ngVLA Memo #52
The 2018 Eruption of Nova V392 Per: A Case Study of the Need for ngVLA

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The primary goal of the Next Generation Very Large Array (ngVLA) is the capability to obtain ultra-sensitive images of thermal emission to milliarcsecond resolution, while also providing unprecedented broad-band images of non-thermal sources. Classical novae present the optimal case for testing these capabilities as they are now understood to be sources of both thermal and non-thermal emission at many different scales as the ejecta evolve. They are also good analogs for many types of stellar outflows, including X-ray binaries, young stellar objects, massive stars, and possibly even supernovae. The *Fermi*-detected nova provided an excellent example of why the ngVLA with very long baselines is needed.

1 Introduction to Classical Novae

A nova outburst results when sufficient mass accretes from the companion star onto the surface of a white dwarf, triggering a thermonuclear explosion. In classical novae the bulk of the emission comes from the warm, expanding ejecta. The prevailing theories assume that the explosion occurs as a single, spherically symmetric ejection event and predict a simple relationship between the white dwarf mass, the accretion rate, and the mass loss and energetics of the explosion (e.g., Yaron et al. 2005). However, observations with modern instruments indicate that nova eruptions are far from simple. Among the recent results are the direct demonstration of the importance of shocks in novae (e.g., Weston et al. 2016a,b) and how these shocks develop internally, possibly after a common envelope phase (Chomiuk et al. 2014). Radio observations have also found evidence of non-spherical geometry (Linford et al. 2015) and even jet-like structures in the ejecta (Rupen et al. 2008, Sokoloski et al. 2008). Furthermore, radio observations suggest that multiple, long-lived outflows are much more common than previously assumed in these explosions (e.g., Nelson et al. 2014).

One of the most surprising discoveries of the *Fermi Gamma-ray Space Telescope* was that novae produce GeV γ-ray emission. While MeV emission from novae was predicted (and yet never observed; Hernanz 2012), GeV emission requires a population of accelerated particles that was not expected to be present in nova explosions. The first nova detected by *Fermi* was V407 Cyg, which had a Mira giant companion (Abdo et al. 2010). The nova was therefore embedded in the dense wind of its companion star, providing an ideal environment for producing strong shocks when the fast nova ejecta slammed into the slow wind material. However, even novae with main sequence companions are capable of producing detectable γ-rays (e.g., Ackermann et al. 2014, Cheung et al. 2016, Franckowiak et al. 2018), which is surprising given the negligible stellar winds leading to low density circumstellar material surrounding these binaries.

In V959 Mon, one of the first classical novae with a main sequence companion detected by *Fermi*, the shocked regions were directly imaged with the Very Long Baseline Array (VLBA) and European VLBI Network (EVN). As shown in Figure 1, the synchrotron-emitting regions did not align with the bipolar structure of the expanding thermal gas, as imaged by the Karl G. Jansky Very Large Array (VLA). Instead, the combined VLBA, EVN, and VLA observations revealed that the compact components were moving on a path roughly 45° to the VLA structure. High-resolution observations with the VLA separated by more than a year also revealed an apparent 90° flip in the orientation of the bipolar outflow (Figure 2). We concluded (Chomiuk et al. 2014) that the nova ejecta had 2 components: a slow flow in the equatorial plane of the binary, and a faster flow in the polar direction. The interaction between these flows led to the shocks seen in the VLBI observations, and inferred from the γ-ray detections.

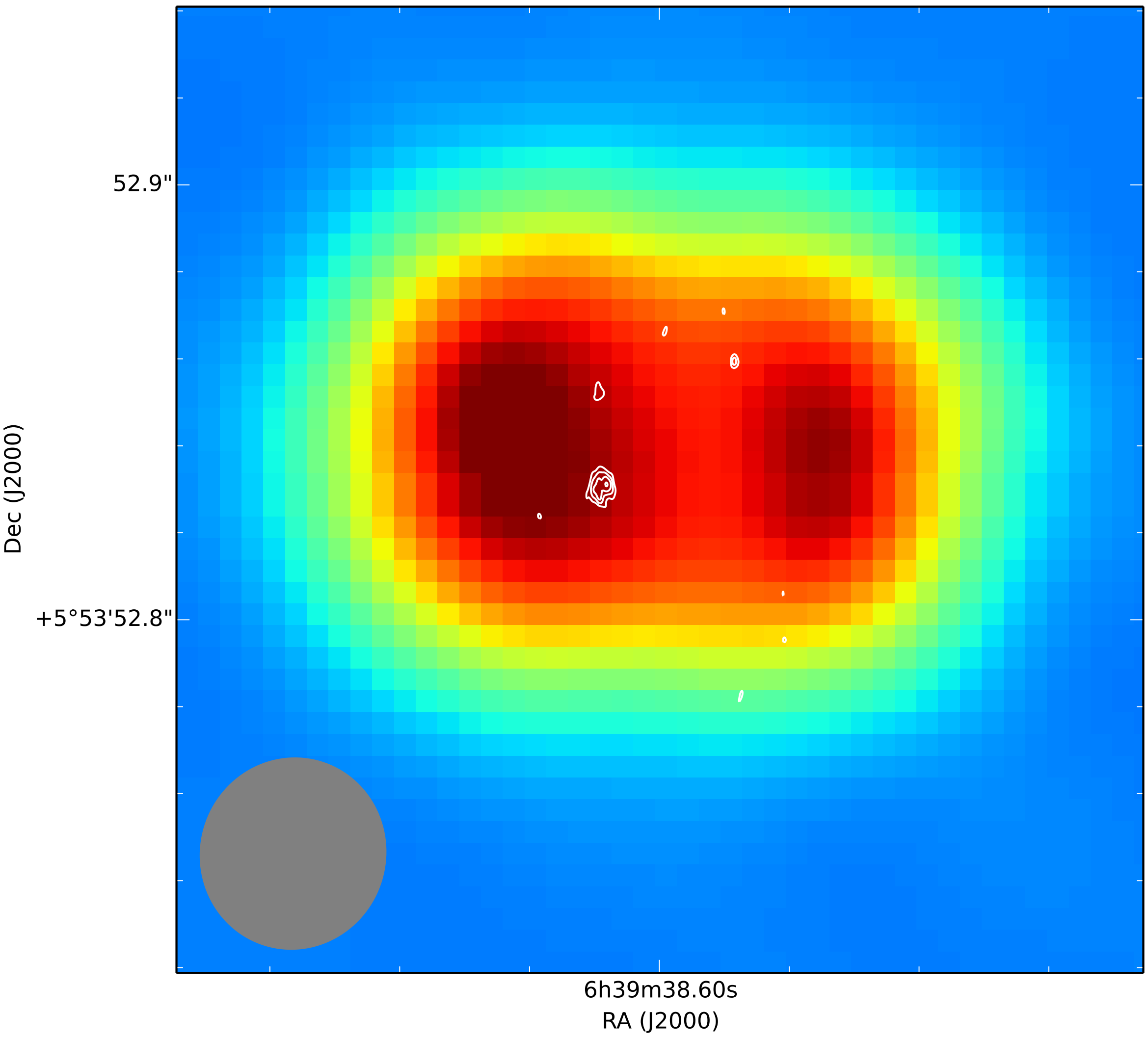

Figure 1: *Locations of synchrotron emission in V959 Mon: VLBA 5 GHz contours (in white) 106 days after initial detection, overlaid on VLA 36.5 GHz image from 126 days after initial detection. The gray ellipse in the lower left corner represents the 36.5 GHz VLA restoring beam. Adapted from Chomiuk et al. 2014.*

In the two-flow model (Figure 3), the initial ejection of material from the nova is relatively slow (a few hundred km s^{-1}). This slow ejecta forms a common envelope around the binary and angular momentum is transferred such that a dense torus forms in the equatorial plane (Porter et al. 1998). Later, a fast wind develops. The wind is confined by the torus and ejected primarily perpendicular to the orbital plane. The fast flow dominated the VLA images during the first year of observing. The slow equatorial flow in the torus remained optically thick much longer, and dominated the VLA images at late times. The collision of the fast flow with the slower torus leads to shocks, creating a population of accelerated particles (Chomiuk et al. 2014, Metzger et al. 2015, Martin et al. 2018). In V959 Mon, these accelerated particles were detected via radio synchrotron emission (Chomiuk et al. 2014). There is new evidence that the shocks are also at least partially responsible for the optical emission. Li et al. (2017) found a correlation between the optical and γ-ray light curves for V5856 Sgr that indicated the optical emission is reprocessed shock emission.

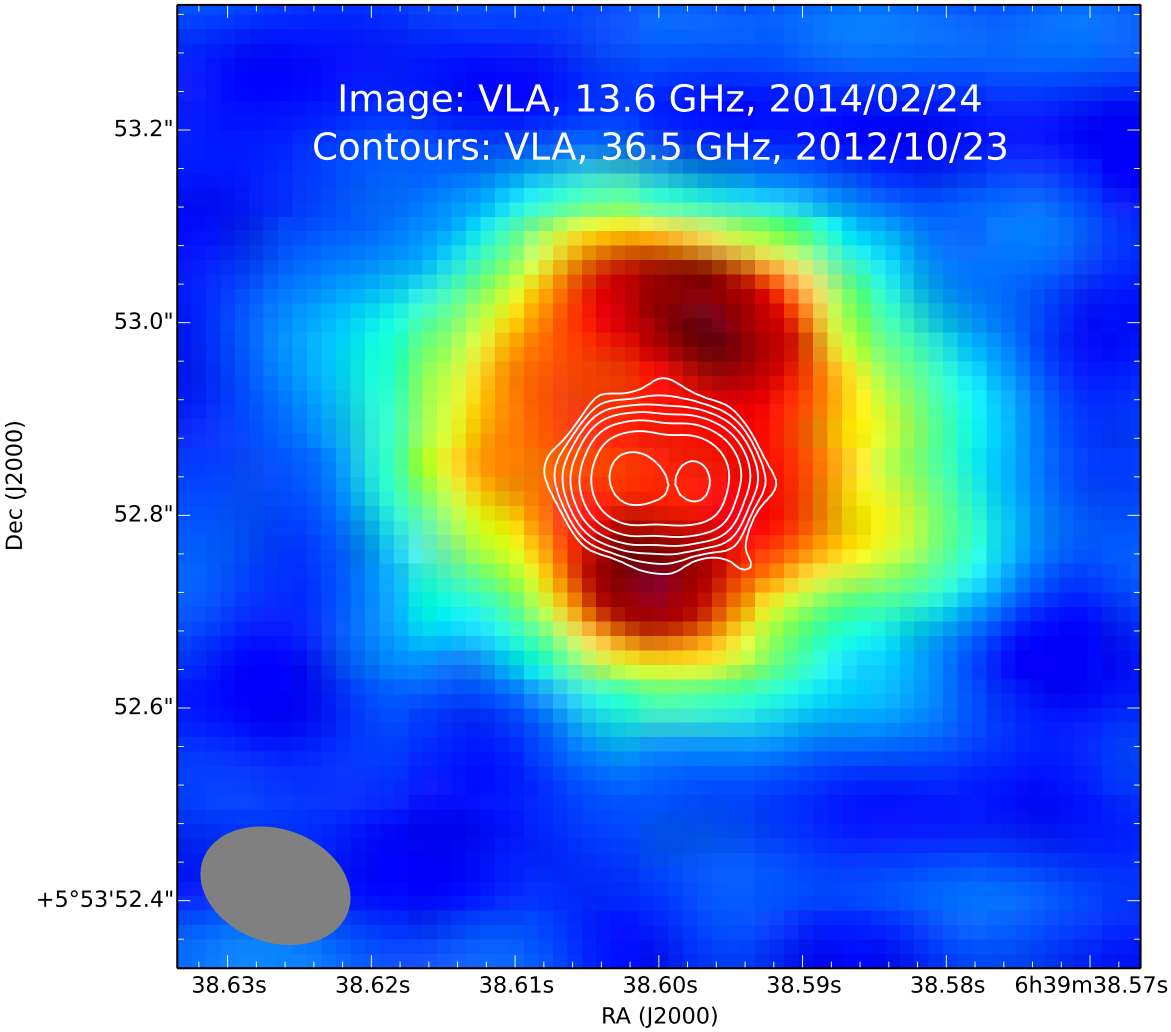

Figure 2: *The evolution of V959 Mon. The plane of the binary system is oriented in the N-S direction.* ***White Contours*** *show the 36.5 GHz image of V959 Mon 126 days after initial detection, which is dominated by the fast bipolar material perpendicular to the orbital plane.* ***Color*** *shows the 13.6 GHz image of V959 Mon 615 days after the initial detection, which is dominated by the slowly expanding torus in the orbital plane. The Gray ellipse in the lower left represents the 13.6 GHz VLA restoring beam. Adapted from Chomiuk et al. 2014.*

2 V392 Per

The known cataclysmic variable system was discovered to have a nova eruption on 2018 April 29 (CBET 4515, ATEL 11588). This is the first recorded nova eruption for this system. We initiated a large, multi-instrument observational effort to monitor the nova at several frequencies and angular resolutions. To date, we have used the VLA, VLBA, EVN, and Arcminute Microkelvin Interferometer - Large Array (AMI-LA). We also have upcoming observations with eMERLIN. Our first radio observation (VLA, 2018 APril 30) was a non-detection, but subsequent observations showed a brightening radio source (see Figure 4; ATEL 11647). Even in A-configuration, the nova ejecta are unresolved at this point. The AMI-LA observations provide excellent high-cadence observations showing multiple peaks in the radio light curve. However, without multi-frequency information at each data point, it is difficult to draw conclusions about what leads

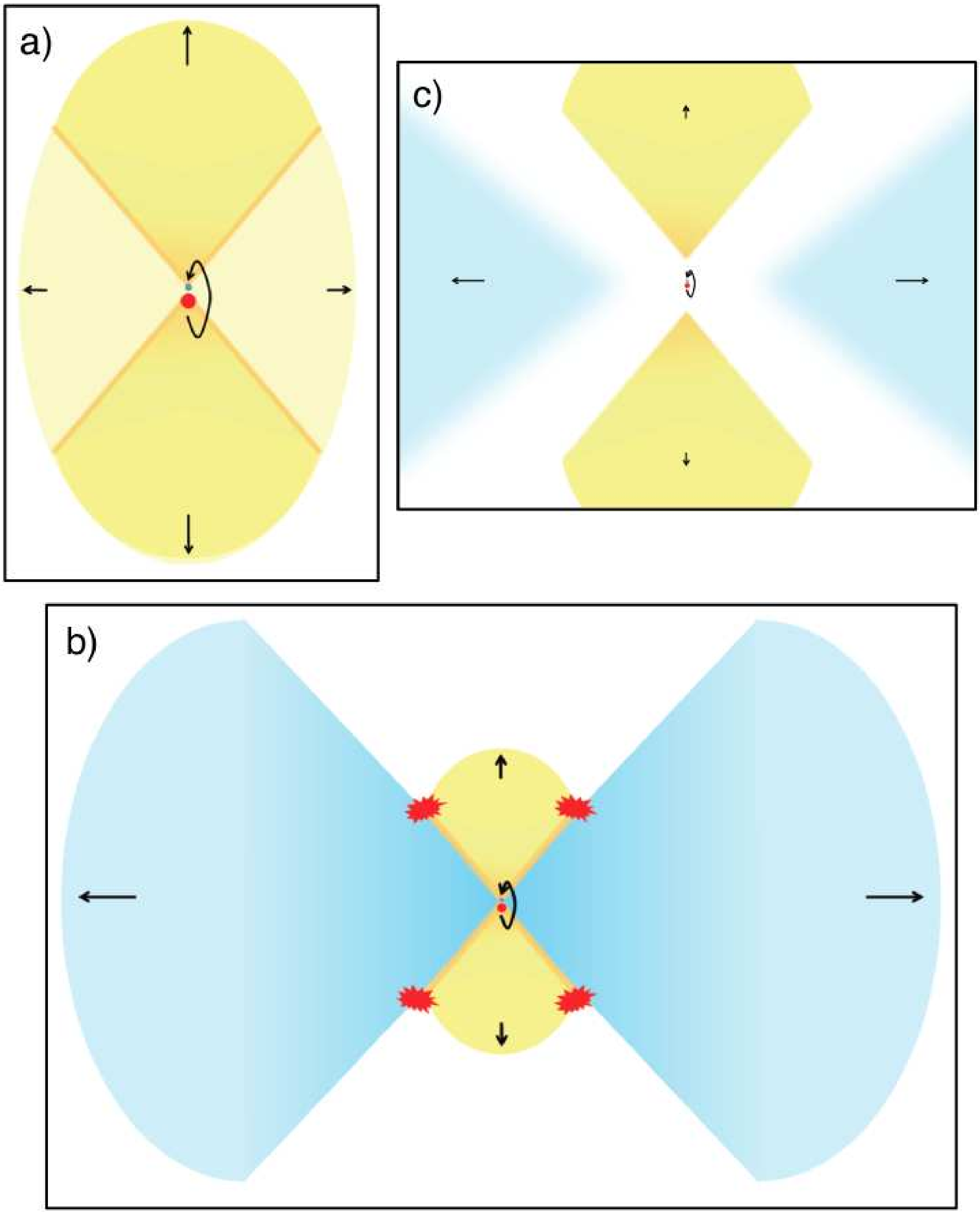

Figure 3: *The evolution of V959 Mon. A) At early times, the ejecta interacts with the binary and a dense torus is formed (darker yellow, oriented vertically). B) Later, a fast wind (blue) shocks against the torus leading to synchrotron and γ-ray emission (red regions). This phase corresponds to the image of V959 Mon in Figure 1. C) At late times, the wind material is too diffuse to detect and the dense torus dominates the radio emission. Adapted from Chomiuk et al. 2014.*

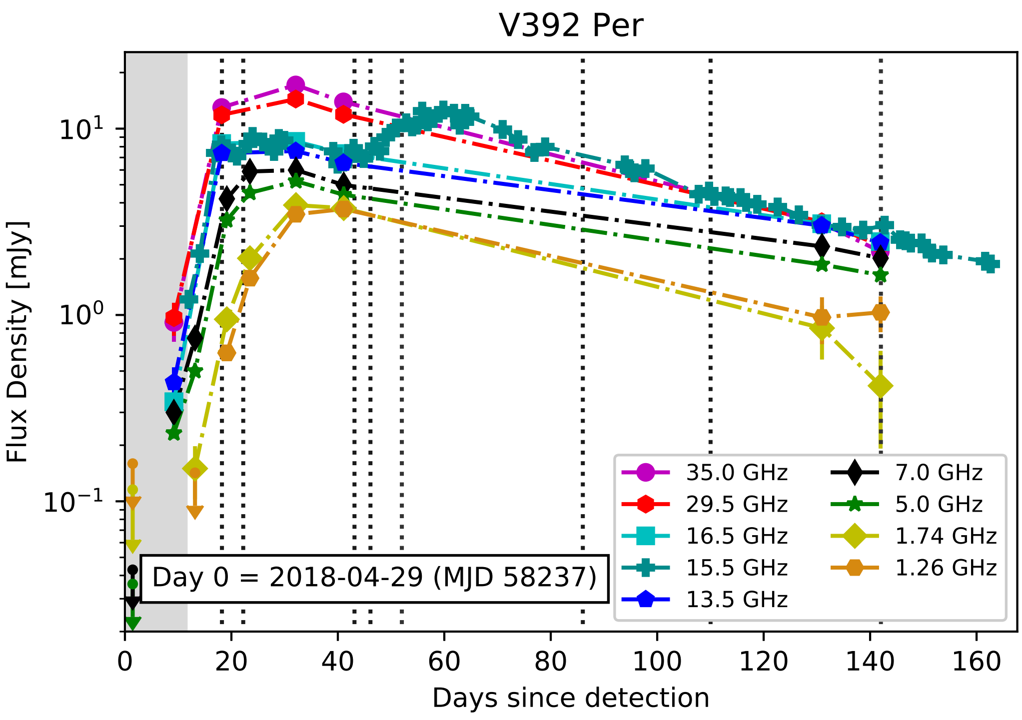

Figure 4: *Preliminary VLA and AMI-LA light curve of V392 Per. The green crosses (15.5 GHz) are from AMI-LA. All other data were obtained with the VLA. The gray region indicates the time when the nova was detected by the Fermi Gamma-ray Space Telescope. The vertical dashed lines indicate observations with the VLBA or EVN.*

to the structures in the light curve.

Once the VLA 5 GHz flux density was above 0.5 mJy, we began observing with the VLBA. The first two VLBA epochs were at 8.4 GHz and 4.9 GHz on 2018 May 17 and 2018 May 21, respectively. The first two VLBA observations clearly showed two compact components and a diffuse component. The observations were separated by about 4 days, and two of the compact components clearly moved during this time (see Figure 5). We are still analyzing our images, but early results indicate the compact knots had brightness temperatures in excess of 10^7 K and were moving with a projected velocity of 1350 km s^{-1} using a distance of 3.9 kpc (Darnley & Starrfield 2018).

Subsequent VLBA observations revealed drastic changes in the morphology of the VLBI-detected emission. While the source is initially dominated by the compact knots shown in Figure 5, later observations show it to be dominated by the diffuse component. The final EVN observation and the VLA light curve hint at a re-brightening in the low frequencies (1–2 GHz) that may indicate the presence of a second shock, similar to what was observed in V1535 Sco (Linford et al. 2017).

Due to the VLA moving into the compact D-configuration shortly after the eruption of V392 Per, we do not know how the compact components relate to the thermal ejecta. Our upcoming observations of the nova with eMERLIN will enable us to investigate the morphology of the thermal ejecta, but with only a single observation. Because of the limited amount of time available on eMERLIN and VLA A-configuration, it is likely that we will miss changes in the morphology of the thermal ejecta. With ngVLA, each data point in the radio light curve would also be a frame in a movie of the ejecta expansion.

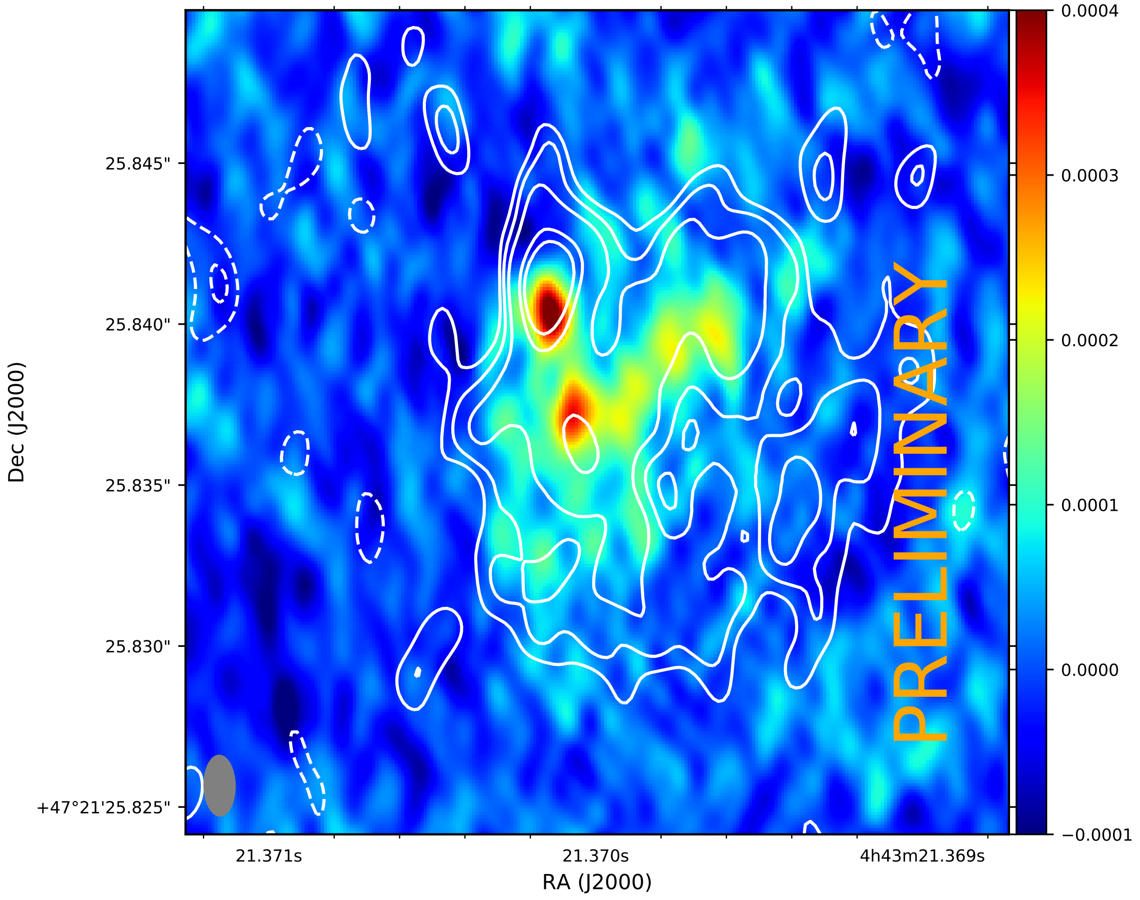

Figure 5: *The VLBA images of V392 Per. Color: 8.4 GHz image from 2018-05-17. Contours: 4.9 GHz image from 2018-05-21. Notice that the two compact components on the left hand side of the ejecta move away from each other along a line roughly oriented north-south. The gray ellipse in the lower left shows the restoring beam for the 8.4 GHz image.*

3 The Role of ngVLA in Addressing Open Questions About Novae

The ngVLA with very long baselines will be an excellent tool to answer the following questions:

1. How are the compact regions related to the bulk ejecta? VLBI observations can resolve multiple compact regions and reveal how they are distributed in/around the thermal ejecta. The thermal ejecta will be detectable earlier with ngVLA compared to the current VLA, thanks to the ngVLA's improved sensitivity. Combined VLBI and sub-arcsecond resolution observations will reveal if the ejecta are dominated by a spherical shell, a ring, or a bipolar structure (e.g., Slavin et al. 1995; Sokoloski et al. 2013). Evidence of a dense equatorial torus, which can lead to the bipolar structure seen in novae such as V959 Mon (e.g., Ribeiro et al. 2009), can be found with ngVLA monitoring. Understanding both the shocked regions and the overall shape of a nova remnant is essential to interpreting photometric measurements at all wavelengths, from radio to γ-rays.

2. What is the density structure and timing of the thermal flows? The multi-frequency radio light curve is sensitive to emission associated with the internal shocks (through synchrotron radiation as well as heating of the ejecta) and to thermal bremsstrahlung from the expanding ejecta. The former tends to dominate early, and the latter at late times. Careful analysis of the radio light curves can determine the epochs of major ejection events, as well as constrain the total mass and speed of the ejecta. The ngVLA will enable us to build these light curves with better sensitivity for the early emission. Furthermore, by utilizing subarrays to observe multiple frequencies simultaneously, the ngVLA will enable us to monitor the later (post ~ 14 days) evolution of the light curve with less observing time. Because we will not need as much time on source for each monitoring observation, we will be able to produce high-cadence light curves with the same (or less) total telescope time we currently use for our VLA monitoing. The high cadence is important to look for bumps and/or flares in the radio light curve (e.g., the late bump revealed by AMI-LA monitoring in V392 Per; Figure 4) that we may be missing due to observing constraints on current instruments. The very large bandwidths of each ngVLA observing band will reduce the number of observations needed to cover multiple radio bands and enable more accurate in-band spectral index measurements compared to the VLA.

3. What is the mechanism for γ-ray production in novae? A population of relativistic particles is needed to produce the γ-rays detected by *Fermi*. VLBI observations can locate the shocks where these particles are accelerated. Directly imaging the shocked regions with VLBI during γ-ray detection has not yet been attempted, so the current knowledge is based on VLBA and EVN imaging after the γ-rays have ceased. Observing the shocked regions during γ-ray detection will directly probe the connection between the shocks and the γ-rays. Combining the VLBI and sub-arcsecond resolution observations provides knowledge of what material is being shocked and what material is doing the shocking. The ngVLA with very long baselines will provide this information with a single instrument, rather than the five we rely on currently.

4. How far away are the novae? Even with *Gaia*, there remain many questions about the distances to Galactic novae. One technique for obtaining these distances is expansion parallax, which relies on high resolution imaging to track the angular size of the ejecta while obtaining spectroscopic measurements to determine the ejecta velocity (Woudt et al. 2009, Linford et al. 2015). Because the ngVLA will have sub-arcsecond resolution at all times, it will be the perfect tool for obtaining the angular expansion rate of novae.

As outlined in these questions, the ngVLA has a large role to play in multi-wavelength studies of these complex stellar outflows. From a high-energy perspective, comparing the velocity of the radio-emitting blast-wave to post-shock temperatures from X-ray observations constrains the amount of energy lost to particle acceleration. Constraining the energy drained from behind the shock, and hence the particle acceleration efficiency, is the best way to distinguish between the two main models for γ-ray production in novae; hadronic production via pion decay, and leptonic production via inverse Compton scattering (e.g., Martin & Dubus 2013). From the optical perspective, ngVLA observations will relate the spectroscopic features to resolved outflows. Changes in spectral lines will be compared to changes in radio morphology and/or angular expansion rates, leading to better understandings of the system dynamics. Evidence of shocks from radio synchrotron emission in the radio light curves can be compared with optical and X-ray photometric measurements to test how much reprocessed shock emission contributes to the optical light curve (e.g., Li et al. 2017).

VLBI observations of nova ejecta are also the only way to get an estimate of the magnetic field strength in the shocked regions (e.g., Rupen et al. 2008, Linford et al. 2017). Knowledge of the magnetic field is important for determining particle acceleration processes (e.g., Caprioli et al. 2015). Furthermore, correlating the angular expansion from VLBI observations with a decreasing absorption column seen in the X-rays would give direct constraints on the relative mass in the shocked and un-shocked ejecta.

Increased sensitivity, especially at very long baselines, will also enable us to measure spectral index of the compact regions. Knowing whether the synchrotron emission is optically thick or thin is crucial for modelling its energetics.

4 Conclusion

The eruption of V392 Per demonstrates the need for a Next Generation VLA and the importance of including very long baselines in its design. In order to study this nova at radio wavelengths, we have had to obtain time on 5 separate instruments throughout the world. With the ngVLA, this could all be done with a single instrument. VLBI observations are the only way to directly image the shocked regions within the ejecta. Simultaneous VLBI and arcsecond resolution imaging will reveal the locations of the shocks within the thermal ejecta and provide direct measurements of how much non-thermal emission is contributing to the total measured radio flux density. Monitoring novae with sub-arcsecond resolution will simultaneously build the radio light curve, providing a measurement of the ejecta mass, and create a movie of the ejecta expansion and interaction with any surrounding material. The ngVLA's wide bandwidths will lead to better spectral index measurements and reduce the number of observations necessary to build the multi-frequency radio light curves.

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