204. The unique AM CVn Gaia14aae

THE AM CVn-type binary Gaia14aae was discovered as Gaia's fifth 'science alert', soon after the alert system went live in 2014 (Hodgkin et al., 2021; and essay 202).

This `specific event` (which, as for all Gaia science alerts, includes the Gaia light curve as well as the low-resolution multi-epoch B_P/R_P spectra) was announced on 2014-08-11, as it brightened, at $G = 16.04$ mag (compared with its historic magnitude, $G = 17.56 \pm 0.20$ mag).

Follow-up spectroscopy at WHT (Rixon et al., 2014), identified it as a H-deficient `AM CVn-type binary`, with double-peaked emission lines, consistent with a compact accreting double-degenerate binary system.

THE AM CVn systems are a rare class of very compact interacting binaries ($P_{\rm orb} \simeq 10-65$ min), comprising a white dwarf accreting He-rich material from a low-mass companion (Nelemans, 2005; Solheim, 2010). They are distinguished from other cataclysmic variables (binaries with significant, irregular brightness increases) by the absence of H in their spectra. Only ~60 have been identified since discovery of the prototype, AM CVn (HZ 29), more than 50 years ago (Smak, 1967).

Ordered by orbital period (e.g. Kotko et al., 2012), AM CVn systems with $P < 12$ min have no accretion disk and show direct impact of the accreting material onto the white dwarf; those with $P = 12-20$ min form a large stable accretion disk, permanently in outburst; those with $P = 20-40$ min have occasional outbursts; and those with $P > 40$ min form small stable accretion disks. The ultra-short periods indicate that both donor and accretor must be degenerate or semi-degenerate objects.

AM CVn systems contribute to the understanding of what is called 'common-envelope evolution' (CEE). In this short-lived evolutionary phase for a wide range of binary stars, the two components orbit inside a single, shared envelope. CEE occupies a possible end point for binary white dwarf evolution, and affects the progenitors of Type Ia supernovae, X-ray binaries and double neutron stars. The systems are also potentially strong sources of gravitational wave emission due to their very compact orbits (Paczyński, 1967 Nelemans, 2003).

IN THEIR EXTENSIVE REVIEW, Ivanova et al. (2013) described common-envelope evolution as *'one of the most important unsolved problems in stellar evolution, and arguably the most significant and least-well-constrained major process in binary evolution.'*

Common-envelope evolution plays a key role in the evolution of many binary systems, and with various outcomes. For example (see Ivanova et al., 2013, Fig. 1, for an informative schematic), SN Ia progenitors can result from double-degenerate mergers, or accretion on a CO white dwarf from a non-degenerate companion (Maoz et al., 2014). And although the fractions of predicted CEE products can be matched to observations using 'binary population synthesis' (e.g., Nelemans et al., 2001; Goliasch & Nelson, 2015), the physics is complex (Ivanova et al., 2013, §2), and particularly challenging both analytically and computationally (e.g., Hatfull et al., 2021).

THREE CHANNELS have been proposed for the formation of AM CVn systems, with one diagnostic being the nature of the donor at the onset of mass transfer. Different channels may dominate for different periods.

In the white dwarf (Paczyński, 1967; Faulkner et al., 1972), and He-star (Savonije et al., 1986; Iben & Tutukov, 1987) channels, the binary passes through two common-envelope stages as each component leaves the main sequence. The surrounding envelope extracts energy from the system, reducing the orbital period to below the minimum for H-dominated, non-magnetic CVs. These two channels differ in the nature of the secondary star following the ejection of the second common envelope; in the former it is left as a low-mass, degenerate or semi-degenerate white dwarf, in the latter it is a non-degenerate He-burning star.

In the evolved cataclysmic variable (or evolved main sequence donor) channel (Tutukov et al., 1985; Podsiadlowski et al., 2003), the donor evolves off the main sequence at around the start of mass transfer. The system then appears as a H-dominated cataclysmic variable in its early evolution, becoming He-dominated as the donor's H envelope is stripped.

OBSERVATIONALLY, eclipsing AM CVn systems, and in particular those where the white dwarf is totally eclipsed, offer excellent prospects for measuring parameters such as component masses and orbit inclination.

However, their extreme mass ratios means that such eclipses are rarely observed. Indeed, only two eclipsing AM CVn systems were known: SDSS J0926+3624 (Anderson et al., 2005; Copperwheat et al., 2011; Szypryt et al., 2014), in which the white dwarf is only partially eclipsed, and PTF1 J191905.19+481506.2 (Levitan et al., 2014), in which only the edge of the accretion disk is eclipsed.

The importance of Gaia14aae, and its role in understanding common-envelope evolution, is as only the third known eclipsing AM CVn system. Its uniqueness is as the first in which the white dwarf is *totally* eclipsed.

GAIA14AAE was seen independently in the alerts reports of ASAS–SN during a separate outburst. A third burst is seen in archival data from Pan–STARRS-1 and ASAS–SN. The three outbursts occurred within a four-month period, while no others are seen in the previous 8 yr of ASAS–SN, Pan–STARRS-1, or CRTS (Catalina Real-time Transient Survey) data (Campbell et al., 2015).

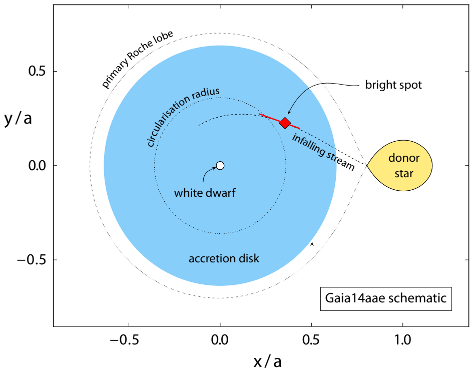
A detailed analysis of the system was reported by Campbell et al. (2015). Their follow-up photometry gave an orbital period of 49.71 min, placing it at the long-period extreme of the AM CVn period distribution. Assuming an orbit inclination $i = 90^\circ$, the contact phases of the white dwarf gave only a lower limit on the mass ratio of $q = M_2/M_1 > 0.019$, and lower mass limits of 0.78 and $0.015 M_\odot$ for the accretor and donor respectively.

They suggested that these masses, and the estimated accretion rate, point to a degenerate donor, and that the system may have resulted from a merging double white dwarf, with a much shorter orbital period in the past as a result of mass transfer (Tsugawa & Osaki, 1997).

They also suggested that the three outbursts within 3–4 months are 'rebrightenings' (aka 'echo outbursts') rather than independent events. And from the observed correlation between period and outburst recurrence time (Levitan et al., 2015), they predict that independent outbursts in Gaia14aae recur only every 10 yr.

FROM high-speed photometry of 53 eclipses over 25 months (see schematic), Green et al. (2018) derived the mass ratio $q = 0.0287 \pm 0.0020$ (compared with the previous upper limit), with $M_1 = 0.87 \pm 0.02 M_\odot$ and $M_2 = 0.0250 \pm 0.0013 M_\odot$, and the most precise measurement of the donor mass of an AM CVn system to date.

But they were left with a puzzle: their measured donor mass and radius do not fit with models for donors descended from white dwarfs or He stars, being more consistent with systems originating from evolved H-dominated cataclysmic variables. But such systems should show spectroscopic hydrogen… which is not seen in Gaia14aae.



Green et al. (2018)

PHASE-RESOLVED SPECTROSCOPY by Green et al. (2019) is consistent with the 'central spike' tracing the motion of the central white dwarf (based on its velocity and phase), but raised other questions about the origin of a second bright spot seen in He I emission. They continued to (marginally) favour Gaia14aae as being an unusual example of an AM CVn system that has formed through the evolved cataclysmic variable channel.

THE LAST PUBLISHED contribution to an understanding of this enigmatic system at the present time is a theoretical study by Sarkar et al. (2023). They considered both Gaia14aae, and another similarly peculiar system ZTF 1637J+49. The latter was discovered in a search for deep eclipses in the ZTF (Zwicky Transient Facility) light curves of white dwarfs selected using Gaia EDR3 parallaxes (van Roestel et al., 2022).

They emphasised that previous work has assumed that the only mechanism which drives the angular momentum loss of AM CVn systems is gravitational wave radiation: for the white dwarf channel (Deloye et al., 2007); for the He-star channel (Yungelson, 2008); and for the evolved CV channel (Podsiadlowski et al., 2003).

As a first step, they showed that white dwarfs with semi-degenerate He-rich donors of mass $0.1 - 0.3 M_\odot$, can explain the observed abundances of H and C in both systems. They then showed that these systems *can* emerge from a common envelope phase if magnetic breaking, as well as gravitational radiation, is included as an energy source in ejecting the common envelope.

DUE TO THE total eclipse of the central white dwarf, the Gaia alert discovery Gaia14aae is the best characterised of all AM CVn-type systems known today.

Campbell et al. (2015) suggest that some 1000 new cataclysmic variables, including a number of evolved systems and AM CVn-type systems, will be found by Gaia over its lifetime. Gaia will also continue to play an important role in their characterisation, in outburst as well as during eclipse. This will further elucidate their formation, and provide further insights into the complex processes of common envelope evolution.