Orbital evolution of R Aquarii

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ABSTRACT

The orbital evolution of R Aquarii was analyzed and investigated using archival photometric data from the American Association of Variable Star Observers (AAVSO). The selected photometric data from 1840 to 2021 to determine the evolution of R Aquarii in a period of 181 years. The use of the Lomb-Scargle periodogram to derive the physical parameters, periodicity, and phase-folding of the R Aquarii star. The N-body simulations, such as Rebound and ReboundX, were used to determine the orbital parameters of the star. The parameters generated from Lomb-Scargle, Rebound, and ReboundX were then simulated using the Modules for Experiments in Stellar Astrophysics (MESA). MESA was also used to determine the mass loss rate of R Aquarii. The decrease in the orbital parameters such as semi-major axis and eccentricity suggests that the orbital period gets smaller as the rotation of the binary gets faster. In addition, the evolutionary path of the binary for the semi-major axis and eccentricity coincides with the binary's mass transfer rate. After the simulation, the mass of the long-period variable is 0.9MΘ while the mass of the companion star is 0.63MΘ as calculated and derived using MESA. The result is consistent with the calculated 44-year period for a binary system.

INTRODUCTION

Many aspects of research on stellar astrophysics rely on optical and orbital monitoring. It is one of the most ancient tools for determining the properties and evolution of astrophysical systems. Long-term light curves can reveal outburst systems, allowing observations from ground and satellite telescopes to determine the fraction of symbiotic stars that have outbursts as well as outburst statistics such as average outburst frequencies and durations (Sokoloski & Kenyon, 2003). There are numerous studies have been conducted to solve and uncover mysteries concerning objects in space, particularly star formation, and evolution (Rubin & Ford, 1970). Several types of stars, including the symbiotic star R Aquarii, are being studied. Its orbital period ranges from a few hundred to thousands of days (Corradi, 2012). White dwarf masses are typically around 0.6 solar mass, as described in a (Gromadzki, M., & Mikołajewska, J. 2009, 2013) study. There are more massive white dwarfs with masses close to the Chandrasekhar Mass limit which are known to exist in symbiotic systems with recurrent nova outbursts or hard X-ray emission (Luna & Sokoloski 2007).

Over 150 objects in our galaxy have symbiotic binary systems. In the optical spectrum of M giant's companion star, (Kenyon, 1986) suspected a faint O or B-type star. According to (Kenyon, 1992), most symbiotic stars are close to the galactic plane, and their scale height and velocity dispersion indicates that they are from the intermediate or old disc population. Astronomers developed single-star models after failing to detect orbital motion in a symbiotic star system (Kondo et al., 1992). Amateur optical monitoring can detect outburst systems and help build a large database of outbursts and quiescent symbiotic light curves. Long-term optical light curves combined with radio and X-ray observations will improve understanding of symbiotic outbursts, jet production, and the relationship between outbursts, jets, and accretion disks in symbiotic stars when new outbursts are discovered (Sokoloski and Kenyon, 2003). To understand the role of interacting binaries with evolved giants in the formation of stellar jets, planetary nebulae, novae, super-soft X- ray sources, and Type Ia supernovae, symbiotic stars must be linked to other families of interacting binaries with evolved giants. Many of these are unresolved issues concerning the late stages of stellar evolution, but they have significant implications for

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Date received: 28 May 2024
Date revised: 06 June 2025
Date accepted: 15 June 2025
DOI: https://doi.org/10.54645/202518SupRMV-19

KEYWORDS

Variable star, R Aquarii, Modules for Experiments in Stellar Astrophysics (MESA), Lomb-Scargle

our understanding of stellar populations, galaxies' chemical evolution, and the extragalactic distance scale.

R Aquarii is a symbiotic system with signatures of both very hot and very cool material when viewed in the visual spectrum; when viewed in the infrared spectrum, the system may be classified as a dusty-type symbiotic binary. Mira variables are a subset of dusty symbiotic systems. These binaries are either systems in which one star's outer envelope has expanded, and it is rapidly losing mass to its companion, or systems in which one star loses its outer layer gradually and the companion sweeps up the material. A hot star is ionizing the gas as a companion. The R Aquarii system is most likely explained by the Mira having a white dwarf companion, with the unusual time variability caused by the two stars' interaction (Whitelock et al., 2003). Symbiotic stars, such as R Aquarii, are useful tracers of late phases of stellar evolution in low- and intermediate-mass stars, as well as a great laboratory for studying many aspects of interactions and evolution in binary systems due to their complex structure (Corradi, et al., 2003). Despite significant progress in obtaining the physical parameters of symbiotic stars such as orbital parameters (inclination, semi-major axis, eccentricity), radii, and mass-loss rates (Mikolajewska, 2011), critical questions about their interactions and evolution remain unanswered. The observations of the system have not yielded consistent orbital parameter values as described in the study of McIntosh and Rustan (2007). McIntosh and Rustan (2007) calculated an eccentric orbit with a period of 34.6 years and an eccentricity of e = 0.52. Their orbital period is significantly shorter than the previous estimates or the period calculated in this study. The other is reasonably accurate if they interpret the system mass as 0.043 M and their system semi-major axis, 3.7 AU, as the Mira component's orbit's semi-major axis. Symbiotic stars, such as R Aquarii, are useful tracers of late phases of stellar evolution in low- and intermediate-mass stars, as well as a great laboratory for studying many aspects of interactions and evolution in binary systems due to their complex structure (Corradi et al., 2003). The mechanism of mass transfer via stellar wind or Roche lobe overflow (RLOF), as well as the possibility of accretion disk formation, is one of the most fundamental questions concerning S-type symbiotic stars. As a result, many fundamental and intriguing questions remain unanswered. There are inconsistent values in determining the orbital parameters of R Aquarii.

In this paper, the primary objectives are clearly defined: (1) to simulate the orbital parameters of the variable star R Aquarii using long-term photometric data, (2) to explore how these parameters evolve due to mass transfer. This simulation to better understand the behavior of the variable star and the critical concerns surrounding their interactions and evolution that remain unanswered.

MATERIALS AND METHODS

1.1 ***Data***

In this study, observational optical data from 1840-2021 were acquired from the American Association of Variable Star Observers (AAVSO) (https://www.aavso.org/) database. The database is considered the largest organization of variable star observers in the world (Hinkle et al., 2002).

2.2 Data Processing

Lomb–Scargle periodogram is a method for efficiently computing a Fourier-like power spectrum estimator from such unevenly sampled data, resulting in an intuitive method for determining the period of oscillation; it is also a least-squares method. It is derived from the principles of Bayesian probability theory and has been shown to be closely related to bin-based phase-folding techniques in some cases (VanderPlas, 2018). Scargle (1982) addressed this issue by examining a generalized form of the periodogram.

$$P(f) = \frac{A^2}{2}\left(\Sigma_n g_n cos(2\pi f[t_n - \tau])\right)^2 + \frac{B^2}{2}\left(\Sigma_n g_n sin(2\pi f[t_n - \tau])\right)^2 \qquad \text{Eq. 1}$$

where A, B, and Tau (τ) are arbitrary functions off and the observing time's (t) (but not the values {gn}). The values of A and B leading to these properties result in the following form of the generalized periodogram:

$$P_{LS}(f) = \frac{1^2}{2}\left\{\left(\Sigma_n g_n cos(2\pi f[t_n - \tau])\right)^2 / \Sigma_n g_n cos^2(2\pi f[t_n - \tau]) + \left(\Sigma_n g_n sin(2\pi f[t_n - \tau])\right)^2 / \Sigma_n g_n sin^2(2\pi f[t_n - \tau])\right\} \qquad \text{Eq. 2}$$

where τ is specified for each f to ensure time-shift invariance:

$$\tau = \frac{1}{4\pi r} tan^{-1}(\frac{\Sigma_n sin(4\pi f t_n)}{\Sigma_n cos(4\pi f t_n)} \qquad \text{Eq. 3}$$

This modified periodogram differs from the classical periodogram only to the extent that the denominator differs from N/2, which is the expected value of each of these quantities within the limit of complete phase sampling at each frequency. Rebound, ReboundX and Modules for Experiments in Stellar Astrophysics (MESA). Rebound and ReboundX were installed on the Anaconda platform (https://rebound.readthedocs.io/en/latest/). This is an *N*- body integrator developed by Tamayo et al., (2019) and the main program is to simulate the evolution of the R Aquarii binary system in different time intervals to evaluate its behavior during mass transfer. REBOUND is free software distributed under the terms of the Free Software Foundation's GNU General Public License, Version 3 or later. REBOUND is maintained by Professor Hanno Rein (https://rein.utsc.utoronto.ca/) (Rein, H., & Choksi, N. (2022). To determine the relationship of its stellar parameters, the Researcher used Modules for Experiments in Stellar Astrophysics (MESA). Parameters that were produced from the Lomb-Scargle and REBOUND, REBOUDX will be simulated (Tamayo et al., 2019). It is a collection of robust, efficient, and thread-safe open source libraries for a wide range of computational stellar astrophysics applications (Paxton et al., 2010, 2015).

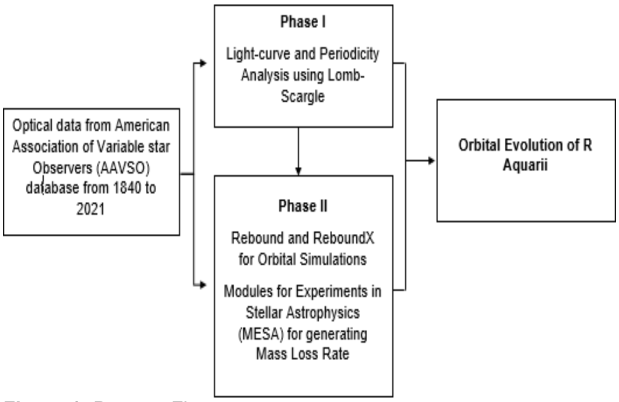

Figure 1: Process Flow

This figure demonstrates the processing of the study. There are two phases to the study. Simulations of the input data's behavior over the specified period are performed using the optical data from the AAVSO database spanning the years 1840 to 2021. To provide preliminary data for the second process, the Phase I simulation process attempted to replicate the system's behavior and variation as well as orbital dynamics. Phase II will use of the procedure will model how the parameters generated and calculated from the Lomb-Scargle analysis (Phase I) evolve. It centers on the potential development of the R Aquarii binary system. The outcomes of the Phase 1 numerical simulation were further supported by the Phase 2 results.

RESULTS AND DISCUSSION

The 181-year dataset enables robust analysis, and the results are supported by graphical representations, including period vs. eccentricity plots and variations in brightness over time. Figure 4, in particular, illustrates how orbital changes correlate with mass transfer events. Uncertainties and potential modelling errors are also discussed. However, due to the discrepancy in the data, the researcher started the plot in 1912. Figure 2 shows the variations of R Aquarii from 1912 to 1940. The period between 1929 to 1935 was quite active; the light of R Aquarii is modulated, which shows these phases of eclipse appeared during the said years. It shows the variations of R Aquarii from 1940 to 1980. Generated light curve using the Lomb-Scargle periodogram shows eclipses appeared in the years 1974 to 1980, as agrees with the earlier proposed by (Wilson 1994) indicating a 44-year period and this eclipse was generated or enhanced by increased mass transfer in the system. However, this would not agree with the study (McIntosh & Rustan, 2007) generated a 34.6-year period and it is also inconsistent with the 17-year orbital period for R Aquarii proposed by Nichols et al., (2010). Moreover, (Merrill, 1950) also proposed a 27-year period based on radial velocity measurements but it was not supported in the study of Wilson et al., (1994) which calculated a 44-year period. The duration of the eclipses is about eight years and occurs at 44-year intervals with the most recent episode occurring between 1974 and 1983.

It shows on the results of the light curve that the recent eclipse happened in the year 2018 and lasted until 2026 as projected in the previous findings.

Figure 3 shows the periodicity and phase-folding of R Aquarii. Based on the simulation derived, it shows the period to be Porb = 386.74d corresponding to the pulsation period of the Mira component supported by the analysis of (McIntosh & Rustan, 2007). The figure displays the phase folding of the 181 years of observations as seen from it the red line corresponds to the sine model of the observed structure of the binary. Furthermore, ellipsoidal light curve variations are clearly observed in many S-type systems with Porb less than 1000d in the study (Mikolajewska 2012). Only systems with a relatively high inclination can detect these changes, and they usually appear only in red and near-infrared light, where the red giant dominates. Most symbiotic stars, on the other hand, only have visual light curves. This is especially true in active Z And-like systems and inactive systems with highly luminous hot components, such as SY Mus, which predominate among S-type symbiotics with shorter periods. Understanding this star may also aid in the resolution of one of modern astrophysics' most pressing problems: the missing progenitors of SNe Ia. They are thought to be caused by thermonuclear disruption of a CO white dwarf reaching the Chandrasekhar mass, either through mass accretion from a non-degenerated companion or mass transfer between and/or merger of two white dwarfs.

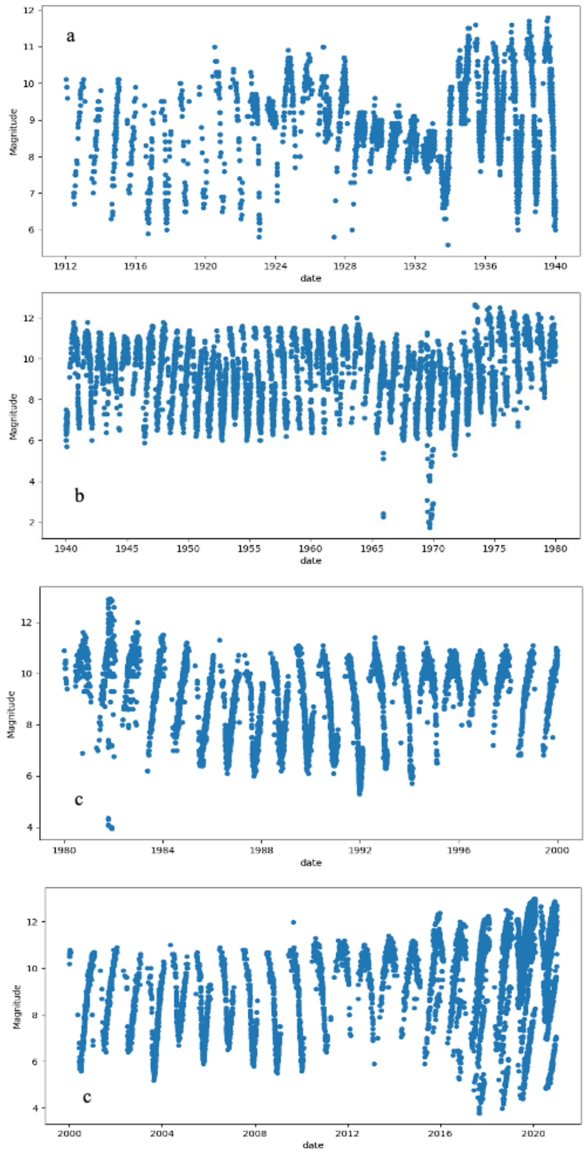

Figure 2: Light curve Analysis of R Aquarii Based on 1912 to 1940 Observations. (a) Light curve from 1912 to 1940, (b) Light curve from 1940 to 1980, (c) Light curve from 1980 to 2000, (d) Light curve from 2000 to 2021

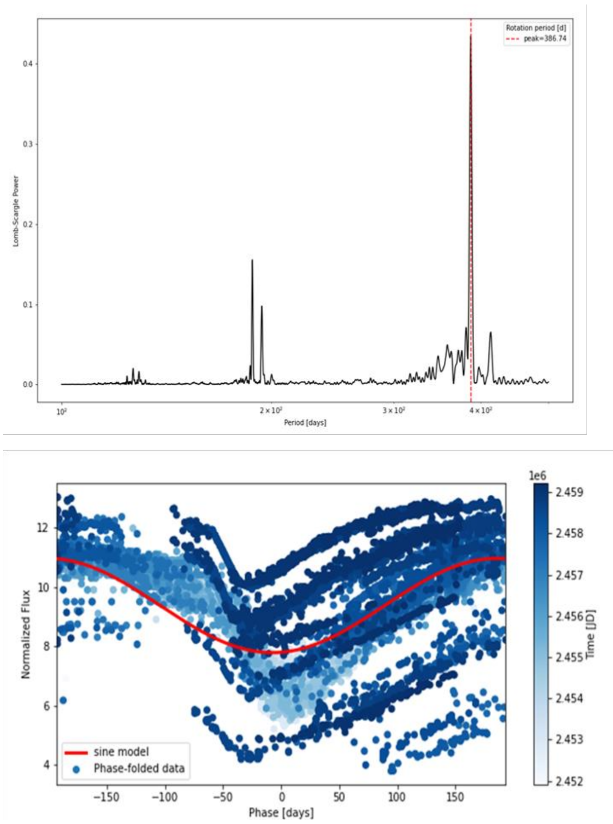

Figure 3: Periodicity of R Aquarii (top), Phase-Folding of R Aquarii (bottom)

Table 1: Generated Orbital Elements for R Aquarii

Element	Derived Value	McIntosh & Rustan (2007)
a sin i	4.8 ± 0.6 AU	3.5± 0.4 AU
Eccentricity	0.52 ± 0.08	0.52 ± 0.08
Inclination (deg)	72	70
Orbital Period (yr)	44	34.6
Mass	2.5MΘ	2.5MΘ

Note: the first column denotes the physical parameters, the second column is the value, and the third column is the value derived by the previous researcher.

Table 2: Values of Orbital Parameters after the Simulation

	Derived Values	Evolution of Parameters After 1 Billion Years
a sin i	4.8 ± 0.6 AU	1.0 AU
Eccentricity	0.52 ± 0.08	0.2
Inclination(deg)	72	72

Table 1 shows the derived and initial results produced by the simulation. Several models and parameters have been derived previously to explain the appearance of R Aquarii. These findings represent a significant advancement over previous work by incorporating modern computational tools like MESA and REBOUND, and extending the analysis to billion-year timescales, an approach not used in earlier studies made by McIntosh and Rustan (2007) and Solf and Ulrich (1985). According to Kafatos and Michalitsianos (1982), the binary has a highly eccentric (0.84 ± 0.92) orbit with 44 years as compared to the derived values. The derived eccentricity is the same as that reported in the study by McIntosh and Rustan (2007). These values indicate an overflow of the Roche lobe at periastron and a significant impact on the system's mass transport. The mass of the long-period variable is 1.5MΘ, the companion star's mass is approximately 1.0MΘ, and the inclination angle is large (Solf & Ulrich 1985). Their orbital period was much shorter than the previous estimates as well as the period calculated in the current study. The study was reasonably accurate if we interpret their system mass as 0.9MΘ, and 0.63MΘ. At the moment, no proposed model for the system is strongly supported by solid observational evidence. The suggestion that R Aquarii is an eclipsing system in which the long-period variable (LPV) is partially obscured every 44 years may be an important step in understanding it. The evolution of the binary system from the semi-major axis and eccentricity coincides with the mass transfer rate of the binary as shown in table 2. The sudden peak in the mass transfer rate can be due to the jet formation and dynamics of the nebulosities around the system which needs to be addressed in future studies. As stated, from the initial eccentricity value of .52 ± 0.08, it falls to 0.2 after a billion years of simulation, the same behavior as the semimajor axis from the initial value of 4.8 ± 0.6, the value after 1 billion years of simulation is 1.0 It means that the orbital period gets smaller as the rotation of the binary gets faster. Using the initial and derived values as seen in the figures, the semi-major axis and eccentricity of the binary are proportional. From the initial value of eccentricity of 0.52 ± 0.08, it goes down to 0.2 after 1 billion years of simulation same behavior as the semi-major axis from the initial value of 4.8 ± 0.6, the value after 1 billion years of simulation is 1.0. It means that the orbital period gets smaller as the rotation of the binary gets faster.

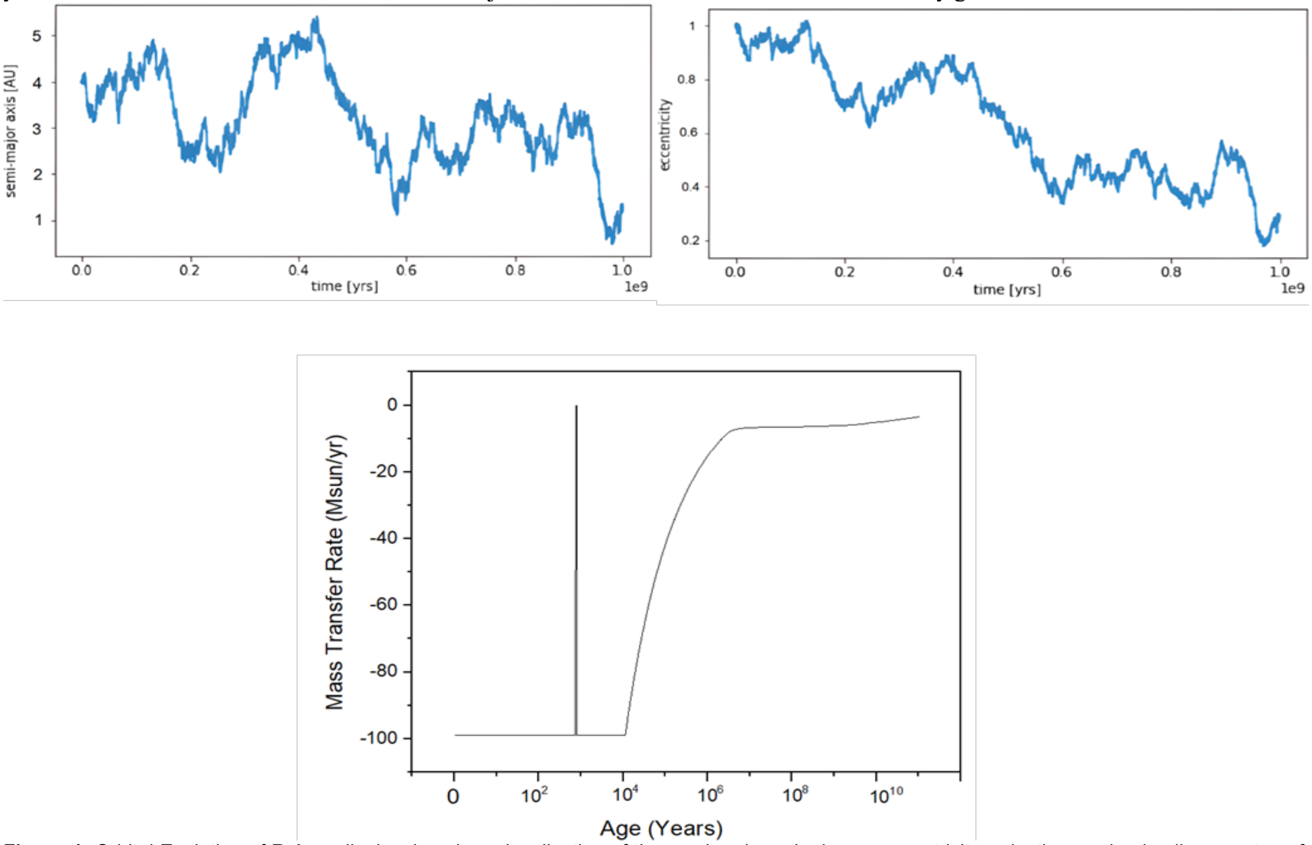

Figure 4: Orbital Evolution of R Aquarii, showing clear visualization of the semi-major axis decay, eccentricity reduction, and episodic mass transfer rates. These visuals are critical in understanding the interplay between mass exchange and orbital reshaping. Semi-major Axis (left), Eccentricity (right), Mass Transfer Rate of the Binary(bottom)

The evolutionary path of the binary from the semi-major axis and eccentricity coincides with the binary's mass transfer rate. When the star is close enough, the Roche lobe overflow (RLOF) occurs, and the Mira transforms into an elongated sphere, beginning to transfer mass to its hot companion. The transferred material forms a disk around the companion and begins to pile on top of it. Since R Aquarii is surrounded by an hourglass shape nebula. This nebula is thought to have been formed by two novae eruptions discovered by Yang et al., (2005) and found this novae eruption in Korean astronomy records. The above figure depicts a sudden peak caused by an unexpected burst of stars as observed by Yang et al. (2005). The outer nebula, on the other hand, is thought to have formed in AD 1073 and 1074 based on the outburst record. The indications of these outbursts have been discovered in Antarctic ice samples in the form of particles created as a result of the novae (Tanabe & Motizuki, 2012). According to the study, another factor influencing the transfer rate is the formation of the Jet in the system (Kafatos & Michalitsianos, 1982). Yang et al., (2005) predicted that the eruption would last 500 years.

CONCLUSION

The researcher obtained an orbital period of 44 years, supporting the idea of a highly evolved binary system. These results contribute to our understanding of binary evolution, particularly in systems involving a Mira variable and a white dwarf. This study helps contextualize R Aquarii within broader frameworks of symbiotic stars, nova progenitors, and jet-producing binaries. and demonstrated that the mass function is consistent with the presence of a typical 1.5MΘ Mira variable accompanied by a 0.6–1.0MΘ white dwarf. A variety of physical factors can cause variations in the system's measurement. The observed data supported the calculated 44-year period based on photometric data. To improve the credibility of the orbital element results, the study acknowledges technical limitations, including data resolution and modeling assumptions. Future research directions include acquiring higher-resolution spectroscopic data and incorporating 3D hydrodynamic models to simulate jet formation more accurately., continued monitoring in various spectral ranges will be required. Furthermore, more observations of R Aquarii in different wavelengths over extended periods of time, as well as concurrent coverage at X-ray and optical wavelengths, would aid in understanding the star's complex physical processes.

ACKNOWLEDGMENTS

The AAVSO (American Association of Variable Star Observers), for providing the archival data needed by the Researcher.

CONFLICT OF INTEREST

The authors declare that there is no conflict of interest.

CONTRIBUTIONS OF INDIVIDUAL AUTHORS

Princess B. Tucio: Conceptualization, Methodology, Code Implementation, Drafting and editing of the manuscript. Custer Deocaris, Ph.D, and M.B.N. Kouwenhoven, Ph.D: Guidance and Supervision, editing of the manuscript.

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