Interferometric Observations of Explosive Variables: V838 Mon, Nova Aql 2005 & RS Oph

Benjamin F. Lane\textsuperscript{a}, Alon Retter\textsuperscript{b}, Joshua A. Eisner\textsuperscript{c}, Robert R. Thompson\textsuperscript{d}, Matthew W. Muterspaugh\textsuperscript{e},

\textsuperscript{a}MIT Kavli Institute for Astrophysics and Space Research, MIT Department of Physics, 70 Vassar Street, Cambridge, MA 02139
\textsuperscript{b}Astronomy & Astrophysics Dept., Penn State University, 525 Davey Lab, University Park, PA 16802-6305
\textsuperscript{c}U. C. Berkeley, Department of Astronomy, 601 Campbell Hall, Berkeley, CA 94720
\textsuperscript{d}Michelson Science Center, 100-22 California Institute of Technology, Pasadena, CA 91125
\textsuperscript{e}Department of Geological & Planetary Sciences, MS 150-21, California Institute of Technology, Pasadena CA 91125

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ABSTRACT

During the last two years we have used the Palomar Testbed Interferometer to observe several explosive variable stars, including V838 Monocerotis, V1663 Aquilae and recently RS Ophiuchi. We observed V838 Monocerotis approximately 34 months after its eruption, and were able to resolve the ejecta. Observations of V1663 Aql were obtained starting 9 days after peak brightness and continued for 10 days. We were able to resolve the milliarcsecond-scale emission and follow the expansion of the nova photosphere. When combined with radial-velocity information, these observations can be used to infer the distance to the nova. Finally we have resolved the recurrent nova RS Oph and can draw some preliminary conclusions regarding the emission morphology.

Keywords: Techniques – interferometric, Novae, Distances

1. INTRODUCTION

With the improving sensitivity limits of ground-based optical interferometers it is over time becoming more likely that eruptive transients such as novae will be bright enough to be observed. The high angular resolution measurements that can be made with such systems should allow observers to directly probe some of the aspects of these explosions. Here we discuss three cases where such observations have been made.

V838 Monocerotis is an explosive variable star that underwent a nova-like event in early 2002\textsuperscript{1,2} with a peak magnitude of $m_V \sim 6.8$ (Fig. 1). However, the eruption was unlike classical novae in that the effective temperature of the object dropped and the spectral type evolved into a very late M and L type.\textsuperscript{3} The eruption mechanism of V838 Mon is not well understood, but is probably a new type of explosive variable. There have been many models proposed: the merger of a main-sequence binary star,\textsuperscript{4} a He-flash on a post-AGB star,\textsuperscript{5} or even the accretion of several planets.\textsuperscript{6}

Classical novae are energetic stellar explosions that occur in systems containing a white dwarf (WD) accreting mass from a late-type stellar companion.\textsuperscript{7} When the amount of accreted material on the surface of the white
A white dwarf reaches some critical value at which a thermonuclear runaway is ignited, giving rise to the observed nova outburst in which material enriched in heavy elements is ejected into the surrounding medium at high velocities.

Nova Aquilae 2005 (ASAS190512+0514.2, V1663 Aql) was discovered on 9 June 2005 by G. Pojmanski & A. Oksanen. At the time of discovery the magnitude was \( m_V = 11.05 \); the source reached \( m_V \sim 10.8 \) the following day, and declined in brightness thereafter. The time to decay 2 magnitudes \( t_2 \) was \( \sim 16 \) days, making V1663 Aql a “fast” nova.

Soon after discovery M. Dennefeld & F. Ricquebourg obtained an optical spectrum with features indicating a heavily reddened nova. The H-\( \alpha \) emission lines exhibited P Cygni line profiles and indicated an expansion velocity in the range of 700 km s\(^{-1}\) (Dennefeld, personal communication) to 1000 km s\(^{-1}\).

Direct observations of the expansion of the nova shell provide an opportunity to accurately determine the distance to the nova. Such observations are usually only possible many years after the outburst, when the expanding shell can be resolved. We have used the Palomar Testbed Interferometer (PTI) to resolve the 2.2\( \mu \)m emission from V1663 Aql and measure its apparent angular diameter as a function of time. We were able to follow the expansion starting \( \sim 9 \) days after the initial explosion; when combined with radial velocities derived from spectroscopy we are able to infer a distance and luminosity of the object.

Recurrent novae are thought to consist of massive white dwarfs orbiting late-type giants; material is pulled from the giant and accreted onto the WD. As in the case of classical novae, a thermonuclear runaway reaction will on occasion blow off large amounts of matter in a bright, rapid explosion. There are a small number of systems which have been observed through many such outbursts, including RS Oph, which showed outbursts in 1898, 1933, 1958, 1967, 1985 and 2006. It has been argued that recurrent nova systems are the progenitors of Type Ia supernovae, as the short duration of the explosions indicate that the WD should be very close to the Chandrasekhar limit.

The Palomar Testbed Interferometer (PTI) was built by NASA/JPL as a testbed for developing ground-based interferometry and is located on Palomar Mountain near San Diego, CA. It combines starlight from two out of three available 40-cm apertures and measures the resulting interference fringes (see Fig. 2 for representative \( uv \)-plane coverage). The high angular resolution provided by this long-baseline (85-110 m), near infrared (2.2\( \mu \)m) interferometer is sufficient to resolve emission on the milli-arcsecond scale.

## 2. OBSERVATIONS

Each nightly observation with PTI consisted of one or more 130-second integrations during which the normalized fringe visibility of the science target was measured. The measured fringe visibilities of the science target were calibrated by dividing them by the point-source response of the instrument, determined by interleaving observations of calibration sources; the calibration sources were chosen to be single stars, close to the target on the sky and to have angular diameters less than 2 milli-arcseconds, determined by fitting a black-body to archival broadband photometry of the sources. For further details of the data-reduction process, see Colavita et al. and Boden et al.

In addition to measured fringe visibilities, we obtain K-band photometry using photon count rates from PTI and K-band magnitudes for the calibrator sources provided by 2MASS. Note that PTI was not designed with high-precision photometry in mind, and hence the K-magnitudes should be treated with some caution.

We observed V838 Mon on 7 nights between 5 November and 13 December 2004, using PTI in the standard K-band mode, with the 85-meter North-West (5 nights) and South-West (2 nights) baselines.

We observed V1663 Aql on 10 nights between 15 June 2005 and 28 June 2005; on six of those nights we obtained data on two or three interferometric baselines.

We observed RS Oph on 2 nights: 24 March and 2 April 2006. Preliminary examination indicates that the source is resolved on our 85-meter baseline.
Figure 1. The V-band light curve of V838 Mon, collected from VSNET circulars.

Figure 2. The $uv$-coverage for one night of observations of V1663 Aql using PTI.

3. MODELS

The theoretical relation between source brightness distribution and fringe visibility is given by the van Cittert-Zernike theorem. For a uniform intensity disk model the normalized fringe visibility (squared) can be related to the apparent angular diameter using

$$V^2 = \left( \frac{2 J_1(\pi B\theta_D/\lambda)}{\pi B\theta_D/\lambda} \right)^2$$

(1)
Figure 3. Left: The measured fringe visibility ($V^2$) of V838 Mon as a function of projected baseline length measured in units of the observing wavelength (2.2µm). Also shown are the best-fit Gaussian and uniform disk models, which are indistinguishable at this projected baseline, but do show that the emission is resolved and that the data is inconsistent with a circularly symmetric emission source. Right: The measured fringe contrast as a function of source hour angle, together with the best-fit models. A binary or inclined disk model is required to account for the data from both baselines. Note that the NW-baseline data has been moved up by 1.0 for clarity. Different symbols are used for different nights. The figure is reproduced from Lane et al.\textsuperscript{17}

Figure 4. Observed visual light curve for V1663 Aql. The observations were collected from VSNET publications. The time taken for the V-band lightcurve to drop by two magnitudes has been shown to be correlated with the maximum source magnitude. For V1663 Aql, the time to drop two magnitudes ($t_2$) was $\sim$ 16 days.

where $J_1$ is the first-order Bessel function, $B$ is the projected aperture separation and given by $B = \sqrt{u^2 + v^2}$ where $u, v$ are two orthogonal components of the projected baseline, $\theta_{UD}$ is the apparent angular diameter of
the star in the uniform-disk model, and $\lambda$ is the wavelength of the observation.

The availability of data taken with multiple baselines with different position angles allows us to distinguish between a circularly symmetric source and elliptical or inclined disk models. For the asymmetric cases we fit for three parameters: size ($\theta$), inclination angle ($\phi$), and position angle ($\psi$). Inclination is defined such that a face-on disk has $\phi = 0$ and $\psi$ is measured east of north. Following the approach of Eisner et al.,\textsuperscript{18} we include $\phi$ and $\psi$ in our models of the brightness distribution via a simple coordinate transformation:

\[
\begin{align*}
    u' &= u \sin \psi + v \cos \psi \\
    v' &= \cos \phi (v \sin \psi - u \cos \psi)
\end{align*}
\]

Substitution of $(u, v)$ for $(u', v')$ in the expressions above yields models with inclination effects included.

We perform least-squares fits of uniform and inclined disk models to the measured fringe visibilities in order to derive sizes and inclination angles.

### 4. RESULTS

#### 4.1. V838 Mon

We have published the results of our observations in a recent letter;\textsuperscript{17} we review these results here. We modeled the 2.2$\mu$m emission from V838 Mon using several simple emission morphologies, including face-on and inclined disks and binary models. We find that the best fits to the data are provided by inclined disk or two-component models. One possibility indicated by the data is that the observed K-band emission is produced by a very elongated structure similar to an edge-on disk. The projected linear dimensions of such a source are approximately $3.5^{+0.2}_{-1.5} \times 0.07^{+0.0}_{-0.07}$ milli-arcseconds ($28^{+2}_{-13} \times 0.5^{+24}_{-6}$ AU).

We suggest that the observed emission from V838 Mon was due to ejecta produced during the eruption. Soon after the peak of the outburst, the expansion velocity of the ejecta was estimated as 50-350 km/s.\textsuperscript{2,19,20} For
the time elapsed since outburst of $\sim 10^8$ s, the distance between the ejecta and the star should be in the range 30–220 AU. This range is consistent with the projected separations we measure. It is also likely that the ejecta are not uniformly distributed, and hence the binary morphology preferred by the data may be “clumpiness” in the ejecta.

4.2. V1663 Aql

We resolved the emission from V1663 Aql on several nights, and find that the measured fringe visibilities generally decrease with time. This implies that the source is expanding. We also find that the data on nights with more than one available baseline are not well matched by a simple uniform disk model, see Fig. 6; in effect the visibility in the “North-South” baseline is too high to be consistent with the “North-West” and “South-West” baselines. There are two morphologies that can fit the observations: the first is an elliptical disk, with an aspect ratio of $\sim 1.4:1$ (an example of such a fit is shown in Fig. 5), the second is a centrally condensed source. We are currently working to further refine models of the emission from this system.

The measured change in apparent angular size is approximately 0.2 mas/day (see Fig. 7); this can be combined with the observed radial expansion velocity inferred from spectroscopic observations to determine the geometric distance to this nova $d \sim 5.5 \pm 1$ kpc. In addition, by extrapolating the linear expansion trend backward in time we can derive the time of the initial explosion: MJD 53526.5 ± 1.3 d. Finally, we note that the two last data points in our series do not follow the simple expansion trend of the previous points. We suggest that we are seeing the optical depth of the ejecta drop, allowing emission from further inside the fireball to escape.

5. CONCLUSIONS

In the past two years we have used the Palomar Testbed Interferometer to observe three eruptive variable stars: V838 Mon (peculiar variable), V1663 Aql (classical nova) and RS Oph (recurrent nova). In each case we were able to resolve the emission and measure its angular size. In the case of V1663 Aql we were able to follow the
Figure 7. The best-fit angular size of the emission from V1663 Aql as a function of time.

expansion and derive a geometric distance. These observations of V1663 Aql are only the second time a classical nova has been resolved by optical interferometry.

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