The jet kinetic power, distance and inclination of GRS 1915+105

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ABSTRACT

We apply a recently developed technique of calculating the minimum jet kinetic power to the major mass ejections of the black hole binary GRS 1915+105 observed in radio wavelengths in 1994 and 1997. We derive for them the distance-dependent minimum power, and the corresponding mass flow rate and the total energy and mass content. We find that a fast increase of the jet power with the increasing distance combined with the jet power estimates based on the bolometric luminosity imply that the source distance is \( \lesssim 10 \) kpc. If the jet in GRS 1915 contains ions, their bulk motion dominates the jet power, which was either neglected or not properly taken into account earlier. We also reconsider the parameters of the binary, and derive the current best estimates of the distance-dependent black hole mass and the inclination based on existing measurements combined with the kinematic constraints from the mass ejections. We also find that the measurement of the donor radius of Steeghs et al. implies the distance to the system of \( \lesssim 10 \) kpc, in agreement with the estimate from the jet power.

Key words: acceleration of particles – radiation mechanisms: non-thermal – stars: individual: GRS 1915+105 – ISM: jets and outflows – radio continuum: stars.

1 INTRODUCTION

GRS 1915+105 is a Galactic black hole binary with a number of highly interesting and unique properties. It is a long-lived transient, whose outburst began in 1992 (Castro-Tirado, Brandt & Lund 1992) and is still lasting. It was the first Galactic source discovered to show superluminal motion (Mirabel & Rodríguez 1994, hereafter MR94). It is unusually highly variable in X-rays (e.g. Belloni et al. 2000), and it is one of the intrinsically brightest Galactic X-ray binaries, occasionally radiating above the Eddington limit (Done, Wardziński & Gierliński 2004). The minimum jet power in the superluminal ejection in 1994 was claimed to be highly super-Eddington (Gliozzi, Bodo & Ghisellini 1999).

Here, we reconsider the minimum kinetic jet power, the mass flow rate and the total energy and mass of the major mass ejections of GRS 1915+105 observed in 1994 (MR94) and in 1997 (Fender et al. 1999, hereafter F99). We use the method developed in Zdziarski (2014, hereafter Z14). It minimizes the kinetic jet power associated with both the jet internal energy content and the ion rest mass, correcting some earlier estimates. We note, in particular, that finding the minimum comoving energy, adding the associated ions and transforming to the observer frame does not give the minimum of the power (Z14). The jet power becomes extremely high close to the maximum kinematically allowed distance for a given ejection, but it also decreases very fast with the decreasing distance.

Recently, the black hole mass and distance to GRS 1915+105 were measured by Steeghs et al. (2013, hereafter S13). We use their results to derive a distance-dependent estimate of the black hole mass. We also use their measurement of the donor radius to derive a constraint on the distance.

2 THE PARAMETERS OF GRS 1915+105

The jet inclination, \( i \), and the velocity, \( \beta_j \), can be measured using the angular velocities of the approaching and receding condensations, \( \mu_a \) and \( \mu_r \), respectively, under the assumption that the ejections were symmetric (MR94). We have the relationships

\[
i = \arctan \frac{2\mu_a \mu_r D}{(\mu_a - \mu_r)c^2}, \quad \Gamma_j = \frac{\mu_a + \mu_r}{2 \left[ \mu_a \mu_r \left( 1 - \frac{2c^2}{\Gamma_j^2 \mu_a \mu_r} \right) \right]^{1/2}}. \tag{1}
\]

where \( D \) is the source distance and \( \Gamma_j \) is the jet Lorentz factor. [Note that \( \sin(\arctan x) = x/(1 + x^2)^{1/2} \), which can be used in equations (4)–(5) below for a given measurement of \( \mu_j \).] From \( \Gamma_j(D) \), we see that there is the maximum possible distance, \( D_{\text{max}} = c(\mu_a \mu_r)^{-1/2} \), corresponding to \( \Gamma_j \to \infty \). The Doppler factors, \( \delta_a = \Gamma_j^{-1}(1 + \beta_j \cos i)^{-1} \), of the approaching and receding ejecta are

\[
\delta_a = \left[ \frac{\mu_a}{\mu_r} \left( 1 - \frac{D^2}{c^2} \mu_a \mu_r \right) \right]^{1/2},
\]

\[
\delta_r = \frac{\mu_r}{\mu_a} \left[ \frac{\mu_r}{\mu_a} \left( 1 - \frac{D^2}{c^2} \mu_a \mu_r \right) \right]^{1/2}.
\tag{2}
\]
respectively. We then calculate the source-frame spectral luminosity from the approaching blob at $v/\delta a$ as

$$L_s(v/\delta a) = 4\pi D^2 F_s(v) \delta a^3,$$  

(3)

where $F_s(v)$ is the measured flux of the approaching blob at $v$. We note that MR94 and F99 found that the observed ratios between the fluxes of the approaching and receding ejecta are somewhat lower than the ratio, $(\delta_r/\delta_l)^{(1+\alpha)}$, where $\alpha$ is the energy spectral index ($F_s(v) \propto v^{-\alpha}$), implied by equation (3). Then, based on the results of MR94 only, Atoyan & Aharonian (1999) proposed that the ejections were not intrinsically symmetric, which could explain the lower observed flux ratio. This seems not confirmed by the results of F99, who also found a lower flux ratio. The ratio could be lower if the emission were from continuous jet and counterjet (Sikora et al. 1997). However, the radio images, showing individual blobs, of MR94 and F99 appear not to be compatible with that. We will use equation (3), bearing in mind this issue as a caveat. Since the obtained values of $\delta a$ are close to unity for the values of $D$ we determine, a possible error due to this assumption is insignificant. Hereafter, we use the standard propagation of errors to calculate the uncertainties on the obtained quantities.

We consider two major ejection events from GRS 1915+105 which began on 1994 March 19 (MR94) and 1997 October 29 (F99). Their measured angular velocities were $\mu_\alpha = 17.5 \pm 0.3$ mas d$^{-1}$ (as updated in Rodríguez & Mirabel 1999) and $23.6 \pm 0.5$ mas d$^{-1}$, and $\mu_\delta = 9.0 \pm 0.1$ mas d$^{-1}$ and $10.0 \pm 0.5$ mas d$^{-1}$, respectively. In addition, three more events with both $\mu_\alpha$ and $\mu_\delta$ measured are listed by Rodríguez & Mirabel (1999, see also Miller-Jones et al. 2007). The implied values of the inclination are consistent with being the same for all five events, though the additional three have much larger uncertainties. In particular, the values implied by the radial velocities for 1994 March and 1997 October are $(67.0 \pm 0.6, 65.6 \pm 1.9)$, $(65.0 \pm 0.6, 63.5 \pm 2.0)$ and $(62.6 \pm 0.7, 61.0 \pm 2.1)$ at $D = 11$, 10 and 9 kpc, respectively. Note that the stated uncertainties on $\mu_\alpha$ and thus on $i(D)$, are significantly lower for the former event than for the latter.

S13 argued, based on the results of Steiner & McClintock (2012, who corrected a numerical error by a factor of 50 in the alignment time-scale given by Maccarone 2002), that the axes of the jet and the binary plane in GRS 1915+105 are likely aligned, which assumption is also commonly adopted in other estimates of the binary parameters of GRS 1915+105. Still, the possibility of a misalignment should be kept in mind, given the lack of full understanding of the alignment process. Assuming alignment, the jet is not precessing, and its inclination angle remains the same for all the observations. Thus, we calculate the weighted average of the inclination and its standard error, though we note that it is strongly dominated by the two major events. Fig. 1(a) shows the values of $i$ and its uncertainty for the two major events separately and for the average as a function of the distance.

We then consider the implications for the binary parameters. We use the recent results of S13, who obtained the orbital period of $P_{\text{orb}} = 33.85 \pm 0.16$ d, the velocity semi-amplitude of $K_2 = 126 \pm 1$ km s$^{-1}$ and the rotational broadening of the donor of $v \sin i = 21 \pm 4$ km s$^{-1}$. Assuming corotation and the donor filling the Roche lobe, we have the standard formulae for the mass ratio, $q = M_2/M_1$ (e.g. Wade & Horne 1988), and the radius of the donor, $R_2$,

$$q^{1/3}(1+q)^{2/3} = \frac{3^{11/3}(v \sin i)}{2K_2}, \quad R_2 = \frac{P_{\text{orb}}(v \sin i)}{2\pi \sin i},$$

(4)

respectively, where the Roche lobe radius ratio for $q \ll 1$ of Paczyński (1971) has been used. The equation for $q$ yields a cubic-polynomial solution, which gives $q = 0.043 \pm 0.023$ (S13). On the other hand, $R_2$ is a function of $i$, which we show in Fig. 1(b).

The black hole mass is

$$M_1 = \frac{P_{\text{orb}}K_2^2(1+q)^2}{2\pi G \sin^3 i},$$

(5)

and $M_2 = qM_1$. S13 used the inclination range of F99. As we note above, it is significantly less accurate than that of MR94. Also, S13 gave their mass estimate including the entire distance-related inclination uncertainty of F99. Fig. 1(c) shows instead the range of $M_1$ as a function of the distance and using the weighted average of the inclination from the available mass-ejection events.

We then consider the distance. The maximum kinematic distances for the 1994 and 1997 events are $D_{\text{max}} \simeq 13.6 \pm 0.1, 11.3 \pm 0.3$ kpc, respectively, and thus the latter gives the current upper limit. The distance implied by the radial systemic velocity is $10.4 \pm 1.3$ kpc (S13). Zdziarski et al. (2005) considered the distance implied by the theoretical K-star surface brightness compared to the observed
magnitude, see their equation 1. This yields the angular diameter of the secondary as \( s \simeq 0.0175-0.0220 \) mas. The corresponding physical radius of the secondary is \( R_2 = Ds/2 \). The minimum \( R_2 \) as a function of \( D \) allowed by the minimum \( s \) above is plotted by the magenta dashed line in Fig. 1(b). We see that the distance compatible with this constraint is \( \lesssim 10 \) kpc. Finally, the new parallax distance from radio VLBA measurements is \( 8.6^{+2.0}_{-1.6} \) kpc (Reid et al. 2014). Combining the above determinations, we find the likely distance range as \( D \simeq 9-10 \) kpc. This is somewhat less than the distance of 11 kpc preferred by Zdziarski et al. (2005) because now both the current measurement of \( \sin i \) of S13 is lower than the previous one by Harlaitis & Greiner (2004) and the determination of the systemic-velocity distance by S13 is lower than the previous one by Greiner, Cuby & McCaughrean (2001). Our current range of \( D \) is still compatible with other observational constraints listed in Zdziarski et al. (2005). Also, a value of \( D \) significantly less than 11 kpc is implied by considering the jet kinetic power, as we show below.

The values of \( M_1 \) for our preferred values of \( D \) are then somewhat higher than \( 10.1 \pm 0.6 \) \( M_\odot \) given as the best estimate by S13, see Fig. 1(c). The reason is simply that our values of \( D \) are lower than 10–12 kpc used by S13 to obtain their range of \( M_1 \).

3 THE JET POWER OF GRS 1915+105

MR94 gave rather accurate estimates of \( \Gamma_j \) and \( i \) for their estimated \( D = 12.5 \) kpc, but, as pointed out by Fender (2003), \( \Gamma_j \) strongly depends on \( D \). This is illustrated in Fig. 2, which shows the dependences of \( \Gamma_j \) (increasing with \( D \)) for the best-fitting values of the radial velocities of the two data sets. Fig. 2 also shows the dependences of the Doppler factor \( \delta_j \), decreasing with \( D \).

The measured peak flux of the 1994 flare was 660 mJy at \( \nu = 8.4 \) GHz on 1994 March 24 (Rodríguez et al. 1995). The observed 1.4–15 GHz spectrum is well fitted by a power law with the spectral index of \( \alpha \simeq 0.43 \) [\( F(\nu) \propto \nu^{-\alpha} \)], see Fig. 3, corresponding to the electron power-law index of \( \gamma \simeq 1.86 \). Rodríguez et al. (1995) give the total fluxes, but the flux of the approaching component dominates (MR94), and thus we use the total values. The measured peak flux of the 1997 flare was 550 mJy at \( \nu = 2.3 \) GHz on 1997 October 29 (F99). The data for that day are at 2.3, 8.3 and 15 GHz. The 2.3–8.3 GHz spectrum has \( \alpha \simeq 0.8 \) (F99), though this slope underpredicts (at \( \approx 120 \) mJy) the average 15 GHz peak flux on that day, see fig. 4 of F99, which would imply a lower average \( \gamma \). That flux also shows strong QPOs, implying a sequence of new ejections. Still, we adopt \( \alpha = 0.8 \) for consistency with F99, corresponding to \( p = 2.6 \).

We assume that the spectrum is emitted from \( \nu_{0} = 0.5 \) GHz to \( \nu_{\text{max}} = 50 \) GHz (observer frame), consistent with the data. This photon energy range spans two decades, corresponding to one decade of the electron Lorentz factor. This is a conservative assumption, which yields good estimates of the minimum jet power. We assume that the only electrons, or e\(^+\), are those in a relativistic power-law distribution yielding the synchrotron power law from \( \nu_{0} \) to \( \nu_{\text{max}} \).

We consider two cases of the jet composition, one with cold ions and the other having a spherical symmetry in its frame and thus we do not apply the relativistic transformation of the length along the jet. We use then the method minimizing the jet power for a given optically thin synchrotron frequency range, see Z14. We use equations (1)–(3) above to determine the jet-frame \( \Gamma_j \) and \( L_{\text{p}}(\nu) \) as functions of the distance. The behaviour of \( \delta_j \) and \( \Gamma_j \) shown in Fig. 2 leads to a fast decline of \( P_{\text{min}} \) with decreasing \( D \).

At \( D = 12.5 \) kpc, we obtain the minimum jet power of \( P_{\text{min}} \simeq 1.5 \times 10^{38} \text{erg s}^{-1} \) of the 1994 flare for the uniform model, which is a factor of \( \approx 4 \) lower than the corresponding estimate by Gioiatti et al. (1999), multiplying their value by 2 to include the counterjet). The main cause of the difference is our more limited range of the electron Lorentz factors, which is \( \gamma \in [4, 440] \), compared to \( [1, 10^3] \) of them. Also, our definition of the jet power is different, see Z14, and the method different, as they assumed a fixed frequency-integrated synchrotron luminosity. Taking into account those differences, our results are fully consistent with those of Gioiatti et al. (1999). They claimed the 1994 flare had to be strongly super-Eddington. However, as we discuss above, the current limit on \( D \) is \( 11.3 \pm 0.3 \) kpc (F99), and \( P_{\text{min}} \) decreases rather fast with decreasing \( D \), which we show below. Thus, their results are no longer applicable to GRS 1915+105.

We then compare our results for the 1997 flare with those of F99. At \( D = 11 \) kpc, we obtain \( P_{\text{min}} \simeq 1.4 \times 10^{41} \text{erg s}^{-1} \) with the uniform model, which is a factor of \( >30 \) higher than the corresponding estimate of F99 (multiplying the power given in their
The minimum total jet power. For the 1997 flare at 10 kpc, we obtain $P_{\text{min}} \simeq 7.5 \times 10^{39}$ erg s$^{-1}$, $B_{\text{min}} \simeq 0.17$ G for the cosmic abundances and $P_{\text{min}} \simeq 1.6 \times 10^{39}$ erg s$^{-1}$, $B_{\text{min}} \simeq 0.09$ G for $e^\pm$ pairs. At the cosmic abundances, we find the ratio of the jet power in electrons to that in ions of $P_e/P_i \simeq 0.18$, 0.08 for the 1994 and 1997 flare, respectively. These estimates are thus insensitive to the assumed source radius, which is the case for the cosmic power dominating (Z14). Indeed, the values of the critical radius below which the solution becomes independent of $r_i$ (Z14) are $r_{\text{cr}} \simeq 4.4 \times 10^{16}$, $\simeq 2.2 \times 10^{17}$ cm for the 1994 and 1997 flares, respectively, which are $\gg$ our values of $r_i$. We note that a possible clumpiness of the jet material, as quantified by the clump volume filling factor, $f$, can reduce the minimum jet power by a factor of $f^{1/3}$ in the case of the dominant ionic power, and $f^{1/7}$ for the case of pair plasma (Z14). If e.g. $f \sim 0.01$, the minimum power can be reduced by a factor of several.

Fig. 4 shows that the kinetic jet power critically depends on the actual distance to GRS 1915+105. We can compare it to the bolometric luminosity of GRS 1915+105, dominated by accretion. The results of Allen et al. (2006) and Merloni & Heinz (2007) show that the jet kinetic power in AGNs is strongly correlated with both the accretion rate and the bolometric luminosity, $L_{\text{bol}}$. In particular, Merloni & Heinz (2007) find the correlation of $\lg(P_j/L_{\text{bol}}) = (0.49 \pm 0.07)\lg(L_{\text{bol}}/L_{\text{Edd}}) - 0.78 \pm 0.36$, where $L_{\text{Edd}}$ is the Eddington luminosity. Thus, we expect $P_j \leq L_{\text{bol}}$ at $L_{\text{bol}} \sim L_{\text{Edd}}$. Furthermore, results of Merloni, Heinz & di Matteo (2003) and Heinz & Sunyaev (2003) show that the same underlying relationship between jets and accretion flow is present in both AGNs and black hole binaries. Indeed, the jet power of Cyg X-1 estimated by Gallo et al. (2005) satisfies the correlation of Merloni & Heinz (2007). Furthermore, the jet power of Cyg X-3 in its bright state has been estimated based on a model of its $\gamma$-ray emission and found $L_{\text{bol}}$, consistent with the above correlation (Zdziarski et al. 2012). The RXTE/ASM monitoring shows that the X-ray state during the 1997 event (F99) was among the brightest ones observed from this source, which implies that its maximum bolometric luminosity was then moderately super-Eddington, $\lesssim 2L_{\text{Edd}}$ (Done et al. 2004). Thus, based on the above considerations, we may expect (but not prove) the jet kinetic power to be approximately sub-Eddington.

Fig. 4 shows that the 1994 and 1997 jets are sub-Eddington provided $D \lesssim 10.1$ and 8.8 kpc, respectively, using the ionic model with the Gaussian density distribution. In the case of pair plasma, the respective jets are sub-Eddington for $D \lesssim 11.4$ and 9.9 kpc.

The minimum ion mass flow rate, $M_{\text{min}}$, for the Gaussian model is shown in Fig. 5(a). We see that if $D \lesssim 10$ kpc, $M_{\text{min}} \lesssim L_{\text{Edd}}/c^2$. The corresponding masses for the ionic model (in the jet frame) are shown in Fig. 5(b). In the case of the pair model, both the minimum $M$ and $M$ are lower by $\sim \mu_e m_p/m_e \sim 0.00$. Fig. 5(c) shows the total energy content corresponding to the minimum jet power for both ionic and pair cases.

The ejecta at the time of the 1994 measurements were optically thin to synchrotron self-absorption; the radial optical depth, $\tau$, at $\nu_{\text{min}} = 0.5$ GHz is $\simeq 0.43$, and $\simeq 10^{-4}$ at $\nu = 8.6$ GHz. Similar values are found for the 1997 flare.) The peak 8.6-GHz flux, corresponding to $\tau \sim 1$, was thus achieved earlier than on 1994 March 24, and the minimum power at that time was higher. On the other hand, the blob expanded after March 24, which caused the electrons to cool adiabatically, and also reduced the magnetic field strength. The synchrotron luminosity should then decrease, and the fluxes in table 1 of MR94 are consistent with this. When we apply the minimum jet power method to those later stages, we find the minimum total power decreasing. On the other hand, there was no
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4 CONCLUSIONS

We have calculated the minimum jet power for the major mass-ejection events of GRS 1915+105 in 1994 and 1997. We have taken into account the power component associated with the ion bulk motion, which we have found to dominate, and which was neglected in an earlier estimate. We have found that the jet power becomes very high close to the maximum allowed kinematically for a given ejection event. On the other hand, it becomes much lower and in agreement with the average relationship between the jet power and the bolometric luminosity for accreting black holes at a distance \( \lesssim 10 \) kpc. We also have calculated the mass flow rate in the jets and their total mass and energy content.

We have also updated the distance estimate based on a theoretical relationship of the donor radius and its magnitude for K stars (Zdziarski et al. 2005) using the \( v \sin i \) measurement of S13. We obtained \( D \lesssim 10 \) kpc, in full agreement with the estimate based on the jet power. In addition, we have presented a relatively accurate estimate of the black hole mass as a function of the distance using the weighted average of the inclination from the observed mass ejections together with the optical measurements of S13.

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