

Nebulosities of the Symbiotic Binary R Aquarii - A Short Review

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In this proceeding, we present a short review of the fascinating nebulosities of symbiotic binary R Aquarii. The R Aquarii system, comprising the central binary and surrounding nebular material, has been the subject of near-continuous study since its discovery, with a few hundred papers listed in ADS. As such, it is impossible to provide here the comprehensive review that R Aquarii deserves, instead we chose to focus on the nebulosities – covering both our own research and other relevant results from the literature.

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1. Introduction

R Aquarii (R Aqr) is a symbiotic binary, of orbital period 43.6 years [1], comprising a mass-losing pulsating Mira (with period 387d) and a hot white dwarf (WD). It is surrounded by an hour-glass nebula and a curved S-shape jet (Figure 1). At a kinematic distance of about 200 pc (e.g. [2], [3]) it is the closest known symbiotic system and stellar jet. Therefore, its environs are very well studied in all wavelengths but still provide many intriguing results and open questions. In addition, it is a case study of stellar jets, symbiotic phenomena, mass transfer, as well as mass loss in interacting binaries.

2. Optical imaging data

We observed R Aqr with the Nordic Optical Telescope exploiting the instrument ALFOSC on 18th and 24th of July 2019 within Spanish CAT service time proposal. A narrow band filter [O III] with a central wavelength of 500.7 nm and a FWHM 3 nm (NOT filter # 90) was used. On both dates, one short (10s) and one long (180s) exposure were acquired. Images were reduced using standard procedures in IRAF¹.

3. Hour-glass nebula

The hour-glass nebula of R Aqr, discovered by [4] in 1922, has been shown to expand ballistically. It has a knotty and filamentary structure in the low-ionisation lines (red in Figure 1), such as H α , [N II], [O I]. In higher ionisation lines, such as [O III], the nebula is more diffuse. Using the expansion of the nebula several authors, e.g. [5], [2], [3], have derived kinematic ages which all agree that the current age of the R Aqr nebula is about 670 years. It is believed to have been created by the red giant star in a nova-like event. It was shown in [3] that the nebula does not present noticeable changes during the years 1991 to 2012. Considering our data from 2019 we can confirm that the nebula has had a stable morphology for almost the last 30 years.

4. New extended features

Fainter features extending further out beyond the hour-glass nebula, have been discovered by [3]. These comprise a thick arc, visible in [O III], with a length of 6'.4 and a thinner and fainter H α arc reaching 2'.8 from the central star. It is concluded in [3] that these features are most likely related to the mass loss from the red giant and/or a nova eruption from the white dwarf in an earlier evolutionary stage of the system.

5. Jet

Unlike the stable bipolar nebula, the evolution of the jet is more complex and irregular. The jet has a collimated appearance with a prominent S-shape consisting of multiple knotty, filamentary, and diffuse structures (Figure 1).

¹IRAF is distributed by the National Optical Astronomy Observatory, which is operated by the Association of Universities for Research in Astronomy (AURA) under cooperative agreement with the National Science Foundation.

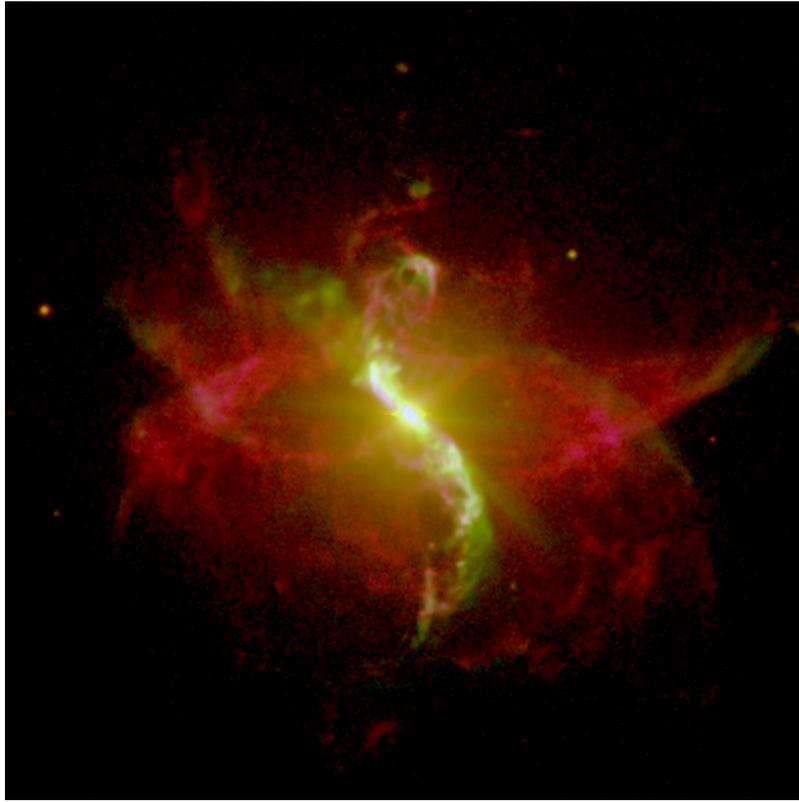


Figure 1: R Aquarii nebulosities. In red the hour-glass nebula, in greenish-yellow the jet. North up, East left. $3' \times 3'$. [3].

The jet of R Aqr was discovered by [2]. However, [6] showed from the Lowell Observatory photographic plates that the jet was present already as early as 1934. The jet presents remarkable brightness, structural, and kinematical variations on both large and small scales but the overall large-scale S-shape (see Figure 1) has remained the same over the years.

While the jet of R Aqr is still active (e.g. [7, 8]), the ages of outer components are up to 300 years old [3]. The jet is formed during the periastron passage of the binary components, when the mass transfer on to the white dwarf and surrounding accretion disc is enhanced.

At earlier times, detailed study of the innermost $5''$ of the jet was only possible with high resolution radio data (e.g. [9], [10]). In 1991, the innermost $3''$ jet was observed with the Hubble Space Telescope (HST) in the ultraviolet (see Figure 2 left and [11]). With the current instruments, it is also possible to probe these central regions in the optical range. [7] observed the R Aqr binary and its jet using the SPHERE instrument on the VLT. Their very detailed map of the most central $3''$ is presented in Figure 2 right, as a comparison with the HST data from 1991. Large differences in brightness and morphology between the datasets, taken 23 years apart, are evident. In particular, in 1991 the northern jet was considerably brighter than the southern one. In addition, in the earlier image the northern filaments were elongated in the North-East direction while currently the Northern filaments are stretched out in the North direction, which is the overall jet expansion direction (Figure 3). In the South, the SHPERE data shows a bright “zig zag” structure which does not seem to be present in 1991. These changes are explained by [7] as resulting from the very dynamic

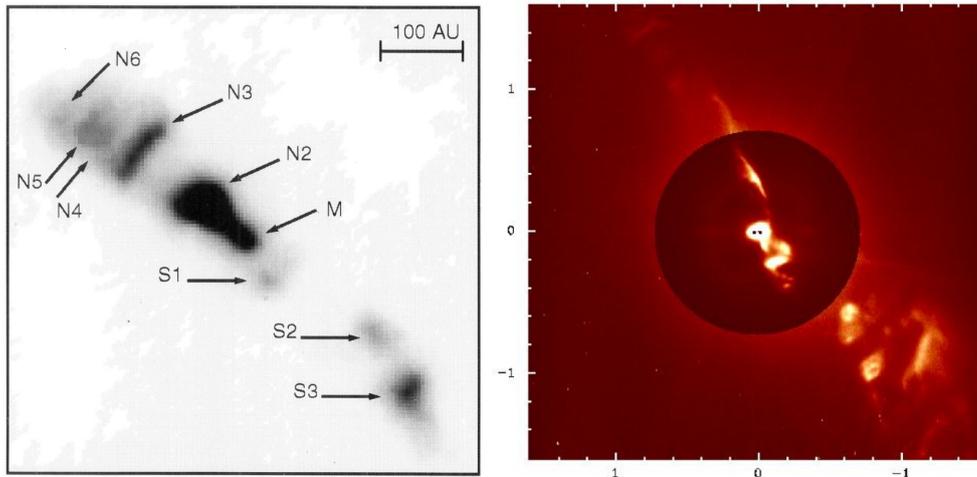


Figure 2: *Left:* R Aquarii innermost jet with the HST in UV at 1991. Figure from [11]. *Right:* VLT+SPHERE H α image from 2014. Figure from [7]. Images have the same FOV, $3' \times 3'$. North up, East left.

nature of the jet. However, as it was shown by [3], jet features can have a different brightness and morphology depending on the wavelength, which could be an additional cause of the mentioned changes in the appearance of the jet between the 1991 HST UV and the 2014 VLT+SPHERE H α .

Significant changes in the brightness and morphology of the larger scale jet have also been seen by [3] and in the present work. In Figure 4, we present the evolution of the jet on large scales from 2002–2012 (data taken from [3]), and in 2019 (this work). As was described in [3], the brightness of the features of the jet changes on timescales of about 10 years, in parallel to morphological changes (features tend to get elongated in the direction of the overall expansion and eventually separate into two components). This is especially true for the North-East jet, while the evolution of South-West jet is more uniform.

Considerable brightness, and possibly also a morphological, changes can be seen between the last image of [3] (2012) and our image from 2019: the features closest to the central star (highlighted with a white arrow on Figure 4, or named as A and G by [3]) have completely disappeared or at least are no longer detectable on our three minute exposure. We would like to point out that all the data on Figure 4 have comparable exposure times, indicating that the non-detection is unlikely to be due to a difference in data quality (indeed in 2019, we acquired two epochs roughly one week apart, with the features not visible in either data set) but rather due to the nature of R Aqr and its environs. Furthermore, HST images from 2013 [12] and 2017 (MAST archive), show that the differences between 2012 and 2019 have been gradually occurring in the interim period. The area highlighted with the white arrow has been getting dimmer over the years, until disappearing in 2019. We propose that this large structural change could be related to the ongoing period of reduced variability of the Mira in the R Aqr system which started at spring 2019 (see AAVSO alert notice 665²). These low Mira states appear to occur every ~ 44 years, synchronised with the orbital period and are associated with the fact that the gas cloud surrounding the WD and its

²<https://www.aavso.org/aavso-alert-notice-665>

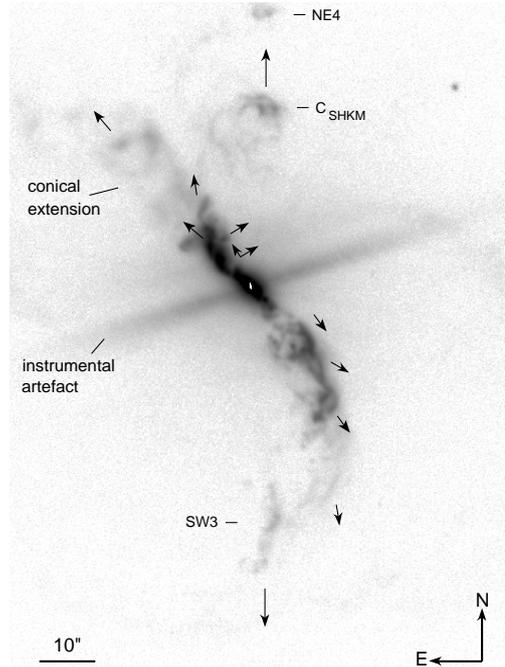


Figure 3: Overall expansion pattern of the R Aqr jet. Note laterally pointing arrows near the central star in the North-East jet. Figure depicted from [3].

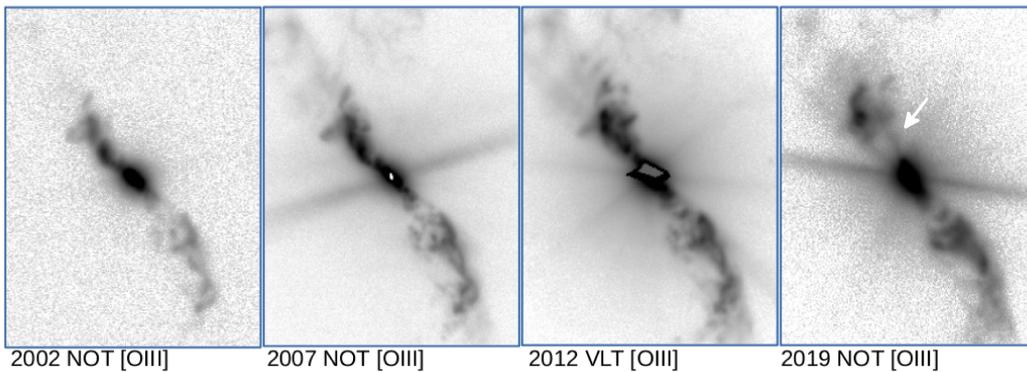


Figure 4: R Aquarii jet evolution from 2002 to 2019. Diffuse diagonal spikes across the whole FOV, emanating from the central star, are instrumental artefacts due to the saturated central area.

accretion disc are eclipsing the Mira [13]. Considering the refined orbital parameters presented in [8] (see their Figure B.1), it is feasible that the eclipse has indeed started. If that is true, then when looking from the Earth, the WD is eclipsing the Mira. However, at the same time, when looking from the point of view of the North-East jet, the Mira star is eclipsing the light of the WD, which is probably responsible for ionising and illuminating the jet in the first place. Therefore, it is not surprising that we see large brightness changes that could be associated with the blocking of the ionisation/illumination source. The low state of the Mira usually lasts about 8 years, although the passage of the WD and the disc should not take much longer than 2 yrs. Therefore, a second explanation to the current low state of the Mira is the dimming due to the enhanced mass-loss from

the AGB in the direction of the WD, which would also be caused by the periastron passage of the system. There is an indication of a dust-rich flow of this kind in the ALMA maps [8]. In reality, probably both reasons are playing a role in the current reduced brightness variation period of R Aqr. In any case, whatever is the cause, if the brightness of the disappearing jet features resumes after 8 years, their fading would almost certainly have been related to the current low state of the system.

[3] presents additional details of the curious nature of R Aqr jet. They detect lateral fast moving features up to 900 km/s (see Figure 3), which is several times larger than the rest of the velocities measured in the jet (e.g. velocities along the line of sight are approximately ± 100 km/s [3]). They attribute these fast moving features as a changing ionisation/illumination effects rather than a real matter moving.

[3] also measure the northern jet to be mostly red-shifted and southern blue-shifted while previous authors ([2], [14], [15]) have found it to be the opposite. This is interpreted as being a consequence of the complex line profiles and the evolution of the jet which shows significant brightness and morphological changes in the time frame between the data in [3] and the previously published radial velocity data. Moreover, the data used in [3] has a much higher spectral and spatial resolution than any other dataset published before.

Considering all the above mentioned intriguing results and the jet's kinematical behaviour, it is worth emphasising that the overall large scale expansion pattern of the jet can be still considered ballistic (Figure 3 and [3]).

6. Conclusions

We have presented a short review of the R Aqr nebulosities together with the surprising morphological and brightness changes observed during the last 7 years. The latter we believe is associated with the current possible eclipse of the Mira by the WD and its accretion disc or by the dimming due to the enhances mass-loss from the AGB, both caused by the periastron passage. From all this it is clear that the evolution of the R Aqr jet cannot be described by purely radial expansion. A combination of physical matter moving, together with changing ionisation, illumination, shocks, and precession has to be taken into account. However, which processes from those listed is more important in the evolution of individual features remains an open question.

Acknowledgments

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DISCUSSION

VALENTIN BUJARRABAL: you mentioned an East-West "bipolar nebula", different from the jets you are mainly interested in. But, in view of its velocity field and structure, I would say that it is probably a ring in expansion. Possibly, it defines the plane of symmetry of the whole extended nebula. Do you agree?

TIINA LIIMETS: yes