141. White dwarf pulsars

WHITE DWARFS have featured in a number of my essays so far. Gaia is providing well-defined samples in the solar neighbourhood, with more than 260 000 classified from Gaia DR2 (essay #29). Resulting insights include the study of exoplanetary 'pollution' of their atmospheres (#73); constraints on variations in the gravitational constant (#101); white dwarf–white dwarf mergers (#131); and their importance for studies of accretion disks in cataclysmic variables (#140).

I look here at the recent discovery of the new class of 'white dwarf pulsars'. As of today, there are just two members of this exclusive class, AR Sco and J1912–4410. Gaia is contributing to their understanding, as well as assisting searches for further examplars.

WHITE DWARFS are the end evolutionary product for most stars $\lesssim 8M_\odot$. Isolated objects emit most of their energy from the ultraviolet to near-infrared, cooling on timescales of many multiples of the age of the Universe as they radiate their residual thermal energy.

They also comprise the dominant form of compact object binaries. In close orbits with main sequence stars (the 'cataclysmic variables', essay #140), white dwarfs can strip material from their companions via Roche lobe overflow. The mass transfer process results in atomic line and X-ray emission and, if the white dwarf is magnetic, radiation extending to the near- and mid-infrared.

IN 2016, the star AR Sco, classified since the early 1970s as a periodic variable of the common δ-Scuti type, was instead found to be a close binary of 3.56-hr period, with an M star companion, the system being at a distance of just 116 pc (Marsh et al., 2016). Most surprisingly, it was also found to be pulsing in brightness with a period of 118 s, much shorter than the orbital period.

The intense optical pulses were found to increase by a factor of four within 30 s and, unusually for cataclysmic variables, they were also detected at radio frequencies. Marsh et al. (2016) concluded that the optical pulses reflect the spin of a magnetic white dwarf, which they found to be slowing down on a timescale of 10^7 yr.

The pulsations actually comprised two components of very similar frequency. Assuming that the white dwarf spins in the same sense as the binary orbit, Marsh et al. (2016) concluded that the higher frequency component is associated with the spin period of the white dwarf (117 s), while the stronger lower frequency counterpart is a re-processed or 'beat' frequency (118 s). In other words, although the pulsations are driven by the white dwarf's spin, they mainly originate from the cool star.

The intense optical pulses at the white dwarf's spin period led to the classification of AR Sco as a 'white dwarf pulsar'. Its broadband spectrum is indeed characteristic of synchrotron radiation although, as I will detail further below, the source of such relativistic electrons is still considered to be uncertain.

INTERESTINGLY, and especially so in the absence of any observed pulsations, Ikhsanov (1998) had already suggested that the the close binary AE Aqr was a white dwarf pulsar. Inferring that the spin-down power of the compact object exceeded the system's bolometric luminosity, he suggested that a streaming (disk-less) mass-exchange model implied a pulsar-like mechanism of particle acceleration and polar-cap heating.

Since the discovery of pulsations in AR Sco, at least three other systems have been suggested to be white dwarf pulsars (Kato & Kojiguchi, 2021; Kato et al., 2021), including the Gaia transient Gaia22ayj (Kato, 2022). But none of these have yet been confirmed.

A targeted search for properties similar to AR Sco was carried out by Pelisoli et al. (2023a), based on non-thermal infrared colours, variability, and location in the Gaia colour–magnitude diagram (Pelisoli et al., 2023b).

Amongst a number of possible candidates, high-speed photometry with NTT–ULTRACAM revealed that one object, J1912–4410, shows strong pulses with a period of 5.3 min, during which the optical flux increases by up to a factor of four. It was also detected as an X-ray source with eRosita, and identified as a compact binary candidate due to its associated optical properties inferred from the Gaia data (Schwope et al., 2023).

LET ME EXPAND on the contribution of Gaia to the understanding of J1912–4410, and the problems that these two objects, AR Sco and J1912–4410, pose for understanding their physical properties. In the case of J1912–4410, the Gaia EDR3 distance of 237 ± 5 pc allowed Pelisoli et al. (2023a) to constrain the radius of the M dwarf from spectral fitting, from which they could estimate the system masses to be $M_1 = 1.2 \pm 0.2 M_\odot$ and $M_2 = 0.25 \pm 0.05 M_\odot$, with the companion then implicated as filling over 90% of its Roche lobe.

In addition, the measured spectral energy distribution, combined with the Gaia distance, yields a bolometric (total) luminosity of $\sim 10^{26}$ J s^{-1}, well in excess of the total *stellar* luminosity of some 10^{24} J s^{-1}. The excess is even higher than in AR Sco, implying either a faster spin-down rate, or another source of energy such as accretion.

Various models have been put forward for the origin of the optical emission. But here I will focus on how these results have been interpreted in terms of the evolution of the white dwarf's spin, and its magnetic field.

THE KEY PROBLEM, for both objects, is that while the measured spin-down of the rapidly-rotating white dwarf evidently provides enough energy to power the pulses, it is not obvious how to reconcile the present rapid spin-down rate with the rapid spin of the white dwarf. Specifically, because non-interacting main sequence stars rotate more slowly as they age, resulting in rotation periods of order days for their white dwarf remnants, the observed spin period requires previous spin-up, presumably via mass accretion.

Only white dwarfs in cataclysmic variables have rotation periods comparable to that of AR Sco, which is explained by angular momentum gain via mass accretion from the companion. However, whereas the spin-down rate of AR Sco suggests that a strong magnetic field (~5000–10 000 T) provides the synchronising torque, the rapid spin can only be achieved with typical mass transfer rates via Roche lobe overflow if the magnetic field is much smaller, of order 100 T.

IN THE CASE OF AR Sco, a solution has been proposed by Schreiber et al. (2021). In their model, the white dwarf was originally non-magnetic, allowing for normal accretion-driven spin-up. But when crystallisation started to occur in the core of the cooling white dwarf (a phenomenon first observationally identified in the Gaia data by Babusiaux et al. (2018), essay 42), strong density stratification combined with convection created the conditions for a dynamo, generating the magnetic field (Isern et al., 2017; Ginzburg et al., 2022).

With a strong enough field, the rapid transfer of spin angular momentum into the orbit would causes the binary to detach, and mass transfer to briefly cease, leading to a rare evolutionary-phase system such as AR Sco.

After a few million years, the system comes into contact again due to reduced magnetic braking and gravitational radiation, giving rise to a rapidly rotating and accreting magnetic white dwarf. As well as explaining the formation of a system like AR Sco, the proposed model also provides a solution to a long-standing problem in the understanding of white dwarf binaries: the discrepancy between the fraction of magnetic white dwarfs in detached versus accreting binaries.

As emphasised by Pelisoli et al. (2023a), strongly magnetic white dwarfs are largely absent in detached white dwarf binaries (Liebert et al., 2015; Parsons et al., 2021), whereas more than a third of those in accreting systems are magnetic (Pala et al., 2020). The dynamo mechanism offers an explanation: magnetic accreting white dwarfs are typically old and cool enough to have crystallised, and spun up by accretion to short periods such that the dynamo effect is intensified.

An implication of this rotation- and crystallisation-driven dynamo model is that binary white dwarf pulsars like AR Sco are a possible evolutionary stage in accreting magnetic white dwarfs. Though the timescales in the model cannot be precisely established, given the existence at the time of only one object available to calibrate it, the properties of AR Sco itself suggest that other binary white dwarf pulsars should exist. Specifically, given its distance of only 117 pc, more objects should be found in deeper surveys, while its spin-down rate suggests that the lifetime in such a stage is several million years.

This model also predicts that the white dwarfs in AR Sco-like systems should be cool enough to have crystallised, with their companions close to filling their Roche lobe, and that such pulsars will have orbit periods of 3–5 hr. Indeed, Pelisoli et al. (2023a) concluded that J1912–4410 supports the idea of such a rotation- and crystallisation-driven dynamo model as the origin of magnetic cataclysmic variables.

IS THE TERM 'white dwarf pulsar', here, a misnomer? In the absence of *coherent* optical or radio emission, and therefore arising from a very different physical emission mechanism, Katz (2022) has argued that AR Sco does not display the properties of a 'true' pulsar.

Meanwhile, he suggests that the low-frequency radio source GLEAM-X J162759.5–523504.3 is, in fact, a white dwarf pulsar, with a moment of inertia orders of magnitude greater than for neutron stars, and a spin period of 18.18 min, hundreds of times longer than those of confirmed radio pulsars. But there are other models (Loeb & Maoz, 2022; Ekşi & Şaşmaz, 2022), with different predictions for the brightness of the optical counterpart.

SEMANTICS ASIDE, these new binary white dwarf systems are clearly fascinating... and Gaia should assist the discovery and characterisation of many more.