Giant repeated ejections from GRS 1915+105

R. P. Fender\textsuperscript{1} and G. G. Pooley\textsuperscript{2}

\textsuperscript{1} Astronomical Institute ‘Anton Pannekoek’, University of Amsterdam, and Center for High Energy Astrophysics, Kruislaan 403, 1098 SJ, Amsterdam, The Netherlands rpf@astro.uva.nl

\textsuperscript{2} Mullard Radio Astronomy Observatory, Cavendish Laboratory, Madingley Road, Cambridge CB3 OHE ggp1@cam.ac.uk

ABSTRACT

We report simultaneous millimetre and infrared observations of a sequence of very large amplitude quasi-periodic oscillations from the black hole X-ray binary GRS 1915+105. These oscillations are near the end of a sequence of over 700 repeated events as observed at 15 GHz, and are simultaneous at the mm and infrared wavelengths to within our time resolution (\(\leq 4\) min), consistent with the respective emitting regions being physically close near the base of the outflow. One infrared event appears to have no mm counterpart, perhaps due to highly variable absorption. The overall radio–mm–infrared spectrum around the time of the observations does suggest some absorption at lower frequencies. We calculate the energy and mass-flow into the outflow for a number of different assumptions, and find that the time-averaged power required to produce the observed synchrotron emission cannot be much less than \(3 \times 10^{38}\) erg s\(^{-1}\), and is likely to be much larger. This minimum power requirement is found regardless of whether the observed emission arises in discrete ejections or in an internal shock in a quasi-continuous flow. Depending on the similarity of the physical conditions in the two types of ejection, GRS 1915+105 may be supplying more power (and mass, if both have the same baryonic component) to the jet during periods of repeated oscillations than during the more obvious larger events.

Key words: binaries: close – stars: individual: GRS 1915+105 – infrared: stars – radio continuum: stars – ISM:jets and outflows

1 INTRODUCTION

The ‘microquasar’ GRS 1915+105 is one of the most celebrated and widely-studied astrophysical objects of recent years. The system is extremely luminous and variable in both hard and soft X-rays (e.g. Foster et al. 1996; Morgan, Remillard & Greiner 1997; Belloni et al. 2000) and is a source of relativistic jets observed on arcsec and milliarcsec angular scales (Mirabel & Rodríguez 1994, hereafter MR94; Fender et al. 1999, hereafter F99; Rodríguez & Mirabel 1999, hereafter RM99; Dhawan, Mirabel & Rodríguez 2000). Sams, Eckart & Sunyaev (1996) have reported extended infrared emission from GRS 1915+105, but its relation to the radio ejections is at present unclear.

X-ray dips on timescales of minutes have been interpreted by Belloni et al. (1997a,b) as the repeated disappearance and refill of the inner accretion disc, possibly due to extremely rapid transitions between ‘canonical’ black hole accretion states (Belloni et al. 2000). Pooley & Fender (1997; hereafter PF97) reported radio oscillations associated with such dips, and Fender et al. (1997; hereafter F97) discovered infrared analogs of these oscillations. The flat spectrum and correlated radio : infrared behaviour suggested that non-thermal synchrotron emission extended from the radio to the infrared regimes, the first time such high-frequency synchrotron emission had been observed from an X-ray binary (F97). Combined with the unstable accretion disc model of Belloni et al. (1997a,b) we suggested that a fraction of the inner disc was being repeatedly accelerated and ejected from the system (F97; PF97). Eikenberry et al. (1998a) confirmed the association between X-ray and infrared events, and Mirabel et al. (1998, hereafter M98) clearly observed the correlation between X-ray, infrared and radio behaviour in the source. Additional simultaneous observations (Fender & Pooley 1998, hereafter FP98) showed a very clear correlation between sequences of oscillations at radio and infrared wavelengths. Delays between different radio bands (PF97; M98) and between the infrared and radio bands (M98; FP98) clearly indicate that optical depth effects play an important role in the observed emission from these ejections.
Figure 1. Simultaneous mm (1.3 cm) and infrared K-band (2.2 µm) light curves of GRS 1915+105. The infrared data have been dereddened by $A_K = 3.3$ mag. These are the largest repeated oscillations ever observed from GRS 1915+105.

Eikenberry et al. (1998b) showed that infrared emission line strengths vary in proportion to the continuum during oscillations. A single X-ray dip, spectrally associated with the temporary disappearance of the inner accretion disc, was also found to coincide with a small radio flare (Feroci et al. 1999). More recently Eikenberry et al. (2000) report faint infrared flares whose association with the X-ray behaviour is uncertain, and Ogley et al. (2000) report significant flux from GRS 1915+105 at sub-millimetre wavelengths.

2 OBSERVATIONS

GRS 1915+105 was observed simultaneously on 1999 May 20 with the United Kingdom Infrared Telescope (UKIRT) and the James Clerk Maxwell Telescope (JCMT), both located on Mauna Kea, Hawaii.

2.1 UKIRT

GRS 1915+105 was observed with IRCAM3 in the infrared K-band (2.2µm) on 1999 May 20, simultaneously with the longer duration of JCMT SCUBA observations (see below). Data reduction and calibration were performed with IRAF, along the lines described in F97. Five clear oscillation events were detected. The under reddened infrared flux densities reached 25 mJy at the peak of the oscillations, the largest amplitude oscillations reported to date in the infrared. The data are plotted in Figs 1 & 2, dereddened by $A_K = 3.3$ mag (F97; this value is still rather uncertain).

2.2 JCMT

The 1350 µm detector of the SCUBA instrument (Holland et al. 1999) on JCMT was used in the photometry. Each integration lasted approximately 4 min. Calibration of the flux-density scale used observations of Mars and Uranus. The airmass ranged from 1.01 to 1.92 during the observations, and the optical depth at 1350 µm was less than 0.2 throughout. The data are plotted in Figs 1 & 2.
2.3 Radio

In order to piece together the composite radio–mm–infrared spectrum of the source at the epoch of our observations, we have utilised radio data from two different monitoring programs. Firstly we have used public data at 2.3 & 8.3 GHz from the Green Bank Interferometer (GBI) monitoring program (e.g. Waltman et al. 1994). Observations at 15 GHz with the Ryle Telescope (RT, e.g. PF97) reveal strong oscillations for at least 9 days before and 2 days after the simultaneous UKIRT/JCMT observations (Fig 3), with a slowly rising trend in mean level and amplitude.

3 TEMPORAL AND SPECTRAL BEHAVIOUR

The JCMT observations reveal a sequence of 15 millimetre-wavelength oscillations with a quasi-period of ~23 min. Four of the oscillations have been observed simultaneously in the near-infrared, and both the (dereddened) near infrared and mm oscillations have an amplitude of 300–350 mJy. These are by far the largest amplitude oscillations ever observed from GRS 1915+105, including radio wavelengths at 8.3 GHz (≡ wavelength oscillations with a quasi-period of ~23 min. The radiative luminosity of these oscillations is large – for a non-relativistic non-baryonic ejection with filling factor only.

A striking feature of the light curves in Figs 1 & 2 is the infrared oscillation which starts around MJD 51318.59 which does not appear to have a mm counterpart, unlike the other four simultaneously observed events. We have carefully checked the data reduction techniques to see if this was due to human error, but found no evidence of this. We have no clear physical interpretation of this phenomena, except to suggest that it was due to strong and variable absorption which only significantly affected the lower-frequency emission (for example the optical depth to free-free absorption, \( \tau \propto \nu^{-2.1} \)). As noted above, the overall radio–mm–infrared spectrum at the time of these observations (Fig 4) was steeper than previously observed, perhaps also indicative of some absorption. If this is a correct interpretation of the ‘failed’ mm event, then we would have expected the radio emission to have been completely absorbed at this time also.

4 ENERGETICS AND MASS OUTFLOW RATE

The radiative luminosity of these oscillations is large – for a flat spectrum of amplitude 300 mJy from 1 GHz to 1.4 \times 10^7 GHz (\( \approx 2.2\mu m \)), at a distance of 11 kpc, it is 3 \times 10^{37} \text{ erg s}^{-1} (the time-averaged radiative luminosity is around half this value). As is the case for all synchrotron emitting plasmas for which adiabatic expansion losses dominate, this is likely to be a significant underestimate of the power being supplied to the jet. Furthermore we assume the emission arises in a partially self-absorbed jet which retains the same power-law distribution of electrons (i.e. \( p = 2.6 \) where \( N(E)dE \propto E^{-p}dE \)) as observed in optically thin ejections (PF99). In this situation the flat spectrum is produced by a conical, partially self-absorbed jet (e.g. Blandford & Königl 1979; Reynolds 1982).

In addition several factors which can further affect the energy budget are uncertain, in particular whether or not the small ejections share the same bulk relativistic motions as the larger ejections, whether each radiating electron has an associated cold proton, and what the filling factor (i.e. the effective volume) of the ejections is. The procedure for calculating the energy and mass of the ejections is as follows:

- Transform observed flux densities and frequencies back to their rest frame (identical if no bulk relativistic motion).
- Integrate rest-frame luminosity.
- Calculate maximum emitting volume – in this case based on the five-minute rise time this is 3 \times 10^{39} \text{ cm}^3. The effective emitting volume is this volume multiplied by a ‘filling factor’, \( f \).
- From the volume, spectrum and luminosity, calculate equipartition magnetic field, and corresponding minimum internal energy.
- For baryonic case, add one proton for each electron.
- For cases with bulk relativistic motion, add in kinetic energy and multiply by two, under the assumption that observed emission was dominated by one (approaching) component only.
- Divide by repetition quasi-period of oscillations to obtain time averaged energy and mass outflow rate.

We have tabulated results for different cases in table 1; for bulk relativistic motion we have used the Doppler factors corresponding to \( \beta = 0.98, \theta = 66^\circ \) from F99.

A significant constraint is that the lack of evidence for synchrotron losses (based on the similarity of decay rates at widely different wavelengths) at 2.2\mu m on a timescale of ~10 min, implies that \( B_{\text{max}} \lesssim 30 \text{ G} \). For bulk motions with Doppler factor \( \delta \), this limit is shifted slightly to \( B_{\text{max}}\delta^{-1/3} \) which, for \( \delta = 0.34 \) in this case means the limiting field is ~40G, instead of ~30G, not a major difference. Thus while reducing the emitting volume via the filling factor (see Table 1) decreases the minimum energy, the stronger derived equipartition magnetic field is irreconcilable with the observed minimum lifetimes. As already noted in F97, a field of order 10 G will cause a cut-off in the spectrum of the oscillations around the optical band. Reducing the magnetic field below the equipartition value results in the internal energy being dominated by the electrons, for which total energy \( E \propto B^{-1/2} \). Because of this constraint, the realistic minimum energy cannot be reduced much below the value for a non-relativistic non-baryonic ejection with filling factor \( f = 1.0 \), which is 4 \times 10^{41} \text{ erg}, with a corresponding time-averaged power requirement of 3 \times 10^{38} \text{ erg s}^{-1}. This corresponds to a radiative efficiency for the outflow of \( \lesssim 5\% \).
Figure 3. Ryle Telescope observations of GRS 1915+105 before and after the JCMT/UKIRT observations. Each of the top panels corresponds to 0.2 days, and their distribution with respect to the JCMT/UKIRT observations is indicated in the lower panel. It is clear that strong radio oscillations were occurring before and after the JCMT/UKIRT observations, with a similar quasi-period, but lower amplitude. In fact the RT observations show that the oscillations were probably continuous between MJD 51309–51320.

Table 1. Calculation of radiative luminosity, equipartition magnetic field, total energy and jet power & mass-flow rate for the oscillations reported here, given different physical assumptions. $\Gamma$ is the bulk motion Lorentz factor, $f$ is the ‘filling factor’. In these calculations a distance of 11 kpc and Doppler factors for relativistic bulk motion which are the same as those reported in F99 are all assumed. Mass flow rate $\dot{M}_{\text{jet}}$ and jet power $P$ are based upon one ejection every 20 min. For more details, see main text.

| Case | $f$ | $L_{\text{erg}}$ | $B_{\text{eq}}(G)$ | $E_{\text{min}}(\text{erg})$ | $M_{\text{g}}$ | $P_{\text{erg s}^{-1}}$ | $M_{\text{jet}}(\text{g s}^{-1})$ |
|------|----|-----------------|-------------------|------------------|---------|-----------------|-------------------|
| $e^+:e^-$, $\Gamma = 1$ | 0.91 | $3 \times 10^{37}$ | 145 | $6 \times 10^{40}$ | – | $5 \times 10^{37}$ | – |
| $e^+:e^-$, $\Gamma = 1$ | 0.1 | $3 \times 10^{37}$ | 75 | $2 \times 10^{41}$ | – | $2 \times 10^{38}$ | – |
| $e^+:e^-$, $\Gamma = 1$ | 1.0 | $3 \times 10^{37}$ | 40 | $4 \times 10^{41}$ | – | $3 \times 10^{38}$ | – |
| $e^+:e^-$, $\Gamma = 5$ | 1.0 | $4 \times 10^{39}$ | 115 | $3 \times 10^{43}$ | – | $3 \times 10^{40}$ | – |
| $p^+:e^-$, $\Gamma = 1$ | 1.0 | $3 \times 10^{37}$ | 40 | $4 \times 10^{41}$ | $2 \times 10^{23}$ | $3 \times 10^{38}$ | $2 \times 10^{20}$ |
| $p^+:e^-$, $\Gamma = 5$ | 1.0 | $5 \times 10^{39}$ | 115 | $1 \times 10^{46}$ | $3 \times 10^{24}$ | $8 \times 10^{42}$ | $4 \times 10^{21}$ |

5 DISCUSSION

M98 have shown that the wavelength-dependent time delays (radio-radio and radio-infrared) observed from GRS 1915+105 can be approximated by a ‘van der Laan’ (1996) model for an expanding plasmon. However, as discussed in FP98 such a model does not well describe the observed flat spectrum, which seems instead to be better modelled by a partially self-absorbed conical jet of the type developed for AGN (e.g. Blandford & Königl 1979; Reynolds 1982).

More recently Kaiser, Sunyaev & Spruit (2000) have further applied a internal shock model to the major 1994 radio outburst of the source reported in MR94. In their model they require approximately the same amount of energy to be associated with the events as calculated for a plasmon model in MR94, but the power requirement is less as they spread the energy input over a much longer period. However, with repeated oscillations as observed here, this cannot be the case, where an entire accretion – ejection cycle is repeated on the timescale of $\sim 20$ min which we have used to calculate $P$ and $M_{\text{jet}}$ in Table 1. Therefore this model cannot be used to evade the enormous amount of continuous power required to generate the observed repeated ejection events (this is not an argument against their model, but one against

only a factor of three). Only in the case of baryonic ejections at high velocities does the large number of lower energy electrons become significant, as each has an associated proton. As a result it does not matter whether the emission arises in a discrete ‘plasmon’ or an internal shock in a quasi-steady flow. It is interesting to compare the power for baryonic ejections with $\Gamma = 5$, $2 \times 10^{39}$ erg s$^{-1}$, with that calculated for the same criteria for the ‘major’ ejections in F99, $2 \times 10^{39}$ erg s$^{-1}$. This is due to the observed optically thin cm spectrum, $S_{\nu} \propto \nu^{-0.8}$, being assumed in F99 to have no high-frequency excess, and therefore a much lower integrated luminosity than the flat spectrum oscillations reported here. Further prompt mm and infrared observations during ‘major’ outbursts are required to investigate this.
using it to evade the huge power requirements). Importantly, unless (a) there is a bright mm–infrared contribution from the large ejections which has not to date been observed, and (b) it is only the spatially resolved ejections (F99; RM99) which have bulk relativistic motion and a baryonic content, then GRS 1915+105 injects more energy and matter into the outflow during periods of repeated small events than it does during the large events.

Note also that Belloni, Migliari & Fender (2000) have found that jet power, calculated as above, appears to be anticorrelated with accretion rate as inferred from X-ray spectral fits, for a small sample of observations with quasi-simultaneous infrared and X-ray coverage.

6 CONCLUSIONS

We have reported giant repeated oscillation events from the black hole system GRS 1915+105 observed simultaneously at mm and infrared wavelengths. Contemporaneous radio observations indicate that these observations were near the end of a sequence of \( \geq 10 \) days of oscillations with \( \sim 20 \)-min quasi-periods (i.e. \( \sim 700 \) discrete ejection events). We have investigated in depth the energy and mass flow associated with such events, seeking to minimize the very large required power. However the magnetic field has an upper limit imposed by the lack of observed radiation losses in the infrared band, so that reducing the effective volume by means of a quasi-period

\[ \text{Wavelength (\mu m)} \]

\[ \text{Radio} \]

\[ \text{Infrared} \]

\[ \text{Ultraviolet} \]

\[ \text{GRS 1915+105} \]

\[ 1999 \text{~May~18–22} \]

Figure 4. The mean radio–mm–infrared spectrum of GRS 1915+105 in the interval MJD 51316–51320, centred on our simultaneous infrared/mm observations. The spectrum appears to be significantly inverted at longer wavelengths. Vertical bars on each point are the statistical standard deviation for the data set, and reflect the relative amplitude of observed variability at each wavelength (not measurement errors).

We would like to thank John Davies, Graeme Watt, Fred Baas, Ian Robson, Iain Coubold, Andy Adamson, Garret Cotter, Will Grainger, Mark Lacey, Susan Ridgeway, Tim Carroll and Thor Wold for assistance in the realisation of these observations, and Christian Kaiser for stimulating discussions. The JCMT is operated by The Joint Astronomy Centre on behalf of the UK Particle Physics and Astronomy Research Council (PPARC), the Netherlands Organisation for Scientific Research and the National Research Council of Canada. UKIRT is operated by The Observatories on behalf of the PPARC. We thank the staff at MRAO for maintenance and operation of the RT, which is supported by the PPARC.

REFERENCES

Belloni T., Migliari S., Fender R.P., 2000, A&A, 358, L29
Belloni T., Mendez M., King A.R., van der Klis M., van Paradijs J., 1997a, ApJ, 479, L145
Belloni T., Mendez M., King A.R., van der Klis M., van Paradijs J., 1997b, ApJ, 488, L109
Belloni T., Klein-Wolt M., Mendez M., van der Klis M., van Paradijs J., 2000, A&A, 355, 271
Blandford R., Königl A., 1979, ApJ, 232, 34
Dhawan V., Mirabel I.F., Rodríguez L.F., 2000, ApJ, in press
Eikenberry S.S., Matthews K., Morgan E.H., Remillard R.A., Nelson R.W., 1998a, ApJ, 494, L61
Eikenberry S.S., Matthews K., Murphy T.W., Nelson R.W., Morgan E.H., Remillard R.A., Muno M., 1998b, ApJ, 506, L31
Eikenberry S.S., Matthews K., Muno M., Blanco P.R., Morgan E.H., Remillard R.A., 2000, ApJ, 532, L33
Fender R.P., Pooley G.G., 1998, 300, 573 [FP98]
Fender R.P., Pooley G.G., Brockopp C., Newell S.J., 1997, MNRAS, 290, L65 [F97]
Fender R.P., Garrington S.T., McKay D.J., Muxlow T.W.B., Pooley G.G., Spencer R.E., Stirling A.M., Waltman E.B., 1999, MNRAS, 304, 865 [F99]
Feroci M., Matt G., Pooley G., Costa E., Tavani M., Belloni T., 1999, A&A, 351, 985
Foster R. S., Waltman E. B., Tavani M., Harmon B. A., Zhang S. N., Paciesas W. S., and Ghigo F. D. 1996, ApJ, 467, L81
Holland W. S., et al. 1999, MNRAS, 303, 659
Kaiser C.R., Sunyaev R., Spruit H.C., 2000, A&A, 356, 975
Mirabel I.F., Rodríguez L.F., 1994, Nature, 371, 46 [MR94]
Mirabel I.F., Dhawan V., Chati S., Rodríguez L.F., Martí J., Robinson C.R., Swank J., Geballe T.R., 1998, A&A, 330, L9 [M98]
Morgan E.H., Remillard R.A., Greiner J., 1997, ApJ, 482, L155
Ogley R.N., Bell Burnell S.J., Fender R.P., Pooley G.G., Waltman E.B., 2000, MNRAS, in press
Pooley G.G., Fender R.P., 1997, MNRAS, 292, 925 [PF97]
Reynolds S.P., 1982, ApJ, 256, 13
Rodríguez L.F., Mirabel I.F., 1999, ApJ, 511, 398 [RM99]
Sams B., Eckart A., Sunyaev R., 1996, Nature, 382, 47
van der Laan, H., 1966, Nature, 211, 1131
Waltman E.B., Fiedler R. L., Johnston K. J., Ghigo F. D., 1994, AJ, 108, 179
© 0000 RAS, MNRAS 000, 000-000