THE RADIO OUTBURST FROM GRO J1655–40

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Abstract. Strong variable radio emission from the bright transient X-ray source GRO J1655–40 (X-ray Nova Scorpii 1994) has been detected at 843 MHz with the Molonglo Observatory Synthesis Telescope (MOST). As the hard X-ray intensity from the 1994 August outburst declined the radio output increased rapidly, reaching a peak of nearly 8 Jy some 12 days after the first X-ray peak. VLBI images obtained at this time showed two main components separating with an apparent transverse velocity $>c$. The evolution of the radio spectrum suggests that the time delay between X-ray and radio emissions is due, at least in part, to opacity effects associated with this expansion.

1. Introduction

The discovery of GRO J1655–40 ($\equiv$ X-ray nova Sco 1994) by BATSE and the subsequent optical, radio and X-ray observations are summarised in an accompanying paper (Paciesas *et al.* 1995). We concentrate here on the discovery and monitoring of the radio emission from this interesting object at 843 MHz, using the Molonglo Observatory Synthesis Telescope (MOST; Robertson, 1991) operated by the University of Sydney.

Following the initial report from BATSE on 1994 August 4 (Zhang *et al.* 1994) we were able to schedule short ($\sim$3 hour) observations with MOST on August 6.60 and 11.59 UT (mid-exposure). Our field of view, $70'$ (RA) $\times$ $70'$cosec(δ) (Dec), covered the original BATSE error circle of radius 0.3°. The raw images showed a strong point source, $\sim$40′ North and 10′ West of the BATSE position, which had increased by more than a factor of two between the two epochs. The source position agreed precisely with the position of the proposed optical counterpart reported by Bailyn

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et al. (1994) and the result was reported immediately (Campbell-Wilson & Hunstead, 1994a). It is interesting to note that the radio counterpart of GRO J1655–40 was close to the edge of the MOST synthesised field in these first images, and was discovered only because the BATSE position error was predominantly in declination (more than twice the quoted error), matching the elongation of the MOST field of view.

In this paper we present the MOST light curve through to the end of August. Our more extensive database, including time-resolved measurements when the source was strong, will be published elsewhere (Hunstead *et al.* 1995).

2. Observations

The early observations of GRO J1655–40 with MOST consisted of partial syntheses, and the reported flux densities (Campbell-Wilson & Hunstead, 1994a,b) were measured from raw images obtained at the telescope. We have since carried out a more thorough calibration of all observations, resulting in small adjustments to the reported values. The unexpectedly large increase in flux density seen between August 12.33 (950 mJy) and 14.58 UT (5100 mJy) triggered an intensive monitoring campaign with MOST and provided the impetus for similar campaigns with the Australia Telescope Compact Array (Hunstead *et al.* 1994; McKay & Kesteven 1994), the SHEVE VLBI array (Reynolds & Jauncey 1994; Tingay *et al.* 1995), the VLA (Hjellming 1994a,b; Hjellming & Rupen 1994a,b,c,d) and VLBA (Hjellming & Rupen 1994d).

The MOST 'light' curve for GRO J1655–40, shown in Fig. 1, includes flux density measurements from two separate modes of observing. The data points were obtained either (a) by fitting a theoretical transit beam in real time to short observations (typically 4 minutes), bracketed by 3–5 MOST calibrators (SCAN observing mode: Campbell-Wilson & Hunstead 1994c), or (b) by carrying out a similar fit to individual 24 s data samples from a standard synthesis observation (3–12 hours), with calibration sources observed at the beginning and end. In the latter case the fits were carried out with more sophisticated software which took account of confusing sources in the MOST fan beams; because of source variability we did not attempt to make measurements directly from images. In Fig. 1 we show separately the *mean* flux densities obtained by each method, which emphasises their internal consistency. Points are plotted at the mean epoch of observation and the errors, usually $\pm 3\%$, come mainly from the uncertainty in calibration. Also shown on Fig. 1 is the BATSE light curve (Paciesas *et al.* 1995) for comparison.

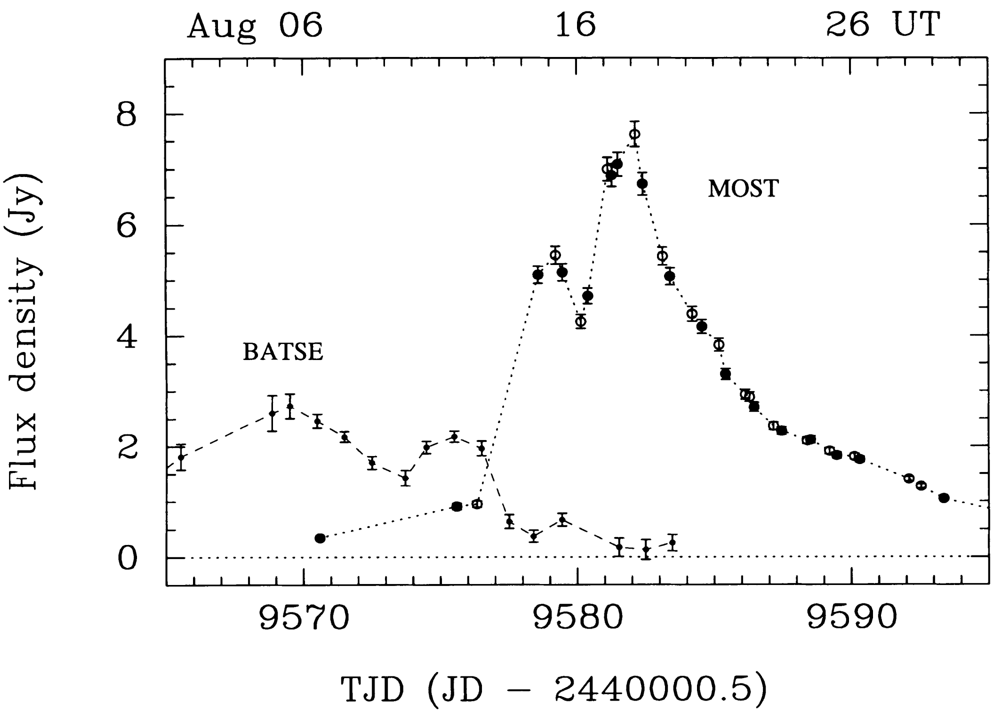

Figure 1. MOST 843 MHz flux density of GRO J1655–40 over the period 1–31 August 1994; open circles refer to SCAN measurements while filled circles are averages spanning each synthesis observation (see text). Points have been joined with a dotted line simply to show the overall pattern of variability. The BATSE one-day averages and statistical errors are plotted as small filled circles joined with a dashed line. The numerical ordinate values correspond to the 20–100 keV flux in photons $cm^{-2}\,s^{-1}$ multiplied by 10.

3. Discussion

The 2.29 GHz VLBI observations reported by Tingay *et al.* (1995) show a basic double structure with the components moving apart at a rate of 65 ± 5 mas d^{-1}, corresponding to an apparent transverse velocity of $1.5\pm0.4\,c$ at their estimated distance of 3.0–5.0 kpc. Extrapolation of the outermost radio components back to zero separation, assuming a constant expansion rate, gives an outburst origin time of 1994 August $13.5^{+0.5}_{-0.8}$ UT. It can be seen from Fig. 1 that this epoch corresponds to both a rapid fall in X-ray intensity and a rapid rise in 843 MHz flux density. Unfortunately the sampling of the radio light curve is too coarse to give the true rate of rise; for an exponential increase, the limit on the time constant is $\tau \leq 1.3$ d.

While it is tempting to associate the origin of the VLBI components with the rapid increase in flux density at 843 MHz, it seems likely that the rise may be associated more with a sudden fall in source opacity than with a

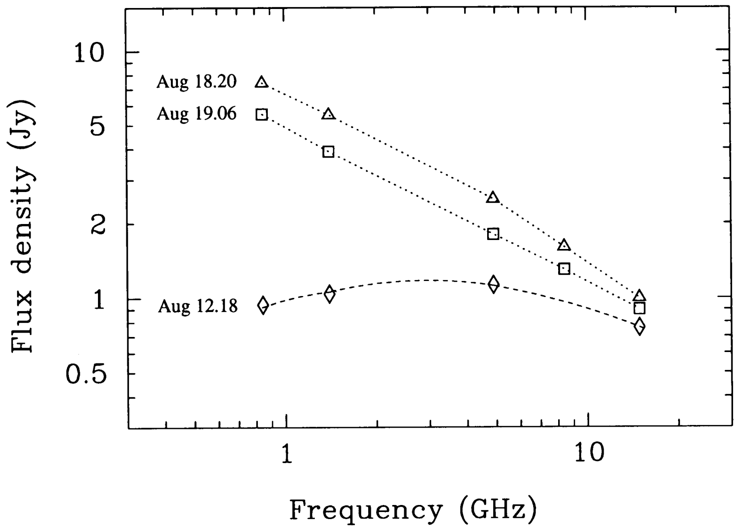

Figure 2. **Radio spectra of GRO J1655–40 at three epochs: August 12.18, 18.20 and 19.06. The 843 MHz points are interpolated from Fig. 1 and the higher frequency points are from Hjellming (1994a,b). The dashed line joining the August 12.18 points is an approximate fit by eye to the data.**

specific event at August 13.5 in the radio. This point is best demonstrated by Fig. 2 which shows the radio spectrum on August 12.18 (Hjellming 1994a) peaking at ~3 GHz, with a shape characteristic of synchrotron self absorption. Even at this epoch the radio flux density was substantial at all frequencies, with little increase thereafter at the highest frequencies. The spectra for August 18.20 and 19.06 (Hjellming 1994b), obtained at and just beyond the main 843 MHz peak, show that the source had then become transparent with a spectral index $\alpha \simeq 0.6$ ($S_\nu \propto \nu^{-\alpha}$). These observations are consistent with the simple expanding synchrotron bubble models of Van der Laan (1966) and Hjellming & Johnston (1988). Measurements made at later epochs with the Australia Telescope Compact Array (Hunstead *et al.* 1994) confirm that the radio spectrum remained transparent ($\alpha \sim$ 0.4–0.6) during the decline in flux density.

While there is a clear delay between the outbursts at X-ray and radio wavelengths, it is not obvious, because of the opacity effects mentioned above, how the delay should be measured. It has also been suggested that the radio emission may initially have been inhibited by the very mechanism responsible for the X-ray outburst (Tingay *et al.* 1995).

The two peaks in the radio light curve (Fig. 1) cannot readily be explained in terms of Doppler enhancements and time delays associated with approaching and receding jets. However, it is possible that they may be related instead to the overall modulation of the X-ray intensity. The time-averaged BATSE data plotted in Fig. 1 show two clear peaks located at TJD $= 9569.5 \pm 1$ and 9575.5 ± 1. If we relate these to the radio peaks at TJD $= 9579.0 \pm 0.5$ and 9581.8 ± 0.5, the corresponding time delays are 9.5 ± 1 and 6.3 ± 1 d respectively. There is even marginal evidence for a third X-ray peak near TJD = 9580 which may correlate with a weak radio feature at TJD = 9585, a delay of 5 d. While such associations are clearly speculative, they define a trend towards shorter time delays which appears to continue with the later X-ray outburst in 1994 September 6–16 (Paciesas *et al.* 1994; Harmon *et al.* 1994; Campbell-Wilson *et al.* 1994).

GRO J1655–40 has several X-ray and radio properties which single it out from other X-ray transients, and it is likely that a better understanding of its nature and evolution will only be possible when a more complete observational database becomes available.

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