PROCEEDINGS OF SCIENCE

E-EVN observations of the first gamma-ray nova V407 Cyg

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In 2010 March, the Large Area Telescope (LAT) on board *Fermi* revealed a transient high-energy > 100 MeV gamma-ray source, positionally coincident with the optical nova in the symbiotic binary, V407 Cyg. This event marked the unexpected discovery of gamma-ray emission from a nova and triggered a wealth of follow up campaigns at all frequencies. Taking advantage of the real time capabilities and of the extraordinary sensitivity of the European VLBI Network (EVN), we rapidly obtained a $> 5\sigma$ detection of a compact radio source at the position of V407 Cyg. Encouraged by this finding, we continued to monitor the source at 1.7 and 5 GHz for six months and observed its expansion and brightening. Our data reveal an asymmetric expanding shell and an emitting feature of uncertain nature outside the shell. We show here for the first time the resolved radio images obtained from our campaign on this unique target.

11th European VLBI Network Symposium & Users Meeting,
October 9-12, 2012
Bordeaux, France

*Speaker.

 http://pos.sissa.it/

PoS(11th EVN Symposium)047

1. Introduction

The Large Area Telescope (LAT) is a pair conversion telescope designed to cover the energy band from 20 MeV to greater than 300 GeV; it flies on board the *Fermi* Gamma-ray Space Telescope launched on June 11, 2008. The LAT scans the full sky every ~ 3 hours, thus providing a deep all-sky map in gamma-rays with uniform sensitivity. This provides an unprecedented opportunity for both population analysis and for single source studies. For populations, we refer mainly to the second *Fermi*-LAT source catalogue (2FGL, [11]), which includes 1873 sources, mostly blazars (60%, see also the 2LAC, i.e., the second catalogue of Active Galactic Nuclei detected by *Fermi*-LAT [9]) and pulsars. For studies of single sources, the uniform and continuous sky coverage provides great opportunities for multi-wavelength (MWL) campaigns, as highlighted in several talks at this conference. Indeed, more than 200 Astronomer's Telegram issued by the LAT-collaboration have triggered prompt reaction at several MWL facilities, both for flares of known targets and for unexpected transient sources, typically for fluxes above $10^{-6}\,\mathrm{ph\,s^{-1}\,cm^{-2}}$ at $E > 100\,\mathrm{MeV}$.

One such event occurred in March 2010, when routine *Fermi*-LAT processing of the all-sky data revealed a transient gamma-ray source (named Fermi J2102+4542 [3]) in the Galactic Plane, with $E > 100\,\mathrm{MeV}$ flux of $(1.0 \pm 0.3) \times 10^{-6}\,\mathrm{ph\,s^{-1}\,cm^{-2}}$ on March 13rd and $(1.4 \pm 0.4) \times 10^{-6}\,\mathrm{ph\,s^{-1}\,cm^{-2}}$ on March 14th. The gamma-ray transient was proposed to be associated with optical nova in the symbiotic binary, V407 Cyg because of the spatial and temporal coincidence of the gamma-ray and optical discoveries, with early *Swift* observations indicating a faint X-ray counterpart. Indeed, subsequent analysis of the LAT data indicated the first gamma-ray detection on March 10th, the same day as the observed optical peak [10]. This marked the first γ-ray detection of any nova and more generally the first clear γ-ray detection of any source associated with a white dwarf [1].

Since VLBI observations of a previous nova outburst had revealed important details about the physics [12], we immediately proposed to observe this unprecedented and unexpected event with VLBI. In particular, we decided to exploit the advantages offered by the European VLBI Network (EVN), namely the possibility to obtain information in real-time, thanks to the so-called e-VLBI technique, and the extraordinary sensitivity provided by the large apertures and the high data rate acquisition. In this paper, we present a basic report of the VLBI observational campaign, while more details will be given in a forthcoming publication.

2. Observations

We observed V407 Cyg six times between 2010 March and September, alternatively at 5 GHz (March 30, May 19, Sept 8) and 1.7 GHz (April 23, June 9, Sept 29); hereafter epochs (A, C, E) and (B, D, F), respectively. The first four observations were allocated in a series of Target-of-Opportunity proposals, exploiting the fast turnaround time granted by the real-time mode of the EVN. The first observation lasted for 9 hours, at a 1 Gbps data rate, using the stations of Effelsberg, Medicina, Onsala, Jodrell Bank (Lovell), Cambridge, Knockin, Westerbork, Shanghai, and Yebes. We adopted the phase referencing technique, using J2102+4702 as a calibrator, achieving a rms noise of $\sim 25\,\mu\mathrm{Jy\,beam^{-1}}$ and a naturally weighted beam of 8.1 mas $\times$ 6.6 mas at position angle (PA) $= 84^\circ$. At the later epochs, we adopted a similar strategy with long runs, large apertures and

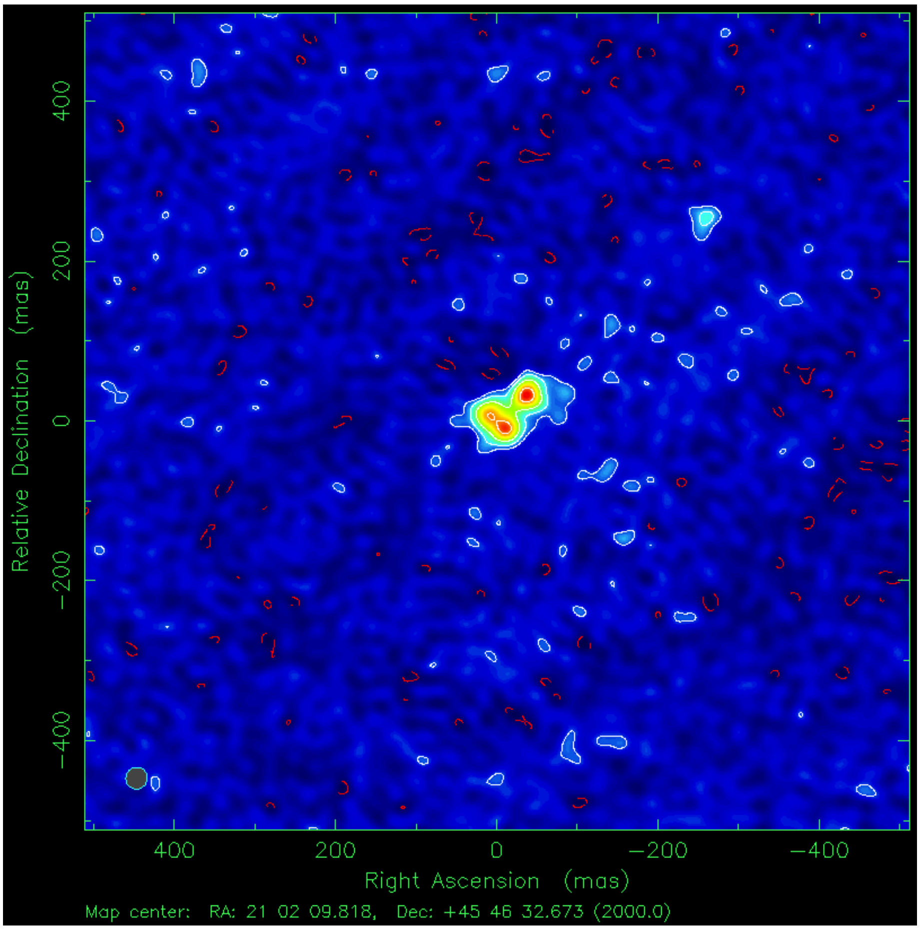

Figure 1: EVN image of V407 Cyg at 1.7 GHz on 2010 April 23 (44 days after optical peak). Contours are traced at $(-1, 1, 2, 4, 8) \times 70\,\mu$Jy beam^{-1}. The restoring beam is 27.4 mas $\times$ 26.5 mas in PA = $-22.1°$.

data rates, and phase referencing, thus resulting in similar values for the sensitivity and resolution. The frequency dependence of the angular resolution resulted $\sim$ 25 mas (FWHM) beamwidths for the 1.7 GHz observations. A more detailed description of each individual run will be given in Giroletti et al. (in prep.).

For all epochs, data were transmitted and correlated in real time at the JIVE correlator. A priori calibration was performed in AIPS using dedicated pipeline scripts, while final imaging and analysis were carried out in Difmap. No self-calibration was attempted due to the low signal-to-noise ratio in the data.

3. Results

The first observation (at 5 GHz), obtained 20 days after the optical peak (i.e., March 30), resulted in a $\sim 6\sigma$ significance level excess in a position consistent with V407 Cyg. A visibility modelfit in Difmap with a circular Gaussian component provided J2000 coordinates of RA = $21^h02^m09.8180^s$, Dec= $+45°46'32.673''$, a flux density $\sim$ 0.2 mJy and a nominal deconvolved

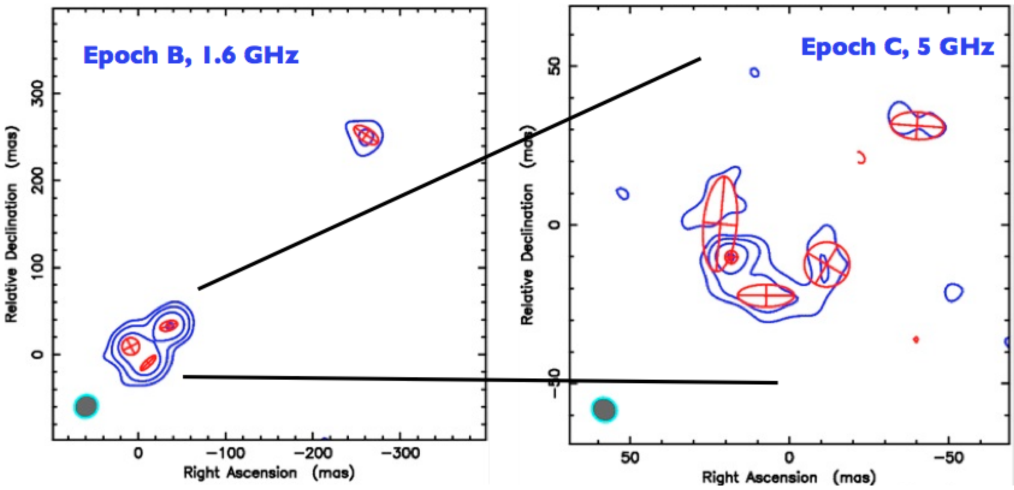

Figure 2: Model-fit Gaussian components (in red) and total intensity contours (in blue) for V407 Cyg. Left: 1.7 GHz data (Apr 23), showing the large $0.5'' \times 0.5''$ field; right: 5 GHz data (June 9), showing the zoom in the central shell-like region.

FWHM diameter ~ 3 mas [8]. A fair amount of extended emission was also present, but impossible to image or model fit reliably with the spatial frequencies available to VLBI. We note that the Allen Telescope Array measured a flux density of 5.8 ± 0.9 mJy at the same frequency just two days earlier [2], clearly indicating that the majority of the flux density at this epoch and frequency is emitted on larger angular scales.

In the following observations, the detected flux density increased, up to a maximum of 8.3 mJy at 5 GHz on May 19 (day 70) and 4.4 mJy at 1.7 GHz on June 9 (day 91). It then decreases again, yet the source remains detected significantly above the noise in all epochs, the last of which was performed over 6 months after the optical event.

The images reveal clearly a complex morphology, characterized by a main set of features in a shell-like structure within the inner 100 mas and a more distant component ~ 400 mas north west. In Fig. 1, we show the 1.7 GHz image obtained on April 23 (day 44), with the inner set of components visible at the center of the field and the more distant feature to the northwest. The inner region resembles a shell-like structure but is clearly asymmetric, being brighter at the south-eastern end, in these epoch as well as in the following ones. The far component at the north west is consistently detected only in the 1.7 GHz images.

We analysed the visibility data by means of the model fit routine in Difmap using bi-dimensional elliptical Gaussian components. The inner shell-like structure is typically described by a few such components, between 2 and 5 depending on the observing frequency and epoch. The outer feature can be modelled with just one component at 1.7 GHz and is not detected at 5 GHz. We present a basic illustration of the model-fit components in Fig. 2, while we will report their precise parameters (position, size, flux density) in Giroletti et al. (in prep.).

4. Discussion

The discovery of gamma-ray emission from V407 Cyg came as a real surprise, as novae were not expected to produce high energy emission. Novae result from a thermonuclear outburst in binary systems consisting of a white dwarf (WD) accreting material from a stellar companion. Accreted material accumulates until pressure on the white dwarf surface produces a thermonuclear ignition. The result is the ejection of a shell expanding into its surroundings. The rapid expansion causes shocks which heat the gas, resulting in X-ray emission. Interestingly, V407 Cyg is a symbiotic system, i.e. the companion star is not a low-mass object but a Mira-type red giant (RG).

Since γ-ray emission from novae was not expected, the MWL observations helped initially to identify the source of high energy emission. Later on, they were essential to sketch the basic details of the emission processes [1]: the interaction between the nova shell and the dense ambient medium of the red giant seems able to accelerate protons, and ultimately produce γ rays through pp collisions and π^0 decay; alternatively, γ rays could be produced by inverse Compton scattering of the RG radiation.

However, only the superior resolution of VLBI can provide a direct image of the nova shell and a measurement of its expansion. Previous examples include the other symbiotic system RS Oph, in which VLBI images tracked an expanding shock wave producing synchrotron radio emission [12]; quite surprisingly, in RS Oph, the ejection appeared jet-like. In V407 Cyg, our images suggest a more spherical shell-like emission, although with some brightness asymmetries. From a qualitative look at the images and the model fit results, it is also clear that the shell is expanding. Preliminary results of a quantitative analysis suggest that the expansion starts with a velocity of ~ 0.7 mas day^{-1}, and then slows down to little more than 0.1 mas day^{-1}. Assuming $d = 2.7$ kpc, the initial velocity would be about 3300 km s^{-1}, in agreement with the half width zero intensity of the Hα line measurement on 14 March [1].

The more distant feature visible at 1.7 GHz is more difficult to interpret. If it had origin at the same place of the main shell, it had to travel very quickly in the first ~ 40 days, and then slow down significantly. Alternatively, it could be a more or less stationary feature in the surrounding environment. We remind that the total radio emission from the whole arcsecond scale region is much larger, and actually the VLA radio light curve is dominated by the wind of the Mira RG companion, rather than the nova ejecta themselves [7]. Indeed, our observations are remarkable in that they provide the only evidence for the non-thermal emission associated to the expanding shell.

Further details and interpretation will be provided in an upcoming publication. In addition, other insights on the physics of these unexpected systems will be offered by two more recent gamma-ray novae detected by *Fermi*: Nova Sco 2012 [5] and Nova Mon 2012 [4, 6], the latter of which has also been detected by the EVN and is resolved into a double structure [13], in contrast to the shell like morphology we observed in the case of V407 Cyg. Such resolved VLBI images provide critical information on the source morphology and give context to the spatially unresolved higher energy X-ray and gamma-ray emission observed in novae.

Acknowledgments

The European VLBI Network is a joint facility of European, Chinese, South African and other radio astronomy institutes funded by their national research councils. C.C.C. was supported at NRL by a Karles' Fellowship and by NASA DPR S-15633-Y.

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