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First e-VLBI observations of GRS 1915+105

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ABSTRACT

We present results from the first successful open call electronic very-long-baseline interferometry (e-VLBI) science run, observing the X-ray binary GRS 1915+105. e-VLBI science allows the rapid production of VLBI radio maps, within hours of an observation rather than weeks, facilitating a decision for follow-up observations. A total of six telescopes observing at 5 GHz across the European VLBI Network (EVN) were correlated in real time at the Joint Institute for VLBI in Europe (JIVE). Constant data rates of 128 Mbps were transferred from each telescope, giving 4 TB of raw sampled data over the 12 hours of the whole experiment. Throughout this, GRS 1915+105 was observed for a total of 5.5 h, producing 2.8 GB of visibilities of correlated data. A weak flare occurred during our observations, and we detected a slightly resolved component of 2.7 × 1.2 ms with a position angle of $140^\circ \pm 2^\circ$. The peak brightness was 10.2 mJy per beam, with a total integrated radio flux of 11.1 mJy.

Key words: ISM: jets and outflows – X-ray binaries: individual: GRS 1915+105.

1 INTRODUCTION

The use of the Internet for electronic very-long-baseline interferometry (e-VLBI) data transfer offers a number of advantages over conventional recorded VLBI, including improved reliability due to real-time operation and the possibility of a rapid response to new and transient phenomena. Decisions on follow-up observations can be made immediately after the observation rather than delayed by potentially weeks due to problems in shipment of tapes/discs to the correlator. The first open call with a suitable Greenwich Sidereal Time range for observations of GRS 1915+105 using the e-EVN (electronic European VLBI Network)[1] gave us the opportunity to test e-VLBI under operational conditions. A number of recent test runs have shown that 128 Mbps data rates can be obtained reliably for the six European telescopes; Cambridge, Jodrell Mk2, Medicina, Onsala, Torun and Westerbork, currently connected via national and international research networks to the EVN correlator at Joint Institute for VLBI in Europe (JIVE). Steps are currently being taken to improve the reliability of 256 and 512 Mbps connections, and also to develop 1 Gbps transmission as part of the EXPReS[2] project.

Microquasars are ideally suited for study by e-VLBI as they often have flares associated with the ejection of radio-emitting clouds in the form of jets. Time-scales of this emission are in the range of hours to days at cm wavelengths, and decisions about subsequent observations need to be taken quickly.

The X-ray binary GRS 1915+105 was first discovered in 1992 (Castro-Tirado, Brandt & Lund 1992) by the WATCH instrument on the *Granat* satellite. The system comprises a low mass, K-M III star (Greiner, Cuby & McCaughrean 2001b) companion and a $14 \pm 4\,M_\odot$ black hole (Greiner, Cuby & McCaughrean 2001a). It was the first Galactic source observed to display superluminal motion, and is well known for its rapid variability and strong variable radio flux. It spends the majority of its time in relative radio-quiescence, with low radio and X-ray brightness, and with a characteristic low/hard state X-ray spectrum. In such a state the source is thought to be 'jet-dominated' (Fender, Gallo & Jonker 2003), with a ∼50 au scale inner radio jet (Dhawan, Mirabel & Rodríguez 2000) present. Transitions to the soft state are often accompanied by strong radio flares with the ejection of a high velocity component out to distances of

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[1] http://www.evlbi.org/evlbi

[2] http://www.expres-eu.org

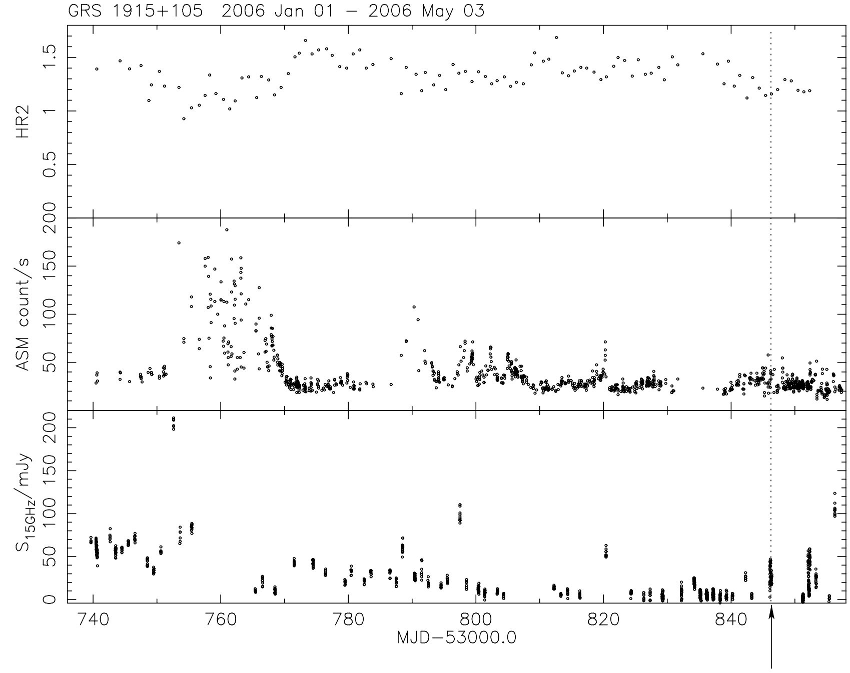

Figure 1. *RXTE* X-ray and Ryle telescope 15-GHz flux density monitoring of GRS 1915+105, observed between 2006 January 1 and May 3. The data of the e-VLBI observation (MJD 53846), is marked by the dotted line. The top shows the X-ray spectral hardness ratio (5–12 keV)/(3–5 keV), the middle shows the *RXTE* ASM count-rate and the bottom shows the 15-GHz radio flux density.

several hundred mas or $\sim 10^4$ au; these transitions have been studied by the Very Large Array (VLA) and the Multi-Element Radio Linked Interferometer Network (MERLIN) (Mirabel & Rodriguez 1994; Fender et al. 1999; Miller-Jones et al. 2005). Long-term, high-sensitivity VLBI monitoring of motions in the core is necessary to understand how the inner jets relate to the larger scale ejections. This is not possible without the strategy in place enabling rapid decisions on follow-up VLBI observations.

The large-scale ejections have apparent superluminal knots or clouds with velocities of $> 0.9c$ (Miller-Jones et al. 2005). Observations with MERLIN in 2001 March/April and July at 5 GHz gave support for the internal shock model (Kaiser, Sunyaev & Spruit 2000); an increase in the velocity of the jet material forms shocks in the outflow and superluminal knots are observed. Ideally, observing the source during a state change would reveal the most information.

Over the first few months in 2006, GRS 1915+105 has been consistently flaring in radio (Fig. 1). A 300-mJy (at 4.8 GHz) steep spectrum, optically thin flare was detected by the Radio Astronomy Telescope of the Academy of Sciences (NAUK) (RATAN) 600 telescope on 2006 February 23, suggesting that the source may have undergone a transition to the high/soft state. This triggered a MERLIN target of opportunity (ToO) on transient sources which detected another outburst in 2006 March (Miller-Jones et al., in preparation). One aim of the project was also to develop a strategy for rapid response (ToO) e-VLBI observations for when this technique is more mature.

2 OBSERVATIONS AND RESULTS

On 2006 April 20–21 the e-EVN observed GRS 1915+105 at 4.994 GHz. This observation was scheduled to be interleaved with a companion project on Cyg X-3 (Tudose et al., 2006) to allow a better *uv*-distribution for both objects in the available observation period. GRS 1915+105 and its phase-reference source were observed between 23:39 and 10:45 UT for a total time on source of 5.5 h.

In this e-VLBI experiment, the data were transferred from the telescope to the correlator using Mark 5A disc-based VLBI data systems. These units have been fitted with 1 Gbps Network Interface Cards which allow the units to transfer the telescope data to the correlator over the Internet and private optical networks at rates exceeding 100 Mbps. Production Internet connections for institutions within each participating country are provided and controlled by the local and national network providers. Most of the telescopes connect to the national networks, and then are connected to the GÉANT 2 network[3] allowing pan-European multi-gigabit connectivity. The exceptions are Westerbork Synthesis Radio Telescope (WSRT) which has its own direct fibre connection to JIVE, and Jodrell Bank with a private connection to Manchester followed by a light path to JIVE. SURFnet provides the connection from GÉANT 2 from Amsterdam to JIVE over multiple optical fibres. Further details on the Internet connections will be presented by Szomoru et al. (in preparation) and Strong et al. (in preparation).

Each station sustained a transfer rate of 128 Mbps across the e-VLBI network. This transmission rate supports two 8-MHz dual-polarisation basebands channels, providing a total bandwidth of 32 MHz. The observations were made using the phase-reference mode with a cycle of 5 min on source and 3 min on the phase reference, J1925+1227. A bright compact radio source, J2002+4725 was used as a fringe finder and was scheduled at the beginning and toward the end of the observing run.

The initial data reduction was performed using the National Radio Astronomy Observatory (NRAO) software package AIPS. The system temperature and gain calibration was initially calculated using

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[3] http://www.geant2.net

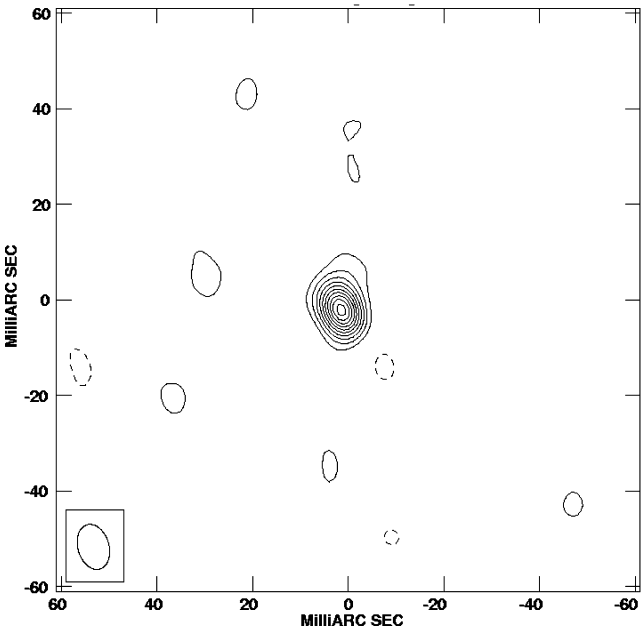

Figure 2. e-EVN map of GRS 1915+105 at 5 GHz using 6 telescopes centred at R.A. $19^{\rm h}15^{\rm m}11\overset{\rm s}{.}548 \pm 0\overset{\rm s}{.}001$ and Dec. $10^\circ56'44\overset{''}{.}71 \pm 0\overset{''}{.}01$ (J2000) on 2006 April 21. Contour levels are (−1, 1, 2, 4, 6, 8, 10) times 1 mJy per beam, with an rms of 0.3 mJy. The beam size was 9.6 × 9.5 mas and was deconvolved with the source revealed an extended component of 2.7 × 1.2 mas at a position angle of 140°(±2°).

the EVN PARSELTONGUE (Kettenis et al. 2006) pipeline written in PYTHON by Cormac Reynolds. The AIPS task FRING was used to solve for the delay across the basebands with the fringe finder. Then, combining the basebands to give a better signal-to-noise ratio, the phase, rates and delay of the phase calibrator were solved again using FRING. A self-calibrated image of the phase calibrator was produced using the Caltech VLBI Software Package DIFMAP (Shepherd 1997), enabling further calibration using AIPS to be performed. The calibrated *uv* data of GRS 1915+105 was then Fourier transformed and the CLEAN algorithm was applied using the AIPS task IMAGR.

The radio image of GRS 1915+105 on 2006 April 20–21 is shown in Fig. 2 using a *uv* weighting robustness parameter of 0 (Briggs 1995). The source had a position of RA $19^{\rm h}15^{\rm m}11\overset{\rm s}{.}548 \pm 0\overset{\rm s}{.}001$ and Dec. $10^\circ56'44\overset{''}{.}71 \pm 0\overset{''}{.}1$ (J2000). The position is consistent with that expected from the known proper motion (Miller-Jones et al. 2005).

The sources appears marginally resolved and was deconvolved from the beam using the AIPS task JMFIT (the full width at half maximum, FWHM, was 9.6 × 6.5 mas). This revealed an extended component estimated at 2.70 ± 0.10 × 1.2 ± 0.05 mas (FWHM), with a position angle of 140° (±2°). This is similar to the position angle (P.A.) of the large-scale jets previously observed (e.g. Fender et al. 1999). The total integrated radio flux density was 11.1(±0.6) mJy.

2.1 Ryle Radio Telescope and *RXTE* monitoring of GRS 1915+105

The Ryle Radio Telescope and the *Rossi X-ray Timing Explorer* (*RXTE*) All-Sky Monitor (ASM)[4] regularly observes GRS 1915+105. Fig. 1 shows the XRB flux density between 2006 January–April at 15 GHz and 2–10 keV in the bottom and middle plots respectively. The top plot in Fig. 1 shows the X-ray spectral hardness ratio (5–12 keV)/(3–5 keV).

The date of the e-VLBI observation (MJD 53846) is marked. The flux entered a period of relative radio quietness in the two weeks before the e-VLBI observation. During the observation, the ASM count rate was about 40 s^{-1}, which is ∼0.5 crab (Levine et al. 1996). The X-ray spectral hardness changed just before the epoch of the observation to a slightly softer state.

3 DISCUSSION AMD CONCLUSIONS

Fig. 3 shows the Ryle Radio Telescope data on 2006 April 21 between 01:27–08:32 UT. A flare of 40 mJy was detected, which quickly decayed to ∼20 mJy within 4.5 h. Assuming that the flare expands isotropically; the minimum energy in the magnetic field and energetic electrons can be calculated assuming equipartition within a synchrotron radiation field (Fender 2006). For a distance of 11 kpc (Fender et al. 1999) the minimum energy is 2×10^{41} erg. Using the deconvolved size from the image rather than assuming spherical expansion, we find a minimum energy of 1×10^{40} erg, a lower value due to the source being collimated.

The radio emission for this and similar weak flares (see Fig. 1) decays rapidly (<1 d). This is unlike the major flares studied by the VLA and MERLIN (Fender et al. 1999; Mirabel & Rodriguez 1994; Miller-Jones et al. 2005) where the decay is over several days and the ejecta can be followed for up to 2 months after the flare. The behaviour of the strong flare is consistent with the shock-in-jet model (Miller-Jones et al. 2005); however the short flares seem to show the charateristic of an expanding source without continuous ejection of relativistic electrons.

The relationship between the radio and X-ray flare is consistent with that for other black holes in the hard state (Gallo, Fender & Pooley 2003). Such sources have compact jets and flat spectra. The spectrum measured in our observations between 5 and 15 GHz is flat or slightly inverted, and futhermore the source is aligned with the P.A. of major ejections observed by Mirabel & Rodriguez (1994). This further supports the idea that radio jets are present when X-ray binaries are in the low/hard state. We note that though still in the hard state, the hardness ratio is shown in Fig. 1 to fall slightly in coincidence with the occurrence of a weak radio flare.

The use of e-VLBI enabled us to obtain images within approximately a day of the VLBI run, rather than the many weeks needed for conventional recording based observations. It is possible to shorten the time between observations and image production even further, so that strategic decisions on future observations can be made for rapidly changing sources. The correlator needs to be stopped before correlated data can be off-loaded. Suitable gaps in the observing schedule could enable this to happen rather than waiting until the end of the run. The time to convert the data to an AIPS data file

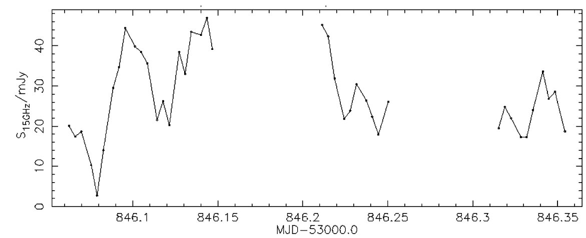

Figure 3. Ryle Radio Telescope 15-GHz flux monitoring of GRS 1915+105, observed at 2006 April 21 01:27–08:32 UT.

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[4] Quick-look results provided by the ASM/*RXTE* team.

could be reduced by software improvements and finally avoidance of weekends would increase efficency.

This initial e-VLBI observation showed that the work load at observatories is decreased, while the load on correlator staff is increased considerably. Due note of this should be taken for resource allocation.

This work clearly shows the ability of the e-EVN to produce high-resolution radio maps in real time, hence eliminating the need of tape/disc recording. In the future, e-VLBI transmission rates will keep increasing with network development, yielding higher sensitivities, and longer baselines will be achieved with the addition of more telescopes to the network. Announcements of opportunity with information on applications are made on the e-VLBI web site (http://www.evlbi.org/evlbi) currently every ∼2 months. This is a positive step in the development of a more dynamic and flexible network.

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