
128. The enormous dwarf galaxy Antlia II

FOR A SPACE MISSION which targets accurate star positions, mainly for stars in our Galaxy, it may seem surprising that Gaia is also making a significant contribution to cosmology. Certainly, its contribution to the distance scale, and therefore the Hubble constant, and hence further characterisation of the Λ CDM ‘big bang’ cosmological paradigm, was a long-held objective.

But even 25 years ago, when the foundations of Gaia’s scientific case were being prepared, it was clear that the accurate morphological and dynamical characterisation of our Milky Way galaxy and, to the extent possible, of the Local Group of galaxies, would provide a fundamental testing ground for the detailed predictions of structure formation in the Universe.

I have touched on a number of these aspects already: on the motion of globular clusters and dwarf spheroidal galaxies, and the discovery of halo streams and the Gaia phase-space spiral, amongst others. And in essay #118 I mentioned four specific galaxy-scale ‘problems’ that have been important in attempts to reconcile observations with Λ CDM simulations: the ‘missing satellites’ problem, the ‘core-cusp’ problem, the ‘too-big-to-fail’ problem, and the ‘plane of satellites’ problem.

In essay #118 I focussed on the ‘plane of satellites’ problem. Here I will look further at the ‘core-cusp problem’, another of the areas in which Gaia is contributing, and in particular with the discovery, by Gaia in 2019, of the enormous dwarf galaxy Antlia II.

AROUND THE early 1990s, measurements of the rotation curves of dwarf irregular galaxies showed that their circular velocities increased roughly linearly with radius near their centres, indicating that the surrounding dark haloes had a constant density ‘core’ of radius comparable to the luminous radius of the galaxy.

This was at variance with the results of N-body simulations in a cold dark matter Universe which have density profiles that diverge near the centre as r^{-1} (e.g. Navarro et al., 1996); in this context, the term ‘core’ refers to a region of constant density near their centres, which should not exist in simulated Λ CDM haloes.

OUR LOCAL GROUP of galaxies, dominated by the Milky Way and Andromeda and their associated satellites, includes of order 100 members, most of which are dwarf galaxies. These come in a number of types, including dwarf ellipticals, dwarf spheroidals, dwarf irregulars, ultra-compact dwarfs, ultra-diffuse dwarfs, and ultra-faint dwarfs.

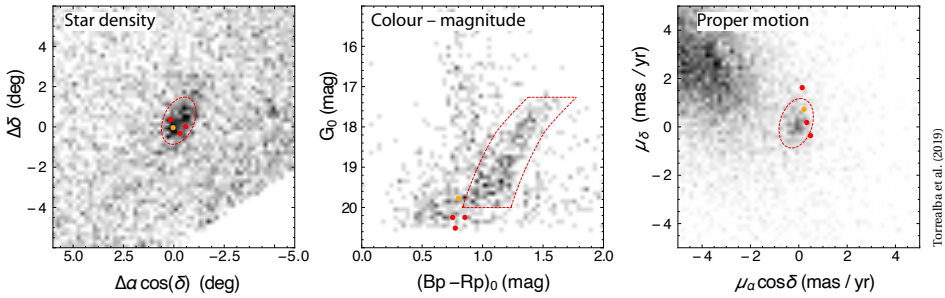
The latter contain very few stars, of order 100 000, and are the faintest of all galaxies. While resembling globular clusters, they are more extended, and include the most dark matter-dominated systems known, with mass-to-light ratios in the range 10–1000.

Ultra-faint dwarfs were discovered only with the advent of digital sky surveys. The first, SDSS J1049+5103, represented a drop in faintness by a factor of about 100 (Willman et al., 2005). Since then, more than 60 have been discovered, some of the most recent with the Dark Energy Camera, DECam (e.g. Mau et al., 2020; Cerny et al., 2023). Meanwhile, Λ CDM simulations predict that numerous ultra-faint Milky Way satellites remain to be discovered (Garrison-Kimmel et al., 2018).

CHARACTERISED BY their small number of stars, their faintness, and their (generally) high dark matter content, they are also some of the least metal-enriched. They are believed to have formed at high redshift, likely before the epoch of reionization. They therefore provide a fossil record of the assembly and chemical enrichment history of their host galaxies. Their high dark matter content, and proximity, has also made them targets for the indirect detection of dark matter via γ ray emission from WIMP annihilation (e.g. Ackermann et al., 2014).

Their high dark matter content is not believed to be due to baryon deficiency at the time of their formation, but rather to ‘dark matter heating’, the effect of feedback from stellar winds and supernovae that can expel a significant fraction of the original baryonic component, causing the dark matter halo to expand (e.g. Dekel & Silk, 1986; El-Badry et al., 2016; Chan et al., 2018).

Tidal-stripping may also affect the very lowest surface brightness galaxies (e.g. Charles et al., 2023).



WITH MANY of the recent Local Group dwarf satellite discoveries piling up around the edge of detectability at a surface brightness of ~ 30 mag arcsec $^{-2}$, even fainter systems have consequently been expected.

One of these, the Crater II dwarf, was found in the VST-ATLAS survey (Torrealba et al., 2016). At a distance of 120 kpc, and with a surface brightness of 30.6 mag arcsec $^{-2}$, Crater II became the fourth largest Milky Way satellite (after the LMC, SMC and the Sgr dwarf).

Pozo et al. (2022) showed that its low velocity dispersion could be understood as a typical dwarf spheroidal that lost most of its halo mass to tidal stripping. This argument is supported the Gaia EDR3 analysis by Ji et al. (2021), which indicates a small pericentre of ~ 20 kpc, and hence significant tidal stripping by the Milky Way.

THE COMBINED USE of Gaia's photometric, astrometric and variability information has actually allowed discoveries to be made at surface brightnesses far below those attainable with photometry alone. The first such discovery was in the 'zone of avoidance', at low Galactic latitude, a region difficult to survey because of its high extinction and high density of foreground disk stars.

Torrealba et al. (2019) used Gaia DR2 parallaxes to filter out the foreground stars, and the proper motions to identify overdensities of stars sharing common kinematics. They also used the Gaia DR2 RR Lyrae catalogue (Clementini et al., 2019), exploiting the fact that all of the currently known Milky Way dwarfs contain at least one RR Lyrae star (Baker & Willman, 2015), and yielding precise distances out to ~ 100 kpc.

Their discovery, an ultra-faint dwarf satellite in the constellation of Antlia, Antlia II, is located behind the Galactic disk at latitude $b \sim 11^\circ$, and extends over $1^\circ 26'$, which gives a size of 2.9 kpc at a distance of 130 kpc. While similar in spatial extent to the Large Magellanic Cloud, Antlia II became by far the lowest surface brightness system known, at 31.9 mag arcsec $^{-2}$.

It was confirmed with archival DECam imaging, which also revealed a contribution of blue horizontal branch stars. Spectroscopy using AAT-AAOMega identified 159 members. From these, they derived a systemic velocity 290.9 ± 0.5 km s $^{-1}$, a velocity dispersion of 5.7 ± 1.1 km s $^{-1}$, and a mean metallicity $[\text{Fe}/\text{H}] = -1.4$.

Torrealba et al. (2019) concluded that Antlia II has one of the least dense dark matter haloes. Dynamical modelling suggests that a combination of a core dark matter profile, along with strong tidal stripping, may explain its observed properties. The origin of this (non- Λ CDM) core of Antlia II may be consistent with 'aggressive' feedback or may, they suggest, require alternatives to cold dark matter such as ultra-light bosons.

THERE HAVE already been a number of interesting consequence of the discovery of Antlia II that have been reported, also relying on the Gaia data.

Chakrabarti & Blitz (2009) had previously suggested that the long-standing puzzle of the planar warp-like disturbances seen in the outer H I disk of the Milky Way (Levine et al., 2006) could be explained by a 1:100 mass ratio perturber on a near co-planar orbit with a close pericentre approach of ~ 5 kpc, and at current distance of ~ 90 kpc. Chakrabarti et al. (2019) showed that the current location of Antlia II closely matches that prediction. If it is indeed the perturber, it would have a specific range of predicted proper motions that can be tested with future Gaia data releases.

Ji et al. (2021) extended the analysis of Antlia II (and Crater II) to include proper motions from Gaia EDR3. They concluded that dynamical models of Antlia II require it to have lost over 90% of its stars to tides. Overall, the new kinematic measurements support a tidal disruption scenario for the origin of these large and extended ultra-faint dwarf spheroidal galaxies.

A more detailed study of the RR Lyrae variables in the Antlia II field by Vivas et al. (2022) also confirmed this tidal disruption picture, albeit somewhat less extreme.

IN OTHER studies of ultra-faint dwarf galaxies, various recent DECam discoveries have been confirmed, e.g. Centaurus I with Gaia DR2 (Mau et al., 2020), and Pegasus IV with Gaia EDR3 (Cerny et al., 2023).

Pace et al. (2022) used Gaia EDR3 to derive the systemic proper motion, and orbits, of 52 dwarf spheroidal satellite galaxies of the Milky Way. Again, they predict that Antlia II (along with Boo III, Cra II, Gru II, and Tuc III) should be undergoing a process of tidal disruption by the Milky Way.