# Filming the evolution of symbiotic novae with VLBI: The 2021 explosion of RS Oph

PROCEEDINGS OF SCIENCE

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Fifteen years after its previous outburst, the symbiotic recurrent nova RS Oph exploded again on 2021 Aug 8th, its first outburst during the *Fermi* era. In symbiotic novae, the material ejected from the surface of the white dwarf (WD) after the thermonuclear runaway drives a strong shock through the dense circumstellar gas produced by the red giant (RG) wind. This nova is a perfect real-time laboratory for studying physical processes as diverse as accretion, thermonuclear explosions, shock dynamics and particle acceleration; in many ways it is like a supernova remnant on fast forward. The experience of its previous outburst and that of 2010 for V407 (the symbiotic nova that has been extensively observed during the *Fermi* era), indicates that a large sensitivity and a broad range of baseline lengths are necessary to follow its evolution over a period of several weeks. This would provide unique constraints on major outstanding problems, including the emission mechanisms, the physical processes at work, the presence and location of shock acceleration, the geometry of the system, and the density of the RG wind. We present preliminary results from the EVN+e-MERLIN observations carried out on weeks/months time scales after the August explosion.

*15th European VLBI Network Mini-Symposium and Users' Meeting (EVN2022)*
*11-15 July 2022*
*University College Cork, Ireland*

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PoS(EVN2022)038

## 1. Introduction

In its basic description, the outburst of a *classical* nova is a thermonuclear runaway (TNR) event occurring in the shell accreted by a white dwarf (WD) from a low-mass companion. In a *symbiotic* binary, the WD is companion to and accretes from a red giant (RG), a powerful mass-loser, and the circumstellar space is filled by its slowly expanding, dense wind extending up to great distances ($10^2 - 10^3$ AU). A nova eruption within a symbiotic binary is a rather spectacular affair: contrary to classical novae, the fast ejecta expelled by the WD have to plough their way through the pre-existing dense RG wind. In the process they are violently decelerated [e.g. 1], and the associated shocks produce copious non-thermal emission from radio to high energy [e.g. 2–5], in addition to free-free radiation from the ionized wind [6].

Given the high mass-transfer rate from the RG, and the WD mass approaching the Chandrasekhar limit, basically all symbiotic novae are recurrent on human time-scales. The typical separation between eruptions is however above a decade, meaning that these events are rather unique opportunities and that the observational landscape changes significantly from one outburst to the next. For instance, no gamma-ray observations were possible for any nova before the advent of *Fermi*. The first symbiotic nova observed in gamma-rays so far was V407 Cyg [5], for which EVN and VLBA observations provided spectacular images of the shocked ejecta as they expand through the RG wind [7, 8].

Among symbiotic novae, RS Oph holds the record of observed eruptions (in 1898, 1933, 1958, 1967, 1985, and 2006) but it never turned on during the *Fermi* era, until it was detected as a $\sim$ 5th magnitude and gamma-ray bright object on $t_0$ = 2021 Aug 8th [9]. Remarkably, even higher energy (TeV) emission was soon detected with H.E.S.S. [10] and MAGIC [11], and not surprisingly the source was intensively monitored in a variety of other bands [e.g. 12–14]. In radio, a first report of activity was obtained between 1.4 and 15 GHz with MeerKAT, e-MERLIN and AMI-LA [15], starting as soon as $\sim$ 1 day after the explosion; low-frequency observations up to day 222 are reported in [16].

In the present paper, we show some preliminary results from the EVN+e-MERLIN campaign that we carried out to follow the structural evolution. An in-depth comparison of one of our observations with constraints obtained from optical spectroscopy is presented in [17], while a more complete discussion of the results of the whole campaign will be presented in a forthcoming publication. Throughout this work, we assume a distance $d = 2.68 \pm 0.17$ kpc, as reported by Gaia DR3 [18], and therefore 1 mas $\sim$ 2.7 AU $\sim 4.0 \times 10^{13}$ cm.

## 2. Observations

We observed RS Oph in 10 sessions (RG012A-J), grouped in five epochs ($1-5$), each consisting of two runs observed in consecutive days, one at 5 and another at 1.6 GHz. The first observation took place on 2021 Aug 22nd ($t_0 + 14$ days) and the last one on October 12 ($t_0 + 65$ days). A detailed log of the observations is given in Table 1.

Each observation lasted for 8 hours. The observing bandwidth was of 256 and 128 MHz at 5 and 1.6 GHz, respectively. The corresponding data rates were of 2 and 1 Gbps, although some stations were limited to a narrower bandwidth. The first four runs only used EVN stations, while for

| Epoch | Code RG012- | Date in 2022 | $t - t_0$ (days) | Freq. (GHz) | Restoring beam (mas × mas, °) | Peak brightness (mJy beam$^{-1}$) | Participating arrays |
|---|---|---|---|---|---|---|---|
| 1 | A | Aug 22 | 14 | 5 | 5.5 × 4.6, −77.2 | 5.7 | EVN (9)$^a$ |
| | B | Aug 23 | 15 | 1.6 | 16 × 2.2, 80.2 | 16 | EVN (7)$^a$ |
| 2 | C | Sep 1 | 24 | 5 | 11 × 6.8, −12.4 | 7.0 | EVN (8)$^a$ |
| | D | Sep 2 | 25 | 1.6 | 44 × 11, 10 | 21 | EVN (8)$^a$ |
| 3 | E | Sep 11 | 34 | 5 | 12 × 9.4, −8.5 | 2.0 | EVN (13)$^a$ + e-MERLIN |
| | F | Sep 12 | 35 | 1.6 | 34 × 9.1, 2.2 | 8.5 | EVN (12)$^a$ + e-MERLIN |
| 4 | G | Sep 26 | 49 | 5 | . . .$^b$ | . . .$^b$ | EVN (14)$^a$ + e-MERLIN |
| | H | Sep 27 | 50 | 1.6 | . . .$^b$ | . . .$^b$ | EVN (13)$^a$ + e-MERLIN |
| 5 | I | Oct 11 | 64 | 5 | 9.0 × 5.1, −6.5 | 0.7 | EVN (14)$^a$ + e-MERLIN |
| | J | Oct 12 | 65 | 1.6 | 45 × 13, −4.0 | 4.1 | EVN (13)$^a$ + e-MERLIN |

**Table 1:** Log of observations. Restoring beam and peak brightness refer to the images shown in Fig. 1 and should be considered as preliminary. (*a*): values in parenthesis indicate the number of EVN stations participating in each session. (*b*): the runs from epoch 4 were affected by an hardware problem and are not discussed here.

the last six observations also e-MERLIN outstations joined the array, to better probe the expanding structure. We observed in phase reference mode, alternating scans on the target and on the nearby (1°.67 separation) calibrator J1745−0753. Data reduction was based on the JIVE pipeline, follwed by standard hybrid mapping procedures in Difmap.

We would like to point out that this campaign pushed the network to its limits. A total of 80 hours of observations were carried out in Target of Opportunity mode over a time span of 51 days, starting in the middle of the summer and with very little anticipation. Since spectral index information was critical for the interpretation of the emission mechanisms, but the source was rapidly evolving, dual frequency observations in adjacent days were performed, challenging the standard operation mode of the EVN. For these reasons, we wish to express our gratitude and appreciation to the EVN Directors and Officers, and to all the personnel involved in the observations at the stations and at JIVE.

## 3. Results and discussion

The source is detected in every observation, and we show *preliminary* images in Fig. 1. Already in the first run, at $t_0 + 14$ days, the structure is clearly extended, with a total size of about 20 mas (28 AU), mostly distributed to the west of the extrapolated Gaia position. The total flux densities at 1.6 and 5 GHz are $S_{1.6} = 25$ and $S_5 = 43$ mJy, corresponding to a rising spectral index $\alpha = 0.5$ ($S_\nu \sim \nu^{+\alpha}$).

The total flux density increases in the following observations, peaking first at 5 GHz (in epoch 2) and later at 1.6 GHz (in epoch 3), and then decreasing as the source expands. The integrated spectral index accordingly transitions to negative values, corresponding to a change to optically thin emission.

In terms of morphology, starting from epoch 2, emission becomes detected also on the eastern side, well separated from the core by a ~ 20 mas gap, which we ascribe to absorption by a density enhancement on the orbital plane [17]. In the third epoch, three main regions of emission are well

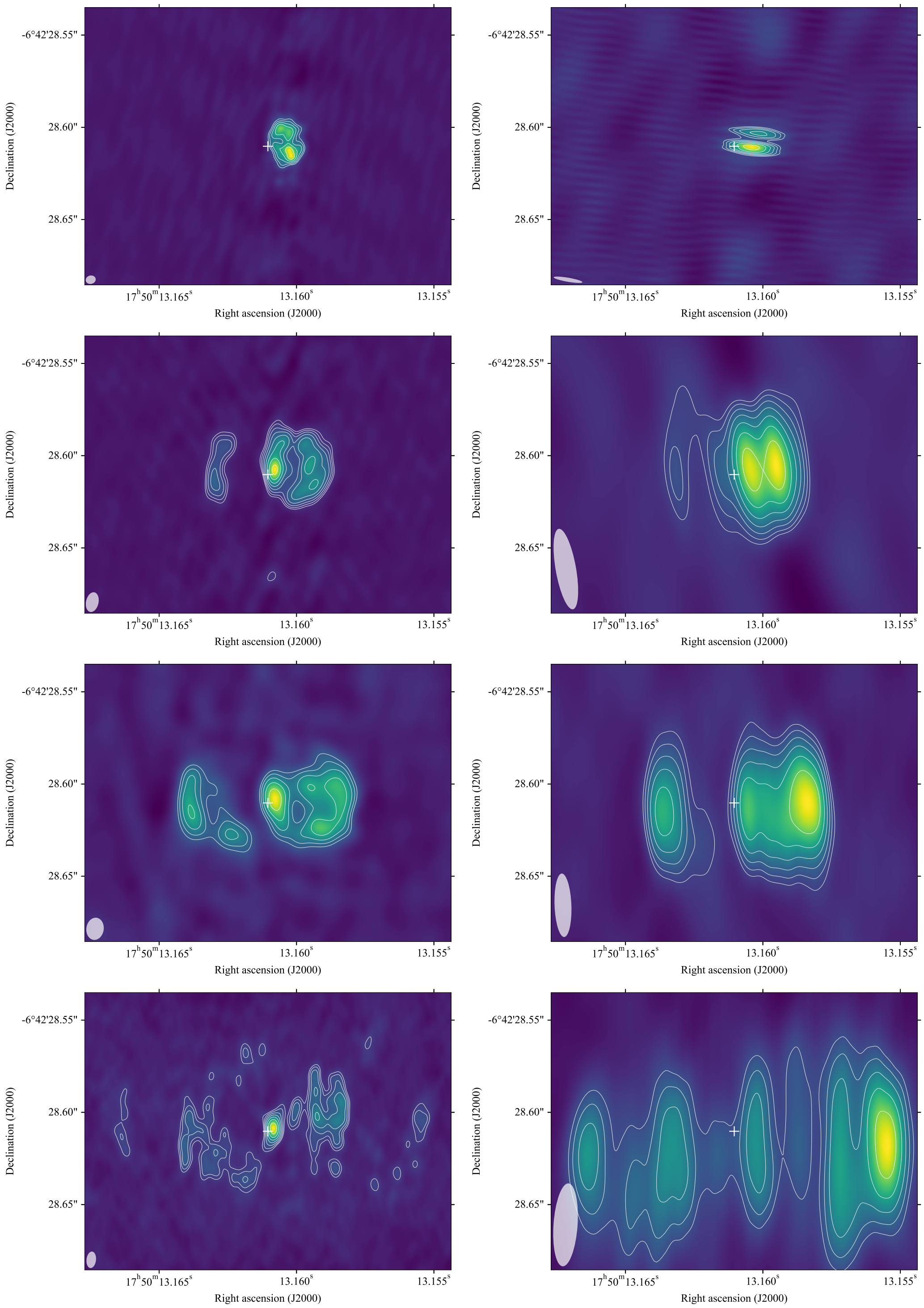


**Figure 1:** Preliminary RS Oph images after the 2021 outburst. From top to bottom: epochs 1, 2, 3, and 5; left column: 5 GHz, right column: 1.6 GHz. Image maxima and restoring beam sizes are reported in Table 1. The central white cross indicates the coordinates of the Gaia position.

recognisable in the image, a central compact core in the proximity of the Gaia position, a brighter western lobe and a fainter eastern one. A hardware problem with the e-MERLIN WIDAR correlator resulted in the loss of short-baseline visibilities and a largely degraded image. While this prevented us from obtaining accurate quantitative information, it remains a clear indication of the continued expansion of the source. The fifth and final epoch indeed shows a largely resolved structure in the outer lobes, with a total extension of about 180 mas (250 AU). The spatial distribution of the spectral index in the spatially resolved images is not uniform, with the central component displaying flatter values than the rest of the emission.

The overall structure, and its evolution, is remarkably similar to that observed after the 2006 outburst [2–4]. However, the availability of the Gaia position and its coincidence with the central compact component allows us to interpret the data in a much clearer way. As discussed in [17], we infer the presence of a strong density enhancement on the orbital plane, which is oriented at $i = 54°$ inclination. This enhancement confines the nova ejecta into two lobes, expanding in opposite directions normal to the plane, with the western lobe in foreground and the eastern lobe in background. The bright central component could be the place of impact of the ejecta on the inner radius of the density enhancement. Based on the size observed at the last epoch, the average advance velocity on each side during the first 65 days is 6400 km $s^{-1}$.

## 4. Conclusions and outlook

The EVN performed incredibly well under the rather extreme circumstances mandated by the 2021 RS Oph outburst: short lead time, intense monitoring, dual frequency, rapid observation turnout. This confirms that astrophysical transients are and will remain an important area of impact for the network in the coming years, as anticipated in the VLBI20-30 EVN science roadmap [19]. The preliminary results presented here and the comparison with the optical spectroscopy information [17] indicate that this dataset will be extremely valuable in order to address open points such as the identification of the loci of shock-acceleration resulting in high energy emission, the determination of the geometrical configuration of the ejecta, and the discernment between free expansion and deceleration induced by the sweep-up of the RG wind.

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