V723 Cas (Nova Cassiopeiae 1995): MERLIN observations from 1996 to 2001

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ABSTRACT

MERLIN observations of the unusually slow nova V723 Cas are presented. Nine epochs of 6 cm data between 1996 and 2001 are mapped showing the initial expansion and brightening of the radio remnant, the development of structure and the final decline. A radio light curve is presented and fitted by the standard Hubble flow model for radio emission from novae in order to determine the values of various physical parameters for the shell. The model is consistent with the overall development of the radio emission. Assuming a distance of 2.39 (±0.38) kpc and a shell temperature of 17000 K, the model yields values for expansion velocity of 41.4 ± 0.1 kms\(^{-1}\) and shell mass of 1.13 ± 0.04 × 10\(^{-4}\) M\(_{\odot}\). These values are consistent with those derived from other observations although the ejected masses are rather higher than theoretical predictions. The structure of the shell is resolved by MERLIN and shows that the assumption of spherical symmetry in the standard model is unlikely to be correct.

Key words: stars: individual: V723 Cas – novae, cataclysmic variables – stars: winds, outflows – radio continuum: stars

1 INTRODUCTION

Classical novae are interacting binary systems and the most energetic type of cataclysmic variable. The central system consists of a white dwarf primary and a main sequence secondary which fills its Roche lobe. Hydrogen-rich matter is accreted from the secondary onto the white dwarf via an accretion disc. Once the pressure at the base of the accreted envelope reaches a critical level, thermonuclear reactions begin in the accretion disc. Once the pressure at the base of the accreted envelope reaches a critical level, thermonuclear reactions begin. The central system consists of a white dwarf primary and a main sequence secondary which fills its Roche lobe. Hydrogen-rich matter is accreted from the secondary onto the white dwarf via an accretion disc. Once the pressure at the base of the accreted envelope reaches a critical level, thermonuclear reactions begin in the accretion disc. Once the pressure at the base of the accreted envelope reaches a critical level, thermonuclear reactions begin. 

V723 Cas (Nova Cassiopeiae 1995) was discovered at V = 9.2 mag on 1995 August 24 by M. Yamamoto (Hirosewa et al 1995) which for the purposes of this paper will be defined as day zero. The nova reached visual maximum of V = 7.1 mag 115 days later on December 17. The light curve characteristics of V723 Cas display very slow evolution with a long pre-maximum halt (Hachisu & Kato 2004) and have led it to be classified as a very slow nova alongside HR Del and RR Pic (Chochol & Pribulla 1997). Oscillations in the light curve are evident post-maximum, a feature also seen in the evolution of HR Del. Optical spectroscopy (Iijima, Rosino & Della Valle 1998, Munari et al 1996) prior to maximum light revealed fairly narrow emission components (full width half maximum FWHM ~ 90 kms\(^{-1}\)) with P Cygni absorptions blueshifted ~ 100 kms\(^{-1}\) relative to the emission peak. Munari et al (1996) report that post-maximum the emission lines increase by a factor of several times in intensity and broaden to FWHM ~ 550 km s\(^{-1}\) whilst the absorption components remain at a similar width to pre-maximum. Ground and space-based infrared observations (Evans et al 2003) show line profiles with FWHM ~ 330 km s\(^{-1}\) and indicate an ejected mass of 2.6 × 10\(^{-5}\) M\(_{\odot}\) from the Br\alpha line and 4.3 × 10\(^{-4}\) M\(_{\odot}\) from the free-free emission (assuming a distance of 4 kpc).

Radio emission in novae typically arises due to free-free emission from gas at temperatures of approximately 10\(^{4}\) K (Seaquist 1989). Non-thermal components have been detected in a few novae, the most notable example being...
GK Per which exhibits a non-thermal ridge coincident with the south-west portion of the optical shell (Bode, O'Brien & Simpson 2004). This is generally attributed to the collision between the nova ejecta and the previously shed common-envelope of a pre-nova phase, most likely following a `born-again' AGB star phase (Dougherty et al 1996). Higher temperature emission detected in some nova outbursts (e.g. QU Vul, Taylor et al. 1987; V1974 Cyg, Pavelin et al 1993) suggests that, at least for some novae, there is shocked material within the ejected shell.

This paper presents results obtained from ten MERLIN observations of V723 Cas, nine at a wavelength of 6 cm and one at 18 cm. The 6 cm epochs produce maps and the shell structure is discussed. Radio flux measurements lead to a determination of the radio light curve to which standard models are fitted in order to determine values for the physical parameters of the nova outburst.

2 OBSERVATIONS

V723 Cas was observed using MERLIN between 1996 December 13 and 2001 October 26 resulting in ten epochs of data. A summary of the observations can be found in Table 1. The fitted beam is a 2D Gaussian fit to the point spread function for each observation.

The observing wavelength was 6 cm (4994 MHz) for all epochs except 6 April 1998 when it was 18 cm (1658 MHz). The nova was observed in phase-referencing mode, switching to phase-reference source 0102+511 (J2000) at regular intervals. The point source OQ208 was used as an amplitude calibrator and was flux calibrated against 3C286 using the Baars scale (Baars et al 1977). The data were edited and flagged using the MERLIN package imfit and the total flux density in this Gaussian and its uncertainty was determined from the rms variation in an off-source region of the map.

A 50 mas circular restoring beam was used to create each map. The December 1996 and January 1997 maps show that the source is unresolved by MERLIN at this early stage. As the shell expands over the next few epochs it appears to become extended along a north-south direction. Over a year later in February 2000 this north-south axis is still apparent although it now gives the appearance of being one side of a partial shell. The April 2000 data are rather noisy (see section 3.2) and only the two brightest peaks aligned with the north-south ridge are believed to be real emission from V723 Cas. The next image, taken 9 months later in January 2001, suggests that the north-south components have been replaced by ones aligned east-west. This structure then fades over the remaining two epochs.

3 RESULTS

3.1 The 6 cm radio maps

The nine radio maps at 6 cm are presented in Figure 1. Natural weighting of the data was used during mapping to maximise the signal to noise ratio and the cleaning process was terminated when the total cleaned flux reached a maximum value. A 50 mas circular restoring beam was used to create each map.

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3.2 Radio flux densities

Two methods were used for estimating the total flux density at each epoch. Firstly, the total flux density in the region of the source in the final cleaned map was measured using imstat and the uncertainty was determined from the rms variation in an off-source region of the map. Secondly, the area was re-imaged using uvtaper to weight down the longer baselines. Tapering values of 500 kλ, 1000 kλ and 2000 kλ were applied to the data and the data were also imaged with no tapering. This is particularly useful at epochs where the source is resolved since in these circumstances an interferometer cannot fully sample all the scale-sizes within the source. A Gaussian was then fitted to the source using imfit and the total flux density in this Gaussian and its uncertainty were recorded. The clean depths used for each of the methods were 1σ, 2σ and 3σ and the data were also imaged by cleaning down to the first negative clean component. The ten final flux measurements used from the set of 160 produced by these methods were chosen on the basis of the single imaging method which consistently gave the highest flux density. Using the two techniques allows an appreciation of the systematic uncertainties in the fluxes and
Figure 1. 6 cm MERLIN maps of V723 Cas. The contour levels are (-3, 3, 3√2, 6, 6√2, 12, 12√2...) × 0.15 mJy. The greyscale runs from 3 mJy to 20 mJy. The horizontal bars show the expected diameter of the shell assuming a particular distance and expansion velocity as discussed in the text.

leads to the estimates presented in Table 1. Figure 2 shows the resulting radio light curve for V723 Cas. The April 2000 observation appears to have unusually high flux density. Examination of the flux density of the phase calibrator reveals that it is also suspiciously high and that the data has poor phase calibration as a result. It is highly unlikely that the flux density value for this epoch is trustworthy.

4 INTERPRETATION

4.1 The radio light curve

The radio light curve is consistent with the classic 3-phase evolution for nova light curves (Hjellming 1990). The expanding shell is assumed to emit via thermal bremsstrahlung. In the earliest stages, Phase I, the shell is optically thick and the observed flux increases as the shell expands, the photosphere being coincident with the physical shell boundary. The flux is therefore expected to be proportional to \( \nu^2 t^2 \), where \( \nu \) is the frequency of the radio observation and \( t \) is the time since outburst. During Phase II the
effective photosphere lags behind the physical shell boundary as the shell becomes optically thin. Eventually the shell is entirely optically thin and, if it is isothermal, the flux declines as $\nu^{-0.1} t^{-3}$. Hjellming suggests that the flux in Phase II varies approximately as $\nu^{0.6} t^{-4/3}$.

It is possible to make a simple check on the spectral index of the emission using the flux densities from the contiguous observations on 1998 March 4 at 6 cm and on 1998 April 6 at 18 cm. This leads to a spectral index of 0.54 which implies that the turnover into optically thin emission has begun by this stage. However, by using the 6 cm flux density from March 4 rather than April 6 the spectral index is underestimated. This is consistent with the simple model proposed by Hjellming which predicts a spectral index between 0.6 and 2 for this phase of the evolution.

### 4.2 Hubble flow model for radio emission from novae

By fitting a model for the emission to the light curve of Figure 2 it is possible to estimate the values of a number of physical parameters such as the mass of the shell and its ejection velocity. The standard model employed here is known as the Hubble flow model (Seaquist and Palimaka 1977; Hjellming et al. 1979). It assumes an isothermal spherically-symmetric shell resulting from an instantaneous mass ejection with a linear velocity gradient. Hence as the shell expands it grows thicker with internal and external boundaries determined by the assumed range of ejection velocities.

In each case the flux density expected at a given epoch and frequency is calculated by integrating the radiative transfer equation through the shell assuming a temperature of 17000 K and a distance of 2.39 kpc.

| Model parameter     | Best-fitting value |
|---------------------|--------------------|
| Ejected mass $M_e$  | $1.13 \pm 0.04 \times 10^{-4}$ M$_\odot$ |
| Outer shell velocity $v_1$ | $414.4 \pm 0.1$ km s$^{-1}$ |
| Inner shell velocity $v_2$ | $102 \pm 4$ km s$^{-1}$ |

Figure 2. Radio light curve for V723 Cas. Nine 6 cm epochs and one 18 cm epoch are presented. Note the discussion in the text about the anomalously high flux density at day 1697.
Figure 3. Best fitting model light curve for the Hubble flow model overlayed on the flux density measurements from the 6 cm MERLIN observations.

![Figure 3](image3.png)

Figure 4. Best fitting mass contours for a range of temperatures and distances. The best fitting mass at any point in the plane is the contour value \( \times 10^{-4} M_\odot \).

![Figure 4](image4.png)

The ratio of inner to outer velocity are all well constrained and that the likelihood peaks at the best fit value.

Figure 5 shows the best fitting Hubble flow model light curve. The best fit for these models depends on both the distance to the nova and the temperature. Figures 4 and 5 show how the values of mass and velocity vary for different pairs of temperature and distance. The ratio of inner to outer velocity is fixed at 0.248 for all these model runs. These plots are the result of 10000 model runs resulting from 100 values each for temperature and distance.

The estimate of ejected mass derived from the radio lightcurve modelling of around \( 1.1 \times 10^{-4} M_\odot \) is about 25% of that obtained from the free-free infrared continuum observations of Evans et al. (2003). However they assume that the distance is 4 kpc. At the same temperature (17000 K), Figure 4 shows the ejected mass estimate from the radio emission rises to around \( 4 \times 10^{-4} M_\odot \). However, for this distance, assumption of a higher temperature (Evans et al use a value of 3.2 \( \times 10^5 \) K) would reduce the mass estimate again to around \( 0.8 \times 10^{-4} M_\odot \). As Evans et al (2003) point out, the estimates derived observationally are generally about an order of magnitude greater than those resulting from simulations of the thermonuclear runaway.

The higher temperature cited above is thought to arise from 'coronal' gas around the nova. It is unlikely that this component of the ejecta makes anything other than a negligible contribution to the radio flux of the nova. This claim is based on the fact that RS CVn stars have radio fluxes comparable to that of a nova shell arising from coronal gas at temperatures in excess of \( 10^8 \) K. (Hjellming & Gibson, 1980; Kuijpers & van der Hulst, 1985). It is therefore unlikely that coronal gas at \( 3.2 \times 10^5 \) K would significantly affect the results presented in this paper, although inclusion of this emission is an aspect which would improve the accuracy of future models.

Despite the reasonable fit to the radio light curve the Hubble Flow model cannot be an entirely accurate representation of the truth. The smooth mass distribution which the model is based on is misleading as images of nova shells, including the radio maps presented in this paper, show that the ejecta are far from uniform. In reality the material is highly clumped with polar and equatorial features of enhanced density (e.g. Harman & O’Brien 2003).

A simple statistical treatment for the clumping of the ejecta has been applied to investigate the effects that a non-uniform distribution of material may have on the best fitting parameters of the shell model. A similar method has been used to investigate mass-loss from OB stars (Abbott, Bieging & Churchwell 1981) and from Wolf-Rayet stars (Nugis, Crowther & Willis 1998). A correction factor is applied to the optical depth equations when solving the radiative transfer through the shell. The correction factor is governed by two parameters; \( x \) is the ratio of the lower density background to the high density clumps, and \( f \) is the filling factor, the fractional volume occupied by the high density clumps, or alternatively the fractional length along any line of sight which passes through the high density material. In this case, for \( x \geq 0.3 \) the clumping changes the parameters by no more than a few percent, however for strong clumping (\( x \sim 0.01, f \sim 0.01 \)) the best fitting mass can drop to approximately one third of the smooth shell case. The velocity of the outer shell boundary may increase by \( \sim 7\% \) for strongly clumped shells although generally the effect on this parameter is very small, probably due to it being well constrained during the optically thick stage. The inner shell velocity increases by up to a factor of 3 as \( f \) and \( x \) decrease, suggesting that increasing the density condensations in this model results in a
Expansion velocities are measured spectroscopically from the Fe VII line for V723 Cas from O’Brien et al (in prep). The flux scale is relative and the data were taken on 1999 February 4 with the Intermediate Dispersion Spectrometer on the Isaac Newton Telescope.

An interesting effect is seen between the 2000 April and 2001 January observations. The north-south structure appears to be replaced by an east-west alignment of the brightest peaks. A possible explanation for the switching of the dominant emission axis involved optical depth effects caused by the ejecta being non-uniform. Initially the ejecta are optically thick so in the early radio observations only the photosphere is visible. The brightness of the source is dependent only upon its temperature and angular size. As the remnant expands the density decreases and the radio photosphere begins to lag behind the physical shell boundary. This is the point where structure in the shell may become evident in the radio observations. However, the higher density regions scattered throughout the shell would remain optically thick for longer than the low density regions and would appear as bright peaks in the radio maps. As the expansion continues it is possible that the bright peaks that appear in one observation may become optically thin and be replaced by high density regions at different positions in the shell giving the impression that the axis of the dominant emission regions has rotated. Nova shells are known to exhibit coherent regions of increased density such as polar caps and tropical rings (e.g. FH Ser – Gill & O’Brien, 2000) and these features would be ideally placed for the apparent north-south / east-west switching observed between epochs.

This apparent rotation is an effect that has been seen in other interferometric observations of classical novae e.g. V1974 Cyg (Eyres et al 1996) and V705 Cas (Eyres et al 2000). The 6 cm maps for V1974 Cyg show north–south structure developing for the first five epochs only to be replaced by east–west features in the final epoch. The corresponding 18 cm maps show the same effect but occurring at a later time. Since the emission at 18 cm will become optically thin at a later time than the 6 cm emission this may support the hypothesis that an optical depth effect is responsible.

Figure 6. [Fe VII] line for V723 Cas from O’Brien et al (in prep).
5 CONCLUSION

Radio emission from V723 Cas has been detected at both 6 cm and 18 cm 477 days after discovery of the nova and has been monitored for a further 1778 days. The radio maps show non-uniform structure with a N-S ridge feature that develops over time and splits into two peaks which then switch to E-W alignment in the next map. The radio light curve is consistent with the evolution of other novae of faster speed classes.

A simple Hubble-flow model is applied to the radio flux measurements yielding values for expansion velocity \((414.4 \pm 0.1) \text{ km s}^{-1}\) and shell mass \((1.13 \pm 0.04) \times 10^{-4} \text{ M}_\odot\) for a distance of \(2.39 (\pm 0.38) \text{ kpc}\) and temperature 17 000 K. Although the value for ejected mass is consistent with previous estimates for classical novae there is still significant discrepancy between the mass predicted from the theory of the outburst (e.g. Starrfield, Truran & Sparks 2000) and the mass derived from modelling of observations such as those presented in this paper. Expansion velocities are similar to those derived from spectroscopic observations although the latter show that certain assumptions of the standard Hubble-flow model for radio emission are naive.

Asphericity of the shell and clumping of the ejected material are evident in many novae and future models should take these factors into account. The radio maps show how the morphology of the shell evolves and further understanding of this will only be gained when simulated model images are convolved with the uv distribution of the array and true synthetic images are produced. This will also provide insight into how nova shells will be seen by the next generation of interferometry networks such as e-MERLIN.

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