Dwarf galaxies with giant reach

Our Collection on dwarf galaxies brings together a series of articles that showcase the breadth of research in this field, with links to galaxy formation and evolution, cosmology, dark matter and the interstellar medium.

Dwarf galaxies, with masses below a few billion solar masses, are often characterized by a higher fraction of dark to luminous matter compared to more massive galaxies. Recent advances in understanding have revealed links to other fields where dwarf galaxies may provide answers to open questions. These include the formation of the first stars and the chemical enrichment of the Universe, the growth of galaxies and of the black holes within them, and the existence and properties of dark matter. We present a living Collection of articles on the science of dwarf galaxies to capture the current state of knowledge of the field, which we will update over time.

It is unclear whether these dwarf galaxies are of primordial origin (remnants of the early Universe that failed to grow to the size of Milky Way-like galaxies) or the result of other processes (for example, mergers, or gas or stellar stripping). Their origin aside, dwarf galaxies have emerged as key components in helping us understand the evolution of galaxies and provide stringent tests on the standard cosmological ΛCDM model. Denija Crnojević and Burçin Mutlu-Pakdil set the stage with a Q&A article in which they explore how the discoveries and characterizations of the smallest galaxies over the past 20 years have pushed the limits of observational and theoretical advancements alike, and how they will continue to do so.

The rest of the Collection falls into two clear areas in the field of dwarf galaxies that are of special interest and have led to significant debate in the community.

Dwarf galaxies as a probe of ΛCDM

The number density, mass distribution and spatial distribution of dwarf galaxies around massive galaxies are key predictions of ΛCDM yet there appear to be discrepancies between what is expected and what is observed (for example, the 'missing satellites' problem and the existence of planes of satellites). In a Comment, Marcel Pawlowski points out that the Milky Way, Andromeda and Centaurus A galaxies all host flattened arrangements of satellite dwarf galaxies with correlated kinematics. As such structures in cosmological simulations are rare, Pawlowski cites this discrepancy as a major problem for the ΛCDM model, with no obvious solution in sight. In response, Michael Boylan-Kolchin agrees that the existence of planes of satellites has been a cosmological surprise. However, Boylan-Kolchin believes that the evidence for stable, long-lived satellite planes is generally tenuous, and that they are unexpected in all current models of galaxy formation, even beyond ΛCDM.

We also present a number of in-depth Reviews. Dwarf galaxies are particularly suited to testing dark matter models because their dynamical mass (from kinematic observations) outweighs their baryonic (gas and matter) mass. Federico Lelli examines gas dynamics in dwarf galaxies, such as rotation curves and mass models. Star-forming dwarf galaxies extend the dynamical laws of spiral galaxies and show small scatter around them, implying a tight coupling between baryons and dark matter. Looking more closely at the galaxies of the Local Group, Giuseppina Battaglia and Carlo Nipoti review their properties from the point of view of their stellar dynamics and dark matter content and distribution, as inferred from the combination of observed data and dynamical models. Adding dark matter haloes into the mix, Laura Sales, Andrew Wetzel and Azadeh Fattahi consider the most notable challenges to ΛCDM regarding dwarf galaxies and their haloes, and discuss how recent cosmological numerical simulations have pinpointed baryonic solutions to these challenges. They highlight the need to understand how baryonic matter populates and affects dark-matter haloes within galaxy evolution models.

And taking up this challenge, Jorge Moreno and colleagues show in a state-of-the-art cosmological simulation that low-mass galaxies can form with far less dark matter than expected, due to extreme close encounters with massive neighbours. Their results match some observed characteristics. Their Article predicts that roughly one-third of massive central galaxies may host at least one such dark-matter-deficient satellite.

Galaxy formation and evolution

If dwarf galaxies are indeed primordial in nature, these systems could provide hints to the first galaxies formed in the Universe. On the other hand, the properties of dwarf galaxies might have been altered due to the presence of supermassive black holes and intense star formation through feedback processes that can impact their stellar and chemical properties or internal dynamics.

Vasily Belokurov and Wyn Evans summarize our understanding of early-type dwarfs, which are the end-points of the evolution of low-mass galaxies. Their primaeval stellar populations provide a unique laboratory for studying the physical conditions on small scales at epochs beyond redshift $z = 2$. For nearby (<20 Mpc) star-forming galaxies, Francesca Annibali and Monica Tosi round up what we know about their stellar and chemical properties. These objects resemble the earliest formed galaxies and may therefore represent a window on the distant, early Universe.

Turning now to feedback processes that shape galaxies, we start with black holes, which were traditionally thought to exist solely in giant galaxies. In a Perspective, Amy Reines discusses massive black holes in dwarf galaxies and presents insights into the demographics of nearby dwarf galaxies to help constrain the black hole occupation/active fraction as a function of mass and dwarf galaxy type. Based on observational evidence for star formation feedback, Michelle Collins and Justin Read discuss in their Perspective the important role of external ionizing radiation for the smallest galaxies and show how this feedback directly impacts their properties, such as their star-formation histories, metal contents, colours, sizes, morphologies and even their inner dark matter densities.

At the cross-section of these two lines of enquiry lie the recently discovered ultra-faint dwarf galaxies. These galaxies appear to have almost no stars but a lot of dark matter. How such systems could form, how common they are and even whether they actually exist are open questions, given the observational uncertainties in estimating their properties. Whatever their true nature, these objects represent edge cases that will provide key insights into stellar physics, dark matter and the ΛCDM model. Ignacio Trujillo covers the ongoing debate as to whether ultra-diffuse galaxies are regular dwarf galaxies with a low degree of star formation or massive 'failed' objects that quenched their star formation in the early Universe — suggesting that current evidence seems to support the former.

As this is a living Collection, please keep checking for updates as the field grows in size and stature. ❐

Published online: 14 September 2022
https://doi.org/10.1038/s41550-022-01797-7