasota 2001) show that the surface density crosses the $\Sigma_{\rm max}$ threshold in the *inner* region of the disc. Indeed, the model presented in Figure 15 of Dubus, Hameury & Lasota (2001) shows that Σ follows $\Sigma_{\rm max}$ closely only in the inner 10 - 15 % of the disc and flattens off somewhat at larger radii. If the surface density profile of the disc in GRS1915+105 follows a similar structure, we calculate the total disc mass to be much smaller than the value given in Section 2 above. Very simply, assuming that $\Sigma = \Sigma_{\rm max}$ for $0 \leqslant R \leqslant 0.1R_{\rm disc}$ and $\Sigma = \Sigma_{\rm max}(R = 0.1R_{\rm disc})$ for $0.1R_{\rm disc} \leqslant R \leqslant R_{\rm disc}$, we have

$$M_{\rm disc} = M(R < 0.1R_{\rm disc}) + M(R > 0.1R_{\rm disc}). \quad (7)$$

In practise, the first term is negligible, and to a very good approximation

$$M_{\rm disc} = \int_{0.1R_{\rm disc}}^{R_{\rm disc}} 2\pi R\Sigma_{\rm max}(0.1R_{\rm disc}){\rm d}R, \quad (8)$$

or

$$M_{\rm disc} = 1.3\times10^{28}\left(\frac{\alpha_{\rm c}}{0.02}\right)^{-0.86}\left(\frac{M_1}{14}\right)^{-0.35}R_{\rm disc,12}^{2}. \quad (9)$$

Note that the coefficient in equation 9 is specific to this system, because it assumes a value for $R_{\rm disc}$ that depends on the binary parameters. With $R_{\rm disc,12} = 2.7$, $\alpha_{\rm c} = 0.02$ and $M_1 = 14$, this gives $M_{\rm disc} = 9.5\times10^{28}$ g, reducing the maximum outburst time to about 160 years (again assuming zero mass loss in a wind).

However, this is the maximum mass of the cold disc at the start of the outburst, but in an accretion disc as large as the one in GRS1915+105, a significant fraction of the outer parts of the disc may be too cool to support an outburst at all (Hameury & Lasota 2005). The only way that a significant fraction of such a large disc can remain in the hot, ionised state is by self-irradiation. Heating by incident X-ray radiation produced near the accretor (or scattering of some small fraction of the radiation back down onto the disc by some form of corona) prevents the disc from switching back into the cool state, so prolonging the outburst (Dubus, Hameury & Lasota 2001). The radius of influence of the incident X-rays, $R_{\rm irr}$ is usually estimated by matching the irradiation temperature to the hydrogen ionization temperature such that

$$T_{\rm irr}^4 = T_{\rm H}^4 = \epsilon\frac{L_{\rm X}}{4\pi\sigma R_{\rm irr}^2} = \frac{\epsilon\eta\dot{M}c^2}{4\pi\sigma R_{\rm irr}^2} \quad (10)$$

where the constant of proportionality ϵ depends on the geometry of the disc, the nature of the illuminating X-ray source and the X-ray albedo of the gas. We will refer to ϵ as the *irradiation efficiency* to distinguish it from the *accretion efficiency*, η. This notation differs slightly from that used by Dubus, Hameury & Lasota (2001), who use C for the irradiation efficiency. King, Kolb & Burderi (1996) and King (2000) have pointed out that the Eddington limit for accretion imposes a limit on $R_{\rm irr}$, leading to the conclusion that systems with orbital periods longer than about 2 days must be transient, because at these periods $R_{\rm irr}$ can never be larger than $R_{\rm disc}$, even for accretion beyond the Eddington limit. The parameters used in this model give

$$R_{\rm irr} = 2.3\times10^{11}\left(\frac{\eta}{0.1}\right)^{\frac{1}{2}}\dot{M}_{18}^{\frac{1}{2}}\ {\rm cm} \quad (11)$$

$R_{\rm irr}\times 10^{12}\,{\rm cm}$	$\epsilon\times 10^{-3}$	$M\times 10^{28}\,{\rm g}$	$t_0\,({\rm yr})$	$t_{\rm wind}\,({\rm yr})$
0.5	0.17	0.29	4.7	2.3
1.0	0.69	1.3	21	10
1.5	1.6	2.9	47	23
2.0	2.8	5.2	85	42
2.5	4.3	8.2	130	66
2.7	5.1	9.5	160	76

Table 1. Predicted maximum outburst durations for various irradiated fractions of the accretion disc. The calculation of the available disc mass is described in Section 3 and the durations assume that all of the mass inside $R_{\rm irr}$ is accreted during the outburst. The irradiation efficiency, ϵ, is calculated from equation 13. Columns 4 and 5 give the predicted maximum duration assuming $\langle \dot{M}_{\rm wind}\rangle = 0$ and 2×10^{19} ${\rm gs}^{-1}$ respectively.

(King & Ritter 1998; Truss & Wynn 2004), where $\dot{M}_{18}$ is the central accretion rate in units of $10^{18}{\rm gs}^{-1}$. For accretion at the Eddington limit, with efficiency $\eta = 0.1$, this predicts

$$R_{\rm Edd} \simeq 10^{12}\,{\rm cm}. \tag{12}$$

Other models - with an equally sound observational footing - predict a more efficient irradiating flux than the one assumed by King & Ritter (1998). Dubus et al. (1999) and Dubus, Hameury & Lasota (2001) use a constant of proportionality that is typically about seven times larger in equation 10, which leads to an estimate for $R_{\rm Edd}$ more than twice as large. Indeed, the alternative spherical inner X-ray source geometry considered by King & Ritter (1998) also leads to a larger estimate for $R_{\rm Edd}$. If we make no assumptions about the irradiation efficiency, we can write the more general expression

$$R_{\rm irr} = 2.7\times 10^{11}\left(\frac{\epsilon}{10^{-3}}\right)^{\frac{1}{2}}\left(\frac{\eta}{0.1}\right)^{\frac{1}{2}}\dot{M}_{18}^{\frac{1}{2}}\ {\rm cm}. \tag{13}$$

We will return to this point in more detail in Section 4, but for the time being we use equations 11 and 12 as our example, because they give the smallest value of $R_{\rm Edd}$ and hence leads to the shortest possible predicted outburst duration.

Since the mean source luminosity of GRS1915+105 is observed to be around Eddington, $R_{\rm Edd}$ represents the maximum radius of the hot, outburst region of the disc. The remainder of the disc outside this point stays too cool to participate in an outburst, so the fraction of total disc mass accreted is much less than unity for a large disc (Shahbaz, Charles & King 1998). Adding this piece of information to the more realistic estimate of the surface density profile allows us to calculate the maximum available mass of gas for the outburst. Repeating the calculation described above, but now using a maximum radius of 10^{12} cm gives $M_{\rm max} = 1.2\times 10^{28}$ g. This is simply the disc mass inside 10^{12} cm. If the mean accretion rate continues at its current value (which is approximately $2\times 10^{19}\,{\rm gs}^{-1}$) and 100% of the mass originally inside $R = 10^{12}$ cm is accreted, we expect the outburst to last approximately 20 years if there is no mass lost in the form of a jet or a wind.

However, there is considerable evidence for mass loss in this system via a wind. Relativistic velocities which might be appropriate for a jet mean that its mass loss rate can be small compared to the mass accretion rate, even if it makes a significant contribution to the energy budget (Nayakshin, Rappaport & Melia 2000). The same is *not* true for a much slower outflow such as a wind. Numerical simulations by Proga & Kallman (2002) show that accretion in Galactic binary systems with high Eddington fractions can power a strong disc wind. These are driven by radiation pressure on the electrons as opposed to line driven as the material is so highly ionised it has little absorption opacity. At Eddington, the mass loss rate in this wind should be comparable to the mass accretion rate (Proga & Kallman 2002), and there is observational evidence for such high mass loss rates in GRS1915+105 from detection of blueshifted, extremely ionised X-ray absorption lines (Lee et al. 2002). If approximately $\dot{M}_{\rm Edd}$ is being lost to the wind, then the outburst timescales need to be halved. Table 1 shows the predicted maximum outburst durations for a range of irradiated disc fractions, with and without a significant wind mass loss rate. We interpret these two durations (no wind and an Eddington-rate wind) as reasonable upper and lower limit estimates for the outburst timescales for each given irradiated fraction of disc. If an Eddington wind loss rate is taken into account, we can see immediately that since the outburst has already progressed for at least 13 years, this supports the assertion made by King & Ritter (1998) that the more appropriate source geometry for a black hole system in outburst is in fact that of a central point source, leading to slightly stronger irradiation and a hot area of disc beyond 10^{12} cm. Furthermore, it is clear that for $R_{\rm irr} \lesssim 1.5\times 10^{12}$ cm, the total mass of irradiated gas will be consumed in the next few years and we would expect the outburst to terminate.

4 DISCUSSION

We have shown that the total mass of the accretion disc in GRS1915+105 just before the onset of an outburst is of order $\sim 10^{29}$ g. At the current mean mass accretion rate, inferred for an accretion efficiency $\eta \sim 0.1$, this is enough to power the outburst for 160 years. However, given the large scale of the disc, we surmise that a large fraction of the outer regions will remain too cool to sustain an outburst. Thus even the mass added to the outer edge of the disc from the companion star cannot replenish the hot inner disc region. Instead, it is stalled at larger radii where it does not participate in the outburst. In this scenario, equation 2 only involves the mass accretion rate and the wind loss rate. This is important, because the outburst time-scale is not affected by uncertainties in the mass transfer rate, which is extremely sensitive to the secondary core mass (King et al. 1997; Ritter 1999).

In fact, the values in Table 1 are calculated including $-\dot{M}_2 = 10^{-8}{\rm M}_{\odot}{\rm yr}^{-1}$ in equation 2, but since $-\dot{M}_2 << \dot{M}_1$, this is no different from the case $-\dot{M}_2 = 0$. If $-\dot{M}_2$ is higher than our estimate, either due to uncertainties in the evolutionary state of the system or due to an irradiation-induced burst of mass-transfer from the companion star, the outburst still cannot be prolonged because the additional mass remains in the cool outer disc. We can estimate the required $-\dot{M}_2$ at which this assumption breaks down. Dubus, Hameury & Lasota (2001) give an expression for the mass transfer rate required to trigger a heating wave at the outer edge of the disc:

$$\dot{M} = 3.3\times 10^{16}\,\delta^{-0.5}\left(\frac{\alpha}{0.02}\right)^{0.2}\left(\frac{M_1}{7}\right)^{-0.9}\left(\frac{T_{\rm c}}{2000\,{\rm K}}\right)R_{\rm disc,11}^{2.6}\ \ {\rm gs}^{-1} \tag{14}$$

where δ is a parameter with typical value $0.05 - 0.1$. So, for GRS1915+105 at $R_{\rm disc,11} = 27$, $\delta = 0.1$ and $T_{\rm c} = 1000$K, we have a required mass transfer rate $\dot{M} = 1.5\times 10^{20}\,{\rm gs}^{-1} \sim 2\times 10^{-6}{\rm M}_{\odot}{\rm yr}^{-1}$. While this is below the rate required to make the source persistent, it is still more than two orders of magnitude larger than would be expected from standard theories of binary evolution.

It is instructive to quantify the potential effect on our calculations of uncertainties in the accretion process itself and in the observed parameters of GRS1915+105. Taking the simplest case where $\dot{M}_{\rm wind} = 0$ and $-\dot{M}_2 = 0$, we see from equations 1 and 2 that $t_{\rm max} \propto M_{\rm disc}/\dot{M}_1$. Using equations 9 and 10, we find that

$$t_{\rm max} \propto M_1^{-0.35} \alpha_{\rm c}^{-0.86} \eta\epsilon, \tag{15}$$

allowing us to immediately identify the relative importance of uncertainties in the different parameters. It is surprising - but nevertheless a very desirable aspect of the model - that neither the luminosity nor the inferred accretion rate enter this relation at all. A lower accretion rate leads to a lower $R_{\rm irr}$ and a smaller available mass of hot gas. This means that the effect that any uncertainties in the distance have on the outburst time-scale is weakened. In fact, in our simple model for the surface density of the disc, where the profile is flat at most radii, we find in equation 9 that the mass scales as R^2. In this case, since $R_{\rm irr} \propto L_{\rm X}^{\frac{1}{2}}$, the accretion rate doesn't appear in equation 15. This is very important, because observational uncertainties in the distance - here we use $d = 12.5$kpc after Mirabel & Rodríguez (1994) but a more recent work using proper motions of jet components places the source about $2\,$kpc closer (Miller-Jones et al. 2005) - do not make any difference at all to the predicted outburst duration.

The black hole mass enters equation 15 rather weakly, though the observational uncertainties in this quantity are large. If the system is aligned with the jet, Harlaftis & Greiner (2004) state that $M_1 = 14 \pm 4.4\,{\rm M}_\odot$ for a jet inclination $i = 66 \pm 2^\circ$ (Fender et al. 1999). If the jets are misaligned with the plane of the disc and are precessing, the range of possible masses widens. Harlaftis & Greiner (2004) consider a system inclination offset by 10° to the jets. At the extremes of this range, the mass could be anything from $11.6 \pm 3.3\ {\rm M}_\odot$ to $16.9 \pm 5.9\,{\rm M}_\odot$. Over the entire range of possible masses $8{\rm M}_\odot < M_1 < 23{\rm M}_\odot$, our predicted outburst duration only changes by a maximum of 21%.

The quiescent viscosity, $\alpha_{\rm c}$ is a much more significant uncertainty. While the origin of viscous shear is well-understood for hot, ionized gases in terms of the magneto-rotational instability, our understanding of viscous processes in a cool, neutral gas is very limited. Therefore, an appropriate value for $\alpha_{\rm c}$ is hard to estimate. Our choice of $\alpha_{\rm c} = 0.02$ is well-motivated by the disc instability model and observations of quiescent intervals in dwarf novae, although rather different values have been suggested. Meyer-Hofmeister & Meyer (2001) argue that $\alpha_{\rm c} = 0.05$ based on a study of the quiescent intervals of shorter period X-ray transients. This would *decrease* our predicted time scales in Table 1 by a factor of two. Similarly, the accretion efficiency η could be higher than 0.1 given that the black hole is spinning. A higher efficiency means that a smaller accretion rate is required to power the same luminosity, and would result in a longer outburst. $\eta = 0.1$ is appropriate for a black hole spin $a \simeq 0.7$; at $a = 0.9$, $\eta \simeq 0.15$ is more appropriate, leading to an outburst duration 50% longer.

The key parameter in determining the size of the mass reservoir to power the outburst is the irradiation efficiency, ϵ. Of the disc irradiation models considered, the smallest fraction of irradiated disc is predicted by the inner disc source geometry described in King & Ritter (1998). Here, even for accretion at the Eddington limit, only the parts of the disc inside $R = 10^{12}\,{\rm cm}$ are illuminated by the incident X-rays. Defining this region as the only part of the disc capable of supporting an outburst, we calculate that its mass, of order $\sim 10^{28}$ g, is only sufficient to power an outburst for approximately 20 years assuming no wind loss. More efficient irradiating geometries mean that more of the disc can be illuminated, so increasing the mass available to power the outburst and hence its duration.

The only uncertainty not present in equation 15 is the magnitude of the mass loss in a wind, and we can see immediately from Table 1 that there is a factor of two difference in outburst duration between the case of zero and Eddington wind losses. The observed wind loss rate is substantial (Lee et al. 2002), but this depends on the (unknown) opening angle of the wind. Numerical simulations suggest that this should be fairly large (Proga & Kallman 2002), in which case the inferred mass loss rates are comparable to the accretion rates required to sustain the outburst. In this case, the reservoir of available disc mass will last only half as long as expected from accretion alone.

5 CONCLUSIONS

We have calculated upper and lower limits for the outburst time scale of GRS1915+105 for different values of the irradiation efficiency (i.e. different irradiation geometries). These limits correspond to zero and Eddington wind mass loss rates respectively. The time scales in Table 1 are computed for reasonable values of black hole mass, disc viscosity and accretion efficiency. The sensitivity of our results to uncertainties in these properties are discussed in Section 4, in particular equation 15.

The crucial factor that remains to be discovered is how efficient the irradiation actually is. It is clear that the mass budget for GRS1915+105 already seems very tight given all the competing factors. We are faced with the very interesting possibility that the outburst will come to an end in the next few years. If the outburst continues for substantially longer then we would have to conclude that there are additional factors at work.

The outer disc is the only feasible additional mass source in the system, and one way to tap this is via the wind. Scattering in this material can enhance the illumination of the outer disc, and there is observational evidence for this effect inferred from a detailed consideration of the outburst characteristics of neutron stars and black holes (Dubus et al. 1999). Indeed, scattering of this kind may be the only way to irradiate the disc at all: many simulations of discs irradiated by a central source show that the disc puffs up and self-shields itself from the X-rays (Cannizzo, Chen & Livio 1995; Dubus et al. 1999), in contradiction with observations showing conclusively that discs in these systems *are* irradiated.

The fraction of X-rays scattered onto the disc $C \sim \tau_{es}\Omega/2\pi$, where τ_{es} is the electron scattering optical depth and $\Omega/2\pi$ is the solid angle subtended by the material. The wind simulations of Proga & Kallman (2002) show $\Omega/2\pi \sim 0.3 - 0.5$, while the column density measured in the ionised absorber in GRS1915+105 implies $\tau_{es} \sim 0.01$ (similar optical depths are inferred for the accretion disc coronal sources) i.e. $C \sim 5 \times 10^{-3}$. If we assume that all of this X-ray flux incident on the disc goes into heating the gas, then $C \sim \epsilon$, giving a heated disc radius $\gtrsim 2 \times 10^{12}\,{\rm cm}$. However, if only a fraction of the incident X-rays heat the gas, we would expect ϵ and $R_{\rm irr}$ to be smaller.

The presence of the wind can give rise to a interesting feedback. A high accretion rate can lead to a strong wind that may be associated with more efficient irradiation. This will lead to a further increase in the central accretion rate. However, this cannot continue unchecked, because too strong a wind will deplete the mass in the inner disc region, and the accretion rate will fall. We will explore these ideas in a later paper.

Our calculation can be applied to the outbursts of shorter period X-ray transients. In many ways these are far simpler, because we would expect the whole disc to become irradiated and participate in the outburst. For example, taking the parameters of the black hole systems A0620-003 and GS2000+25, which both have orbital periods around 8 hours, we find that the total mass consumed during each outburst is about 55-70% of the calculated initial total disc mass. This assumes $\eta = 0.1$, zero wind mass loss and an exponential decay in central accretion rate calculated from the data given in Chen, Shrader & Livio (1997). However, we should point out that we do not expect this simple approach to work in all cases: while in general it is true that longer period systems tend to radiate more energy (and thereby have a higher inferred accretion rate), this is not always the case. For example, Aql X-1, with an orbital period of about 19 hours, does not undergo rare long outbursts, but frequent very short ones.

It is clear that there is still much to be learnt about accretion disc structure and how it is affected by irradiation in X-ray transients: for example, can the disc be directly illuminated or are the X-rays scattered down onto the disc? How efficient is the irradiating flux? If the current outburst of GRS1915+105 goes on and on, the conclusion that a large fraction of the disc is irradiated is inescapable. Since GRS1915+105 has the longest orbital period of any known transient (by some distance) and hence the largest disc, we may be faced with the possibility that *all* discs in X-ray transients can be fully, or almost fully, irradiated. The corollary of this is that should the outburst terminate in the next few years, we will have the exciting opportunity to determine the fraction of the disc that was irradiated and learn much about the efficiency of the process and the importance of mass loss in a wind.

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