

LETTER TO THE EDITOR

# Global e-VLBI observations of the gamma-ray narrow line Seyfert 1 PMN J0948+0022

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## ABSTRACT

**Context.** There is growing evidence of relativistic jets in radio-loud narrow-line Seyfert 1 (RL-NLS1) galaxies.

**Aims.** We constrain the observational properties of the radio emission in the first RL-NLS1 galaxy ever detected in gamma-rays, PMN J0948+0022, i.e., its flux density and structure in both total intensity and polarization, its compactness, and variability.

**Methods.** We performed three real-time e-VLBI observations of PMN J0948+0022 at 22 GHz, using a global array including telescopes in Europe, East Asia, and Australia. These are the first e-VLBI science observations ever carried out with a global array, reaching a maximum baseline length of 12 458 km. The observations were part of a large multiwavelength campaign in 2009.

**Results.** The source is detected at all three epochs. The structure is dominated by a bright component, more compact than 55  $\mu$ s, with a fainter component at a position angle  $\theta \sim 35^\circ$ . Relativistic beaming is required by the observed brightness temperature of  $3.4 \times 10^{11}$  K. Polarization is detected at a level of about 1%.

**Conclusions.** The parameters derived by the VLBI observations, in addition to the broad-band properties, confirm that PMN J0948+0022 is similar to flat spectrum radio quasars. Global e-VLBI is a reliable and promising technique for future studies.

**Key words.** galaxies: active – galaxies: Seyfert – galaxies: jets – instrumentation: high angular resolution – instrumentation: interferometers

## 1. Introduction

Radio-loud (RL) narrow-line Seyfert 1 (NLS1) active galactic nuclei (AGNs) have received considerable attention in recent years, since they pose a challenge to current unified schemes (Urry & Padovani 1995). NLS1 AGNs are characterized by an optical spectrum with narrow permitted lines  $FWHM(H\beta) < 2000 \text{ km s}^{-1}$ , a ratio of the equivalent widths of  $[OIII]\lambda 5007$  to  $H\beta$  smaller than 3, and a bump caused by FeII (see, e.g., Pogge 2000, for a review). They also exhibit prominent soft X-ray excesses (Boller et al. 1996; Grupe 2004). These properties are indicative of very high (near Eddington) accretion rates and relatively low black hole masses ( $10^6$ – $10^8 M_\odot$ ). Only a small percentage ( $\sim 7\%$ ) of NLS1 are radio-loud. In these cases, their flat radio spectra and VLBI variability suggest that several of them

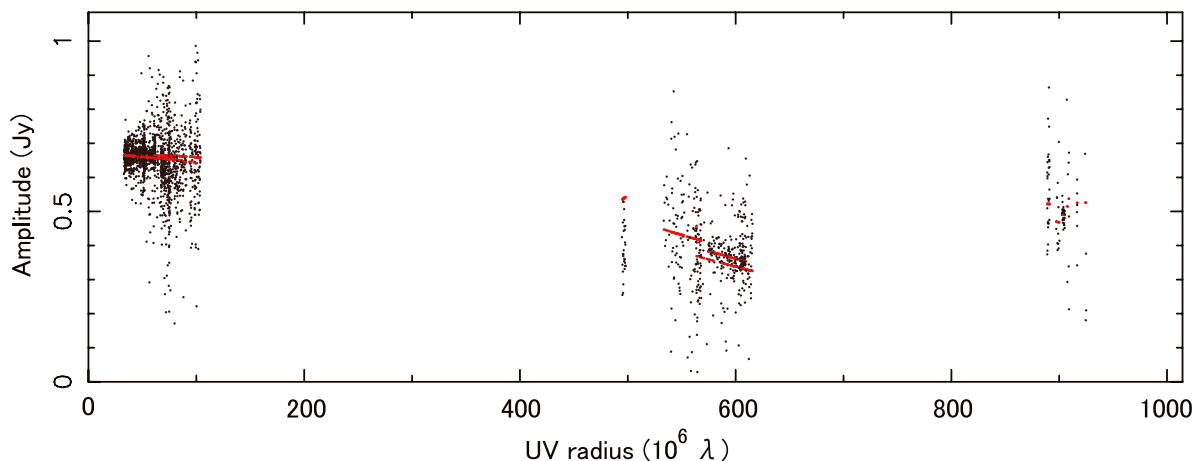
could host relativistic jets (Zhou et al. 2003; Komossa et al. 2006; Doi et al. 2006).

The detection by *Fermi*/LAT of gamma-rays from a handful of RL-NLS1 has provided definitive confirmation of the presence of relativistic jets in these sources (Abdo et al. 2009b,d; Foschini et al. 2010a). A multiwavelength (MWL) campaign was organized in March–July 2009 to investigate the properties of PMN J0948+0022 with simultaneous observations covering gamma-rays, X-rays, UV, optical, and radio. This campaign has delivered some interesting results on the emission processes in this  $z = 0.585$  source (Abdo et al. 2009c). The direct observation of simultaneous variability across the electromagnetic spectrum has confirmed the identification of the gamma-ray source with the lower energy counterpart. This coordinated variability is also characteristic of the relativistic jets present in the central regions

**Table 1.** Log of observations.

Epoch #	Day of 2009	Freq. (GHz)	Participating telescopes	Longest baseline (km)	beam <i>FWHM</i> (mas × mas, °)	<i>S</i> (mJy)
0	Apr. 21	1.6	Ef, Cm(+Da), Jb1, Mc, On, Tr, Wb	Jb-Tr, 1 388	35.4 × 22.9, 11.7	173 ± 20
1	May 23	22.2	Sh, Mp, Ho, Ks, Ef, Mc, On, Cm, Jb2	Ef-Ho, 12 359	0.38 × 0.15, 39.1	665 ± 130
2	Jun. 10	22.2	Sh, Mp, Ho, Ks, Ef, Mc, On, Mh, Ys, Cm, Jb2	Ys-Mp, 12 458	0.43 × 0.14, 43.3	345 ± 70
3	Jul. 04	22.2	Sh, Ks, Mp, Ho, Pa, AT, Ef, Mc, On, Mh, Cm, Jb2	Ks-Mc, 8 811	0.42 × 0.35, 39.5	445 ± 90

**Notes.** The two-letter station abbreviations are: AT – Australia Telescope Compact Array (ATCA, 6 × 22 m), Cm – Cambridge (32 m, limited to 128 Mbps in all experiments), Da – Darnhall (25 m, limited to 128 Mbps in all experiments), Ef – Effelsberg (100 m), Ho – Hobart (26 m, limited to 128 Mbps and a single polarization in all experiments), Jb1 – Jodrell Bank (Lovell Telescope, 76 m), Jb2 – Jodrell Bank (MarkII telescope, 32 × 25 m), Ks – Kashima (34m, limited to 128 Mbps and a single polarization in all experiments), Mc – Medicina (32 m), Mh – Metsahovi (14 m), Mp – Mopra (22 m), On – Onsala (20 m), Pa – Parkes (64 m), Sh – Shanghai (25 m), Tr – Torun (32 m), Ys – Yebes (40 m), Wb – Westerbork Synthesis Radio Telescope (WSRT, 12 × 25 m).



**Fig. 1.** Visibility amplitude versus  $(u, v)$ -radius for the observations on 2010 May 23. Stokes “LL” is shown, since Hobart only observed at LCP. The red points show the amplitude visibility of a Gaussian component with flux  $S = 665$  mJy and  $FWHM$   $0.205 \times 0.055$  mas in PA  $53.1^\circ$ .

of blazars. Overall, the multiwavelength observational properties of J0948+0022 seem therefore to indicate that the physics of RL-NLS1 and blazars are similar, and in particular a relationship between RL-NLS1 and the powerful, high accretion, flat-spectrum radio quasars.

In this Letter, we present additional details of the very long baseline interferometry (VLBI) observations carried out during this campaign. Section 2 describes the procedures of the real-time e-VLBI observations (Szomoru 2008), which were the first application of this technique using a global array of antennas in an astronomical program. Section 3 presents the results, and Sect. 4 discusses conclusions and prospects.

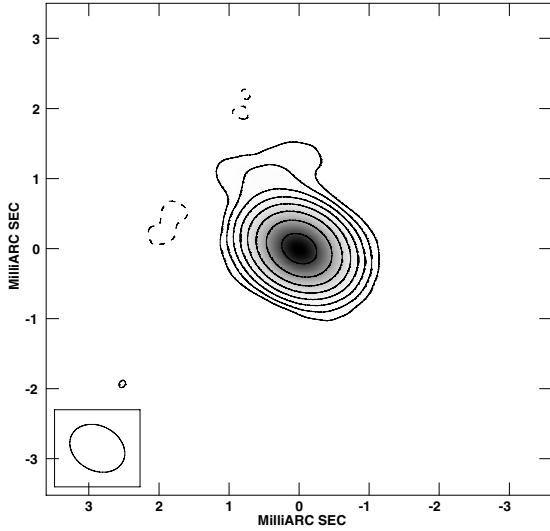
## 2. Observations and data reduction

The observations took place on 2009 April 21, May 23, June 10, and July 4 using a subset of the European VLBI Network (EVN) and the Long Baseline Array (LBA) in Australia, and the 34 m Kashima telescope in Japan. For a complete list of participating telescopes and other observational parameters, we refer to Table 1. The initial observations on 21 April were performed at 1.6 GHz for two hours with the EVN only at 512 Mbps data rate. These observations served as a pilot project designed to assess the feasibility of the experiment; we refer to them as epoch 0.

The other three experiments (epochs 1, 2, 3) were carried out with a global array at 22 GHz for maximum resolution, although Australia-Europe baselines could not be formed at the third epoch because of the availability constraints of the Australian telescopes. Each observation lasted for about 11 h and was preceded by a 2–3 h preparation and clock-search run for

the Australian-Asian array, and later included an hour of clock-search and re-referencing for the whole array including the EVN. The fringe-finders used were 0420–014, OJ287, and 1055+018. Additional nearby calibrators 0736+017 and 0805–077 were regularly observed for continuous fringe monitoring; these later also served as amplitude calibration check sources. The total flux densities of these compact sources were obtained from single-dish Effelsberg (2nd epoch) and synthesis-array ATCA (3rd epoch) measurements. The total bit rate per telescope was 512 Mbps, divided into four 16 MHz sub-bands in both polarizations. The data were streamed in real-time from the stations to the EVN data processor (Schilizzi et al. 2001) at JIVE in all experiments. Plots of the real-time fringes as well as the final coverage of the  $(u, v)$ -plane are shown in Giroletti et al. (2010c). The longest baseline in our array was the Yebes-Mopra on June 10, reaching 12 458 km.

The data were processed using the NRAO Astronomical Image Processing System (AIPS). Amplitude calibration was done with the measured gain curves and system temperatures. For the LBA stations, nominal SEFDs were used. The  $T_{\text{sys}}$  data were corrected for atmospheric opacity assuming standard weather conditions for a subset of stations that had opacity-free calibration data. This in general worked well except for the lowest elevations below  $10^\circ$ . All the sources were fringe-fit separately, no phase-referencing being applied. All of the stations produced fringes, but Kashima had setup problems in the first two experiments and Hobart had a setup problem in the first part of the first experiment. After fringe-fitting, the station amplitudes were further adjusted using the calibrator sources. Phase



**Fig. 2.** Total intensity contours for J0948+0022 at epoch 2, with levels traced at  $(-1, 1, 2, 4, \dots) \times 1.5 \text{ mJy beam}^{-1}$ . The central pixel corresponds to RA =  $09^{\text{h}}48^{\text{m}}57.320^{\text{s}}$ , Dec =  $+0^{\circ}22'25.560''$ .

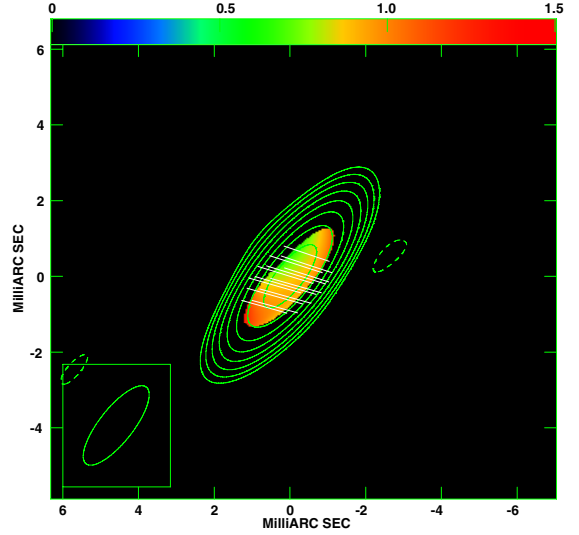
and amplitude self-calibration were performed in Difmap to produce the final images.

The phase response of the right- and left-handed polarized signals with parallactic angle was corrected before fringe-fitting for all stations, including the new 40m Yebes radio telescope. For this Nasmyth offset mount antenna, we used the routines of the 31DEC10 version of AIPS, following the procedures described in Dodson (2009); no RR/LL phase difference was seen on Yebes baselines after this calibration. The observations had not originally been designed to analyze full cross-polarizations; however, we tried to solve for the D-terms using the bright calibrator 1055+018, limiting ourselves to the European stations at the second epoch (when there were the largest number of stations). Reasonable solutions were found, which allowed us to study the source polarized flux. We did not however correct for the polarization angle because of the unknown R-L phase difference at the reference antenna.

### 3. Results

The source is clearly detected at all epochs and frequencies. Inspection of both the visibility plots and the image plane shows that the structure is dominated by a bright compact component. The flux density is difficult to constrain to better than 20% because of a somewhat incomplete information about the system temperature and gain curve from some stations. It is clear however that there is a flux density of several hundreds milliJanskys revealed at all epochs, with possibly some variation. The overall non-simultaneous spectral index between 1.6 and 22 GHz is clearly inverted, with  $\alpha = 0.3\text{--}0.5$  ( $S(\nu) \propto \nu^\alpha$ ). Flux densities from visibility model fitting at all epochs are given in Col. 7 of Table 1.

In Fig. 1, we plot the visibility amplitude as a function of  $(u, v)$ -distance at the first epoch, which is the one with the longest mutual visibility on the longest baselines. Despite the uncertainty in the absolute flux level, the relative amplitude scales between telescopes in Europe and Australia are reliably calibrated, as shown by the consistent values across the short  $(u, v)$ -distances. We are therefore confident that the ratio of the visibility amplitudes on the longest to short baselines is reliably measured, which suggests that that some substructure is



**Fig. 3.** Polarization image from epoch 2, European baselines only. Green contours show total intensity at  $(-1, 1, 2, 4, \dots) \times 1.2 \text{ mJy beam}^{-1}$ , with a peak of  $250 \text{ mJy beam}^{-1}$ ; white vectors show total polarization ( $1 \text{ mas} = 1.2 \text{ mJy beam}^{-1}$ , PA not corrected); color shades show fractional polarization (between 0 and 1.5%).

present. The fitting of an elliptical Gaussian model to the visibilities yields a component size of  $0.205 \times 0.055 \text{ mas}$  at PA  $53.1^\circ$ . The minor axis corresponds to about one third of the synthesized beam; this means that the source was indeed resolved, thanks to the length of baselines in this intercontinental observation (up to 12 359 km between Effelsberg in Europe and Hobart in Australia).

Moreover, the baselines to Shanghai provide visibilities at an intermediate range ( $\sim 500\text{--}600 \text{ M}\lambda$ ) in NS and EW direction. A smaller visibility amplitude relative to that for the longest baselines indicates that there is structure in the direction transverse to the longest baselines (PA  $\sim -45^\circ$ ). In the second epoch, the Fourier transform of the visibility plane, cleaning, and self-calibration are able to more clearly constrain the total intensity structure. A jet component is found at  $r = 0.86 \text{ mas}$  from the core in PA  $\theta = 35.4^\circ$  (see Fig. 2). This is also consistent with the lower frequency structure, which shows a resolved jet feature in PA  $\sim 30\text{--}40^\circ$  (Doi et al. 2006; Abdo et al. 2009c; Foschini et al. 2010b).

The brightness temperature in the source rest-frame based on the model-fit is  $\sim 3.4 \times 10^{11} \text{ K}$  for the first epoch, which is comparable to the equipartition brightness temperature (Readhead 1994). Given the length of the minor axis derived by the model fit, it is conceivable that the size of the core along the major axis is not well-constrained only because of the relatively insufficient baseline lengths. Therefore, the major axis of the elliptical-Gaussian model component represents only an upper limit, and the resulting brightness temperature is only a lower limit. This confirms that the source must be relativistically beamed, since the observed  $T_b$  exceeds the equipartition brightness temperature (see Doi et al. 2006; Zhou et al. 2003).

Polarization could only be studied for the second epoch and using intra-European baselines. Figure 3 provides a polarization map for this epoch. The mean fractional polarization is 0.9% (peak of 1.3%), which is barely in excess of the one reported from MOJAVE at 15 GHz at the same epoch. The absolute polarization angle cannot be determined for our data. To our knowledge, this is the first report of a VLBI polarization experiment using the new 40 m Yebes radio telescope.

## 4. Discussion and conclusions

### 4.1. Scientific implications of the results

The census of extragalactic gamma-ray sources throughout the EGRET era has been dominated by blazars (flat spectrum radio quasars and BL Lac type objects). The discovery of gamma-ray emission from radio-loud narrow-line Seyfert1 nuclei by *Fermi* is therefore of great importance to the study of relativistic jets in AGNs (Abdo et al. 2009d). First, it has confirmed that these relativistic structures exist in radio loud NLS1, as proposed by Zhou et al. (2003) and Doi et al. (2006). Moreover, exploiting the sensitivity and the surveying capability of *Fermi*, it has triggered the organization of the large MWL campaign including the global e-VLBI observations presented here (Abdo et al. 2009c).

The MWL campaign has revealed variability at all energies, and permitted the estimate of the physical parameters of the jet, such as the dissipation radius ( $r = 6.7 \times 10^{16}$  cm), the magnetic field ( $B = 4.1$  G), and the jet total power (Abdo et al. 2009c). A bulk Lorentz factor  $\Gamma > 1$  was implied by the large Compton dominance; in particular,  $\Gamma = 10$  was assumed as a typical value. Our lower limit to the brightness temperatures estimated by elliptical Gaussian model fitting to the global e-VLBI visibilities is a few  $\times 10^{11}$  K and provides an independent confirmation that this jet has a Doppler factor greater than one (see also Doi et al. 2006; Zhou et al. 2003), as well as in other RL-NLS1 (Gu & Chen 2010). Because of the uncertainty in the overall amplitude scaling, a Doppler factor estimate based on the variability brightness temperature is not discussed in this study. However, a trend in the total flux density from our observation is present, with a peak measured on 2009 May 23 and a decrease in the following epochs, which are also characteristic features of blazar-like emission. This result also agrees with other independent variability measurements requiring  $\delta > 1$  reported at various frequencies in Abdo et al. (2009c).

Significant fractional polarization is also a characteristic of *Fermi* detected jets (Hovatta et al. 2010). In J0948+0022 itself, Foschini et al. (2010b) reported an increase in the fractional polarization up to 3% and a swing of the EVPA of about  $90^\circ$  in possible connection with the 2010 gamma-ray outburst. This is similar to what has been reported for other blazars, such as PKS 1502+106 (Abdo et al. 2010), and might be related to the physical mechanisms responsible for enhanced gamma-ray activity. In this context, our detected value of  $\sim 1\%$  fractional polarization seems more characteristic of an intermediate state of activity, consistent with the transition to a low state at high energy observed towards the end of the 2009 MWL campaign (Abdo et al. 2009c).

### 4.2. Prospects for the use of global e-VLBI

In this Letter, we have presented radio interferometric observations in real-time e-VLBI mode (Szomoru 2008), using, for the first time, a global array spanning three continents. The feasibility of transferring data across continents and correlating them in real time has been demonstrated in a number of tests and in particular in the LBA observations of SN 1987A, which were correlated at JIVE (Tingay et al. 2009; Ng et al. 2011). However, these are the first astronomical e-VLBI science observations on a global scale.

From the very beginning of VLBI, global baselines have been routinely achieved between e.g., Europe and the US, and some examples exist of truly global collaborations between arrays on three different continents (see e.g. Fomalont et al. 2001). However, it has always been a challenge to organise these

experiments, especially in the case of time-critical observations such as our coordinated MWL campaign. The advantages of performing such observations in real time e-VLBI (when transporting the data through high-speed networks is possible from all participating telescopes) include the ability to monitor the network performance in real-time and the possibility of delivering prompt results (Giroletti et al. 2010a,b). But most importantly, with the standardization of the data formats and transport protocols (Whitney et al. 2009), it will become much easier to create ad-hoc global networks at relatively short notice, providing excellent *uv*-coverage and unique long baselines, as well as greatly increased sensitivity due to the increase in sustainable data rates and the number of telescopes.

Our pioneering global e-VLBI efforts, in spite of some initial technical difficulties, have convincingly demonstrated the operational feasibility of this type of observation. Using global baselines and a high observing frequency, we have probed the innermost region at or above the self-absorption frequency, thus obtaining the most valuable information as far as the comparison to high energy activity is concerned. The overall success of the MWL campaign and in particular of the global e-VLBI observations presented here is highly encouraging for the continuation of the synergy between high energy astrophysics and VLBI.

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