

# Excess sub-millimetre emission from GRS 1915+105

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## ABSTRACT

We present the first detections of the black hole X-ray binary GRS 1915+105 at sub-millimetre wavelengths. We clearly detect the source at 350 GHz on two epochs, with significant variability over the 24 hr between epochs. Quasi-simultaneous radio monitoring indicates an approximately flat spectrum from 2 – 350 GHz, although there is marginal evidence for a minimum in the spectrum between 15 – 350 GHz. The flat spectrum and correlated variability imply that the sub-mm emission arises from the same synchrotron source as the radio emission. This source is likely to be a quasi-steady partially self-absorbed jet, in which case these sub-mm observations probe significantly closer to the base of the jet than do radio observations and may be used in future as a valuable diagnostic of the disc:jet connection in this source.

**Key words:** binaries: close - stars: individual: GRS 1915+105 - stars: variables: other - radio continuum: stars - X-rays: stars

## 1 INTRODUCTION

Since its discovery in 1992, simultaneously with the SIGMA instrument on the *Granat* satellite and the BATSE instrument on the *CGRO* satellite (Castro-Tirado, Brandt, Lund, 1992; Harmon, Paciesas, Fishman, 1992), GRS 1915+105 has been one of the most extensively studied sources of recent times. The popularity of this source is due to its highly complex and variable nature at all wavelengths from gamma rays to radio. The many unusual features include relativistic jets (Mirabel & Rodríguez 1994; Fender et al. 1999), X-ray Quasi-periodic Oscillations (QPOs) (Morgan & Remillard 1996) and accretion instabilities resulting in jet formation (Pooley & Fender 1997; Eikenberry et al. 1998; Mirabel et al. 1998).

The system exhibits a wide variety of radio behaviour on timescales from minutes to weeks (Foster et al. 1996; Pooley & Fender 1997). High time resolution observations using the Ryle Telescope (RT) and more continuous coverage on hourly time-scales, revealed new aspects of the radio emission (Pooley & Fender 1997 hereafter PF97). Both 20–

40 min period QPOs associated with soft X-ray variations (first reported in the radio by Pooley (1995,1996)) and a change of QPO period, were clearly visible during some individual observations.

The infrared variability from this source is similar. Following observed 1 and 2 mag variations in the *J*, *H* and *K*-band fluxes (Castro-Tirado et al. 1993; Mirabel et al. 1994; Chaty et al. 1996), Fender et al. (1997) reported rapid infrared flares which had amplitudes, rise, decay and recurrence time-scales strikingly similar to those of the radio flares observed with the RT 8 hours later, suggesting infrared synchrotron emission. Further RT observations taken simultaneously with the William Herschel Telescope (WHT) showed 26-min oscillations in both the radio and infrared emission (Fender & Pooley 1998). From these observations, the authors showed that the radio variations were delayed by 33 (or perhaps 59) minutes relative to the infrared.

Is there a correlation between the radio or infrared emission and the X-rays? There is clearly some correlation between X-ray states and radio emission (*CGRO* Burst And Transient Source Experiment (BATSE) correlation reported by Foster et al. 1996, *Rossi X-ray Timing Explorer* Proportional Counter Array (*RXTE* PCA) correlation reported by PF97), and PF97 were also the first to observe frequency-

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dependent delays in the radio emission. Quasi-periodic flaring in the infrared, reported by Fender & Pooley (1998), was also observed by Eikenberry et al. (1998), who had simultaneous observations with *RXTE* PCA. The source of these flares is consistent with infrared emitting plasmons from *ejected disc material*, following rapid X-ray variability and an X-ray dip. The confirmation of such a hypothesis was presented by Mirabel et al. (1998) with simultaneous *RXTE* PCA, United Kingdom Infrared Telescope (UKIRT) and Very Large Array (VLA) data. Several X-ray dips and subsequent infrared and radio flares were observed.

## 2 PHOTOMETRY

We obtained sub-mm data over two days on MJD 51026 and 51027, when GRS 1915+105 was moderately active, with periods of quiescence interspersed. Co-ordinated with this were quasi-simultaneous observations at radio wavelengths. The radio data were taken using the Green Bank Interferometer (GBI) at 2.25 and 8.3 GHz, and the RT at 15 GHz. Sub-mm data at 350 GHz was taken using the James Clark Maxwell Telescope (JCMT) using the SCUBA array, and X-ray data were obtained at 2–12 keV from the *RXTE* ASM instrument.

The GBI monitored GRS 1915+105 simultaneously at 2.25 and 8.3 GHz with integrations 10–15 minutes in length several times daily. The calibration procedure is reported in detail in Waltman et al. (1994). The RT is an 8-element east–west array operating at 15-GHz; details of the operation can be found in PF97. The JCMT Sub-mm Common User Bolometer Array (SCUBA) observed GRS 1915+105 over two nights on MJD 51026 and 51027 (1998 Aug 01 and 02) in photometric mode at 450 and 850  $\mu\text{m}$  wavelengths – for a description of the instrument see Holland et al. (1999). Regular skydips were taken throughout the observations, and after focusing, aligning and pointing the array, flux calibration was performed using either Uranus or G45.1 (RA(1950) = 19<sup>h</sup> 11<sup>m</sup>, Dec. (1950) = 10° 45′). A total of 15 observations of GRS 1915+105 were made over the two nights, each observation included 50 integrations of 10 s (except for the observation at 51026.574 which included 26 integrations).

Fig. 1 shows photometry over two nights: MJD 51026 and 51027. In the figure, the top panel shows the X-ray flux from the *RXTE* ASM instrument, whereas the bottom panel shows the radio and sub-mm flux. Table 1 presents the flux range during observations, a typical observation error for each photometric point, a weighted mean, a projected flux (detailed below), and errors on these fluxes.

## 3 INTERPRETATION

In all radio, sub-mm and X-ray bands our data show GRS 1915+105 to be variable. At all wavelengths, there is a general trend to lower fluxes and smaller variability over the timescale of our observations. Fig. 2 shows the photometry from the GBI at 8 GHz and the RT at 15 GHz for 7 d around the time of our SCUBA observations. The flux is in general decaying, with some fluctuations around days 51023 and 51025. The decay becomes steadier around the time of the sub-mm observations on days 51026 and 51027.

**Table 1.** Photometric flux over the two epochs. Data given is the flux range, the average photometric error, a weighted mean, a weighted error, a projected flux and error (see text).

$\nu$ (GHz)	Range (mJy)	Error (mJy)	$\bar{S}$	$\sigma_s$	$\bar{S}_p$ (mJy)	$\sigma_{S_p}$
MJD 51026						
2.25	30–46	4	38.1	2.2	26.1	1.9
8.3	16–38	6	25.3	2.7	18.7	2.3
15	12–32	4	16.1	2.1	12.4	1.6
350	13–31	5	20.5	2.8	20.8	2.8
MJD 51027						
2.25	8–23	4	14.7	2.0	11.7	1.5
8.3	6–16	6	10.3	1.3	8.2	0.9
15	2–14	4	10.2	1.4	5.8	0.8
350	3–13	3	11.5	1.3	11.2	1.3

We have modelled the decay of the last three days shown in Fig. 2 at all three radio wavelengths with a linear fit. This provides a plausible estimate to the cm-wave fluxes when interpolated to the times when the sub-mm data were taken, providing there were no rare sharp outbursts. Averaged projected fluxes using this method are given in Table 1.

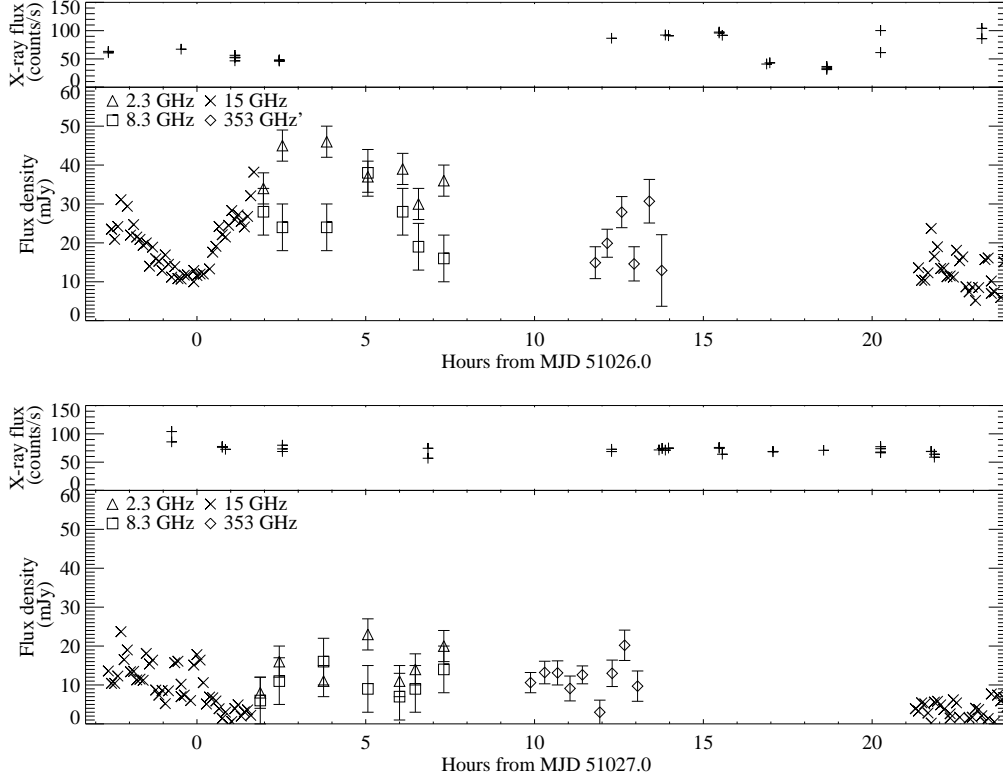
### 3.1 Evidence for a high frequency excess

The main difficulty in interpretation of these data is the validity of extrapolating a variable source using a simple constant decay. If data at all radio frequencies follows the simple decay law, and no additional flares were produced at the time of the SCUBA observations, then the spectra over the two epochs in Fig. 3 shows a clear sub-mm excess. While these last two assumptions may be over simplifying the reality of GRS 1915+105 (e.g. fig. 4 in PF97 shows a large short-lived flare), previous observations have shown a high-frequency excess at infrared compared with radio observations (Fender & Pooley 1998; Mirabel et al. 1998). Photometric observations by these authors have shown that over a large range in radio flux (10–100 mJy), and with multiple oscillations, the radio spectrum at a time when the flux is low ( $\simeq 20$  mJy) is very similar to that in this paper (e.g. fig. 1 in Mirabel et al. 1998), and during times when the radio flux at 8 GHz is around 15 mJy, the 2.2  $\mu\text{m}$  flux is 35–40 mJy.

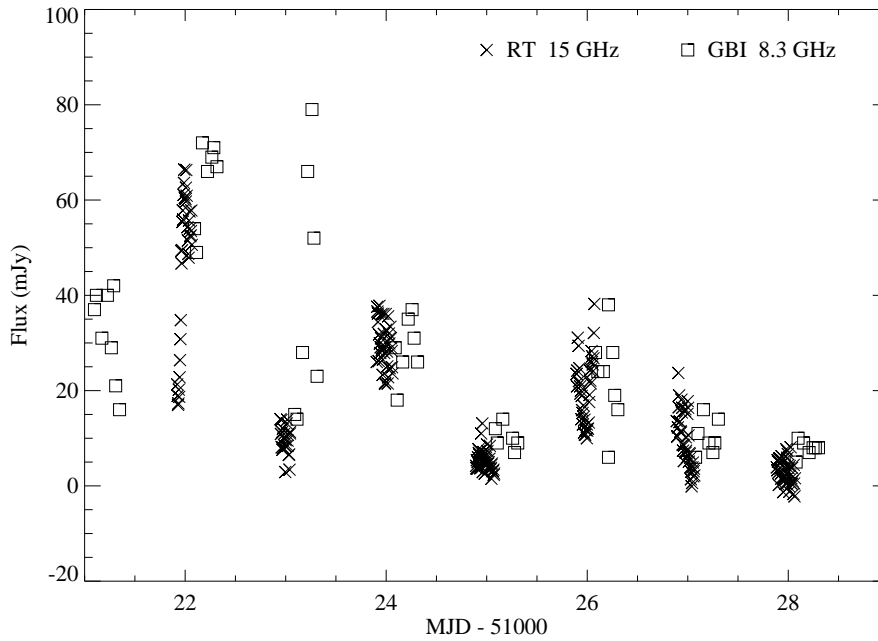
### 3.2 Origin of the sub-mm excess

The flat spectrum ( $\equiv$  high-frequency excess) presented here is seen in other X-ray binaries where there exists significant emission at the mm and sub-mm regimes. Both Cyg X-1 (Fender et al. 2000) and Cyg X-3 (Fender et al. 1995; Ogley et al. 1998) have spectra with indices  $\alpha \simeq 0$ , deviating from the expected optically thin,  $-1 \leq \alpha \leq -0.5$ , steep spectrum observed during an outburst (where spectral index  $\alpha$  as  $S_\nu \propto \nu^\alpha$ ).

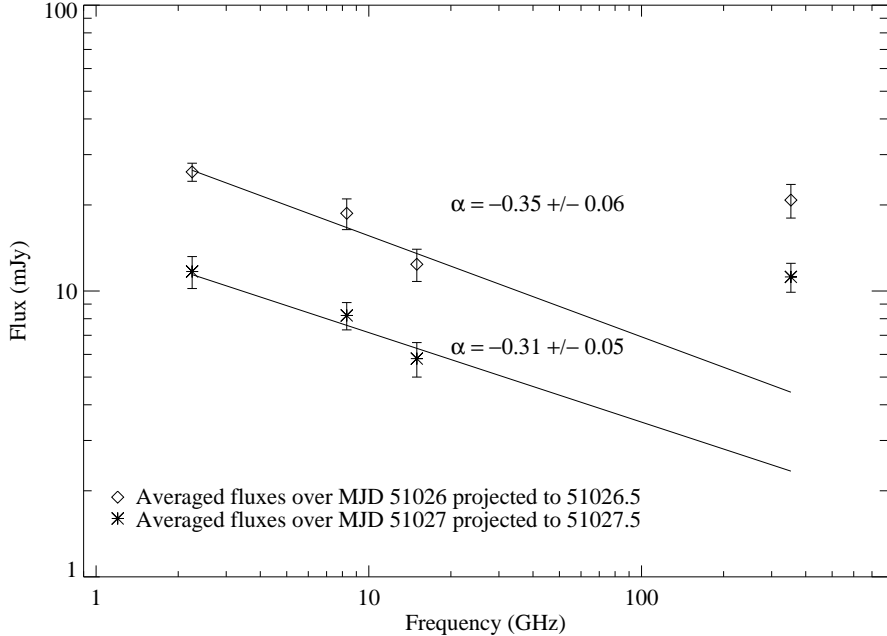
As discussed by other authors, a sub-mm excess and approximately flat synchrotron spectrum are likely to originate in a partially self-absorbed jet (Blandford & Königl 1979; Hjellming & Johnston 1988; Fender et al. 2000). In such a scenario higher frequencies probe smaller emitting regions



**Figure 1.** Detailed photometry at radio, sub-mm and X-ray wavelengths. The upper panel in both plots shows the X-ray flux from the *RXTE* ASM, whereas the lower panel shows the radio and sub-mm data. Radio data at 2.25 and 8.3 GHz is from the GBI, 15 GHz is from the RT and 350 GHz is from the JCMT.



**Figure 2.** Detailed photometry at 8.3 and 15 GHz. One can see that apart from MJD 51023, behaviour at the two frequencies is similar. Data from MJD 51022–51025 are rather variable, however the source appears to be quietening down during the time of the SCUBA observations at MJD 51026 and 51027.



**Figure 3.** Two spectra using the averaged projected fluxes given in Table 1. Diamond-shapes are the average projected flux over MJD 51026 and the star-shapes are the average projected flux over MJD 51027. Note that the spectral slope over all the data is similar and there appears to be a sub-mm excess during each epoch.

close to the base of the outflow. Indeed, for an ideal Blandford & Königl conical jet characteristic size  $\propto \nu^{-1}$ , and so the regions responsible for the emission observed at 350 GHz may be only 5% as far downstream as those observed at 15 GHz. Dhawan, Mirabel & Rodríguez (1998) present a VLBI image of the core of the system in which the 15 GHz emission arises on an angular scale of a few milliarcsec. At 350 GHz, the emission may therefore be coming from angular scales as small as 200 microarcsec – at 11 kpc (Fender et al. 1999) this corresponds to a physical scale of about an astronomical unit. For a velocity of  $\geq 0.9c$  (Mirabel & Rodríguez 1984; Fender et al. 1999) this distance would be traversed within a few tens of seconds. Pooley & Fender (1997), Mirabel et al. (1998) and Fender & Pooley (1998) report frequency-dependent delays in the synchrotron emission, in the sense that higher frequencies rise and peak earlier. Mirabel et al. (1998) fit the delays to the form  $\Delta t \propto \nu^{-2/3}$ , although in the self-similar regime of an ideal Blandford and Königl jet this should be  $\Delta t \propto \nu^{-1}$ . Either way, for an observed delay of tens of minutes at 15 GHz, we would also expect from this scaling that the sub-mm emission arises less than a minute downstream in the flow from the base of the jet. So scaling with respect to both direct imaging and frequency-dependent delays show that sub-mm observations are ideal for studying emission near the base of the jet (and do not suffer the interstellar extinction which can be so dramatic for  $\lambda \leq 5\mu\text{m}$ ).

Fig. 3 shows the radio–(sub)mm spectrum observed from GRS 1915+105 on the two consecutive days of observation. The similar fractional decrease in all bands strongly supports our interpretation of the sub-mm emission as being a high-frequency extension of the synchrotron spectrum observed at cm wavelengths. As noted above, the flow time of

electrons from the disc/black hole to the sub-mm-emitting region is likely to be much shorter than the interval between the observations, and so we are likely to be observing two different populations of electrons on the two days of observations. The similarity of the spectra is therefore an indication of the steadiness of the disc:jet coupling and of the outflow itself. The decrease in mean flux density between the two days may reflect a small decrease in accretion rate. If there had *not* been a renewal of the electron population over the 24 hr between the observation, this would require the magnetic field at the site of the 350 GHz emission to be  $\leq 10$  G in order that synchrotron losses had not become significant.

We do not have a good explanation at present for the apparent minimum in the spectrum between 15 – 350 GHz, but given the non-simultaneity of the data and notoriously unpredictable nature of the source, we will not discuss it further here. In addition we note that radio–mm observations of GRS 1915+105 presented in Fender & Pooley (2000) constitute evidence that the radio–infrared spectrum can steepen from  $\alpha \sim 0$  to more positive values.

## 4 CONCLUSIONS

We have obtained the first sub-mm photometry of GRS 1915+105 at 350 GHz (850- $\mu\text{m}$ ), together with radio data on two separate epochs during a time when the source was mildly active. At all frequencies a significant amount of variability was observed, with a roughly flat spectral index, supporting the hypothesis that emission from radio to infrared wavelengths is dominated by synchrotron emission. Scaling with respect to both direct VLBI imaging and radio–mm–infrared time delays indicate that future sub-mm observa-

tions have the potential to probe very close to the base of the jet.

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