

Symbiotic Eclipsing R Aquarii: Metallicity and Pulsation Analysis

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Abstract— A staple in binary symbiotic research, R Aquarii is revisited again. This study aimed to address the absence of direct, published spectroscopic metallicity analyses of R Aqr's stellar components by conducting pulsation (light) curve analysis and metallicity analysis. Utilizing long-standing UVBRI photometric data from the AAVSO International Database, Period04 software was employed for light curve analysis, while MESA simulated stellar parameters and chemical evolution. Key findings include a primary Mira variable pulsation period of 311.36 days, and a second frequency period of approximately 2.51 days. The 1974-1983 and 2018-present eclipses showed significantly dimmer light curves (8th - 11th magnitudes) compared to the 1928-1934 eclipse (6th - 8th magnitudes), with the light curve displaying quasi-periodic behavior and a long-timescale modulation of oscillation amplitude. The metallicity is within the expected diversity of molecular gases, with hydrogen gases at lower solar mass attributed to the surrounding nebula, and ⁴He and ¹⁶O line profiles suggesting co-location within the same structures. A mass loss rate of approximately $\sim 6.3 \times 10^{-7}$ to $6.5 \times 10^{-7} M_{\odot}/\text{yr}$ was estimated. The researchers recommend more high-resolution observations to fully understand R Aqr's circumstellar envelope and jet kinematics, along with revisiting the primary frequency's link to the jets.

Keywords— *R Aquarii, symbiotic star, variable star, metallicity*

INTRODUCTION

A symbiotic binary is a specific type of interacting binary star system that consists of a cool, evolved star, such as an aging red giant, partnered with a much hotter, compact companion, typically a white dwarf or a neutron star. The defining characteristic of these systems is the transfer of material from the cool giant to its dense companion (Merc, 2025; Mikołajewska, 2007; Perko, 2021).

R Aqr is one of the closest known symbiotic systems (Vasquez-Torres et al., 2024), located approximately 650 to 710 light-years (200-218 parsecs) from Earth, which allows for detailed observation of its intricate outflows and stellar dynamics (ESA, 2024; Toalá et al., 2022). Its system comprises two profoundly different components: a mira variable (red giant), and a white dwarf companion (ESA, 2024).

Further, its primary star is an aging red giant that has exhausted its core hydrogen fuel and expanded to a colossal size, estimated to be more than 400 times the diameter of our Sun (Andreoli, 2025; ESA, 2024). It undergoes powerful pulsations, causing its brightness to dramatically change by a factor of up to 750 over a roughly 385- to 390-day period (AAVSO, n.d.; ESA, 2024; Gromadzki & Mikołajewska, 2009b; Perko, 2021; Tucio et al., 2025). Its mass is estimated at 1 to 1.5 solar masses (M_{\odot}), luminosity around 4,780 solar luminosities (L), and temperature approximately 2,800 Kelvin (K). This pulsation behavior has been documented in detail for over 180 years (AAVSO, n.d.; ESA, 2024; Tucio et al., 2025).

Its companion is a compact, hot, and dense white dwarf,

representing the end-stage core of a star. It is surrounded by an accretion disk, which is continuously fed by the mass lost from its giant companion, primarily through a stellar wind. When the material, rich in hydrogen, accumulates to a critical mass and pressure on the white dwarf's surface, it triggers spontaneous bursts of thermonuclear fusion, akin to a colossal hydrogen bomb. These outbursts violently eject excess material and energy. Its mass is estimated at 0.6 to 1 M_{\odot} , a radius greater than 0.1 R_{\odot} , luminosity 5 to 20 L, and temperature around 60,000 K (ESA, 2024; Gromadzki & Mikołajewska, 2009b; Hinkle et al., 2022).

R Aqr is enveloped by an intricate hourglass-shaped nebula called Cederblad 211, believed to be the remnant of past explosive episodes. It also features a prominent, S-shaped bipolar jet that ejects material at immense speeds and actively shapes the larger nebular structures. Historical records suggest that nova-like outbursts occurred around 1073 AD and the 1770s, forming rings of material that are still observed today (Andreoli, 2025; ESA, 2024; Toalá et al., 2022).

R Aqr serves as a unique astrophysical laboratory for investigating stellar evolution, mass transfer, and high-energy phenomena. Its jets exhibit properties similar to those produced by supermassive black holes, making it a crucial scaled-down laboratory for studying jet and accretion disk physics. It is also considered a critical object for understanding the late stages of stellar evolution, potentially being a progenitor of planetary nebulae and Type Ia supernovae (Toalá et al., 2022; Tucio et al., 2025).

While light curve analysis has been exceptionally suc-



successful in understanding R Aqr, the sources indicate the need for continued, long-term monitoring to capture future outbursts and eclipses. This ongoing observation is essential to refine our understanding of this dynamic and volatile stellar system. The success of predicting and observing the 2022 eclipse, based on long-term data and multi-wavelength campaigns, highlights that continued light curve analysis can still address the continuous "gap" in fully characterizing and predicting every aspect of the system's complex, accretion-driven events and their impact on the stellar environment (Hinkle et al., 2022; SAO, 2023; Tucio et al., 2025). This also indirectly contributes to resolving issues like the kinematics of the jet, which still presents discrepancies requiring future high-resolution spectroscopic campaigns (Liimets et al., 2018), as multi-wavelength light curve data provides crucial context for such studies (Hinkle et al., 2022).

A significant and explicit gap identified in the research for R Aqr is the absence of direct, published spectroscopic metallicity analyses of the stellar components themselves. The sources note that while R Aqr is recognized for its role in releasing heavy elements into the interstellar medium, there is no formal quantitative data on the photospheric metallicity of its stars. This presents a clear opportunity for future spectroscopic studies to address this known challenge in the field of symbiotic stars (ESA, 2024; Gromadzki & Mikołajewska, 2009a; Hinkle et al., 2022; Mikołajewska et al., 2005).

To further understand the dynamic processes, behavior, and stellar composition of R Aqr, this paper conducted a pulsation (light) curve analysis using Period04 and a metallicity analysis using MESA. The following sections outline the details of the study's methodology, data, processing, and the instruments used. The Results and Discussion section relates the results of the study's pulsation and metallicity analysis to existing studies in symbiotic binaries.

METHODOLOGY

A. Data and Processing

Figure 1 shows the data acquisition and processing workflow of the study. The development of novel devices over the last several decades and their use by amateur astronomers has played an essential role in gathering good observational photometric data (Kalaei & Hasanzadeh, 2019), which can better understand R Aquarii behavior. Photometric data for R Aquarii is obtained from the American Association of Variable Star Observers (<http://www.aavso.org>) database. The data archived came from the British Astronomical Association Variable Star Section and Royal Astronomical Society of New Zealand with data dated as early as the 1800s until the present. The observations include the Julian date of the observation and the visual magnitude of the variable at the reported time. The data includes other bands such as the ultraviolet and infrared noted as U and I, respectively. Around 2018, R Aquarii data includes UVBRI and other bands useful for understanding the peculiarity of its pulsation and system.

B. Instruments Used

An essential issue in time series analysis is the effects of external factors on the signals, such as the extent of variability in the data caused by measurement error caused by external perturbations. There is a lack of evidence that there are oscillations in the dynamics instead of random perturbations (Kaplan & Glass, 1995). Fourier Transform is an effective technique for detecting critical characteristics of a time series. Period04 software packages were used (Lenz & Breger, 2005), which combines Fourier and least-square algorithms. The Fourier transform (FT) was used to investigate the irregular behavior of the R Aquarii light curve from January 1970 to December 2023 only, which includes the current eclipse and its predecessor. To detect frequency and amplitude evolution, a time-frequency technique was used. The time plot string, Fourier Transform, Frequencies, and Amplitudes were all processed and computed in Period04. We used Python language to perform basic statistics graphs and plots. To obtain more information about the evolution of the light curve, we have referred to the work of Kalaei and Hasanzadeh (2019) about the time series analysis of R Scuti's light curve. Time series were divided into 49 sections, each with a length of about three years, long enough to consider the behavior of the prominent peaks. For a detailed study, the values of peak frequencies and amplitudes for every section were extracted and plotted into a line graph to look for variations. Then, for binary evolution, the researchers used Modules for Experiments in Stellar Astrophysics (MESA) to determine its stellar parameters. This open-source library suite is designed for a variety of computational stellar astrophysics applications. It is efficient, thread-safe, and built to handle complex calculations reliably (Paxton et al., 2011). MESA can fully integrate nuclear networks containing hundreds of isotopes, enabling precise simulations of advanced burning stages essential for developing supernova progenitor models. MESAbinary is a MESA module designed for evolving binary star systems using MESAstar. It can simulate a full stellar model alongside a point mass companion or simultaneously evolve both stars' structures. The module also includes options for modeling stellar rotation, assuming each star's rotational axis is perpendicular to the orbital plane, and incorporates the effects of tidal interactions and spin-up caused by accretion (Paxton et al., 2015).

$$\begin{aligned} \dot{Y}_i = & \sum_j c_i \lambda_j Y_j + \sum_{j,k} \frac{c_i}{|c_j|!|c_k|!} \lambda_{j,k} Y_j Y_k \\ & + \sum_{j,k,l} \frac{c_i}{|c_j|!|c_k|!|c_l|!} \lambda_{j,k,l} Y_j Y_k Y_l. \end{aligned} \quad (1)$$

Equation 1 describes the continuum limit of reacting nuclei, "where Y_i is the abundance of isotope i , λ is a reaction rate, and the three sums are over-reactions that produce or destroy a nucleus of species i with 1, 2, and 3 reacting nuclei, respectively e.g., (Meyer et al., 1998); (Hix & Meyer, 2006); (Guidry et al., 2013); (Longland et al., 2014). The positive or negative stoichiometric coefficients c_i account for the number of nuclei created or destroyed in a reaction.

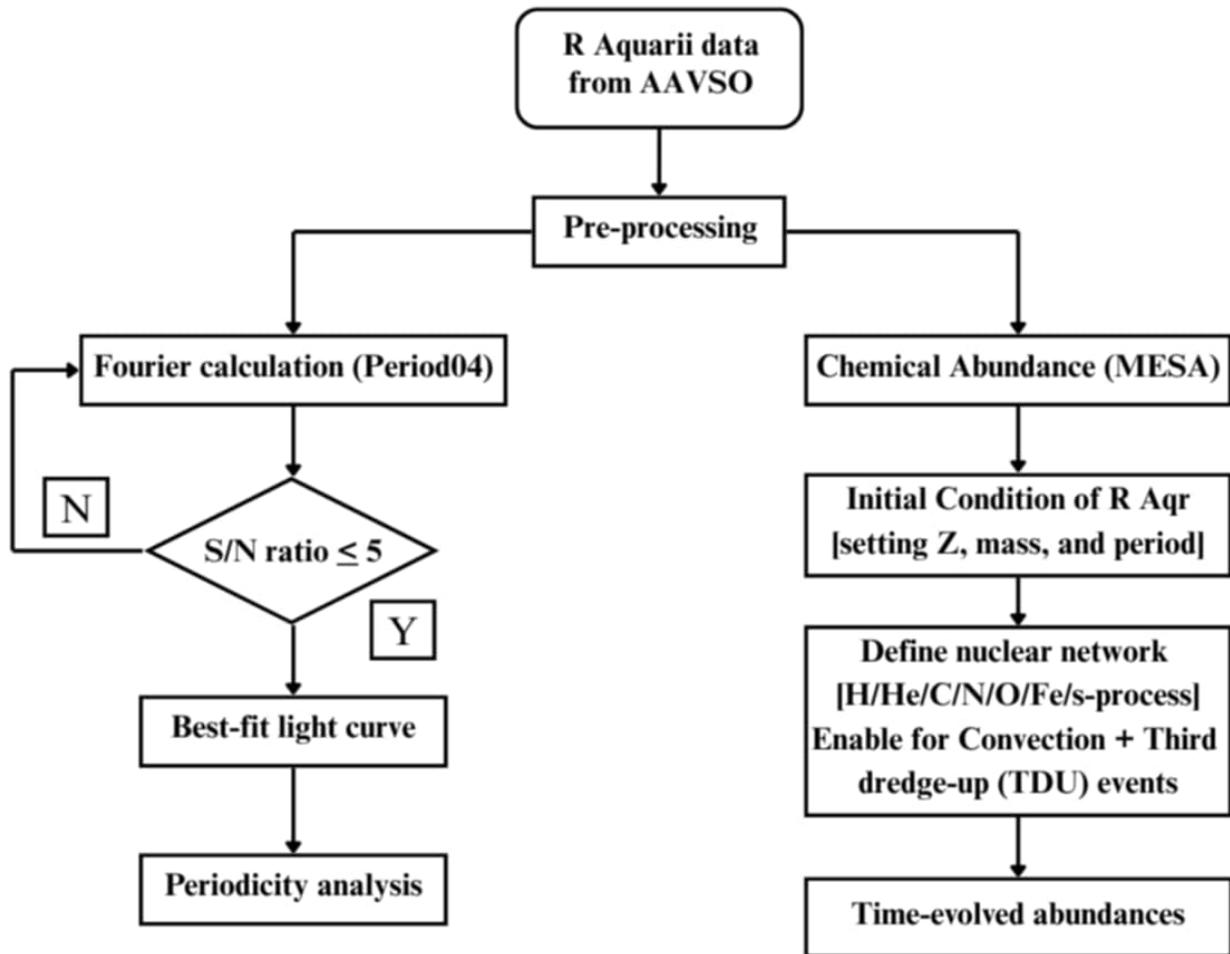


Figure 1 Data and Processing Workflow

The factorials in the denominators avoid double counting of identical particles” (Paxton et al., 2015). Matplotlib was used to visualize the simulation’s data in real-time and generate graphs for the duration of the simulation.

RESULTS AND DISCUSSION

A. Light Curve Analysis

A light curve’s record of brightness changes can aid astronomers in comprehending mechanisms at work within the object they observe and identify specific categories (or classes) of stellar occurrences (TheImagineTeamNASA, 2013). Based on the observations and on the processed time series plot, R Aquarii appears to brighten and dim from time to time . The obscuration in R Aquarii was explained in terms of orbitally related eclipses of the Mira by pre-existing dust. It has been suggested that similar events occur in other symbiotic Miras (Kastner et al., 2000). The last eclipse of R Aquarii was in 1978 and is currently experiencing an eclipse, which happens every 44 years (AAVSO, 2021) and lasts for about 8 years (AAVSO, n.d.). Figure 2 summarizes the eclipsing phenomenon of the binary and also shows the usual dimming and brightness of the Mira

star aside from the eclipse. The usual depth of the light curve at around 11 magnitudes and reaches up to 5th magnitudes. Between 1928 and 1934, R Aquarii brightened from the 11th magnitude to 9th and even as bright as 6th magnitude until it faded back to its usual brightness (AAVSO, n.d.). These are different to the 1974 eclipse and to the ongoing eclipse which have relatively dimmer values. We note that the light curve has decreased since the Mira-type star will soon pass through the line-of-sight of its companion high-energetic star. Since white dwarfs are magnetic, this might have been the cause of the sparring of this light series. It can also be seen on the last panel; the series of light periods were observed in the much shorter time. The same observation was made by Liimets et al. (2020) in their research on R Aquarii, focusing on its jet. By comparing the jet evolution of R Aquarii from 2002 to 2012 with that of 2019, Liimets et al. (2020) detected significant structural, morphological, and brightness changes in the system’s jet after 7-years, suggesting a continuing phase of reduced variability in the Mira star. It was suggested that these changes were related to either the dimming brought on by enhanced mass-loss from the AGB or the continuing eclipse of the Mira by the White Dwarf and its accretion disc, which be-

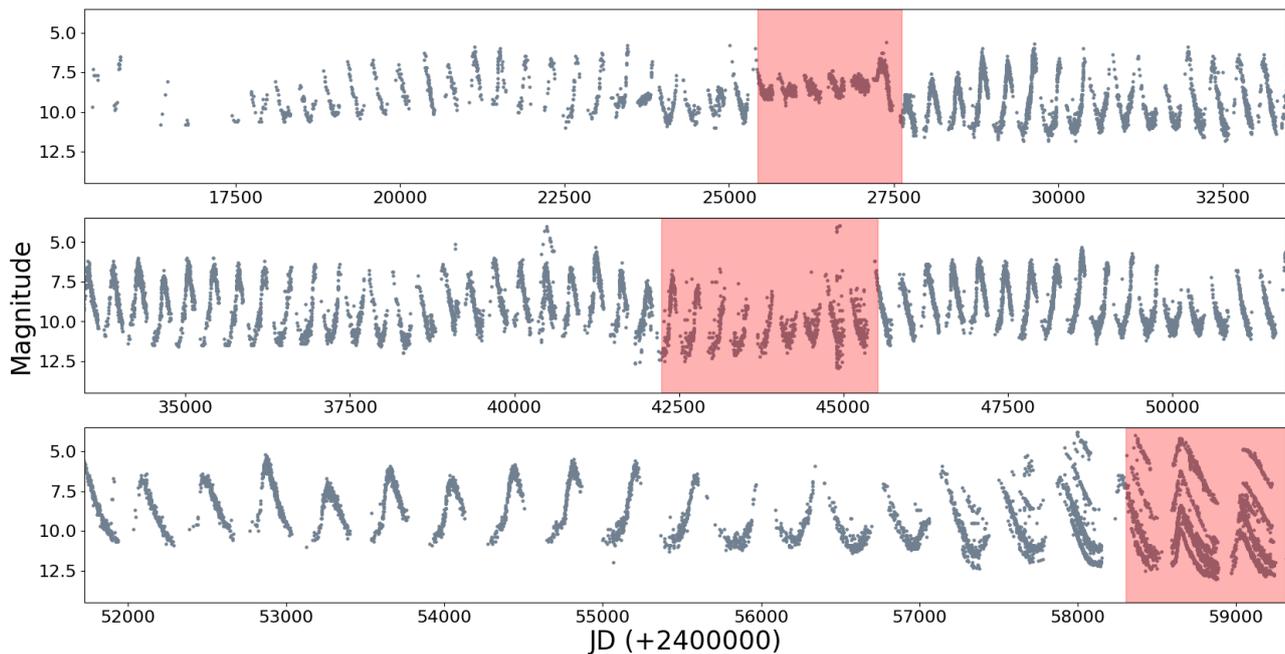


Figure 2 Light Curve of the R Aquarii from 1900 to 2024. In red panels: (a) top panel shows the 1928-1934 eclipse, (b) middle panel shows the 1974-1983 eclipse, and (c) the bottom eclipse of the R Aquarii started in 2018.

Table 1 Values of peak frequencies and amplitudes of R Aquarii during 1970-2020

Years	freq 1 (day^{-1})	amp 1 (mmag)	freq 2 (day^{-1})	amp 2 (mmag)	freq 3 (day^{-1})	amp 3 (mmag)
1970-72	0.0051125330	0.6730859320	0.0016827712	0.7296595460	0.0104533295	0.4494951950
1971-73	0.0024649811	1.6540032500	0.0056564965	0.5295205660	0.0076292242	0.5778104320
1972-74	0.0025271611	1.7947124600	0.0077802162	0.6122333230	0.0036037557	0.2891474530
1973-75	0.0025737063	1.7504429600	0.0079163562	0.5766494870	0.0037831480	0.2242109200
1974-76	0.0025728079	1.7332344100	0.0078028263	0.6003378890	0.8146812170	0.2732256240

gan in 2018.

We investigated the observations for the R Aquarii for the past 51 years. There were two observations with the most replicates (Figure 2), at around 7th and 10th magnitudes. Other memorable values are in between the said magnitudes. This suggests that for the several decades, R Aquarii appears dimmer at almost 11th magnitude and shines at 7th magnitude. From the obtained time string plot and Fourier graph, we observed that the light curve of R Aquarii follows a particular increase and decrease pattern from time to time. Hack and Dous (2018) states that the mean light curve of R Aquarii exhibits a broad minimum lasting 6 to 7 months, followed by a rapid rise to maximum. The shape and amplitude of the light curve vary significantly from cycle to cycle. In some cases, the variability was almost non-existent. This occurred, for example, in the years 1905-10, 1928-30, and 1974-78. As a result, the light curve exhibits a type of long-timescale "modulation" of the oscillation amplitude. From 2015 until 2020, more observations occurred as AAVSO released an observation campaign and alert notices on R Aquarii as it enters the eclipse (AAVSO, 2021). We were able to detect two

dominant frequencies from the first calculation of the frequency alone, at around 0.0051 and 0.0025 which translates to 196.07 days and ~ 400 days of the R Aquarii from 1970-2020. These values might be the effect of the symbiotic system. The presence of two dominant peaks suggests that a double-cycle sinusoidal model, rather than a single sine wave, could be a better fit (Kalae & Hasanzadeh, 2019). The second frequency shows more diverse values ranging from 0.0012 to 3.002 and is similar to the known values in the variety of literature. We can see a recurring pattern with an element of unpredictability that does not lend itself to precise measurement, thus showing a quasi-periodic behavior. Majority of the frequencies and amplitudes in Table 1 corresponds to similar value $\sim 0.0025 day^{-1}$ and ~ 1.6 mmag. Since 1800's, R Aquarii has been a consistent nest for astrophysics studies on light curve analysis, the mentioned values we got are very distinct to the known and established frequency and magnitude of the R Aquarii. On the other hand, we noticed the 196 period to be foreign. We suspect that this might be attributed to the fitting of the spectral data in the Period04 based on the original data. At the same time, the researchers intend to extend this explo-

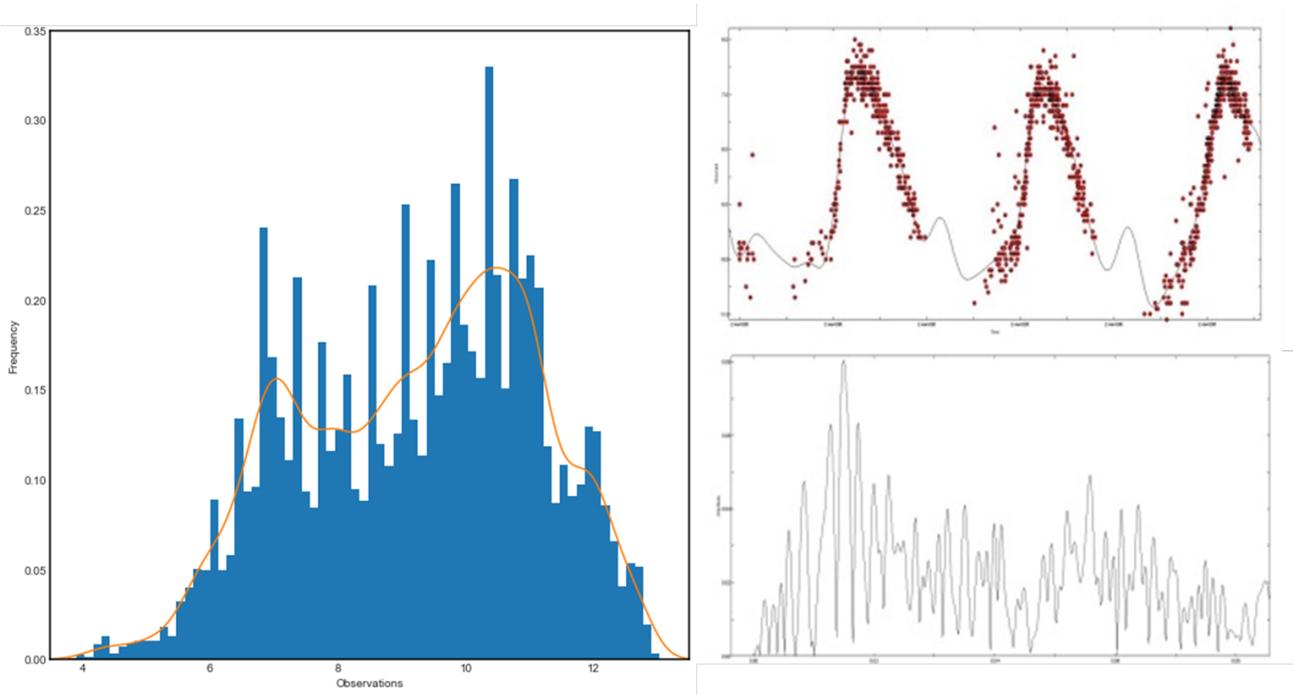


Figure 3 Left panel shows the histogram of observed magnitudes of the R Aquarii, upper right shows the best-fit light curve and its periodogram at the bottom during 1987-1989.

ration on a separate study.

B. Metallicity Analysis

Aside from the drifting materials from the Mira variable to the supposed white dwarf, the R Aquarii binary system sits within a cloud of potential accreting materials. The nebular cloud may affect how we see the R Aquarii especially on exploring its metallicity.

Figure 3 illustrates the thermodynamic conditions present in the core regions of the binary star during its late evolutionary stages. At these high temperatures, the initial composition, which starts as pure ^3He , rapidly shifts in comparison to ^{16}O . The isotopes ^4He and ^{16}O dominate the $Y_e \sim 0.5$ nuclear statistical equilibrium composition between ~ 102 s and 106 s. Because T are constants, only changes in Y_e can affect the abundances. At ~ 102 s, a second period of intense rearrangement begins and ends at ~ 105 s. The spectrum shows strong lines of He, O, Mg, and Ne that were also seen in the study of (Michalitsianos et al., 1980). The identification of ^5N and ^2Si , is doubtful due to the absence of other lower excitation lines of nitrogen, and similarly for silicon, Si II is not found. Several Fe II features in different multiplets have also been identified in the previous studies which are not visible in the simulated data. Carpenter and Wing (1979) discovered “low-excitation lines of Fe II and Mg II in the spectra of single late-type stars, and the presence of the above lines”, along with “O I and Si II in R Aquarii’s UV spectrum”, strongly support a cool chromosphere $T \leq 10,000\text{K}$ for the primary M7 star (Linsky, 2017). As seen from the graph, a series of flat and slight continuums towards higher masses was visible. Furthermore, at a distance of 260 pc, a central ion-

ized cloud with scale size $L = 2 \times 10^{14}$ cm has an electron density of $n_e = 1.5 \times 10^7 \text{cm}^{-3}$, which is sufficient to explain the observed recombination continuum as described by Michalitsianos et al. (1980). The continuum suggests that the density cannot exceed $\sim 10^8 \text{cm}^{-3}$, as this would require the surrounding nebula to be nearly $\sim 5 \times 10^{13}$ cm in size—comparable to the dimensions of red giants, making it physically implausible (Michalitsianos et al., 1980).

C. Thermodynamic Conditions in the Core Regions of R Aquarii During Late Evolutionary Stages

The abundance profiles shown in the figure provide crucial insight into the thermodynamic conditions present in the core regions of R Aquarii’s Mira-type component during its late evolutionary stages. The left panel clearly demonstrates hydrogen depletion in the inner regions (within about $0.35 M_\odot$), a result of earlier core hydrogen burning during the main-sequence phase. The corresponding enrichment of helium isotopes reflects hydrogen fusion via the CNO cycle, which operates efficiently at the elevated core temperatures of asymptotic giant branch (AGB) stars, typically on the order of $10^7 - 10^8$ K (Karakas & Lattanzio, 2014). At these high temperatures, the initial composition, which starts as pure ^4He , rapidly shifts in comparison to ^{16}O . The isotopes ^4He and ^{16}O dominate the $Y_e \approx 0.5$ nuclear statistical equilibrium composition between 10^2 s and 10^6 s. Because temperature remains nearly constant in this regime, only changes in Y_e can significantly affect the abundances. At roughly 10^2 s, a second period of intense rearrangement begins, lasting until about 10^5 s. This transition is consistent with the spectral signatures observed in R Aquarii, which show strong lines of He, O, Mg, and Ne (Michalitsianos et

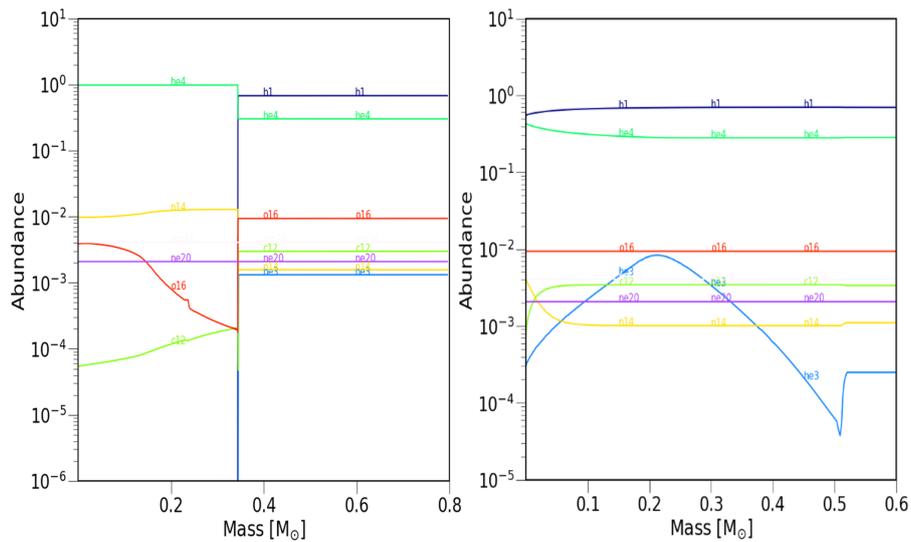


Figure 4 Evolution of the composition inside the binary star. Before weak reactions drive a second period of rearrangement, several orders of magnitude of time pass. A second nuclear statistical equilibrium quiescent period with $Y_e \geq 0.403$ is established within $\sim 10s$.

al., 1982).

The increase in carbon and oxygen isotopes, particularly ^{12}C and ^{16}O , highlights the thermodynamic imprint of the triple-alpha process and subsequent alpha-capture reactions during helium burning. These patterns point to the establishment of a carbon-oxygen degenerate core, a defining characteristic of AGB stellar evolution (Herwig, 2005). The right panel reveals additional details about shell burning and mixing. The bump in carbon and oxygen abundances in the mid-mass regions ($0.2 - 0.4M_{\odot}$) is indicative of dredge-up events, where convective mixing transports nuclear-processed material into higher layers. The persistence of isotopes such as ^{12}C , ^{13}O , and ^{20}Ne , albeit at low abundances, further reflects the role of secondary nucleosynthesis and s-process enrichment in the outer layers (Busso et al., 2001). Meanwhile, spectral studies of R Aquarii indicate features such as Fe II multiplets, Mg II, and O I lines, pointing to the presence of a cool chromosphere ($T \approx 10,000K$) around the primary M7 giant. Notably, Si II and N V lines are weak or absent in both observation and simulation, underscoring uncertainties in the identification of high-excitation species.

As seen in the abundance graphs, a relatively flat continuum toward higher mass coordinates reflects the stratification of lighter elements in the stellar envelope. Furthermore, the observed nebular conditions surrounding R Aquarii are consistent with the thermodynamic and compositional structure implied by these profiles. At a distance of 260 pc, a central ionized cloud with a scale size of $L = 2 \times 10^{14}$ cm has an electron density of $n_e = 1.5 \times 10^{14} cm^{-3}$, sufficient to explain the observed recombination continuum (Michalitsianos et al., 1982). However, the continuum also constrains the density not to exceed $10^8 cm^{-3}$, as this would require a nebular size comparable to the dimensions of a red giant ($\approx 5 \times 10^{13}$ cm), which is physically implausible. For R Aquarii, a symbiotic binary consist-

ing of a Mira-type AGB star and a white dwarf companion, these conditions are critical. The development of a carbon-oxygen core, the presence of extended ionized gas, and the observed chromospheric lines all point to the dynamic mass loss and accretion processes that drive recurrent nova-like outbursts and jet activity in this system (Hollis et al., 1999; Skopal, 2015).

CONCLUSION

The popular R Aquarii symbiotic system, the light curves exhibit a broad minimum lasting 6 to 7 months, followed by a rapid rise to maximum. The average values achieved 0.003 cycle/day and 1.548 for main frequencies and amplitudes, suggesting that the first frequency period had a value of approximately 311.36 days. The second frequency period had a value of approximately 2.51 days. A recurring pattern was noticeable in R Aquarii's amplitude with an element of unpredictability that does not lend itself to precise measurement, thus showing a quasi-periodic behavior. Fourier transform and time series analysis results indicate that external factors, such as R Aquarii being a symbiotic variable star, play a role in the behavior of the light curve and the seasonal variations in amplitude. The eclipses practically brightened the R Aquarii, however, the current eclipse did not posit the same behavior. The coalescence of the clouds shows the evolution of the molecular and isotope clouds as the star ages. The presence of gases such as molecular hydrogen is justifiable due to the position of the binary stars in the nebula. The line profiles for 4He and ^{16}O present similar shapes but vary in magnitude. It implies that they may be in the same structure. The mass loss rate for R Aquarii was estimated to be $\sim 6.3 \times 10^{-7}$ to $\sim 6.5 \times 10^{-7}$ M/yr based on line intensities and chemical composition.

This study of the R Aquarii symbiotic system has con-



tributed to our understanding of binary stars, which is important for studying stellar evolution and powerful jets. Our findings suggest that R Aquarii's varying brightness and quasi-periodic changes are due to both its internal pulsations and external factors within its symbiotic nature, which highlights the need for continuous observation to track its evolving behavior. Initial insights were also gained from the metallicity composition of R Aquarii, along with its role in enriching space with heavy elements, and identified that the surrounding nebula influences its observed composition. The estimated rate at which R Aquarii loses mass provides crucial data for understanding how these systems evolve. Although this research clarifies much about R Aquarii, the study also supports the necessity for more detailed, high-resolution observations to fully grasp the complex movements of R Aquarii's surrounding gas and the prominent jets. Further investigation into whether the primary stellar pulsation is connected to these powerful jets could reveal fundamental aspects of energy transfer in such unique stellar systems.

REFERENCES

- AAVSO. (n.d.). *R aquarii: First and foremost*. Retrieved June 13, 2021, from https://www.aavso.org/vsots_raqr
- AAVSO. (2021). *Alert notice 738: R aquarii monitoring needed in support of chandra and hst observations*. aavso.%20https://www.aavso.org/aavso-alert-notice-738
- Andreoli, C. (2025). *R aquarii (wfc3 image)*. Retrieved September 11, 2025, from <https://science.nasa.gov/asset/hubble/r-aquarii-wfc3-image/#:~:text=R%20Aquari%20i%20belongs%20to%20a,times%20larger%20than%20our%20Sun>.
- Busso, M., Gallino, R., Lambert, D. L., Travaglio, C., & Smith, V. V. (2001). Nucleosynthesis and mixing on the asymptotic giant branch. iii. predicted and observed s-process abundances. *The Astrophysical Journal*, 557(2), 802–821. <https://doi.org/10.1086/322258>
- Carpenter, K. G., & Wing, R. F. (1979). Survey of the ultraviolet spectra of late-type stars [Provided by the SAO/NASA Astrophysics Data System]. *Bulletin of the American Astronomical Society*, 11, 419. <https://ui.adsabs.harvard.edu/abs/1979BAAS..11..419C>
- ESA. (2024). *Hubble captures intricacies of r aquarii*. Retrieved September 11, 2025, from <https://esahubble.org/news/heic2413/>
- Gromadzki, M., & Mikołajewska, J. (2009a). The spectroscopic orbit and the geometry of r aquarii. *Astronomy & Astrophysics*, 495(3), 931–936. <https://doi.org/10.1051/0004-6361/200810052>
- Gromadzki, M., & Mikołajewska, J. (2009b). The spectroscopic orbit and the geometry of r aquarii. *Astronomy & Astrophysics*, 495, 931–936. <https://doi.org/10.1051/0004-6361/200810052>
- Guidry, M. W., Billings, J. J., & Hix, W. R. (2013). Explicit integration of extremely stiff reaction networks: Partial equilibrium methods. *Computational Science & Discovery*, 6(1), 015003. <https://doi.org/10.1088/1749-4699/6/1/015003>
- Hack, M., & Dous, C. L. (2018). *The universe and beyond*. Academic Press.
- Herwig, F. (2005). Evolution of asymptotic giant branch stars. *Annual Review of Astronomy and Astrophysics*, 43(1), 435–479. <https://doi.org/10.1146/annurev.astro.43.072103.150600>
- Hinkle, K., Brittain, S., Fekel, F., Lebzelter, T., & Boogert, A. (2022). The 2020 eclipse of r aquarii in the near-infrared: Mid-eclipse observations of disk distress. *The Astrophysical Journal*, 937, 98. <https://doi.org/10.3847/1538-4357/ac8a47>
- Hix, W. R., & Meyer, B. S. (2006). Thermonuclear kinetics in astrophysics [Special Issue on Nuclear Astrophysics]. *Nuclear Physics A*, 777, 188–207. <https://doi.org/10.1016/j.nuclphysa.2004.10.009>
- Hollis, L., McGeer, J. C., McDonald, D. G., & Wood, C. M. (1999). Cadmium accumulation, gill cd binding, acclimation, and physiological effects during long term sublethal cd exposure in rainbow trout. *Aquatic Toxicology*, 46(2), 101–119. [https://doi.org/10.1016/S0166-445X\(98\)00118-0](https://doi.org/10.1016/S0166-445X(98)00118-0)
- Kalaei, M., & Hasanzadeh, A. (2019). A time series analysis of light curve of r scuti star from 1970 to 2017. *New Astronomy*, 70, 57–63. <https://doi.org/https://doi.org/10.1016/j.newast.2019.02.007>
- Kaplan, D., & Glass, L. (1995). *Understanding nonlinear dynamics*. Springer New York, NY. <https://doi.org/https://doi.org/10.1007/978-1-4612-0823-5>
- Karakas, A. I., & Lattanzio, J. C. (2014). The dawes review 2: Nucleosynthesis and stellar yields of low- and intermediate-mass single stars. *Publications of the Astronomical Society of Australia*, 31, e030. <https://doi.org/10.1017/pasa.2014.21>
- Kastner, J. H., Soker, N., & Rappaport, S. A. (2000). *Asymmetrical planetary nebulae ii: From origins to microstructures: Proceedings of a conference held at massachusetts institute of technology at cambridge, massachusetts, usa, 3–6 august 1999*. Astronomical Society of the Pacific. <https://books.google.com.ph/books?id=QIXvAAAAMAAJ>
- Lenz, P., & Breger, M. (2005). Period04 user guide [Provided by the SAO/NASA Astrophysics Data System]. *Communications in Asteroseismology*, 146, 53–136. <https://doi.org/10.1553/cia146s53>
- Liimets, T., Corradi, R. L. M., Jones, D., Kolka, I., Santander-García, M., & Sidonio, M. (2020). Nebulosity of the symbiotic binary r aquarii: A short review. <https://arxiv.org/abs/2003.10753>
- Liimets, T., Corradi, R. L. M., Jones, D., Verro, K., Santander-García, M., Kolka, I., Sidonio, M., Kankare, E., Kankare, J., Pursimo, T., & Wilson, P. A. (2018). New insights into the outflows from r



- aquarii. *A&A*, 612, A118. <https://doi.org/10.1051/0004-6361/201732073>
- Linsky, J. L. (2017). Stellar model chromospheres and spectroscopic diagnostics. *Annual Review of Astronomy and Astrophysics*, 55(1), 159–211. <https://doi.org/10.1146/annurev-astro-091916-055327>
- Longland, R., Martin, D., & José, J. (2014). Performance improvements for nuclear reaction network integration. *Astronomy & Astrophysics*, 563, A67. <https://doi.org/10.1051/0004-6361/201321958>
- Merc, J. (2025). Symbiotic stars in the era of modern ground- and space-based surveys. *Galaxies*, 13(3). <https://doi.org/10.3390/galaxies13030049>
- Meyer, B. S., Krishnan, T. D., & Clayton, D. D. (1998). Theory of quasi-equilibrium nucleosynthesis and applications to matter expanding from high temperature and density. *The Astrophysical Journal*, 498(2), 808–817. <https://doi.org/10.1086/305562>
- Michalitsianos, A. G., Kafatos, M., Feibelman, W. A., & Hobbs, R. W. (1982). Ultraviolet observations of four symbiotic stars [Provided by the SAO/NASA Astrophysics Data System]. *The Astrophysical Journal*, 253, 735–744. <https://doi.org/10.1086/159674>
- Michalitsianos, A. G., Kafatos, M., & Hobbs, R. W. (1980). Iue observations of circumstellar emission from the late type variable r aqr (m7+pec) [Provided by the SAO/NASA Astrophysics Data System]. *The Astrophysical Journal*, 237, 506–512. <https://doi.org/10.1086/157895>
- Mikołajewska, J., Gromadzki, M., & Hinkle, K. H. (2005). Abundance analysis of symbiotic stars. *Proceedings of the International Astronomical Union*, 1(S232), 278–280. <https://doi.org/10.1017/S1743921306000718>
- Mikołajewska, J. (2007). Symbiotic stars: Continually embarrassing binaries [Provided by the SAO/NASA Astrophysics Data System]. *Baltic Astronomy*, 16, 1–9. <https://ui.adsabs.harvard.edu/abs/2007BaltA..16....1M>
- Paxton, B., Bildsten, L., Dotter, A., Herwig, F., Lesaffre, P., & Timmes, F. (2011). Modules for experiments in stellar astrophysics (mesa). *The Astrophysical Journal Supplement Series*, 192(1), 3. <https://doi.org/10.1088/0067-0049/192/1/3>
- Paxton, B., Marchant, P., Schwab, J., Bauer, E. B., Bildsten, L., Cantiello, M., Dessart, L., Farmer, R., Hu, H., Langer, N., Townsend, R. H. D., Townsley, D. M., & Timmes, F. X. (2015). Modules for experiments in stellar astrophysics (mesa): Binaries, pulsations, and explosions. *The Astrophysical Journal Supplement Series*, 220(1), 15. <https://doi.org/10.1088/0067-0049/220/1/15>
- Perko, M. (2021). Symbiotic binaries. *Matrika*, 8(2), 1–12. <https://matrika.fmf.uni-lj.si/letnik-8/stevilka-2/perko.pdf>
- SAO. (2023). *R aquarii animations*. Retrieved September 11, 2025, from <https://chandra.harvard.edu/photo/2017/raqr/animations.html>
- Skopal, A. (2015). Multiwavelength modelling the sed of supersoft x-ray sources i. the method and examples. *New Astronomy*, 36, 116–127. <https://doi.org/10.1016/j.newast.2013.10.009>
- TheImagineTeamNASA. (2013). *Light curves and what they can tell us*. Retrieved June 13, 2021, from <https://imagine.gsfc.nasa.gov/science/toolbox/timing1.html>
- Toalá, J. A., Sabin, L., Guerrero, M. A., Ramos-Larios, G., & Chu, Y.-H. (2022). An xmm-newton epic x-ray view of the symbiotic star r aquarii. *The Astrophysical Journal Letters*, 927(1), L20. <https://doi.org/10.3847/2041-8213/ac589d>
- Tucio, P. B., Deocaris, C., & Kouwenhoven, M. B. N. (2025). Orbital evolution of r aquarii [Publisher Copyright: © 2025, Philippine-American Academy of Science and Engineering. All rights reserved.]. *SciEnggJ*, 18, 196–201. <https://doi.org/10.54645/202518SUPRMV-19>
- Vasquez-Torres, D. A., Toalá, J. A., Sacchi, A., Guerrero, M. A., Tejada, E., Karovska, M., & Montez, J., R. (2024). The impact of periastron passage on the x-ray and optical properties of the symbiotic system r aquarii. *Monthly Notices of the Royal Astronomical Society*, 535(3), 2724–2741. <https://doi.org/10.1093/mnras/stae2538>