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WDJ220838.73+454434.04: a White Dwarf Companion in the AR Lacertae System

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Published June 2022 • © 2022. The Author(s). Published by the American Astronomical Society.

Research Notes of the AAS, Volume 6, Number 6

Citation Thomas P. Bickle *et al* 2022 *Res. Notes AAS* **6** 127

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1. Received May 2022
2. Accepted June 2022
3. Published June 2022

https://doi.org/10.3847/2515-5172/ac780a

Binary stars; Eclipsing binary stars; White dwarf stars

Abstract

We present WDJ220838.73+454434.04 (hereafter WD2208+454), a wide, co-moving white dwarf companion to the eclipsing binary system, AR Lacertae. The companion was discovered through the Backyard Worlds: Planet 9 citizen science collaboration. It has a separation of 21.″9 on the sky from the central eclipsing pair, translating to a projected separation of ~930 au. We present a review of the physical properties and orbital parameters of this new addition to the system.

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1. Introduction

The Backyard Worlds: Planet 9 (BYW; Kuchner et al. 2017) citizen science project engages the public to inspect images from the Wide-field Infrared Survey Explorer mission (WISE; Wright et al. 2010) in search of objects with significant proper motion. The project focuses on finding nearby brown dwarfs, with a broader goal of searching for the hypothetical Planet Nine (Trujillo & Sheppard 2014; Batygin & Brown 2016). Here we present an addition to the growing list of discoveries made by citizen scientists through the BYW collaboration, with the discovery of a wide white dwarf companion to the AR Lacertae eclipsing binary system.

AR Lacertae (AR Lac) is a well studied RS Canum Venaticorum-type (RS CVn) binary system at a distance of 42 pc. It was first discovered as a new variable star in Pickering (1907), though it was not until Jacchia (1930) that its nature as an eclipsing binary was uncovered. The system consists of G2IV+K0IV components of masses 1.23 $M_{\odot}$ and 1.27 $M_{\odot}$ respectively (Popper 1990). Since its discovery, a number of spectroscopic and photometric studies have been carried out on the system, many of which were collated and summarized in Lu et al. (2012).

2. Discovery of WD2208+454

In an effort to discover previously unnoticed white dwarf companions to nearby stars, we cross-matched Gentile Fusillo et al. (2021)'s catalog of Gaia EDR3 white dwarf candidates with the Gaia Catalogue of Nearby Stars (GCNS; Gaia Collaboration et al. 2021b), looking for results with similar Gaia (Gaia Collaboration et al. 2021a) parallaxes and proper motions. Through this search, WD2208+454 was identified as a possible companion to AR Lac. The members of the central eclipsing pair of the AR Lac system are not individually resolved by Gaia, and have only a single source in the EDR3 catalog. The decl. proper motion values from

Gaia EDR3 differ between the central pair and the white dwarf, though this is likely not a concern as an unresolved binary may be expected to have anomalous motion as the two components orbit their common barycenter, due to the so-called "proper motion anomaly" (Kervella et al. 2022). On a Gaia G, $G_{BP}-G_{RP}$ color–magnitude diagram, WD2208+454 sits on the $\log g = 8$ cooling track, so is consistent with being a single object.

To determine the probability that the central pair and the new companion are gravitationally bound, we ran them through CoMover (Gagné et al. 2021), which uses the BANYAN Σ (Gagné et al. 2018) software's engine to calculate the probability that two stars are co-moving using Bayesian statistics, when provided with the sky position, proper motion, and optionally parallax and heliocentric radial velocity of both components, with respective measurement errors. This yielded a co-moving probability of 100% (with the field having log(P) of –14.7, where P is probability).

Table 1. Properties of AR Lac System

Parameter	Central Pair	WD2208+454	References
Mass ($M_\odot$)	M_1: 1.23±0.05	$0.6^{+0.04}_{-0.09}$	1,2
	M_2: 1.27±0.05		1
Radius ($R_\odot$)	R_1: 1.52±0.04	$0.0125^{+0.0014}_{-0.0012}$	1,4
	R_2: 2.72±0.10		1
R.A. (degrees)	332.16974273562	332.16105304467	3
decl. (degrees)	45.74246076572	45.74303440308	3
ϖ (mas)	23.5246±0.0228	23.5967±0.0529	3
μ_α (mas yr^{-1})	–52.310±0.021	–52.851±0.062	3
μ_δ (mas yr^{-1})	46.931±0.020	55.138±0.047	3
G_{BP} (mag)	6.296±0.007	16.773±0.013	3
G (mag)	5.911±0.004	16.606±0.003	3
G_{RP} (mag)	5.335±0.006	16.252±0.012	3

References. (1) Popper (1990) (2) Gentile Fusillo et al. (2021) (3) Gaia EDR3 (Gaia Collaboration et al. 2021a) (4) This work

The pure-H (DA) atmospheric model of Gentile Fusillo et al. (2021) estimates that if WD2208+454 has a hydrogen-dominated atmosphere then $T_{\rm eff}$=7022±160K, log g=8.02±0.06, and M=0.6±0.04 $M_{\odot}$. The values are slightly lower for the pure-He (DB) model atmosphere, with $T_{\rm eff}$=6897±160K, log g=7.96±0.07, and M=0.55±0.04 $M_{\odot}$. Taking Gentile Fusillo et al. (2021)'s DA model values for log g and mass, we determine the radius of the white dwarf is $0.0125^{+0.0014}_{-0.0012}$ $R_{\odot}$. Follow-up spectroscopy would help to constrain the atmospheric composition of this companion and narrow down these values.

We used wdwarfdate (Kiman et al., submitted) which, when given inputs of effective temperature and surface gravity with respective errors, combines the MIST isochrones (Choi et al. 2016; Dotter 2016) with the Cummings et al. (2019) initial mass-final mass relation and the Bédard et al. (2020) cooling models, to estimate the cooling age, total age and initial mass of WD2208+454. We assumed [Fe/H]=0 and *v/vcrit*=0, where *v*/vcrit is the initial rotation rate as a percentage of critical, or break up, velocity. Assuming the white dwarf is a DA, the cooling age is $1.62^{+0.17}_{-0.14}$ Gyr, the total age is $5.75^{+4.97}_{-2.38}$ Gyr and the initial mass was $1.34^{+0.46}_{-0.27}$ $M_{\odot}$.

Considering the masses of the central pair, it seems unlikely the white dwarf progenitor could have evolved ~1.6Gyr before them if it is at the lower end of our initial mass estimates. The MIST isochrones at solar metallicity suggest a star with initial mass of 1.8 $M_{\odot}$ would evolve off the main sequence within this time frame making it likely the progenitor was at the higher mass end of our estimate.

Using the Gaia EDR3 parallax and angular separation (21.″9), we calculate the projected separation of the white dwarf from the central pair to be ~930 au. Assuming a circular, face-on orbit and taking the mass of the central pair at 2.5 $M_{\odot}$, we estimate an orbital period of ~16,000 yr for the white dwarf.

3. Conclusion

We have presented the discovery of a white dwarf companion to the eclipsing binary system, AR Lacertae. The companion has a projected orbital separation of ~930 au with a period of ~16,000 yr. Assuming it is a DA, it has a cooling age of $1.62^{+0.17}_{-0.14}$ Gyr and a total age of $5.75^{+4.97}_{-2.38}$ Gyr. We determine a co-moving probability between this object and the central eclipsing pair of 100%. With this discovery, AR Lacertae is now a triple system.

The Backyard Worlds: Planet 9 team would like to thank the many Zooniverse volunteers who have participated in this project. We would also like to thank the Zooniverse web development team for their work creating and maintaining the Zooniverse platform and the Project Builder tools. This material is supported by the National Science Foundation under grant Nos. 2007068, 2009136, and 2009177. This work has made use of data from the European Space Agency (ESA) mission Gaia (https://www.cosmos.esa.int/gaia), processed by the Gaia Data Processing and Analysis Consortium (DPAC, https://www.cosmos.esa.int/web/gaia/dpac/consortium). Funding for the DPAC has been provided by national institutions, in particular the institutions participating in the Gaia Multilateral Agreement. This publication makes use of data products from the Wide-field Infrared Survey Explorer, (WISE) which is a joint project of the University of California, Los Angeles, and the Jet Propulsion Laboratory/ California Institute of Technology, funded by the National Aeronautics and Space Administration.

Software: CoMover (Gagné et al. 2021); WiseView (Caselden et al. 2018); wdwarfdate (Kiman et al. submitted)
