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MULTIPLE RELATIVISTIC OUTBURSTS OF GRS 1915+105: RADIO EMISSION AND INTERNAL SHOCKS

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RESUMEN

Presentamos observaciones en 5GHz de MERLIN del microcuasar GRS 1915+105 durante dos episodios de actividad en marzo de 2001 y julio de 2001, siguiendo la evolución de las componentes en el chorro conforme se alejan del núcleo del sistema. Los movimientos propios restringen la velocidad del chorro a $> 0.57c$, pero la incertidumbre en la distancia a la fuente no permite una determinación precisa de la velocidad. No se observa deceleración alguna en las componentes hasta una separación de $\sim$ 300 mas. Nuestros datos proporcionan evidencia a favor del modelo de choques internos en los que la velocidad del chorro aumenta, llevando a choques en el flujo pre-existente antes de que el chorro cese su actividad. El chorro compacto nuclear se establece de nuevo en menos de dos días, y permanece visible durante ambos episodios. Hacemos un balance energético de la fuente para varias distancias posibles, y concluimos que se necesita de una potencia mínima de 1–10 % de $L_{\rm Edd}$ para producir el chorro.

ABSTRACT

We present 5-GHz MERLIN radio images of the microquasar GRS 1915+105 during two separate outbursts in 2001 March and 2001 July, following the evolution of the jet components as they move outwards from the core of the system. Proper motions constrain the intrinsic jet speed to be $> 0.57c$, but the uncertainty in the source distance prevents an accurate determination of the jet speed. No deceleration is observed in the jet components out to an angular separation of $\sim$ 300 mas. Our data lend support to the internal shock model whereby the jet velocity increases leading to internal shocks in the pre-existing outflow before the jet switches off. The compact nuclear jet is seen to re-establish itself within two days, and is visible as core emission at all epochs. The energetics of the source are calculated for the possible range of distances; a minimum power of 1–10 per cent $L_{\rm Edd}$ is required to launch the jet.

Key Words: **ACCRETION, ACCRETION DISKS — ISM: JETS AND OUTFLOWS — RADIO CONTINUUM: STARS — STARS: INDIVIDUAL (GRS 1915+105) — X-RAYS: STARS**

1. INTRODUCTION

GRS 1915+105 was the first Galactic source observed to exhibit superluminal motion (Mirabel & Rodríguez 1994), and studies of its radio jets and jet-disc interactions have been important in developing our understanding of the link between accretion and jet outflows in X-ray binary systems. The source was discovered in 1992 (Castro-Tirado, Brandt, & Lund 1992), and is believed to comprise a $14 \pm 4 M_{\odot}$ black hole (Greiner, Cuby, & McCaughrean 2001) accreting from a K-M III star (Greiner et al. 2001a) via Roche lobe overflow.

Jet outflows now seem to be ubiquitous in accreting systems such as black hole X-ray binaries. Such sources spend the majority of their time in quiescence, with extremely low X-ray and radio luminosities and a relatively hard X-ray spectrum. The radio jets are persistent, steady, and self-absorbed with a flat radio spectrum (Stirling et al. 2001; Dhawan, Mirabel, & Rodríguez 2000b). At a high fraction ($\sim 10^{-1}$) of the Eddington luminosity, the central source makes a transition to a softer X-ray state, passing through the so-called Very High/Intermediate states. As this happens, the jet velocity increases, leading to internal shocks in the steady jet which appear as highly relativistic knots moving away from the core of the system (e.g. Fender et al. 1999). At this stage, the steady-state jet outflow is quenched until the system moves back into its low/hard X-ray state once more. This unified model is presented for generic black hole X-ray binaries by Fender, Belloni, & Gallo (2004), and for the specific case of GRS 1915+105 by Fender & Belloni (2004).

In these proceedings, we present a study of the 2001 March and July outbursts of GRS 1915+105,

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using data from the Multi-Element Radio Linked Interferometer Network (MERLIN).

2. OBSERVATIONS

GRS 1915+105 was observed with MERLIN during two flaring sequences, between 2001 March 24 and 2001 April 5, and also between 2001 July 17 and 2001 July 24. The observing frequency was 4.994 GHz with a bandwidth of 15 MHz. The MERLIN d-programs were used to perform initial data editing and amplitude calibration, and the data were then imported into the National Radio Astronomy Observatory's (NRAO) Astronomical Image Processing System (AIPS) software package for further data reduction. The MERLIN pipeline was then used to image and self-calibrate the phase reference source, and apply the derived corrections to the target source, GRS 1915+105. The pipeline also calculated the instrumental corrections (the D-terms arising from signal leakage from right circular polarisation feeds into left, and vice versa) using B 1919+086, and calibrated the polarisation position angle using 3C 286. Further self-calibration and imaging were then carried out using standard procedures within AIPS, using the phase-referenced images as initial models for each epoch.

2.1. *March 2001 outburst*

Figure 1 shows a composite of the MERLIN images of the March observations. The images have been rotated clockwise through 52.5°, so that the southeastern components appear on the left, and the northwestern components to the right. The core appears to be detected in all epochs, and we clearly observe components moving away to the southeast and the northwest. The southeastern components appear to move faster (Figure 2) and are brighter at a given angular separation from the core, and thus correspond to the approaching jet, while the fainter, slower northwestern components are receding from us. This agrees with the findings of Mirabel & Rodríguez (1994), Rodríguez & Mirabel (1999) and Fender et al. (1999). Over the course of the 13 days of observation, three distinct southeastern components were seen to be ejected and move outwards, with the middle one being fainter than the first and last. These are labelled SE, SE2, and SE3 respectively. Owing to Doppler deboosting of the receding jet flux density and its lower apparent proper motion, only a single northwestern component was observed, labelled NW.

Assuming that the ejecta move ballistically (i.e. with constant velocity), straight-line fits to the angu-

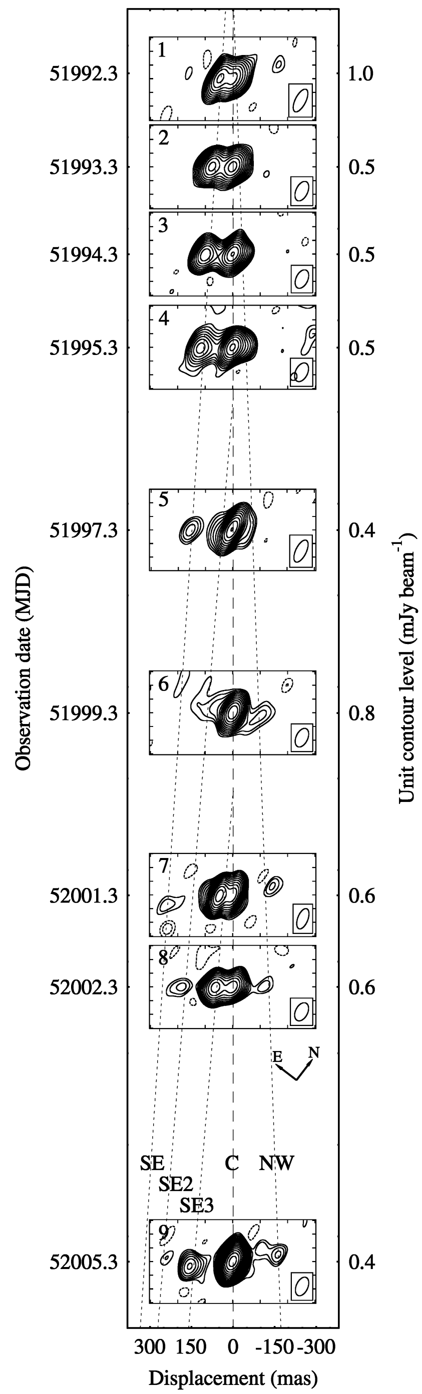

Fig. 1. Contour maps for the March observations. Solid and dashed contours are $(\sqrt{2}^n)$ and $-(\sqrt{2}^n)$ times the levels specified on the right-hand axis. The images have been rotated clockwise by 52.5°. The dotted lines correspond to the fitted ejection dates and proper motions. The vertical dashed line indicates the core position. The component labels are shown above the epoch 9 image, and the orientation on the sky is also indicated.

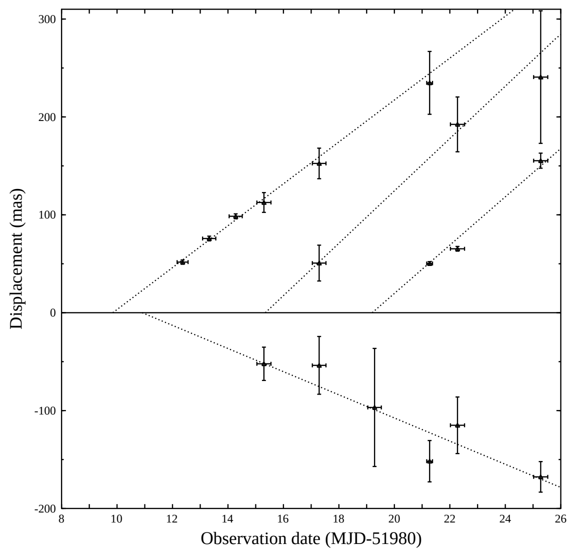

Fig. 2. Proper motions for the March observations. The dotted lines correspond to the best fitting ejection dates and proper motions for the different components, accounting for uncertainties in both time of observation and measured angular separation.

lar separations can be extrapolated to find the ejection dates of the different components. These are given in Table 1 and plotted in Figure 2, and reveal that components SE and NW are consistent with having been ejected simultaneously. The Ryle telescope monitoring program (Pooley & Fender 1997) indicates that the outburst in the 15-GHz flux density of GRS 1915+105 which triggered our MERLIN observations peaked at MJD 51990.4. This, and also the observed sharp rise in 15-GHz flux density, is in good agreement with our zero-separation date of MJD 51989.84 ± 0.42.

2.2. *July 2001 outburst*

During our July observations, from which the images are shown in Figure 3, the flux densities of the core and the jet components were in general much lower than during the March observations. The only epochs in which an unambiguous detection of the NW component was made were 12 and 13. There is marginal evidence in epoch 11 for an elongation of the core in the opposite direction to that of the SE jet component, which could be interpreted as the receding component.

Again assuming ballistic motion, a straight-line fit to the angular separations of the SE component from the core gives a proper motion of $\mu_{\rm app} = 23.8 \pm 2.7$ mas d^{-1}. The fit is good, with $\chi^2_{\rm red} = 0.4$, and implies a zero-separation date of MJD 52106.1 ± 1.4,

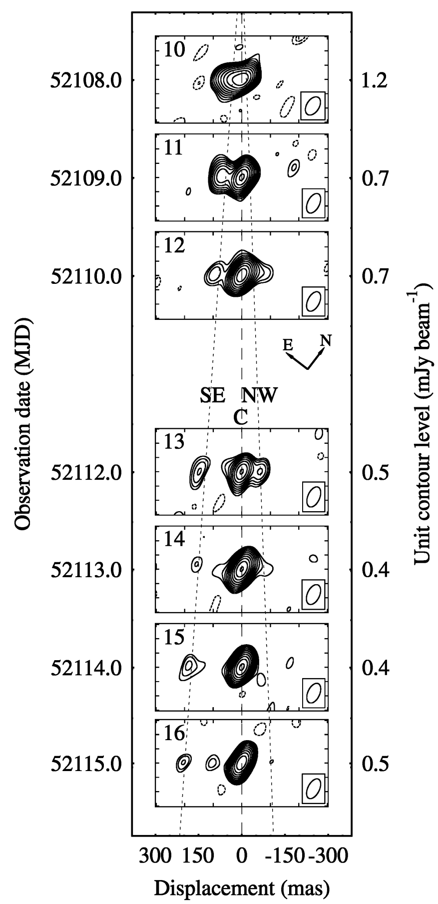

Fig. 3. Contour maps for the July observations. Solid and dashed contours are $(\sqrt{2}^n)$ and $-(\sqrt{2}^n)$ times the levels specified on the right-hand axis. The images have been rotated clockwise by 52.5°. The dotted lines correspond to the fitted ejection dates and proper motions of the components. The vertical dashed line indicates the core position. The beam sizes for each image are plotted in the lower right-hand corner.

which corresponds to July 16 03:21 UT, in good agreement with the start of the outburst determined by Vadawale et al. (2003). A similar fit to the receding component gives $\mu_{\rm rec} = 11.8 \pm 3.5$ mas d^{-1}, and a zero-separation date in agreement with that for the approaching component.

2.3. *Proper motions*

Assuming symmetric ejection, then if the proper motions of corresponding approaching and receding components, $\mu_{\rm a}$ and $\mu_{\rm r}$ respectively, can be measured, it is possible to calculate

$$\beta \cos\theta = \frac{\mu_{\rm a} - \mu_{\rm r}}{\mu_{\rm a} - \mu_{\rm r}}, \quad (1)$$

TABLE 1

FITTED BALLISTIC PROPER MOTIONS AND EJECTION DATES OF JET COMPONENTS

Outburst	Component	Epochs	Proper motion (mas d^{-1})	Ejection date (MJD)	$\chi^2_{\rm red}$
2001 March	SE	1-5,7	21.4 ± 2.0	51989.84±0.42	1.08
2001 March	NW	4-9	11.8 ± 2.0	51990.9±2.2	2.92
2001 March	SE2	5,8,9	26.8 ± 5.9	51995.4±2.6	0.20
2001 March	SE3	7-9	27.4 ± 2.5	51999.6±1.6	1.47
2001 March	SE3	6-9	24.7 ± 1.0	51999.2±0.6	3.09
2001 July	SE	10-16	23.8 ± 2.8	52106.1±1.4	0.41
2001 July	NW	0[a],12-14	11.8 ± 3.5	52106.2±3.8	0.11

[a]To better constrain the fit, the zero-separation date ('epoch 0') derived from the fit to the SE component was also used.

where β is the jet speed v/c and θ is the inclination angle of the jet axis to the line of sight. Setting $\theta = 90°$ allows us to place a lower limit, $\beta_{\rm min}$ on the intrinsic jet velocity. Assuming $\beta = 1$ places an upper limit, $\theta_{\rm max}$, on the inclination angle of the jet axis to the line of sight, and allows an upper limit, $d_{\rm max}$, to be placed on the source distance, given by

$$d_{\rm max} = \frac{c}{\sqrt{\mu_{\rm a}\mu_{\rm r}}} = \frac{173}{\sqrt{\mu_{\rm a}\mu_{\rm r}}} \quad {\rm kpc}, \qquad (2)$$

where the last equality holds when $\mu_{\rm a}$ and $\mu_{\rm r}$ are given in units of mas d^{-1}.

Assuming that the SE and NW components for the March outburst were the approaching and receding components from a single symmetric event, then from the fitted proper motions given in Table 1, we find $\beta \cos\theta = 0.29 \pm 0.09$. This gives $\beta_{\rm min} = 0.29 \pm 0.09$, $\theta_{\rm max} = 73.3 \pm 5.2°$, and $d_{\rm max} = 10.9 \pm 1.0$ kpc. The proper motions from the July outburst give $\beta \cos\theta = 0.34 \pm 0.14$, $\theta_{\rm max} = 70.4° \pm 8.5°$, and $d_{\rm max} = 10.3 \pm 1.6$ kpc, consistent with the values found for the March outburst. Our derived proper motions are also consistent (to within errors) with those found by Fender et al. (1999) with MERLIN and Dhawan et al. (2000) with the VLBA, but greater than those found by Mirabel & Rodríguez (1994) and Rodríguez & Mirabel (1999) with the VLA.

Fitting the measured angular separations with a quadratic function, rather than the straight-line fit required by ballistic motion, showed no conclusive evidence for deceleration. The fitted decelerations were all consistent with zero, and an F-test (e.g. Pfenniger & Revaz 2005) showed that adding in the deceleration parameter was not necessary at any significant level. These data are therefore consistent with purely ballistic motion out to ~ 250 mas from the core.

Fitting a power-law decay with time to the measured jet knot flux densities for components SE and SE3 of the March outburst, and constraining the ejection time to be the extrapolated time of zero-separation given in Table 1, gave power-law indices of 1.8 ± 0.03 and 2.01 ± 0.02 respectively, with $\chi^2_{\rm red}$ values of 3.9 and 1.7 respectively. The indices are Lorentz invariant, so are also applicable to the flux density decay in the knot frame (Rodríguez & Mirabel 1999). Since the motion appears to be ballistic, the flux density decays with angular separation with the same power-law index.

3. THE CORE

Detectable emission seems to be associated with what we interpret as the core of the system at all epochs, although in some of the observations it appears to be blended with an emerging approaching or receding jet component. This is in contrast to the observations of Fender et al. (1999) in which the flux density was always dominated by the jet components. Figure 4 shows the flux density of the core and jet components during the March observations.

Epochs 1 and 6 show that the core flux density faded to very low levels immediately after a flare. This can be identified as the jet suppression in the soft disc-dominated state in the model of Fender et al. (2004). However, by the start of epoch 2, the core flux density had recovered and stabilised at a level of approximately 20 mJy. We attribute this low-level radio emission to the steady, compact nuclear jet. This stable level of $\sim$ 20 mJy at 5 GHz was also seen following the July outburst. This implies that the source has moved back to a harder X-ray state to

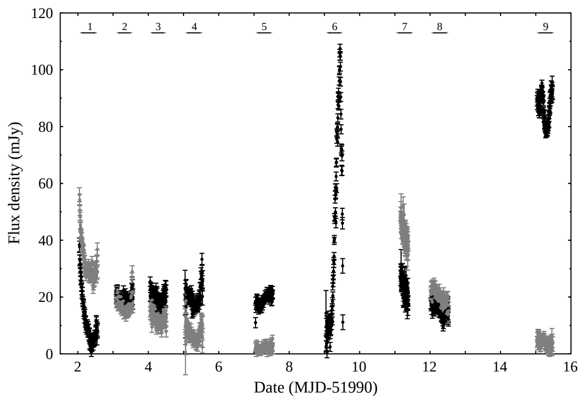

Fig. 4. Flux density of the core during the 2001 March observations. The time range of each observation epoch is indicated at the top of the plot. Epochs 1, 6 and 7 all show a fractional variation of at least 50 per cent. The black points are for the core, and the grey points are for the approaching component, SE for epochs 1–5, and SE3 for epochs 7–9.

the right of the jet-line (Fender et al. 2004) *without* launching a second major ejection. Only crossing the line from right to left in fig. 7 of Fender et al. (2004) (hard to soft X-ray state) gives rise to the internal shocks and the corresponding relativistic ejecta.

The flare in core flux density seen during epoch 6 of the March observations (Figure 4) corresponds to the ejection of component SE3. The core flux density began to rise from a flat base level of 9.8 ± 1.2 mJy at MJD 51999.20 ± 0.02, peaking at 107.4 ± 1.4 mJy 0.24 d later. Assuming the start of the rise phase to be the ejection date of the component, we get an extra constraint on the proper motion of component SE3, used in the fit for epochs 6–9 given in § 2.2 and Table 1.

The low flux density seen during epoch 1 suggests that the steady core jet is not re-established until the increase in core flux density 2.6 d after the ejection event. This is considerably longer than the timescale of 18 h found by Dhawan et al. (2000) for the nuclear jet to reform following the start of a major outburst.

4. ENERGETICS

Taking the rise time of the flare observed during epoch 6 as a constraint on the volume of the emitting region, and assuming that the increase in flux density originates from within this region, then using the formalism of Longair (1994), we can estimate a minimum energy associated with this flare.

$$W_{\rm min} = 3.0 \times 10^6 \eta^{4/7} \left(\frac{V}{\rm m^{-3}}\right)^{3/7} \left(\frac{\nu}{\rm Hz}\right)^{2/7} \left(\frac{L_\nu}{\rm WHz^{-1}}\right)^{4/7} \rm J, \tag{3}$$

where V is the source volume, ν is the frequency at which the luminosity L_ν is measured, and $(\eta - 1)$ is the ratio of energy in protons to that in relativistic electrons. All quantities must be evaluated in the rest frame of the source. The result depends on source distance, and rises sharply as the distance approaches $d_{\rm max}$, but is of order 2–5×10^{34} J. The magnetic field corresponding to this minimum energy (close to but not identical to the equipartition magnetic field), $B_{\rm min}$, may be expressed as

$$B_{\rm min} = 1.8 \left(\frac{\eta L_\nu}{V}\right)^{2/7} \nu^{1/7} \quad \rm T, \tag{4}$$

which equates to 3–10×10^{-6} G for the possible range of source distances, 6–12 kpc. The monochromatic luminosity is $L_\nu = 4\pi d^2 S'_\nu$. We assumed that the filling factor of the source is ~ 1, that the spectral index of the emission is $\alpha = 0.75$ (consistent with the spectral index for the integrated emission derived for this outburst by Fender et al. (2002)), that the radio emission extends over a range in frequency such that $\nu_{\rm max}^{-(p-2)/2} \ll \nu_{\rm min}^{-(p-2)/2}$, and that the observing frequency $\nu = \nu_{\rm min}$, the lowest frequency down to which radio emission is seen. This puts a lower limit on the minimum energy of the outburst. Dividing this by the rise time in the source frame gives the minimum power, $10^{30} < P_{\rm min} < 10^{31}$ W.

Knowing the luminosity of the source (in its rest frame) and the minimum energy field, we can estimate the total number of relativistic electrons as

$$N_{\rm tot} = \frac{L_\nu}{B} \left[A(\alpha)(p-1)(m_{\rm e}c^2)^{p-1} \left(\frac{2\pi m_{\rm e}}{e}\right)^{\alpha} \right]^{-1}, \tag{5}$$

where p is the index of the electron energy spectrum. $A(\alpha)$ is given by (Longair 1994, p. 292), and is equal to 594 for $\alpha = 0.75$. We find $10^{44} < N_{\rm tot} < 10^{45}$.

As explained by Fender et al. (1999), the kinetic energy associated with the bulk motion of the jet knot is given by $(\Gamma - 1)E_{\rm min}$ for an electron-positron jet, or by $(\Gamma - 1)(E_{\rm min} + N_{\rm tot} m_{\rm p} c^2)$ for an electron-proton jet with 'cold' protons, where $m_{\rm p}$ is the proton mass. Unless d is very close to $d_{\rm max}$, these differ only by a factor 2–3, and fall in the range 10^{34}–10^{35} J.

The uncertainties in the source distance should be borne in mind when considering the values derived in this section. The minimum energy, minimum power, and kinetic energy are all lower limits, which would rise if the source was far from equipartition, which is certainly possible given that the jet knot is decaying and expanding, and is thus manifestly not in a steady state. Furthermore, all these estimates would be further increased if, as seems to be the case from the detection of circular polarisation, the electron energy distribution carries on as a power-law down to energies significantly lower than those associated with the observing frequency.

5. CONCLUSIONS

We have observed two flaring sequences from GRS 1915+105 in 2001 March and July. The March sequence showed multiple ejection events, whereas only a single pair of ejecta was observed in July. We measured proper motions consistent with those found with MERLIN by Fender et al. (1999). The 3σ upper limits on the source distance are 13.9 kpc for the March outburst and 15.1 kpc for the July event.

The energetics of the system vary substantially with source distance, which could lie anywhere between 6 and 12.2 kpc according to current estimates. However, the minimum power required for the outburst is 1–10 per cent of the Eddington luminosity for the $14M_{\odot}$ black hole believed to lie at the centre of the system, although this may be increased if either the source lies very close to $d_{\max}$ or does not satisfy the minimum energy criterion.

The data provide support for the internal shock model proposed by Kaiser et al. (2000) and refined by Vadawale et al. (2003) and Fender et al. (2004), whereby the jet velocity increases rapidly at the start of an outburst, before shutting off after the Lorentz factor of the ejected material peaks. The increasing velocity causes internal shocks which light up the underlying outflow and appear as discrete ejecta moving outwards from the core with constant velocity. Shocks are only produced once, on crossing the 'jet line' from a hard to a soft X-ray state; after the initial ejection, no second set of shocks is seen prior to the source moving back to the X-ray state C with steady nuclear jet emission.

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