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Mass transfer from the donor of GRS 1915+105

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Abstract. A scenario for a periodic filling and emptying of the accretion disc of the microquasar GRS1915+105 is proposed, by estimating the mass transfer rate from the donor and comparing it with the observed accretion rate onto the primary black hole. The mass of the Roche-lobe-filling donor ($1.2 \pm 0.2\ M_{\odot}$), the primary black hole mass ($14 \pm 4\ M_{\odot}$) and the binary orbital period of 33.5 d (Greiner et al. 2001b) predict for the donor spectral type and K-magnitude around K6 III and -2.6, respectively. The He-core of 0.28 $M_{\odot}$ of such a giant leads to evolutionary expansion along the giant branch with a conservative mass transfer rate of $\dot{M}_{\rm d} = (1.5 \pm 0.5) \times 10^{-8}\ M_{\odot}$/year. On the other hand, the average observed accretion rate onto the primary is ten times larger: $\dot{M}_{\rm obs} = 2.0 \times (\eta/0.1)^{-1}(d/12.5\ {\rm kpc})^2 \times 10^{-7}\ M_{\odot}$/y, where η is the efficiency of converting accretion into radiation. We propose a duty cycle with (5–10)(η/0.1) per cent active ON-state. The timescale of the (recurrent) OFF-state is identified as the viscosity time scale at the circularization radius (14 $R_{\odot}$) and equals $t_{\rm visc} = 370(\alpha/0.001)^{-4/5}$ years, where α is the viscosity parameter in the α-prescription of a classical disc. If the viscosity at the outer edge of the disc is small and η is close to the maximum available potential energy (per rest mass energy) at the innermost stable orbit, the present activity phase may still last another 10–20 years. We also discuss other solutions allowing a broader range of donor masses (0.6–2.4 $M_{\odot}$).

Key words. stars: binaries: close – stars: individual: GRS 1915+105

1. Introduction

Greiner et al. (2001a) identified the mass-donating secondary star of GRS 1915+105 to be a K-M III giant, indicating that this prototype microquasar is a low-mass X-ray binary (LMXB). Further, using the Very Large Telescope (VLT) and the band-heads of ^{12}CO and ^{13}CO, Greiner et al. (2001b) managed to obtain the radial velocity curve of the secondary. The orbital period of 33.5 days, the large mass function $f(M) = 9.5 \pm 3.0\ M_{\odot}$ and known jet-inclination (70°) permitted constraint of the primary black hole mass between $M_{\rm BH}$ = (10–18) $M_{\odot}$, assuming the donor mass to lie between $M_{\rm d}$ = (1.0–1.4) $M_{\odot}$. The large BH mass points to rapid rotation since the smallest inner disc radii modelled (see e.g. Belloni et al. 1997; Vilhu et al. 2001) are as small as 20 km, close to the last marginally stable orbit (0.5 $R_{\rm g}$) of an extreme prograde Kerr-hole of 14 $M_{\odot}$.

In the present paper we estimate the mass transfer rate from the evolving donor but allowing a broader range (0.6–2.4) $M_{\odot}$ for its mass to include e.g. a possible stripped giant. Further, we estimate the viscosity time scale at the circularization radius and the amount of mass accumulated there. Using the mean observed accretion rate over the past 6 years (via luminosity conversion) we arrive at an estimate for the timescale of the possible duty cycle, relevant also when discussing a link to ultraluminous sources (ULX) in other galaxies (King et al. 2001).

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2. Mass transfer rate from the evolving donor

We assume that the donor fills its Roche lobe and that the mass loss is determined by evolutionary expansion along the giant branch, conserving the orbital angular momentum. The properties along the giant branch (luminosity and radius) depend mainly on the He-core mass and less on the envelope mass. In this case an analytical simplification is possible (Webbink et al. 1983) and the procedure is also presented by Verbunt & van den Heuvel (1995). In particular, the radius and luminosity can be fitted with 3rd order polynomials on the core mass.

The growth of the core mass, resulting in an increase of the radius, is determined by the luminosity due to hydrogen shell burning which, in turn, depends completely on the core mass. In the conservative case, fixing the binary parameters and forcing the secondary to fill its Roche lobe, it is rather simple to compute the core mass and consequently the mass loss from the donor (we use Pop. I abundances $Z = 0.02$; for details see Webbink et al. 1983 and Verbunt & van den Heuvel 1995, p. 482).

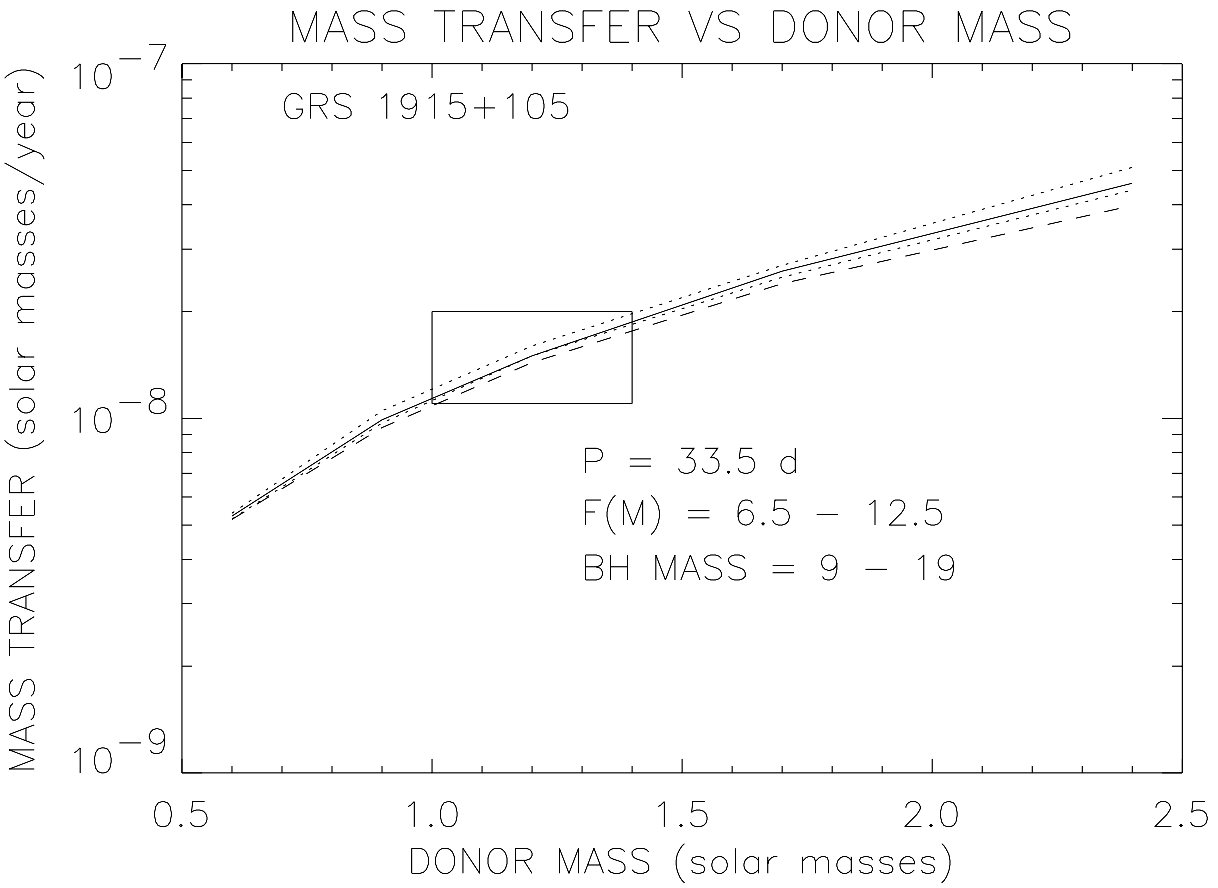

Fig. 1. Conservative mass transfer rates from the evolving K-giant donor of GRS 1915+105 using the analytic methods by Webbink et al. (1983) and Pop. I abundances $Z = 0.02$. The curves were computed for different donor masses (in $M_\odot$) using three mass function values inside the range $f(M) = 9.5 \pm 3.0\ M_\odot$ (Greiner et al. 2001b) with $P_{\rm orb}$ fixed to 33.5 d (solid line: $f(M) = 9.5$, dotted lines: $f(M) = 6.5$ and 12.5). The dashed line represents the analytic expression given by King et al. (2001, their Eq. (12)). The box shows the mass range suggested by Greiner et al. (2001b).

Table 1. Computed parameters for the evolving donor of GRS 1915+105 using $M_{\rm BH} = 14\ M_\odot$, $M_{\rm d} = 1.2\ M_\odot$, $P = 33.5$ day and assuming that the donor fills its Roche lobe (first line), using the analytic methods by Webbink et al. (1983) for $Z = 0.02$. The second line gives the ranges if the donor mass is varied between (0.6–2.4) $M_\odot$. The He-core mass ($M_{\rm He}$), luminosity (L), radius (R), binary separation (a) and the circularization radius ($R_{\rm circ}$) are given in solar units. The mass transfer from the donor ($\dot{M}_{\rm d}$) is in units of solar masses per year. The predicted spectral types and absolute K-magnitudes ($M_{\rm K}$) are estimated from $T_{\rm eff}$ and L using bolometric corrections and colours from Cox (2000).

Sp	$M_{\rm K}$	$M_{\rm He}$	L	R	$\dot{M}_{\rm d}$	a	$R_{\rm circ}$
K6	−2.6	0.28	77	21	1.5×10^{-8}	108	14
K5–M1	−2.2–−2.7	0.26–0.29	50–100	17–27	5×10^{-9}–5×10^{-8}	95–115	12–18

The first line in Table 1 gives the results for the best-fit masses given by Greiner et al. (2001b) ($14\ M_\odot + 1.2\ M_\odot$, $P = 33.5$ d). The second line gives the parameter ranges if the donor mass $M_{\rm d}$ is varied between (0.6–2.4) $M_\odot$ and satisfying the mass function constraint $f(M) = 9.5 \pm 3.0\ M_\odot$. The BH mass varies within these domains between 9–19 $M_\odot$. The mass transfer rate depends mainly on the donor mass as shown explicitly in Fig. 1. It follows closely the analytic expression given by King et al. (2001; their Eq. (12), the dashed line in Fig. 1). In particular, the uncertainties in the mass function have minor effects on this relation.

3. Duty-cycle time scales

In the conservative case, the mass leaving the donor via the L1-point settles down into a Keplerian orbit around the primary BH, the radius of which is called the "circularization radius". This radius is given in Table 1 as computed from the analytic approximation to numerical data (Frank et al. 1992 (FKR), p. 56, Eq. (4.18)):

$$R_{\rm circ} = 4(1+q)^{4/3}(0.500 - 0.227\log(q))^4 P_{\rm day}^{2/3}, \qquad (1)$$

where q is the mass ratio $M_{\rm d}/M_{\rm BH}$.

Due to the viscosity, the torus at $R_{\rm circ}$ will be stretched and flattened into a disc on a viscous time scale (by angular momentum transfer). The size of the viscosity is highly uncertain but in the α-prescription of classical disc theory it is parameterized and the viscous time scale at $R_{\rm circ}$ has a scaling law (see FKR p. 99, Eq. (5.63)):

$$t_{\rm visc} = 370(\alpha/0.001)^{-4/5}(M_{\rm BH}/14)^{1/4}(\dot{M}_{\rm d}/1.5E-8)^{-3/10} \times (R_{\rm circ}/14)^{5/4} \text{ years} \quad (2)$$

where the parameters are scaled to those used in Table 1 for the best-fit binary parameters and $\alpha = 0.001$. We may call this the *recurrence time* during which a new disc is formed if the old one has been rapidly swallowed into the BH. The mass accumulated in the torus around $R_{\rm circ}$ during this time equals to $M_{\rm accum} = t_{\rm visc} \times \dot{M}_{\rm d}$.

Surprisingly, $M_{\rm accum}$ is roughly equal to the mass of a classical viscous disc (using α-prescription, gas pressure and Kramer's opacity) if the outer radius is set equal to $R_{\rm circ}$ and $2 \times 10^{-7}\ M_\odot$/year is used for the disc accretion. This accretion rate can be derived from the RXTE observations over the past six years. The ASM light curve gives a time-averaged mean value of 58 counts/s (0.77 in the Crab-units) between 2–13 keV which corresponds to a total intrinsic luminosity $L = 1.2 \times 10^{39}\ (d/12.5\ \rm kpc)^2$ erg/s using PCA+HEXTE fits by Vilhu et al. (2001). The distance d is scaled to the mean value 12.5 kpc given by Chaty et al. (1996) with ± 1.5 kpc uncertainty. This luminosity is slightly below the Eddington luminosity of a 14 $M_\odot$ star and corresponds to a mass accretion rate

$$\dot{M}_{\rm obs} = 2.0 \times 10^{-7}(\eta/0.1)^{-1}(d/12.5\ {\rm kpc})^2 M_\odot/{\rm year}, \quad (3)$$

if η is the efficiency of converting accretion to radiation ($L = \eta \dot{M}_{\rm obs} c^2$). For a non-rotating black hole the maximum available gravitational potential energy (per rest mass energy) at the innermost stable orbit is 0.06–0.1, while for an extreme Kerr-hole the efficiency may be as high as 0.4 (see FKR, p. 191).

The observed high accretion rate eats the mass from the torus on a timescale $t_{\rm active} = M_{\rm accum}/\dot{M}_{\rm obs}$. We call this the *"activity time"* and it is one order of magnitude shorter than the recurrence time = $t_{\rm visc}$:

$$t_{\rm active}/t_{\rm recurrence} = (0.05\text{–}0.1)(\eta/0.1). \quad (4)$$

Together these two timescales form a *duty-cycle* and their estimates are presented in Table 2.

4. Discussion and conclusions

We have estimated the He-core mass (around 0.28 $M_\odot$) of the donor of GRS 1915+105 for the binary parameters given by Greiner et al. (2001b). The evolutionary expansion of the donor leads to a conservative mass transfer rate $\dot{M}_{\rm d} = (1.5 \pm 0.5) \times 10^{-8}\ M_\odot$/y which is ten times smaller than the accretion rate derived from the mean ASM light curve over the past 6 years, and using an efficiency of 0.1 to convert the mass infall into radiation: $\dot{M}_{\rm obs} = 2.0 \times (\eta/0.1)^{-1} \times 10^{-7}\ M_\odot$/y, for a distance of 12.5 kpc. We propose that these two numbers determine the duty cycle where the active phase (as observed at present) is ten times shorter than the quiescent one.

Table 2. Viscosity time scale $t_{\rm visc}$ (recurrence time) at the circularization radius, the mass $M_{\rm accum}$ accumulated from the donor during $t_{\rm visc}$ and the time scale $t_{\rm active}$ during which the BH swallows $M_{\rm accum}$ with the observed mean accretion rate $2 \times 10^{-7}(\eta/0.1)^{-1}(d/12.5\ {\rm kpc})^2\ M_\odot$/year where η is the accretion to radiation conversion factor and d the source distance. *All the values should be multiplied by* $(\alpha/0.001)^{-4/3}$ where α is the viscosity parameter in the α-prescription of classical discs. The models are the same as in Table 1.

$t_{\rm visc}$ years	$M_{\rm accum}/M_{\rm sun}$	$t_{\rm active}$ / $(\eta/0.1)$ years
370	5.5×10^{-6}	28
200–700	$(3.7\text{–}9.0) \times 10^{-6}$	20–45

We identify the duration of the quiescent phase (*recurrence time*) as the viscous timescale at the circularization radius and estimate its value to be $370 \times (\alpha/0.001)^{-4/5}$ years (α = the viscosity parameter in the α-prescription). The corresponding active phase lasts $28 \times (\eta/0.1)(\alpha/0.001)^{-4/5}$ years and is comparable to the present activity phase which has already lasted for ten years, if the small $\alpha = 0.001$ used can be justified at the outer edge of the disc.

The α-parameter is highly uncertain and consequently so are the timescales derived. However, a comparison can be made with the recurrent X-ray Nova and Soft X-ray Transient A0620-003, using its parameters during quiescence: $M_{\rm BH} = 10\ M_\odot$, $M_{\rm d} = 0.7\ M_\odot$ and $P = 7.75$ hours (Tanaka & Lewin 1995). The accretion rate at the outer disc during quiescence, as derived from optical observations (McClintock et al. 1995), equals $\dot{M}_{\rm d} = 10^{-10}\ M_\odot$/y which we identify as the mass transfer rate from the donor. We note that the observed X-ray luminosity during quiescence implies much smaller accretion in the inner regions of the disc (Narayan et al. 1996). During the maximum outburst the accretion onto the primary black hole probably approached the Eddington rate $\dot{M}_{\rm obs} = 10^{-7}\ M_\odot$/y for $\eta = 0.1$, with an e-folding time of one month (Tanaka & Lewin 1995). The circularization radius is 0.60 $R_\odot$ leading to $t_{\rm visc} = 30$ years (using $\alpha = 0.001$ in Eq. (2)) which is briefly consistent with the two observed outbursts (1917 and 1975) supporting the idea that the disc filling time is equal to the viscosity timescale at $R_{\rm circ}$ with small α. The mass accumulated is small ($3 \times 10^{-9}\ M_\odot$) and consequently the predicted active phase of A0620-003 is short (10 days) but of the same order of magnitude than the observed e-folding time.

At present there are more sophisticated disc-models available than the simple α-prescription used. These include e.g. irradiated disc-models (see King 2000, and references therein). Their usage would affect the viscosity timescale for a fixed α but probably less than the uncertainty in α itself.

If the mass of the donor of GRS 1915+105 is higher (2.4 $M_\odot$, instead of 1.2 $M_\odot$ as used in the above estimate), the mass transfer from the donor will be increased to 5×10^{-8} $M_\odot$/y. Further, if at the same time we increase the efficiency of the BH conversion to radiation to 0.4 (instead of 0.1), like in the case of an extreme prograde Kerr-hole, then $\dot{M}_{\rm d}$ and $\dot{M}_{\rm obs}$ become equal. In this most extreme case the reasons behind the quiescent/active states must be searched elsewhere, e.g. in strong advection (ADAF) during the quiescence. We also checked that the hydrogen ionization zone (at around $R_\odot$) is always inside the circularization radius and may thus be the trigger for the limit-cycle instability lasting for the whole activity phase.

The models in Table 1 (including uncertainties in the donor mass) predict bolometric luminosities $L = (50–100)L_\odot$, surface effective temperatures $T_{\rm eff}$ = 3800–4000 K and gravities $\log(g)$ = 1.7–1.9. These correspond to absolute K-magnitudes between −2.7–−2.2 which are inside the limits (−2–−3) given by Greiner et al. (2001a), but a more accurate value could properly fix the donor mass, and consequently its mass transfer rate.

Another complication which should be studied is the possible effect of X-ray heating of the donor. Hard photons above 10 keV can penetrate through its photosphere into the convective zone affecting its structure (Podsiadlowski 1991; Vilhu et al. 1994). The mean luminosity of GRS 1915+105 above 10 keV is roughly 2×10^{38} erg/s (Vilhu et al. 2001) of which 0.5–1 per cent is captured by the donor, assuming no screening of the disc. If the activity phase lasts 1/10 of the whole cycle then $(10–30)L_\odot$ can be deposited in deep layers of the donor, averaged over the longer thermal timescale of the donor envelope, leading probably to an overestimate of the He-core mass and mass transfer rate.

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References

Cox, A. N. 2000, Allen's Astrophysical Quantities, 4th ed. (AIP Press, Springer-Verlag)

Belloni, T., Mendez, M., King, A. R., van der Klis, M., & van Paradijs, J. 1997, ApJ, 488, L109

Chaty, S., Mirabel, I. F., Duc, P. A., Wink, J. E., & Rodriquez, L. F. 1996, A&A, 310, 825

Frank, J., King, A., & Raine, D. 1992, Accretion Power in Astrophysics, 2nd ed. (Cambridge Astrophysics Series), 21 (FKR)

Greiner, J., Cuby, J. G., McCaughrean, M. J., Castro-Tirado, A. J., & Mennckent, R. E. 2001a, A&A, 373, L37

Greiner, J., Cuby, J. G., & McCaughrean, M. J. 2001b [astro-ph/0111538]

King, A. R., Davies, M. B., Ward, M. J., Fabbiano, G., & Elvis, M. 2001, ApJ, 552, L109

King, A. R. 2000, MNRAS, 315, L33

McClintock, J. E., Horne, K., & Remillard, R. A. 1995, ApJ, 442, 358

Narayan, R., McClintock, J. E., & Yi, I. 1996, ApJ, 457, 821

Podsiadlowski, Ph. 1991, Nature, 350, 136

Tanaka, Y., & Lewin, W. H. G. 1995, in X-ray Binaries, ed. W. H. G. Lewin, J. van Paradijs, & E. P. J. van den Heuvel (Cambridge Univ. Press), 126

Verbunt, F., & van den Heuvel, E. P. J. 1995, in ed. W. H. G. Lewin, J. van Paradijs, & E. P. J. van den Heuvel, X-ray Binaries (Cambridge Univ. Press), 457

Webbink, R. F., Rappaport, S., & Savonije, G. J. 1983, ApJ, 270, 678

Vilhu, O., Ergma, E., & Fedorova, A. V. 1994, A&A, 291, 842

Vilhu, O., Poutanen, J., Nikula, P., & Nevalainen, J. 2001, ApJ, 553, L51