The variable radio emission from GRS 1915+105

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

\textsuperscript{1}Mullard Radio Astronomy Observatory, Cavendish Laboratory, Madingley Road, Cambridge CB3 0HE
\textsuperscript{2}Astronomy Centre, University of Sussex, Falmer, Brighton BN1 9QH

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ABSTRACT
We present data on the monitoring of the Galactic X-ray transient GRS 1915+105 at 15 GHz with the Ryle Telescope. We have found quasi-periodic oscillations with periods in the range 20–40 min which are tentatively associated with the soft-X-ray variations on the same time-scale. The overall behaviour of the radio emission is shown to vary in a strong association with the X-ray emission as recorded by the RXTE all-sky monitor.

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

1 INTRODUCTION
Castro-Tirado et al. (1992) reported the discovery of the hard-X-ray transient source GRS 1915+105, using the WATCH instrument on the GRANAT satellite. Its X-ray emission at both high and low energies has proved to have a rich structure – see, e.g., Paciesas et al. (1996) and Greiner et al. (1996). In the radio regime, the source is no less remarkable; Mirabel & Rodríguez (1994) discovered a double-sided relativistic ejection of radio-emitting material. Adopting a model based on symmetrical ejection, they derive an angle to the line of sight of 70 degrees and a velocity of ejection of 0.92c. The distance, from 21-cm H\textsc{i} absorption, is estimated to be 12.5 kpc, consistent with the relativistic-expansion model. Rodríguez et al. (1995) and Foster et al. (1996) have presented flux-density monitoring data at a range of frequencies.

From this monitoring, it was apparent that the flux density in the radio regime varies on many time-scales, and we started a systematic monitoring program at 15 GHz with the Ryle Telescope in 1995 August. One surprising feature, apparently periodic oscillations with periods in the range 20–40 min, has been reported in two IAU Circulars (Pooley 1995, 1996). This phenomenon, and other patterns of variation including the relationship to the RXTE monitoring data, are considered in more detail in this paper.

2 OBSERVATIONS
The Ryle Telescope (RT: Jones 1991), the upgraded Cambridge 5-km Telescope, is used primarily for observations related to microwave-background studies. It is an E–W synthesis telescope for which the majority of observations have durations of 12 h. In the inevitable gaps in that program, projects such as monitoring of variable sources are often carried out. All observations reported here are centred on 15.2 GHz with a bandwidth of 350 MHz. The linearly-polarized feeds are sensitive to Stokes I+Q; no attempt was made to measure polarization properties.

Since much of the work of the telescope is at modest resolutions, the four mobile aerials are usually set in a compact array configuration within 100 m of the nearest fixed aerial; the resulting 10 baselines give a resolution of some 30 arcsec at 15 GHz when mapping. Atmospheric phase fluctuations are not a serious problem on these baselines. Most of the data reported in this paper are derived from the compact array and not the longer baselines which were also available. One difficulty arises in the compact array from the declination of this particular source, in that some antennas become severely shadowed at extreme hour angles. In practice only hour angles within 3h of the meridian were normally used to avoid shadowing. The observations were interleaved with those of a calibrator, B1920+154, using a 15 + 2.5 minute cycle, so that the instrumental phase variations can be determined and removed. The flux-density scale is set by nearby observations of 3C48 or 3C286, and is believed to conform to the scale of Baars et al. (1977). The measured flux density of B1920+154 was used as a check that the system was working well; they show that the day-to-day calibration of the flux density scale is consistent within 3 percent rms. Data are normally integrated over 32-second (sidereal) intervals, although several observations were made using 8 seconds in order to search for faster variations. The correctly-phased baselines are added to produce, effectively, a phased-array response; since the position of the source is adequately known, the in-phase component then represents an unbiased estimate of its flux density. The typical rms noise on a single 32-second sample when observing in this
mode is 6 mJy. Since the estimates are unbiased, the noise level reduces as the square root of the integration time.

Rodríguez et al. (1995) show a map of nearby sources, including the H II region G45.46+0.06 which has a total flux density of about 5 Jy at this frequency. It lies about 12 arcmin from GRS 1915+105 (compared with a full-width to half-power primary beam of 6 arcmin). Using the RT with the pointing centre on GRS 1915+105 an image of the region shows a response of some 3 mJy at the position of the H II region. Since GRS 1915+105 is variable and the observations are in any case usually too short for satisfactory mapping, there is a very small additional uncertainty in the flux densities when observing in the ‘phased array’ mode; values below about 1 mJy may be unreliable. Some observations were made in a slightly more extended array, when this problem is not significant.

3 RESULTS
3.1 The overall picture
The data presented here run from 1995 Aug 10 to 1996 Dec 31. Individual observations were of varying duration, typically between 1h and 6h. During intervals of pronounced activity it was often possible to observe every day. Fig. 1 shows some 9000 points, each one being a 5-min integration, over the the whole of this time. The overall pattern of variations is apparent from this plot, although the details are not.

Fig. 2 shows a series of individual observations, illustrating the range of behaviours observed. Particular features include:
1. Smoothly-varying flux density during major flares with decay times of hours or days. The flare starting near MJD 50275 (1996 July) was characterised by smooth variations of flux density until it had almost disappeared, at which time the emission became much more erratic.
2. Quasi-periodic oscillations (QPOs) and isolated short flare events, a selection of which is shown in Fig. 2; these are discussed further below.
3. Very low flux densities between active periods (e.g. MJD 50105 – 50220, Fig. 1).

3.1.1 Quasi-periodic oscillations
These remarkable features were first observed in late 1995, and reported in IAU Circulars (Pooley 1995, 1996). One other example has also been reported by Rodríguez & Mirabel (1997).

We note the following features:
1. The ‘periods’ vary in the range 20 – 40 min. The most frequently-observed periods are close to 40 min and 25 min; the event reported by Rodríguez & Mirabel (1997) had a period of 30 min. There are clear instances when a change in the period occurs during an observation (e.g. 1996 May 26, 1996 Sep 18), and there are also instances when the gap between the maxima is erratic. Isolated peaks can be characterised by a rise-time close to 5 min and a decay which is approximately exponential with a time-constant between 12 and 25 min. When the peaks are close together, they appear as quasi-sinusoidal variations, although it is often observed that the rise is more rapid than the fall of each cycle. We suggest that the events themselves are similar, and they are triggered by releases of energy on some short time-scale. The amplitudes of the individual peaks seldom exceed 100 mJy (the maximum flux density recorded in the whole of this dataset is 170 mJy). Individual sequences of oscillations often have nearly constant amplitudes and may have high fractional modulations (see, e.g., 1996 Oct 12).
2. The source seems to have ‘active’ and ‘passive’ periods, with abrupt changes of state between the two. The most prominent example is the sequence of 4 observations on 1996 May 23 – 26 which showed strong QPO activity, but which were surrounded by long passive periods. The abrupt changes sometimes last for about 1 day (e.g. 1996 Sep - Nov, see Fig. 4), and in a few cases the change has been recorded (1996 Sep 16 and 17).
3. The event of 1996 May 24 was observed simultaneously with the VLBA at 8.3 GHz. The two sets of data, over the 2 hours of overlap (limited by the longitude difference between the instruments), are plotted in Fig. 3. There is a delay, in the sense that the 15-GHz data lead the 8.3-GHz, of about 4 – 5 minutes (based on a subjective estimate of the best fit when sliding one relative to the other). There are also substantial changes in spectral index, as can be seen from an inspection of Fig. 3. The flux density observed by the VLBA

Figure 1. Flux density of GRS 1915+105 at 15 GHz from 1995 Aug 10 to 1996 Dec 31. Each point plotted represents an integration of 5 min.
Figure 2. Short-timescale behaviour of GRS 1915+105 at 15 GHz; the integration time is 32 s
at 2.3 GHz during the same run was nearly constant, a result consistent with a model in which lower-frequency emission comes from a larger photosphere, presumably determined by optical-depth effects, and with these emission regions being excited with differing delays. For frequencies where the photosphere exceeds 10 or 20 light-minutes in size, only slow variations would be seen. The increase in the amplitude of variations with increasing frequency is confirmed by inspection of the 2.25 and 8.3-GHz data from the Greenbank interferometer for the flare in 1995 Aug (Foster et al. 1996; see their Fig. 3). Our 15-GHz data on 1995 Aug 11 (Fig. 2), which have only a very short overlap with the Greenbank data, show larger variations.

The 1996 May 24 event is the only one for which dual-frequency data are available; the RT is a single-frequency instrument, and the unpredictability of the source makes it difficult to repeat the observation — but we regard this as important.

### 3.1.2 Comparison with soft X-ray RXTE ASM data

As a first attempt to consider the X-ray/radio correlations, we have used the ‘quick-look’ data from the RXTE ASM experiment, which give integrated count-rates over the 2–10 keV band.

Fig. 4 shows the ASM and 15-GHz data plotted over the same time ranges, from 1996 Feb 23, when the major part of the ASM dataset starts.

The relationship is complex, and changes through the period of the observations.

### Table 1. RXTE pointed observations coinciding with RT data

<table>
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<tr>
<th>Date</th>
<th>RXTE times</th>
<th>RT times</th>
<th>RT data</th>
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<tr>
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<td>0141–0200</td>
<td>0051–0337</td>
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<td>1996 Jun 12</td>
<td>0317–0336</td>
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<td>1996 Jun 25</td>
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<td>1996 Sep 07</td>
<td>1803–2309</td>
<td>1712–2320</td>
<td>Fig. 5a</td>
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<td>1556–1855</td>
<td>marginal detection</td>
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<tr>
<td>1996 Oct 15</td>
<td>1509–2206</td>
<td>1537–2051</td>
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<td>1530–1830</td>
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<td>1334–1838</td>
<td>20 mJy for 30 min</td>
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<tr>
<td>1996 Dec 31</td>
<td>0648–1018</td>
<td>0919–1219</td>
<td>marginal detection</td>
</tr>
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**Figure 2.** Short-timescale behaviour of GRS 1915+105 at 15 GHz; the integration time is 32 s

**Figure 3.** Oscillations on 1996 May 24, observed simultaneously with Ryle Telescope at 15 GHz (dots) and the six shortest baselines of the VLBA at 8.3 GHz (crosses).
Figure 4. Ryle Telescope (upper panels) and RXTE ASM observations (lower) of GRS 1915+105 from 1996 Feb 22 to 1997 Jan 02.
Figure 5. Ryle Telescope (upper) and RXTE PCA (lower) observations on 1996 Sep 07 and Oct 25. The PCA data are in 16-s bins.
3.1.3 Comparison with pointed RXTE data

We have searched for observations which coincided with pointed RXTE data. No significant radio emission was detected (although the coverage was rather sparse) apart from one event on MJD 50146, when a 10-mJy event lasting only 10 minutes was observed. This occurred during a period of somewhat enhanced X-ray activity.

MJD 50226 – 50229 (1996 May 23 – 26): radio emission was observed on each of these 4 days (all are displayed in Fig. 2). They had been preceded by 5 days of enhanced X-ray activity: the X-ray emission during the radio flare was lower on average than in the preceding days, but still appears highly variable.

MJD 50251 – 50260: a minor radio flare, about 20 mJy, which was also associated with a fall in an otherwise active X-ray state.

MJD 50275 - 50310: a major radio flare, with no detected QPOs. The examples of the smooth variation of emission shown in Fig. 2 during this flare are typical. This flare was observed at a number of radio observatories; results will be presented elsewhere. Shortly after the start of the radio flare, the X-ray emission became very steady.

MJD 50310 – 50340: the radio flare faded (but not monotonically). QPOs detected on MJD 50329 (Fig. 2), 50335.

MJD 50340 – 50410: strong QPOs observed on most days, but with interspersed periods of barely detectable flux density. See Fig. 2 for examples.

MJD 50411 – 50450: the X-ray flux fell to low levels at approximately the same time as the radio. There was almost no detectable radio emission, apart from one day (MJD 50439); a similar event was also reported on MJD 50444 using the Greenbank Interferometer (E. Waltman, private communication); it was missed by the RT because of maintenance work.

4 CONCLUSIONS

A wide range of previously unknown phenomena have been recorded in the high-frequency radio emission from GRS 1915+105. A strong link has been established between the radio and X-ray emission. Fender et al. (1997) also report emission in the infrared varying on similar time-scales to those of the radio oscillations reported here. They present evidence that each oscillation is associated with an ejection event, and interpret the infrared flux as the high-frequency tail of a synchrotron spectrum. Belloni et al. (1997) have shown that the soft-X-ray dips on timescales near 30 min can well be explained by the removal of the inner 200 km of the accretion disc. The coincidence of the rise in the radio flux density with the X-ray dip in Fig. 5(b) therefore suggests that at least part of the inner disc is ejected from the system during the oscillations. Important observations remain to be made, including simultaneous observations with high time resolution at as many frequencies as possible. We suggest also that the major radio outburst starting near MJD 50275, and the simultaneous nearly-constant X-ray flux, may have been the results of the removal of a larger part of the inner accretion disc.

Acknowledgements

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