Non-Thermal Radio Emission from Colliding Flows in Classical Nova V1723 Aql

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ABSTRACT

The importance of shocks in nova explosions has been highlighted by Fermi’s discovery of γ-ray producing novae. Over three years of multi-band VLA radio observations of the 2010 nova V1723 Aql show that shocks between fast and slow flows within the ejecta led to the acceleration of particles and the production of synchrotron radiation. Soon after the start of the eruption, shocks in the ejecta produced an unexpected radio flare, resulting in a multi-peaked radio light curve. The emission eventually became consistent with an expanding thermal remnant with mass $2 \times 10^{-4} M_\odot$ and temperature $10^4$ K. However, during the first two months, the $\gtrsim 10^6$ K brightness temperature at low frequencies was too high to be due to thermal emission from the small amount of X-ray producing shock-heated gas. Radio imaging showed structures with velocities of 400 km s$^{-1}$ (d/6 kpc) in the plane of the sky, perpendicular to a more elongated 1500 km s$^{-1}$ (d/6 kpc) flow. The morpho-kinematic structure of the ejecta from V1723 Aql appears similar to nova V959 Mon, where collisions between a slow torus and a faster flow collimated the fast flow and gave rise to γ-ray producing shocks. Optical spectroscopy and X-ray observations of V1723 Aql during the radio flare are consistent with this picture. Our observations support the idea that shocks in novae occur when a fast flow collides with a slow collimating torus. Such shocks could be responsible for hard X-ray emission, γ-ray production, and double-peaked radio light curves from some classical novae.

Key words: novae, cataclysmic variables – binaries: general – stars: variables: general – stars: winds, outflows – white dwarfs – radio continuum: stars

1 INTRODUCTION

The most common type of stellar explosion, a nova occurs when accretion of material onto a white dwarf (WD) from its binary companion ignites a thermonuclear runaway, expelling matter and causing the system to brighten. Because novae occur frequently – an estimated 35 yr$^{-1}$ in our galaxy alone (Shafter 1997) – they can be used to probe stellar explosions, astrophysical outflows, nuclear burning, and accretion. However, to find an accurate model of these eruptions, one must account for the presence of shocks, bipolar outflows, rings, clumping, and other asymmetries that have been shown to be present in different nova systems (e.g Slavin et al. 1995; Shara et al. 1997; Sokoloski et al. 2008; Chomiuk et al. 2014).

Radio observations of novae furnish a useful tool for recording the evolution of a nova’s expanding shell and understanding the properties of the ejecta. In the radio, the ejecta remain optically thick to thermal emission at significantly lower densities than at shorter wavelengths. The ejecta can therefore typically be detected for months to years in the radio. In classical novae, radio emission is generally observed to be dominated by thermal bremsstrahlung radiation, interpreted as emanating from an expanding shell (Hjellming 1979; Seaquist & Palimaka 1977; Bode & Evans 2008).
While non-thermal emission has long been evident in nova systems with red-giant companions, such as RS Oph (Taylor et al. 1989), in classical novae with main sequence companions, the dominant features in historical radio light curves and spectra are generally consistent with an expanding thermal shell producing free-free emission (Hjellming 1979; Seaquist et al. 1980; Hjellming 1996; Bode & Evans 2008). Given some reasonable assumptions about the temperature and morphology of a thermal shell, comprehensive radio spectral coverage as the ejecta transition from being optically thick to optically thin enables observers to infer the density profile of the nova shell and estimate the total mass ejected. Resolved images in radio allow for further constraints on the morphology, temperature, and evolution of the thermal shell. However, only a handful of classical novae have been well observed at multiple radio frequencies from the optically thick rise to the optically thin decay, including HR Del (Hjellming 1979), V1500 Cyg (Seaquist et al. 1980), and V1974 Cyg (Hjellming 1996). This lack is particularly noticeable in the first few months immediately following the outburst, when the thermal radio emission is expected to be faint.

Technological improvements to the Karl G. Jansky Very Large Array (VLA) and other radio telescopes within the past five years have vastly increased the sensitivity of radio observations. Our group has been using the updated capabilities of the VLA in concert with optical and X-ray observations to create a more complete and multi-wavelength picture of the mass-loss history of novae. V1723 Aql was the first classical nova to be discovered in outburst after the upgrade to that facility. Beginning two weeks after the initial discovery of the eruption of V1723 Aql in 2010 September, the observations of Krauss et al. (2011), in combination with the additional radio monitoring presented here, have produced one of the best, most detailed radio light curves of a classical nova to date.

Discovered in outburst at its optical maximum (mag 12.4) on 2010 September 11, and with a magnitude of fainter than 14.0 on 2010 September 10, we take that discovery of V1723 Aql as the start of the outburst, \( t_0 = \text{MJD 55450.5} \) (Yamanaka et al. 2010; Balam et al. 2010). Optical observations revealed V1723 Aql to be a typical ‘fast nova’ (Gaposchkin 1957) of the Fe II spectral type, fading by two magnitudes within 20 days (Yamanaka et al. 2010). Despite the lack of extensive optical or IR followup, the observations in the first few weeks of the eruption showed rapid reddening, implying the formation of dust particles as early as 20 days after the start of the outburst (Nagashima et al. 2013). Emission lines of Hz on the day of discovery had full width at zero intensity of 3000 km s\(^{-1}\), implying a maximum expansion velocity \( v_{\text{obs}} = 1500 \text{ km s}^{-1} \) (Yamanaka et al. 2010). The nova was neither embedded in the wind of an M-giant mass donor nor a recurrent nova – making it representative of the majority of novae (Nagashima et al. 2013).

Although V1723 Aql showed no unusual aspects in its early optical behaviour, the VLA observations revealed an unexpected radio flare peaking roughly 45 days after the start of the optical outburst (Krauss et al. 2011). Krauss et al. (2011) found that during this flare, the radio flux density rose as \( t^{3.3} \), far more rapidly than the \( t^2 \) expected from freely expanding, isothermal, optically thick thermal ejecta. The radio spectrum during the flare was also inconsistent with that of an optically thick thermal source of a fixed temperature (Krauss et al. 2011). With only 175 days of radio monitoring, Krauss et al. (2011) were not able to conclusively determine the origin of this flare, or whether V1723 Aql would evolve according to the more standard picture of radio emission from a classical nova after this unexpected activity. We label the observations between the start of the eruption and day 175, presented in Krauss et al. (2011), as the early-time observations, and the new observations presented here (between day 198 and day 1281) as the late-time observations.

We describe below how the combination of the early-time and late-time radio observations reveals that whereas the late-time observations are dominated by the expected thermal emission from a freely expanding nova shell, there is strong evidence that the early-time flare was dominated by non-thermal emission. In section 2 we present our late-time observations and data reduction procedure; in section 3, we describe the observational findings and data analysis; in section 4, we introduce a thermal model for the remnant after day 200, explore the possibility of the early-time emission being produced by relativistic particles accelerated in internal shocks, and propose that the ejecta from V1723 Aql had a morpho-kinetic structure with internal shocks like that of γ-ray producing nova V959 Mon. In section 5, we highlight our conclusions.

## 2 OBSERVATIONS AND DATA PROCESSING

Building on the work of Krauss et al. (2011), who used VLA observations during the first six months of the outburst of V1723 Aql to identify the bright early-time flare, we present our observations of V1723 Aql with the VLA between 2011 March (day 198) and 2014 March (day 1281) – from six months to three and a half years after the start of the eruption (see Table 1). For completeness, Table 1 additionally lists the early-time observations of Krauss et al. (2011). The late-time observations were taken using the VLA WIDAR correlator at a range of frequencies spanning 2.5-36.5 GHz with bandwidths of 2048 MHz, distributed in two tuneable 1048-MHz sidebands and using 8-bit samplers. The central frequencies in each band may have had some slight variation due to frequency dependent flagging in post-processing to minimize radio frequency interference (RFI). At each frequency, on-source observations were alternated with observations of a nearby phase reference calibrator (J1851+0035, J1832-1035, or J1822-0938), with an additional observation of a standard flux calibration source (either 3c286 or 3c48). We used observations of the unpolarized calibrator J0319+4130 (3c84) for polarization leakage solutions. The late-time data presented here comprise 29.5 hours of observations (14.9 hours on source V1723 Aql) and 658 GB of raw data over three years and two full cycles of VLA configurations. Including the earlier programs presented in Krauss et al. (2011), the data total 1604 GB and 59.5 hours (28.2 hours on source) between 2010 September 25 and 2014 March 15.

We processed all data using NRAO’s Common Astronomical Processing System (CASA) or Astronomical Image Processing System (AIPS). As is standard procedure, we obtained a bandpass solution and used it to solve for gain amplitude and phase, then applied these solutions to the source, using the ‘Perley-Butler 2010’ flux density scale. Imaging was completed using the CLEAN algorithm (Högborn 1974) with Briggs weighting, with the additional use of superresolution techniques (Staveley-Smith et al. 1993) on day 1281 to resolve small structures during that observation. Radio flux densities were measured by fitting two dimensional gaussians to the emitting region in the image plane with the task imfit. We estimated uncertainties in flux density by adding in quadrature the error from the gaussian fit and systematical errors of 1% at frequencies below 19 GHz and 3% at those above, with the results presented in Table 2 and Figs 1 and 2. All error bars correspond to 1σ uncertainties.
Section 3 DATA ANALYSIS AND RESULTS

3.1 Flux density and spectral evolution

Around day 45, the flux densities reached a local maximum and subsequently declined at all frequencies, with another local maximum at all frequencies between days 200 and 400 (see Table 2 and Fig. 1). We refer to the radio brightening that peaked around day 45 as the early-time flare. There was an additional local maximum at all frequencies between these two bright peaks at the higher frequencies. The flux densities at the highest frequencies reached higher values than those at lower frequencies during both major peaks. For example, during the final local maxima (between days 200 and 400), the 36.5 GHz flux density peaked at 12.8 ± 0.39 mJy, whereas the 5.2 GHz flux density peaked at 1.14 ± 0.05 mJy. Moreover, the flux densities at Ka-band (28.5/36.5 GHz) reached their highest values on day 198, whereas the flux densities at lower frequencies peaked later, with C-band flux densities (5.2/6.8 GHz) peaking on day 426 or 490.

During the late-time period, the radio spectrum evolved from one that rose with frequency to one that fell slightly with frequency (see Fig. 2 and Table 3). To obtain spectral indices and their uncertainties, we fit data with a power-law using IDL’s ‘linfit’ function, which minimizes the χ² statistic, with the data and error bars in log space. With the simple single power-law model, we found acceptable fits (χ² < 1.5, where χ² is the reduced χ² value) only for days 198 and 818, between which time the spectral index fell from α = 1.47 ± 0.05 to α = −0.22 ± 0.08.

The late-time transition from a rising to a falling spectrum occurred via the appearances of first one, and then a second, spectral break. We refer to the three distinct portions of the spectrum when two breaks were present as the low-frequency, transition, and high-frequency parts of the spectrum. We refer to the corresponding spectral indices as αlow, αtrans, and αhigh, and the frequencies at which the breaks between the regions of different spectral index occur as νlow (for the break between the low-frequency and transition part of the spectrum) and νtrans (for the break between the transition and high-frequency portion of the spectrum). For epochs where both a poor χ² fit and the residuals of the simple power-law model suggested a spectral break, we fit the data with broken power law models with one or two breaks. Fig. 2 shows the spectra and fits, and Table 3 reports the power law models that combined to minimize χ², with the break frequencies indicating where the power-law models intersect. The uncertainties for the break frequencies correspond to the range of frequencies at which the power-law models intersect given the break frequencies indicating where the power-law models intersect. The uncertainties for the break frequencies correspond to the range of frequencies at which the power-law models intersect. The uncertainties for the break frequencies correspond to the range of frequencies at which the power-law models intersect given the break frequencies indicating where the power-law models intersect.

Late time observations

| Observation Date | MJD | Daya | Epoch | VLA Program ID | Configuration | Observed Bands | Timeb(min) |
|------------------|-----|------|-------|----------------|--------------|---------------|------------|
| 2011 March 28    | 55648.6 | 198.1 | 13 | 11A-254 | B | C, X, Ka | 52 |
| 2011 August 2    | 55775.2 | 324.7 | 14 | 11A-254 | A | C, X, Ka, K, Ka | 116 |
| 2011 August 27   | 55800.2 | 349.7 | 15 | 11A-254 | A | C, X, Ka, K, Ka | 72 |
| 2011 November 11 | 55876.1 | 425.6 | 16 | 11B-170 | D | C, X, Ka, K, Ka | 58 |
| 2012 January 14  | 55940.8 | 490.3 | 17 | 11B-170 | DnC | C, X, Ka, K, Ka | 58 |
| 2012 April 19    | 56037.0 | 586.5 | 18 | 11B-170 | C | C, X, Ka, K, Ka | 58 |
| 2012 December 8  | 56269.0 | 818.5 | 19 | 12B-226 | A | C, X, Ka, K | 20 |
| 2012 December 22 | 56283.6 | 832.5 | 20 | 12B-226 | A | X, Ka | 45 |
| 2013 March 27    | 56378.4 | 927.9 | 21 | 13A-465 | D | C, X, Ka, K, Ka | 106 |
| 2013 August 30   | 56534.1 | 1083.6 | 22 | 13A-461 | C | L, C, X, Ku, K | 98 |
| 2013 November 30 | 56626.7 | 1176.5 | 23 | 13A-465 | B | L, S, X, Ka | 101 |
| 2014 March 15    | 56731.5 | 1281.0 | 24 | 13A-465 | A | X, Ku | 112 |

Table 1. VLA observations of V1723 Aql, between 2010 September and 2014 March.

Early time observations (previously presented in Krauss et al. 2011)

| Observation Date | MJD | Daya | Epoch | VLA Program ID | Configuration | Observed Bands | Timeb(min) |
|------------------|-----|------|-------|----------------|--------------|---------------|------------|
| 2010 September 25| 55464.1 | 13.6 | 0 | 10B-200 | DnC | C, Ka | 57 |
| 2010 October 3    | 55472.1 | 21.6 | 1 | 10B-200 | DnC | C, Ka | 21 |
| 2010 October 6    | 55475.1 | 24.6 | 2 | 10B-200 | DnC/C | C, Ka | 58 |
| 2010 October 15   | 55483.1 | 32.6 | 3 | 10B-200 | C | C, Ka | 48 |
| 2010 October 18   | 55487.1 | 36.6 | 4 | 10B-200 | C | L, C, X | 43 |
| 2010 October 19   | 55488.1 | 37.6 | 4 | 10B-200 | C | C, Ka | 28 |
| 2010 October 24   | 55493.1 | 42.6 | 5 | 10B-200 | C | L, C, X | 43 |
| 2010 October 29   | 55497.0 | 46.5 | 6 | 10B-200 | C | L, C, X, Ka | 71 |
| 2010 November 7   | 55507.8 | 57.2 | 7 | 10B-200 | C | L, C, X, Ka | 74 |
| 2010 December 3    | 55533.9 | 83.4 | 8 | 10B-200 | C | L, C, X, Ka | 84 |
| 2010 December 18   | 55548.9 | 98.4 | 9 | 10B-200 | C | L, C, X | 52 |
| 2010 December 21   | 55551.7 | 101.2 | 9 | 10B-200 | C | C, Ka | 34 |
| 2011 January 14    | 55575.8 | 125.3 | 10 | 10B-200 | C | L,C,X, Ka | 70 |
| 2011 January 30    | 55591.8 | 141.3 | 11 | 10B-200 | ChB | L,C,X, Ka | 63 |
| 2011 March 5       | 55625.5 | 175.0 | 12 | 11A-254 | B | C, X, Ka | 51 |

Notes:

1 Days after initial detection of outburst, 2010 September 11.
2 Total time of observations on-source.
Table 2. Flux densities for late-time observations of V1723 Aql

| Epoch Day | Observed flux density (mJy) |
|-----------|----------------------------|
|           | 2.5 GHz (S band) | 3.3 GHz (S band) | 5.2 GHz (C band) | 6.8 GHz (C band) | 8.7 GHz (X band) | 9.5 GHz (X band) |
| 13 198    | ...               | ...              | 0.75 ± 0.02      | ...              | 1.53 ± 0.03      | ...              |
| 14 325    | ...               | ...              | 0.89 ± 0.03      | ...              | 1.88 ± 0.03      | ...              |
| 15 250    | ...               | ...              | 0.91 ± 0.03      | ...              | 1.97 ± 0.03      | ...              |
| 16 425    | ...               | ...              | 1.14 ± 0.05      | ...              | 2.09 ± 0.04      | ...              |
| 17 490    | ...               | ...              | 1.10 ± 0.03      | ...              | 1.79 ± 0.03      | ...              |
| 18 587    | ...               | ...              | 0.92 ± 0.02      | ...              | 1.39 ± 0.03      | ...              |
| 19 818    | ...               | ...              | 0.70 ± 0.05      | ...              | 0.71 ± 0.02      | ...              |
| 21 928    | ...               | ...              | 0.77 ± 0.04      | ...              | 0.71 ± 0.02      | ...              |
| 22 1084   | ...               | ...              | 0.71 ± 0.05      | ...              | 0.34 ± 0.01      | ...              |
| 23 1177   | 0.42 ± 0.04       | 0.25 ± 0.02      | ...              | ...              | ...              | ...              |

Table 3. Spectral indices. For days where we fit models with spectral breaks, νb refers to the break between the low-frequency and transition parts of the spectrum, and νth refers to the break between the transition and high-frequency portions of the spectrum. αlow, αtrans, and αh are the corresponding spectral indices for these segments. β shows the density profile n ∝ 1/νβ associated with the spectral index α for a spherical shell transitioning between optically thick and optically thin thermal emission (Wright & Barlow 1975), and χ^2 and df are the reduced chi-square statistic and the number of degrees of freedom, respectively.

| Epoch Day | model* | αlow  | αtrans | αh   | νb (GHz) | νth (GHz) | χ^2  | df   | β     |
|-----------|--------|-------|--------|------|---------|----------|------|------|-------|
| 13 198    | SPL    | 1.48 ± 0.02 |       | 0.73 | 0.4     | 7.2      | 0.04 | 0.06 | 2.04 |
| 14 325    | BPL    | 1.44 ± 0.05 | 0.64 ± 0.05 | 13.6 | 0.45    | 7.2      | 0.04 | 0.06 | 2.04 |
| 15 350    | BPL    | 1.54 ± 0.06 | 0.52 ± 0.03 | 11.3 | 2.75    | 7.2      | 1.92 | 0.03 | 0.75 |
| 16 426    | DBPL   | 1.23 ± 0.19 | 0.41 ± 0.04 | 0.03 ± 0.08 | 8.3 | 21.2 | 0.60 | 7   | 1.84 |
| 17 490    | DBPL   | 1.37 ± 0.15 | 0.24 ± 0.04 | -0.64 ± 0.23 | 7.3 | 27.8 | 2.53 | 5   | 1.69 |
| 18 587    | DBPL   | 1.26 ± 0.10 | 0.30 ± 0.05 | -0.08 ± 0.19 | 6.7 | 21.2 | 1.00 | 6   | 1.74 |
| 19 818    | SPL    | -0.22 ± 0.08 |       |       | 1.26 | 3     |       |     |     |
| 20 832    | SPL    | -0.47 ± 1.34 |       |       |       | 0     |       |     |     |
| 21 928    | SPL    | -0.19 ± 0.02 |       |       | 8.40  | 8     |       |     |     |
| 22 1084   | SPL    | -0.10 ± 0.04 |       |       | 2.12  | 8     |       |     |     |
| 23 1177   | SPL    | -0.08 ± 0.03 |       |       | 24.19 | 4     |       |     |     |
| 24 1281   | SPL    | -0.22 ± 0.77 |       |       |       | 0     |       |     |     |

* SPL – single power law fit
BPL – broken power law fit (one break)
DBPL – double broken power law fit (two breaks)

between 0.2 and 0.6, and αh typically had values of approximately -0.2. The spectrum on day 490 (see Fig. 2) shows the characteristic low-frequency, transition, and high-frequency spectral regions most clearly. On day 198, the spectrum was well described by a simple power-law with a low-frequency type spectral index. On day 325, the lowest frequencies maintained a steep rising spectrum of αlow = 1.44 ± 0.05; above 16.1 GHz the spectrum became shallower, with αtrans = 0.64 ± 0.05. The spectra continued to show this break between αlow and αtrans in observations between days 325 and 587, during which time νb decreased from 13.6 GHz to 6.7 GHz. Observations between days 426 and 587 showed the additional break at higher frequencies, νth, above which the spectrum flattened to
Figure 1. Observed flux densities of V1723 Aql between 2010 September and 2014 March. Error bars are as reported in Table 2, but may be too small to be visible.

\( \alpha_0 = 0.13 \pm 0.13 \) on day 426, \( \alpha_0 = -0.64 \pm 0.23 \) on day 490, and \( \alpha_0 = -0.08 \pm 0.19 \) on day 587. While the very small uncertainties in our flux densities reveal some deviation from a single power law during the last five observations, the spectrum was nevertheless approximately described by a fairly flat single power law during that time.

3.2 Resolved images

V1723 Aql was resolved at the highest observed radio frequency on day 832 (Ka-band) and on day 1281 (Ku-band) (see Fig. 3, panel a). The remnant was therefore large enough to be spatially resolved, with the difference between the integrated and the peak flux density greater than five times the root mean square error (RMS). Fig. 3 shows images from the second and third of the three observations during which the VLA was in A configuration (which gives the highest spatial resolution). The image from day 832 (2012 December 22) at 32.4 GHz shows that the radio emitting material was elongated in the NW/SE direction and had visible substructure. The full width half maximum of the brightness profile along the major axis of the fitted gaussian was 160 \( \pm 10 \) milliarcseconds (mas), with the FWHM along the minor axis of 110 \( \pm 20 \) mas. The position angle (PA) of the major axis was 160\(^\circ\) \( \pm 10^\circ \) (where PA is the east of north). The clean beam size was 90 mas by 60 mas, and the peak flux density was 130 \( \pm 20 \) \( \mu \)Jy/beam, with an RMS of 22.6 \( \mu \)Jy/beam. To more accurately estimate the size scale of the source, we fit the brightness profile, deconvolved from the synthesized clean beam, to a Gaussian. Taking the width of the Gaussian along the major axis at a flux density of twice the RMS as an indicator of size, the size scale along the major axis on day 832 was 250 \( \pm 10 \) mas. The substructure showed two resolved components with brightness peaks separated by 70 mas. They were aligned perpendicular to the major axis of the elongated material, with a PA of about 80\(^\circ\).

Taking into account the expected expansion by 50\% between day 832 and day 1281, the size of the radio-emitting remnant on day 1281 indicates that the material that was most extended on day 832 had faded, and only the denser inner structure remained detectable. By day 1281 (2014 March 14; using robust = 0.5 in the CLEAN algorithm), the resolved material was elongated in the NE/SW direction, instead of the NW/SE elongation seen on day 832. The fitted gaussian had a FWHM of 180 \( \pm 10 \) mas along the major axis (which had a PA of 35\(^\circ\) \( \pm 5^\circ \)), and a FWHM along the minor axis of 133 \( \pm 7 \) mas. The peak flux density was 118.5 \( \pm 3.5 \) \( \mu \)Jy/beam, with RMS of 3.32 \( \mu \)Jy/beam, resulting in a size scale of 408 \( \pm 2 \) mas. With a clean beam size of 160 mas by 130 mas, no substructure was resolved. If we consider the two components visible on day 832, and extrapolate from their 70 mas separation, we would have
expected a separation of 108 mas on day 1281 – which was not within the formal resolution limits of this observation. Therefore, we additionally used superresolution techniques (Staveley-Smith et al. 1993) to examine the more detailed structure of the source on this day, deconvolving the source with the slightly smaller beam size of 90 by 90 mas. Using this technique, we uncovered a ring-like structure with dimensions $\sim 0.22 \times 1.5$ arcsec and PA $45^\circ$ (see Fig. 3, panel b), with an RMS of 7.0 $\mu$Jy/beam.

4 DISCUSSION

We propose that the radio emission from V1723 Aql – when considered in the context of published optical and X-ray observations – is most consistent with a picture in which the nova initially generated a slow outflow and then a faster flow. We argue below that the slow flow had a speed of a few hundred km s$^{-1}$, and that it was likely concentrated toward the equatorial plane of the binary. The faster flow had a maximum speed of at least 1500 km s$^{-1}$, and it collided with the early, slow ejecta within a few weeks of the start of the eruption, producing the early-time flare. The collisions led to shocks that heated some of the ejecta to temperatures above $10^7$ K, and also accelerated particles to relativistic speeds. The slow-moving material probably collimated the faster flow into a biconical structure. Fig. 4 shows a cartoon of this toy model. The scenario that we propose for V1723 Aql is consistent with the one that Chomiuk et al. (2014) suggested for the $\gamma$-ray producing nova V959 Mon.

In the discussion below, we present evidence that supports the picture of a fast flow that collided with, and was shaped by, a preceding slow outflow. To diagnose the flows without the complexity of non-thermal emission from the early-time shock, we begin in section 4.1 by describing how the brightness temperature and radio spectral evolution at late times were consistent with a freely expanding thermal plasma with a temperature of around $10^4$ K. The density profile and radio images of this radio-emitting plasma suggest that it had a roughly bipolar or biconical outer structure, and a shell-like inner structure with a likely equatorial density enhancement. In section 4.2, we show that the early-time radio flare was probably dominated by synchrotron emission. Given the low X-ray flux during the flare (Krauss et al. 2011) and high brightness temperatures, it cannot be attributed to thermal emission alone. In section 4.3, we discuss how V1723 Aql relates to other classical novae in its behaviour and shape, including those that produce $\gamma$-rays.

4.1 Origin of the Late-Time Radio Emission: Expanding thermal shell

4.1.1 General physical constraints

We obtained a first estimate of the distance to V1723 Aql by using our maximum extension of the remnant on day 832, when our image had the highest spatial resolution (smallest clean beam).
Table 4. Total ejecta mass \(M\) and minimum velocity \(v_i\) as determined using the spectral breaks visible on days 426, 490, and 587. Mass estimates vary based on the density profile assumed.

| Epoch | Day  | \(v_i\) (km s\(^{-1}\)) | \(\xi = v_i/v_{\text{obs}}\) | \(M (M_\odot), n \propto 1/r^1\) | \(M (M_\odot), n \propto 1/r^2\) | \(M (M_\odot), n \propto 1/r^3\) |
|-------|------|-------------------------|-------------------------|-----------------------|-----------------------|-----------------------|
| 16    | 426  | 360 ± 20                | 0.24 ± 0.01             | 2.7 ± 0.3 \(10^{-4}\)  | 1.6 ± 0.2 \(10^{-4}\)  | 0.9 ± 0.2 \(10^{-4}\)  |
| 17    | 490  | 210 ± 10                | 0.14 ± 0.01             | 4.0 ± 0.4 \(10^{-4}\)  | 1.6 ± 0.2 \(10^{-4}\)  | 0.6 ± 0.1 \(10^{-4}\)  |
| 18    | 587  | 190 ± 20                | 0.13 ± 0.01             | 4.6 ± 1.6 \(10^{-4}\)  | 1.7 ± 0.7 \(10^{-4}\)  | 0.7 ± 0.3 \(10^{-4}\)  |

Figure 3. Top panel: Spatially resolved image of V1723 Aql taken on 2012 December 22 in Ka-band (32.4 GHz). When fitted to a two-dimensional gaussian, the brightness profile has a FWHM along the major axis of 160 ± 10 milliarcseconds (mas) and along the minor axis of 110 ± 20 mas, where the major axis has a position angle of 160° ± 10° east of north. Contour levels are at [-2, 2, 4, 8, 16, 32]×RMS with RMS= 2.26 \(10^{-5}\) Jy. There are two resolved components roughly perpendicular to the major axis of the gaussian profile, with a separation of 70 mas at an angle of 82° E of N. Bottom panel: Spatially resolved image of V1723 Aql taken on 2014 March 14 in Ka-band (14 GHz). When deconvolved with a beam size of 90 × 90 mas, we see a ring-like structure. Contour levels are at [-2, 2, 4, 8, 16, 32]×RMS with RMS=7.01 \(10^{-6}\) Jy.

Figure 4. We propose a picture where a fast, bipolar outflow is shaped by a slow moving equatorial torus. Shocks arose in the collision region between the slow and fast flows.

Since by day 832, some of the outermost material had become optically thin and therefore the remnant might not have a sharp outer edge, we took the maximum size scale to be the extent along the major axis of the gaussian fit, down to a flux density of twice the RMS. When we compare the size scale of 251 ± 7 mas with the expectation for ejecta expanding with a maximum velocity of \(v_{\text{obs}} = 1500 \text{ km s}^{-1}\) (Yamanaka et al. 2010), we obtain a distance of 5.7 ± 0.4 kpc, or ~6 kpc. The assumption that the maximum expansion speed in the plane of the sky is equal to the maximum radial velocity is valid if the remnant is approximately spherical or, for a bipolar flow, has wide opening angles (as is suggested by the \(1/r^2\) density profile, see below).

Other methods of distance determination using optical data are either not possible or extremely unreliable. There are two means of nova distance determination using optical data. The most common utilized method is the Maximum Magnitude Rate of Decline (MMRD) method (Della Valle & Livio 1995); the other method involves utilizing high-resolution spectra to identify absorption lines from intervening interstellar clouds of known distance (e.g. Chomiuk et al. 2012). No high resolution spectra of V1723 Aql were available, making it impossible for us to use the latter method. The MMRD technique has been the subject of serious critiques in recent publications (e.g. Kasliwal et al. 2011; Cao et al. 2012). Further, the episode of dust formation observed in V1723 Aql confounds the determination of \(t_2\), rendering the already dubious MMRD method useless for distance determination.

Using \(d=6\) kpc, we find that the brightness temperature after day 200 was consistent with the late-time radio emission emanating from a thermal remnant with \(T \sim 10^4\) K, where \(T\) is the electron temperature. Brightness temperature is

\[
T_b(v, t) \sim \frac{S_b(v) c^2 D^2}{2 \pi k_b v^2 (v_{\text{obs}} f)^2},
\]

where \(c\) is the speed of light, \(k_b\) is Boltzmann’s constant, \(t\) is the time since eruption, and \(v_{\text{obs}}\) is the observed maximum radial velocity (e.g. Bode & Evans 2008). Using our values from day 200, for example, we find that \(T_b = 1.5 \pm 0.4 \times 10^4\) K at 5.2 GHz,
which is consistent with \( \sim 10^4 \) K. Ionized ejecta from novae are typically found to have electron temperatures of around \( 10^4 \) K, which is also approximately the equilibrium temperature for photoionized plasma that is cooled by forbidden line emission (Seaquist & Palimaka 1977; Taylor et al. 1987; Bode & Evans 2008). This \( \sim 10^4 \) K ejecta temperature can be sustained by photoionization heating by the WD for up to a year after the nova eruption (Cunningham, Wolf & Bildsten 2015). A brightness temperature around this value therefore provides support for thermal bremsstrahlung as the dominant emission mechanism at late times in V1723 Aql.

Moreover, the detailed evolution of the radio spectrum between days 198 and 350 (approximately 6 to 12 months after the start of the outburst) places constraints on the density profile in the outermost regions of the expanding ejecta. We consider the point at which the free-free optical depth at a given frequency \( \tau_r \) is unity, where the emitting material transitions from optically thick to optically thin. The high spectral index of \( \alpha_{\text{low}} \approx 1.5 \) on day 198 indicates that at that time, the ejecta were dense enough to be optically thick for frequencies of up to at least 36.5 GHz. Therefore, these \( \tau_r = 1 \) surfaces were very close to the outer boundary of the ejecta for all frequencies at which we observed on day 198. The appearance of the first spectral break on day 325, however, reveals that by that time, the density of the ejecta had dropped enough that at least part of the ejecta were beginning to become optically thin for frequencies above \( v_h \). Thus, the radii of the \( \tau_r = 1 \) surfaces at frequencies above \( v_h \) were no longer increasing as fast as that of the ejecta. The spectral index above the first spectral break \( (\alpha_{\text{trans}}) \) is directly related to the density profile in these transitioning ejecta. For an isothermal shell with a density profile of the form \( n(r) \propto 1/r^\beta \) (where \( n \) is density and \( r \) is distance from the central binary), the spectral index is given by \( \alpha_{\text{trans}} \approx -4/\beta \) for \( \beta > 1.5 \) (Wright & Barlow 1975). For a measured \( \alpha_{\text{trans}} \), we thus have \( \beta = \frac{31 - \alpha_{\text{trans}}}{2n_{\text{low}}n_{\text{high}} - 3n_{\text{trans}}n_{\text{trans}}} \) (see Table 3). Our measurement of \( \alpha_{\text{trans}} \approx 0.6 \) on days 325 and 350, when only the outermost portions of the ejecta were beginning to become optically thin, suggests that the density profile in the outermost part of the ejecta was proportional to \( 1/r^7 \).

The appearance of a second break in the spectrum on day 426, roughly 14 months after the start of the eruption, shows that the ejecta had become optically thin at frequencies above \( v_h \). Optically thin thermal emission has a spectral index of \( \alpha = -0.1 \) (e.g. Bode & Evans 2008), as we approximately found above \( v_h \). Between the two breaks at \( v_h \) and \( v_b \), the spectral index of the transitioning region \( \alpha_{\text{trans}} \) provides information about the density profile deeper within the ejecta. With a value of approximately 0.3 on days 490 and 587, when these two breaks are clear, \( \alpha_{\text{trans}} \) suggests an average density profile deep within the remnant of roughly \( 1/r^1.7 \) — somewhat flatter than in the outermost regions of the remnant.

The observed evolution of \( \alpha_{\text{trans}} \) is unlikely to be due to a temperature gradient. Although a temperature gradient can in principle affect the spectral index, the effect drops out for a \( 1/r^2 \) density profile (Cassinelli & Hartmann 1977; Barlow 1979). Moreover, a radial decrease in the ionized gas fraction would also only serve to increase the steepness of the spectrum during the transition period (Wright & Barlow 1975), in contrast to what we observed. Therefore, the observed flattening of the \( \alpha_{\text{trans}} \) in the interior of the ejecta is unlikely to have been due to a temperature or ionization gradient.

For a more promising avenue to explain the declining \( \alpha_{\text{trans}} \), Wright & Barlow (1975) note that non-spherical geometries can cause the total number density of the gas to fall off less rapidly than \( n \propto r^{-2} \) for a constant, finite duration flow. For example, a disk geometry would fall off as \( n \propto r^{-1} \) and in a cylindrical geometry \( n \) would be independent of \( r \) (Wright & Barlow 1975). Therefore, that for V1723 Aql \( \alpha_{\text{trans}} \) appears to flatten slightly with time may indicate that the inner remnant is more confined towards the equatorial plane than the outer remnant — as in the case of the biconical flow collimated by a dense, slow torus in V959 Mon (Chomiuk et al. 2014). If this is the case, a bi-polar outflow could result in an over-estimate of mass by up to a factor of two (Ribeiro et al. 2014). Nevertheless, since the density profile of \( 1/r^2 \) in the outer regions of the ejecta suggest that any bipolar flow must have a wide opening angle, we can nevertheless use a spherical model to obtain reasonable estimates of the ejecta parameters.

The flux density near \( v_h \) furnishes a rough estimate of the inner radius of the ejecta on the dates when this break frequency was observable. The ejecta are optically thin, with optical depth \( \tau_r < 1 \), at frequencies above \( v_h \). They are optically thick, with \( \tau_r > 1 \) at frequencies below \( v_h \). Integrating the absorption coefficient for radio emission at \( v_h \) along the line of sight through the ejected envelope therefore gives exactly \( \tau_r = 1 \), suggesting that the photosphere lies near the inner edge of the ejected shell for \( v_h \). At the frequency \( v_h \), the rough angular size of the photosphere is

\[
\theta_{\text{arcsec}} = \frac{S_{\nu_h}}{n_{\text{mJy}}} \left( \frac{T_b}{1200 \text{ K}} \right)^{-1/2} \left( \frac{v_h}{\text{GHz}} \right)^{-1/2}
\]

(Rybicki & Lightman 1979), where \( \theta \) is the full angular diameter of the photosphere. Using the break frequencies \( v_h \) and flux densities at these frequencies from days 426, 490, and 587 (see Fig. 2), and taking \( T_b \approx 10^4 \) K, we find that the inner edge of the ejecta had an approximate radius of between 10 and 15 mas during these observations, which corresponds to an expansion speed \( v_i \) of the slowest, innermost ejecta of between 200 and 1000 km s\(^{-1}\) \((\text{d}/\text{kpc})/(T_b/10^4 \text{ K})^{-1/2} \), assuming all the ejecta were homologous and ejected at \( v_i \). Although these estimates do not provide any evidence that the inner radius increased between days 426 and 587, the estimates are uncertain enough that they do not place meaningful constraints on the actual evolution of the inner radius. The estimates do, however, indicate that the radio-emitting ejecta were geometrically thick (given that the outermost material moved away from the central binary at approximately 1500 km s\(^{-1}\)), though not uniquely or unusually so (e.g. Seaquist & Palimaka 1977).

The radio spectra during the second year of the eruption also enable us to make an estimate of the ejecta mass. We can obtain the emission measure of the ejecta at \( \tau_r = 1 \) radio photosphere at \( v_h \) from the expression

\[
\tau_r = 8.235 \times 10^{-2} \left( \frac{T_b}{K} \right)^{-1.35} \left( \frac{v}{\text{GHz}} \right)^{-2.1} \left( \frac{E M_{\text{rad}}}{\text{cm}^{-3} \text{pc}} \right)
\]

where \( \tau_r \) is the free-free optical depth at frequency \( v \) and \( E M_{\text{rad}} = \rho_b n^2(r) \int_0^r dr \) is the emission measure integrated from the inner radius \( R_i \) to the outer radius \( R_o \) (Lang 1980). With the emission measure, inner and outer radii, and density profile in hand for the observation with the clearest break frequency \( v_h \), we can estimate the mass of the ejecta. For the purpose of this mass estimate, we take a spherically symmetric shell and density proportional to \( 1/r^2 \), as estimated from \( \alpha_{\text{trans}} \) in the outer regions of the ejecta. Using the inner radius on day 426 from above, which gives the velocity of the inner edge as \( v_i \approx 360 \text{ km s}^{-1} \) and outer radius assuming a maximum expansion velocity of 1500 km s\(^{-1}\), we find an approximate ejecta mass of \( 1.6(\pm0.2) \times 10^{-7} \text{ M}_\odot \), which is of the same order of magnitude as is typically found in nova ejecta mass estimates (Bode &
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4.1.2 The Hubble Flow model

The gross properties of the radio-emitting ejecta at late times (after day 200) were consistent with expectations from the so-called “Hubble-Flow” model (Seaquist & Palimaka 1977; Hjellming 1979). In this model, a spherically symmetric shell is ejected from the WD instantaneously, but with a range of velocities, so that the velocity is proportional to the distance from the WD. A 1/r^2 density profile, as we inferred from αtrans, corresponds to the mass being distributed uniformly over the velocities. Such a model has been applied to many historical novae, including V1974 Cyg (Hjellming 1996), V1500 Cyg (Seaquist et al. 1980), QU Vul (Taylor et al. 1988), and V723 Cas (Heywood et al. 2005). Given the brightness temperature after day 200 of near 10^4 K, and the evolution of the radio spectrum from initially rising with frequency (as expected for an optically thick shell) to falling slightly with frequency (as expected for an optically thin shell) via the appearance of two distinct spectral breaks, we conclude that it is reasonable to use a Hubble-flow model to parameterize the ejecta that produced the late-time radio emission from V1723 Aql.

Although the Hubble-flow model does not give a formally acceptable fit to the late-time radio emission, it is roughly consistent with the most dominant features in the data. Fig. 5 shows the Hubble-flow model light curves that best fit the data to the late-time radio data (where we have added eight data points published in Krauss et al. (2011) from days 141 and 175 to our measurements to help constrain the turnover of the high-frequency light curves). Taking the nova to have a distance of 6 kpc and using the expansion velocity measured by Yamanaka et al. (2010) on the day of discovery as the maximum velocity v_{obs} = 1500 km s^-1, ejected at t = 0, and allowing other parameters to vary, our best fitting model has an ejecta mass of M = 1.7 × 10^{-4} M_⊙, a temperature of T = 1.1 × 10^4 K, and a ratio of minimum to maximum velocity ζ = ν/ν_{obs} = 0.17 (see Fig. 5). Given that the ejecta are clearly not spherically symmetric (see Fig. 3), and that the evolution of the spectral index αtrans from 0.6 to 0.3 suggests a flattening of the density profile over time, it is not too surprising that the Hubble-flow model does not provide a formally acceptable fit. Overall, however, the fitting of the late-time radio data with a Hubble-flow model indicates that if the ejecta were approximately spherical, then roughly 2 × 10^{-4} M_⊙ was ejected at a temperature of 10^4 K.

Comparing model light curves for a range of ejecta masses, temperatures, and shell thicknesses provides a measure of the uncertainty on these parameters. Fig. 6 suggests that the best fitting parameters are accurate to within at least a factor of 2. In terms of the effect that modifying these parameters has on the model light curves, changing the distance would have influenced the maximum flux density at each frequency, to which it is inversely related. Increasing the temperature of the shell increases the resulting flux density at all times, and causes the turnover from optically thick to thin to occur earlier. Increasing the maximum velocity also causes this transition to occur at earlier times. The ratio of the minimum and maximum velocity, ζ, relates to the flux density and the decline of the light curve after peak – a higher ratio corresponds to a geometrically thinner remnant, which both raises the maximum flux density and causes a swifter decline in flux density after this peak. Increasing the total ejecta mass in the model also causes an increase in flux density at all times, and causes a slower, later transition from optically thick to optically thin emission at all frequencies.

While our observations are generally consistent with a n ∝ r^{-2} density profile, we can additionally demonstrate the sensitivity of the total ejecta mass to the distribution of mass within the nova shell. For example, if we again use the observed spectral breaks to estimate the inner and outer radii of the shell and calculate the emission measure, we can estimate the mass of the shell with different density profiles. For example, by using the spectral breaks on day 587, we estimate an ejecta mass of M ~ 4.6 × 10^{-4} M_⊙ and M ~ 0.7 × 10^{-4} M_⊙ for densities profiles of 1/r and 1/r^2, respectively (see Table 4). If the ejecta from V1723 Aql were clumpy rather than smooth, the total ejecta mass would be reduced. Clumping increases the flux density of an isothermal shell by up to a factor of f^{-1/3}, where f is the volume filling factor (Abbott et al. 1981). However, clumping would not influence the spectral index, nor the overall shape of the radio light curve, as uniformly distributed clumping would effect the free-free flux similarly at all frequencies (Abbott et al. 1981; Leitherer & Robert 1991; Nelson et al. 2014).

4.2 Origin of the early time flare: particles accelerated in shocks within the ejecta

4.2.1 Brightness temperature of the ejecta

Whereas the late-time emission is consistent with originating in a thermal remnant with T ~ 10^4 K and a strong resemblance to a Hubble flow, the early-time emission is not (see Fig. 7). In fact, the T ~ 10^3 K ejecta were only revealed once the early-time flare faded. The brightness temperature at early times was strongly dependent on both frequency and time, with a maximum T_b of between ∼ 6 × 10^4 K at 36.5 GHz and ∼ 4 × 10^5 K at 1.4 GHz. Brightness temperature is an expression of surface brightness and represents a lower limit on the physical temperature of any thermally-emitting material; for the flare to have been thermal, it would therefore have had to have been emitted by plasma with T_b > 4 × 10^5 K.

During the early-time flare, however, the X-ray flux was too low for the radio flare to have been due to hot (X-ray emitting) plasma. For the radio flare to have been entirely thermal, it would have had to have been produced by plasma that was optically thick at 1.9 GHz, had an electron temperature T_e ≈ 4 × 10^6 K, and had a size scale of 3 × 10^{-4} pc (1000 km s^-1) / (432). The flare could in principal also have been produced by free-free emission from hotter plasma that subtended a smaller solid angle on the sky. Krauss et al. (2011) detected X-ray emission from plasma with T_e > 2 × 10^7 K on day 41 after the start of the eruption. For ejecta with T_b = 2 × 10^5 K to be optically thick, the free-free optical depth would have to have been greater than one:

\[ \tau_{ff} = 3.0 \times 10^{-12} \left( \frac{T}{2 \times 10^5 \text{K}} \right)^{-1.35} \left( \frac{\nu}{1.9 \text{GHz}} \right)^{-2.1} E_{\text{Rad}} > 1. \]  \tag{4}

This requirement corresponds to

\[ \int n_e^2 dl > 3.3 \times 10^{11} \left( \frac{T}{2 \times 10^5 \text{K}} \right)^{1.35} \left( \frac{\nu}{1.9 \text{GHz}} \right)^{2.1} \text{pc cm}^{-6} \]  \tag{5}

A hot plasma with a temperature five times the maximum T_b could in principal have produced the radio flare if it was optically thick at 1.9 GHz and subtended a solid angle that was 20% that of the entire ejecta. A uniform-density spherical shell of that size, with shell thickness ℓ, would therefore require an electron density of

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Figure 5. The late time observations of V1723 Aql between 2011 March and 2014 March, presented here for the first time, with eight previously published data points from days 2011 January 31 and 2011 March 5 used to constrain the high frequency light curves. Model indicates lightcurve of an expanding spherical thermal shell with a density profile of $1/r^2$, mass $M=1.7 \times 10^{-4} M_\odot$, ejecta temperature of $T=1.1 \times 10^4 K$, maximum velocity of $v_{\text{obs}}=1500 \text{ km s}^{-1}$ distance of $d=6.0 \text{ kpc}$, and ratio of minimum to maximum velocity $\zeta = v_i/v_{\text{obs}} = 0.17$.

$n_e > 6 \times 10^7 \times \left( \frac{T}{2 \times 10^7 K} \right)^{0.675} \left( \frac{\nu}{1.9 \text{ GHz}} \right)^{1.05} \left( \frac{\ell}{2.5 \times 10^{15} \text{ cm}} \right)^{-1/2} \text{ cm}^{-3}$ (6)

to be optically thick. Such hot plasma would produce an X-ray emission measure, $E_{\text{M}} \equiv \int n_e^2 dV$ (where $V$ is the emitting volume), of approximately $8 \times 10^{59} \text{ cm}^{-3}$ (independent of $\ell$), and (unless the shell was extremely thin) have a mass of a few times $10^{-6} M_\odot$. On day 41, however, Swift/XRT detected X-rays with an $E_{\text{M}}$ of just $\sim 10^{56} \text{ cm}^{-3}$, indicating that there was not enough $2 \times 10^7 K$ plasma to produce the observed radio flare. Even generating a model of the expected X-ray emission and assuming the highest reasonable absorbing column allowed by the X-ray spectral fit ($3 \times 10^{23} \text{ cm}^{-2}$), the observed X-ray flux was still an order of magnitude lower than would be required to explain the radio flare with thermal emission. The natural alternative to thermal emission is radio synchrotron emission from electrons accelerated in a shock.

The inconsistency between the radio flux density at 1.9 GHz and thermal radio emission expected from the $2 \times 10^7 K$ X-ray emitting plasma is independent of the distance to V1723 Aql. If we were to allow the temperature of the hot plasma to drop below $2 \times 10^7 K$ (despite the constraints from Krauss et al. (2011)), then the evidence for synchrotron emission would in principle depend on the distance to V1723 Aql. However, for the distance to be small enough to explain the radio flare with thermal emission, the outflow velocities become inconsistent with constraints from optical spectroscopy. Therefore, the combination of radio, X-ray, and optical observations appear to support a synchrotron emission mechanism.

4.2.2 Failure of thermal shock emission model

To further assess whether the early-time radio flare in V1723 Aql was thermal or non-thermal (synchrotron) in origin, we consider a one-dimensional, spherically-symmetric model for internal shocks in novae, as presented in Metzger et al. (2014, hereafter M14). Consider a fast outflow of velocity $v_f > 10^3 \text{ km s}^{-1}$ that collides with a slower shell of velocity $v_s \leq v_f$. For simplicity, assume that the mass of the slow shell is comparable to or lower than that of the fast material and is emitted at time $t = 0$. The fast outflow is emitted a time $\Delta t$ after the slow shell, resulting in a collision radius

$$R_c \approx \frac{v_f v_\Delta t}{v_f - v_s} \approx 6 \times 10^{13} \frac{v_f}{v_s} \left( \frac{\Delta t}{\text{ week}} \right) \text{ cm}$$ (7)

and time

$$t_c \approx \frac{R_c}{v_s} = \frac{v_f}{\Delta v} \times \frac{\Delta t}{\text{ week}}$$ (8)
Radio emission from colliding flows in V1723 Aql

Figure 6. Variations of the Hubble Flow model compared to the observed flux densities. Unless otherwise stated, the parameters for the model show distance of 6 kpc, maximum velocity of 1500 km s\(^{-1}\), temperature of 1.1 \times 10^4 K, mass of 1.7 \times 10^{-4} M_\odot, and \(\zeta = 0.17\). The leftmost column shows variation in temperature, with the top panel showing a temperature of 3 \times 10^3 K and the bottom showing a temperature of 5 \times 10^3 K. The middle column shows variation in mass; the top panel shows a model with mass 2.5 \times 10^{-4} M_\odot, and the bottom panel shows 1.2 \times 10^{-4} M_\odot. The right column shows variation in shell thickness, varying the ratio of minimum to maximum velocity \(\zeta\). The top panel shows a ratio of 0.4, and the bottom shows a ratio of 0.08.

Figure 8. Observed flux densities and model flux densities in radio for a thermal shock. Assuming a distance of 6 kpc, the model uses a fast wind with an initial velocity \(v_f = 2100\) km s\(^{-1}\), mass \(M_w = 0.8 \times 10^{-4} M_\odot\), and a characteristic duration of 12 days. The wind collides with a slower moving circumbinary shell with initial velocity \(v_s = 1300\) km s\(^{-1}\) and mass \(M_s = 1 \times 10^{-4} M_\odot\). This results in a post shock velocity of \(v_{sh} = 1500\) km s\(^{-1}\) and total nova ejecta mass as \(1.8 \times 10^{-4} M_\odot\), consistent with our late-time thermal model.

\[ T \approx 1.4 \times 10^7 \left( \frac{\Delta v}{10^8 \text{ km s}^{-1}} \right)^2 \text{K} \approx 1.3 \times 10^8 \left( \frac{\Delta v}{0.3 \text{v}_i} \right)^2 v_{fs}^2 K \quad (9) \]

where \(\Delta v = v_i - v_s\) and \(v_{fs} = v_i / 10^8 \text{ cm s}^{-1}\).

The predicted radio flare following this collision would be powered by the forward shock that emerges from the slow shell at approximately the time of the collision, i.e. \(t_c \approx 50\) days. If both shells are ejected over a timescale less than the duration of the peak optical activity, i.e. \(\Delta t = (\Delta v / v_i) t_c \leq 2\) weeks, then the relative velocity between the shells must be relatively low, \(\Delta v / v_i \leq v_i (\Delta t / t_c) \approx 0.3 v_i\), corresponding to a collision radius \(R_c \sim v_i t_c \leq v_i t_c \approx 10^3\) cm for \(v_i \approx 2 \times 10^3\) km s\(^{-1}\).

The forward shock heats gas to a temperature (M14, eq. 31),

\[ T \approx 1.4 \times 10^7 \left( \frac{\Delta v}{10^8 \text{ km s}^{-1}} \right)^2 \text{K} \approx 1.3 \times 10^8 \left( \frac{\Delta v}{0.3 v_i} \right)^2 v_{fs}^2 K \quad (9) \]

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The forward shock heats gas to a temperature (M14, eq. 31),

\[ T \approx 1.4 \times 10^7 \left( \frac{\Delta v}{10^8 \text{ km s}^{-1}} \right)^2 \text{K} \approx 1.3 \times 10^8 \left( \frac{\Delta v}{0.3 v_i} \right)^2 v_{fs}^2 K \quad (9) \]
Figure 7. Flux densities (top panel) and brightness temperatures (bottom panel) for V1723 Aql between 2010 September and 2014 March. The dashed lines indicate the expected thermal emission from an expanding spherical shell with a density profile proportional to $1/r^2$, mass $M = 1.7 \times 10^{-4} M_\odot$, ejecta temperature of $T = 1.1 \times 10^4 \text{ K}$, maximum velocity of $v_{\text{obs}} = 1500 \text{ km s}^{-1}$, distance of $d = 6.0 \text{ kpc}$, and ratio of minimum to maximum velocity $\zeta = v_i/v_{\text{obs}} = 0.17$. The brightness temperature, which is an expression of surface brightness, is highly frequency dependent and peaks during the early-time flare at all frequencies. The great difference between the brightness temperatures during the early-time flare and the late-time peak highlights the physically distinct nature of the early and late radio brightenings.
exceeds unity for $n \geq 10^7$ cm$^{-3}$, where $X_e = 0.1$ is the assumed mass fraction of CNO elements. This density corresponding to a minimum mass of the slow shell of $M_{sh} \geq 4\pi (R^2 c) n m_p \sim 10^{-4} M_\odot$ for $R_s \sim 10^5$ cm. For values of $n$ below which $\tau_e < 1$, $L_X$ in equation (10) still exceeds the observed X-ray luminosity by at least an order of magnitude; this may suggest that $\nu_{FL} \leq 1$, or that a fraction of the shock power instead emerges at UV/soft X-ray energies below the Swift bandpass.

The maximum radio brightness temperature of radiative shocks at frequency $\nu$ is given by (M14, eq. 65),

$$T_{b,\nu} \approx \begin{cases} 
3 \times 10^5 \ln \left( \frac{\nu}{\nu_0} \right)^{-1} \nu^{\frac{7}{3}} \frac{\Delta v}{v_{f,8}} \nu_{v,18}^2 \left( \frac{\tau}{\tau_0} \right)^{\frac{1}{2}} K & n \geq \eta_n, \\
T_{c,\nu} = 10^5 \nu_8^3 n_8 \left( \frac{\nu}{\nu_0} \right)^{\frac{1}{2}} v_{f,8} \nu_{\nu,10}^{\frac{1}{2}} K & n \leq \eta_n, 
\end{cases}$$

where $\nu_0 = \nu/10$ GHz, $\tau_7 = n/10^7$ cm$^{-3}$ and

$$\eta_n = 4 \times 10^7 \left( \frac{\Delta v}{0.3 \nu_{18}} \right)^{-1} v_{f,8} \nu_{\nu,10}^{\frac{1}{2}} \text{cm}^{-3}$$

defines the pre-shock density above which the layer of X-ray ionized gas ahead of the shock is optically thick to free-free absorption, where a temperature of $2 \times 10^4$ K is assumed for the pre-shock gas. This value, appropriate to the photo-ionized layer slightly ahead of the shock (Metzger et al., 2014), may be slightly higher than the values expected for the bulk of the ejecta later, which our Hubble flow modeling finds is closer to $1 \times 10^4$ K.

The observed peak brightness temperature of V1723 Aql (see Fig. 7) exceeds the range given by equation (13) by more than an order of magnitude, strongly suggesting a non-thermal origin for most of the observed radio emission. Furthermore, equation (13) was derived under the assumption that free-free emission is the sole source of cooling behind the shock. If the effects of line cooling are included, Equation (13) greatly overestimates the brightness temperature, further enhancing the tension with thermal emission models.

It is difficult to produce a thermal model that fits the early time radio data and is also consistent with the X-ray and late radio constraint. In Fig. 8, we applied the M14 model to the early light curve, modeling the shock as the collision of a fast wind with $\nu_s = 2100$ km s$^{-1}$ and mass $0.8 \times 10^4 M_\odot$ and a shell with $\nu_s = 1300$ km s$^{-1}$ with mass $M_{sh} = 1 \times 10^4 M_\odot$. We assumed that the shells were released around $t = 0$, with a characteristic duration of the wind of 12 days, motivated by the observed optical decline rate. These parameters result in a post-shock velocity of $v_{obs} = 1500$ km s$^{-1}$ and a total ejecta mass of $M \sim 1.8 \times 10^4 M_\odot$, consistent with our late-time thermal model. Taking $n \propto 1/r^2$ and distance of 6 kpc, we were unable to reproduce the high radio flux densities over the course of the shocks. We conclude that synchrotron emission must therefore have at least partially powered the early-time flare.

4.2.3 Synchrotron emission from particles accelerated in shocks

The failure of thermal emission to account for the early-time radio flare suggests that the flare was dominated by synchrotron emission from particles that were accelerated in shocks. For one thing, shocks are common in classical novae. Evidence for shocks is provided by X-ray emission from plasma with temperature above $10^7$ K (e.g., Mukai et al., 2008). Such temperatures arise naturally behind shock with speeds on the order of 1000 km s$^{-1}$ (see Equation 9). Furthermore, the recent identification of classical novae as a new class of $\gamma$-ray sources shows that not only are shocks ubiquitous in novae, but that relativistic particles are as well (Ackermann et al. 2014; Metzger et al. 2015a). A natural acceleration mechanism for these particles is Fermi acceleration in the shocks.

In fact, radio observations have illustrated the existence of radio synchrotron emission in a normal nova – in Fermi-detected nova V959 Mon, Chomiuk et al. (2014) identified the location of $\gamma$-ray producing relativistic electrons as the region where a fast outflow collided with, and was shaped by, a dense equatorial torus. Although V959 Mon did not produce a strong early-time radio flare, its early-time radio emission was consistent with being synchrotron (Chomiuk et al. 2014). Whereas existing observations do not constrain the inclination of V1723 Aql, V959 Mon is viewed very nearly edge on (Chomiuk et al. 2014) – it is thus possible that some early non-thermal emission may have been obscured by the optically thick equatorial torus. Moreover, while the early-time flare in V1723 Aql suggests stronger non-thermal radio emission than that seen from V959 Mon, VLA observations of $\gamma$-ray producing nova V1324 Sco (Nova Sco 2012) revealed a double peaked radio light-curve similar to that of V1723 Aql (Finzell et al., in preparation).

Moreover, synchrotron emission is physically plausible for V1723 Aql. We expect the magnetic field behind the shock to be amplified to a characteristic value (e.g. Caprioli & Spitkovsky 2014)

$$B = (6\pi e B_{3,0} \Delta v \nu^{\frac{1}{2}})$$

$$\approx 0.05 \left( \frac{n}{10^7} \right)^{\frac{1}{2}} \left( \frac{\Delta v}{0.3 \nu_{18}} \right) v_{f,8} \mu G,$$
V1723 Aql is around 40 days, as observed. Krauss et al. (2011) did not detect linear polarization at 5.5 GHz on day 48, with a 3σ upper limit of 39 μJy (or 1%). Similarly, on day 57, we detected no linear or circular polarization averaging across 1 GHz of bandwidth centred at 28.2 GHz, with 3σ upper limits of 0.42 mJy (9%) for circular polarization and 0.63 mJy (6%) for linear polarization. Given that the magnetic field geometry was likely to have been complex, the lack of strong polarization is not a concern for the synchrotron picture. That the radio spectrum rose with frequency during the radio flare indicates that the synchrotron emission was either self-absorbed or suffered from free-free absorption. Since synchrotron self absorption would require the synchrotron-emitting region to have been extremely compact (i.e., have had a solid angle multiple orders of magnitude smaller than that of the remnant), whereas a reasonable amount of $10^4$ K ionized gas could have led to observable absorption, we find free-free absorption more likely.

4.3 Nova Shocks in the context of bipolar flows and γ-rays

The perpendicular structures evident in Fig. 3 are reminiscent of the perpendicular structures that Chomiuk et al. (2014) found to be responsible for the generation of shocks and gamma-rays in nova V959 Mon. In V959 Mon, radio observations showed that strong internal shocks produced synchrotron emission coincident with the γ-ray detection (Chomiuk et al. 2014). Radio images of the ejecta showed rapidly expanding bipolar flows, which faded over the course of sixteen months to reveal an inner structure that collimated the outer flow (see Chomiuk et al. 2014, Fig. 2d). Our image from day 1281 (see Fig. 3, panel b) reveals a similar inner structure that may be a shell with an equatorial density enhancement. The evolution of the radio spectrum of V1723 Aql may also indicate that the inner portions of its ejecta had a flatter density profile than the outer regions, as one might expect if an inner structure was more confined to the orbital plane (as in V959 Mon). Furthermore, the resolved image on day 832 showed two distinct components aligned roughly perpendicular to the axis of greatest elongation, which could be indicative of a limb-brightened collimating torus.

By associating V1723 Aql’s multiple, distinct radio structures with different velocities, we identified flows that likely collided and led to shocks and particle acceleration. While optical spectra revealed the presence of a fast flow with maximum radial velocity $v_{\text{PA}} = 1500$ km s$^{-1}$ (Yamanaka et al. 2010), there is optical spectral evidence for slower moving ejecta as well. By using the break frequencies of the radio spectrum as the nova shell transitioned from optically thick to optically thin, we estimated that the slowest ejecta had an expansion speed of $v_{i}$ between 200 and $400$ km s$^{-1}$ (Taylor et al. 1987), as we saw in V1723 Aql. The finding by Metzger et al. (2014) that internal shocks generate a cool, dense post-shock region suggests that the appearance of shocks and dust at approximately the same time in V1723 Aql may be more than a coincidence.
provide an important diagnostic of the shocks and colliding flows that produce γ-rays.

(v) Although the morpho-kinematic structure of the ejecta from V1723 Aql is not tightly constrained, its behaviour is consistent with that of a biconical flow loosely collimated by a slow equatorial torus, as in V959 Mon (Chomiuk et al. 2014). This hypothesis is supported by the existence of the perpendicular structures in the resolved radio images (see Fig. 3). Moreover, the shock speed derived from the difference between the fast radio flow (1500 km s\(^{-1}\)) and the slow radio flow (knots moving at ~400 km s\(^{-1}\)) is consistent with that inferred from the temperature of the post-shock X-ray emitting plasma. The flattening of the density profile seen from the variation in \(\alpha_{\text{trans}}\) could be a consequence of the material being slightly more concentrated towards the equatorial plane in the inner region of the remnant (see Fig. 4).

Radio observations are a powerful diagnostic for the colliding flows and shocks that are crucial for γ-ray production and shaping of the ejecta from novae. The radio emission from V1723 Aql shows that the collision of fast and slow flows resulted in a shock which, although leaving the late-time behaviour of the radio light curve mostly unaffected, produced both thermal and non-thermal emission. With the recent detections of classical novae in γ-rays, the question of relativistic particles in novae becomes even more important. Chomiuk et al. (2014) found the morphology of the shock-producing structures in V959 Mon; our work here extends those findings to other classical novae.

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