eMERLIN imaging of γ-ray nova V959 Mon’s surprising evolution

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Abstract. High resolution radio images of γ-ray nova V959 Mon using e-MERLIN are presented here, at epochs in September 2012, November 2012, February 2013, October 2013 and February 2014. A light curve at C-Band frequency has been produced which is in good agreement with contemporaneous VLA observations. While early e-MERLIN observations of V959 Mon appear to show an east-west elongation in the ejecta morphology, subsequent observations show that the ejecta are now elongated in the north-south direction. Our high-resolution observations of the structure of V959 Mon can assist us in further understanding the mechanisms of mass ejection from novae.

1. Introduction

1.1. Classical Novae

A nova is a cataclysmic variable star in which the white dwarf primary undergoes a thermonuclear runaway on its surface, as a result of build-up of accreted material from the secondary. This leads to a large expulsion of matter from the WD surface, as well as a dramatic increase in the optical magnitude of the system. Novae are also radio sources, primarily due to thermal bremsstrahlung, although synchrotron emission can be detected if there are shocks present.

Models based on the radio light curves of novae assume a uniformly dense shell of expanding ejecta. The Hubble flow model assumes that all the material is ejected at once and expands as a thick, spherically symmetric shell, with the slowest parts of the gas (velocity $V_0$) at the inner radius, and the fastest parts (velocity $V_1$) at the outer radius. This model predicts a $t^2$ rise in radio intensity while the ejecta are optically thick, and a $t^{-3}$ decay once the source has become optically thin. However, some observations of novae indicate poor agreement with such simple models (see for example [9], [6], [7]).

1.2. V959 Mon

V959 Mon (Nova Mon 2012) was first detected in June 2012 by the Fermi Large Area Telescope, as a GeV γ-ray transient source [1]. The presence of γ rays is unexpected in a nova as the Hubble flow model does not predict the high energies required to generate them. VLA spectra shortly after this time had a spectral index of $\alpha \approx -0.1$, indicating synchrotron emission rather than the expected optically thick emission. Ribeiro et al. 2013 report that V959 Mon has a bipolar ejecta structure, with an angle of inclination of $82^\circ \pm 6^\circ$ [13]. Its distance from Earth is 1.5 kpc [10]. Resolved 5 GHz EVN observations of V959 Mon (from September 2012) at 2-7 milliarcsecond (mas) resolution by [11] detected 2 compact components extending north-west and south-east, and moving apart with a proper motion of 0.45 mas/day.
Table 1. Total integrated fluxes of V959 Mon for each image presented in this section. The days since outburst are given with respect to the date of the FERMI detection.

| Epoch          | Days Since Outburst | Total Flux (mJy) |
|----------------|---------------------|------------------|
| 18th Sept 2012 | 91                  | 8 ± 2            |
| 12th Nov 2012  | 146                 | 31 ± 1           |
| 22nd Nov 2012  | 156                 | 27 ± 1           |
| 26th Feb 2013  | 252                 | 14 ± 1           |
| 11th Oct 2013  | 479                 | 11 ± 3           |
| 21st Feb 2014  | 612                 | 5 ± 1            |

Due to V959 Mon’s unusual emission and morphology, the Hubble flow model is unlikely to provide a complete description of its behaviour. Chomiuk et al. 2014 [4] suggest an alternative model in which the ejecta consists of two perpendicular bi-polar components: a slower-moving component which is accelerated by transfer of energy from the orbiting binary system, and a faster-moving component accelerated by winds from the WD surface, and emanating primarily from the polar regions. The faster-moving wind driven component would initially dominate radio images, before becoming optically thin, revealing the slower orbital driven component. At early times, shocks would occur at the interface between the components. This model would explain V959 Mon’s unusual morphology and emission of $\gamma$ rays.

2. Observations
The observations presented here were made with the e-MERLIN array over 6 epochs: September 18th 2012, November 12th 2012, November 22nd 2012, February 21st 2013, October 11th 2013 and February 21st 2014. The observations were made in the C Band (central frequency $\sim$ 5 GHz), providing a resolution of 40 mas, and with a bandwidth of 512 MHz. The bandwidth was divided into 4 intermediate frequency bands (IFs), each containing 512 channels. The data were averaged such that each IF effectively contained 128 channels.

The reduction and imaging of each epoch was carried out with AIPS. J0645+0541 was observed as a phase calibrator, 3C286 as a flux calibrator and OQ208 as a band-pass calibrator. The images were constructed using the different CLEAN restoring beams fitted to each one. They were then re-constructed using the same 70 mas $\times$ 70 mas circular beam for each epoch.

3. Results
Table 1 shows the total integrated flux for each epoch. Fluxes were calculated using two different methods; using the AIPS tasks JMFIT and IMSTAT. The average of the two results was taken, and the uncertainty was taken to be the difference between them. The data in Table 1 were used to construct light curves for V959 Mon, shown in Figure 1. While all the observations were made in the C-band, two different central frequencies were used; 5.7 GHz in 2012 and 5.0 GHz post-2012.

Intensity contour plots of V959 Mon at each epoch are shown in Figure 3. In the first four epochs, the ejecta appear to be elongated in the east-west direction. The elongation appears to become more pronounced with each successive epoch, with the east-west diameter expanding from an estimated 141 milliarcseconds in September 2012 to 280 milliarcseconds in February 2013. In the subsequent epochs (October 2013 and February 2014), the emission is elongated north-south rather than east-west. Again, an estimated increase in north-south diameter was observed between the epochs, with a diameter of 388 milliarcseconds in October 2013 increasing to a diameter of 458 milliarcseconds in February 2014. It is possible that this north-south
structure can be seen to be emerging in the February 2013 epoch, which, though predominately elongated from east to west, also appears to have a north-south component.

4. Discussion

4.1. V959 Mon Light Curve

In Figure 1, a comparison is shown between the light curve of V959 Mon as observed by e-MERLIN, and a simulated light curve fit to the data using the Hubble flow model. When fitting the model to the observations, the distance to the nova (1.5 kpc, [10]) and the electron temperature of the ejecta (2 $\times$ $10^4$ K, [4]) were fixed. The model fitting program returned best fit parameters of $1.1 \times 10^{-4}M_\odot$ for the ejecta mass, 2300 km s$^{-1}$ for the outer velocity of the shell and 470 km s$^{-1}$ for the inner velocity of the shell. Our observations appeared consistent with the light curves predicted by the Hubble flow model. However, only one frequency has been considered here; when multiple frequencies are considered, seeming agreements between model light curves and light curves constructed from observations can break down.

4.2. Morphology

Our resolved images of V959 Mon (Figure 3) display an extension from east to west (perpendicular to V959 Mon’s orbital plane) in the first four epochs. In the final two epochs shown in Figure 2, an emerging north-south structure can be seen. This evolution in the morphology is consistent with the predictions of Chomiuk et al. (2014) [4]. For a further discussion of V959 Mon’s complex morphology, see Healy et al. (2016, in prep).

5. Conclusion

High resolution eMERLIN observations have been presented here of V959 Mon at six epochs ranging from September 2012 to February 2014. The observations were made at C-band (~5 GHz). Resolved images show a complex, aspherical, evolving morphology, which changes its orientation from being elongated east-west to north-south. The variable morphology of V959 Mon is consistent with the hypothesis of Chomiuk et al. 2014 [4] that nova ejecta consists of a slow component driven by orbital energy transferred from the rotating binary, and a faster-moving polar component driven by winds on the white dwarf surface.

To further our understanding of V959 Mon’s unusual behaviour, we will test the model proposed by [4] using radio emission models. By constructing density distributions representative
Figure 2. Intensity contour plots of V959 Mon; from top-left: September 2012 (day 91), 12th November 2012 (day 146), 22nd November 2012 (day 156), February 2013 (day 252), October 2014 (day 479), February 2014 (day 612). The morphology can be seen to change from an east-west orientation, in the first four epochs, to what seems to be a north-south orientation, in the last two epochs. Each image was constructed using a 70 × 70 mas beam. The lowest contour level in each case is equal to three times the rms noise level (according to AIPS task IMSTAT) in the image.

of the ejecta behaviour proposed by [4], we can investigate whether such behaviour results in the radio emission we have observed.

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