119. Brown dwarfs with Gaia

BROWN DWARFS are loosely characterised as objects having masses below the hydrogen-burning limit, i.e. below around $0.07 M_{\odot}$. Although predicted on theoretical grounds in the early 1960s (Kumar, 1962), it was more than 30 years before the discovery of the first, Teide 1 in the Pleiades cluster (Rebolo et al., 1995) and, soon after, a faint object orbiting the nearby star GJ 229 (Nakajima et al., 1995; Oppenheimer et al., 1995).

With their relatively low effective temperatures, they are faint at visible wavelengths, emitting most of their energy in the infrared. Subsequent searches for isolated brown dwarfs have accordingly been made from infrared surveys such as DeNIS, 2MASS and WISE, and (given their proximity) taking advantage of their high proper motions. Searches for faint brown dwarf companions to main sequence stars and white dwarfs include multi-colour imaging and coronagraphy surveys, and radial velocity monitoring for close companions.

AS PROGRESSIVELY cooler objects have been discovered, new spectral classes have been introduced to classify them, according to their effective temperature and spectral features. Accordingly, brown dwarfs comprise late M, L, T, and the coolest Y ($T_{\rm eff} \sim 500 - 600$ K), together often referred to as 'ultra-cool dwarfs'.

Today, several thousand are known, including the nearest, the L/T-type binary Luhman 16 which, at a distance of 2 pc, is the third closest star system to the Sun.

One of the many areas of active brown dwarf research is their role as the link between planets and low-mass stars, with ambiguity still remaining about whether brown dwarfs tend to form like high-mass planets, say above $13 M_{\rm J}$ (e.g. Stamatellos & Whitworth, 2009), or through interstellar cloud fragmentation like low-mass stars (e.g. Reipurth & Clarke, 2001).

They also present great challenges for atmospheric and evolutionary modelling as a result of their complex chemistry and cloud physics (e.g. Burrows et al., 2001).

THE EXPECTED contribution of Gaia falls into the two distinct areas: isolated brown dwarfs, and brown dwarfs in binary systems.

Concerning the former, studies during the preparation of Gaia's scientific case in the 1990s suggested that, since their luminosities fade rapidly with age to very faint absolute magnitudes, objects with $V < 20$ mag will be strongly biased towards very young objects, and those of higher mass. The youngest might be visible out to 400 pc, while the oldest would only be detectable if very nearby. Some 20 000 detections with Gaia were given as an indication, although with much uncertainty.

Despite most being at the faint end of Gaia's survey, their proximity should ensure a high parallax precision. Excellent positioning in the Hertzsprung–Russell diagram would allow the determination of ages and masses by sequence fitting, in turn providing an accurate picture of their recent formation history and mass function.

DUE TO THE large reflex motion they induce in their host stars, early radial velocity surveys were expected to discover brown dwarf companions to solar-type stars with relative ease.

A prominent feature of the early radial velocity exoplanet discoveries, in contrast, was the general absence of close-in ($a < 3 - 4$ au) substellar objects with masses of $10 - 80 M_{\rm J}$, a paucity referred to as the *brown dwarf desert*. Subsequent radial velocity surveys of several thousand stars confirmed this pattern, finding brown dwarf companions out to $P \sim 10$ yr, but yielding only a small number, of order 100, in the mass and separation range characterising the 'desert' (e.g. Wilson et al., 2016).

Notwithstanding their relative rarity, the detailed study by Holl et al. (2022) showed that Gaia's astrometric precision should allow for the detection of (unseen) companions down to Jupiter masses, allowing the efficient detection of large numbers of brown dwarfs. Additionally, Gaia's low-accuracy multi-epoch radial velocity measurements for $G_{\rm RVS} < 12$ mag should provide additional detections for the more massive, while a further small sample will have detectable transits in the Gaia photometry.

From astrometry alone, they predicted 30–40 000 detections out to several hundred parsecs for the nominal 5 year mission, and 45–55 000 for a 10-year mission.

TURNING TO THE recent Gaia advances, I will first look at the results for isolated objects.

With Gaia DR1, Smart et al. (2017) identified 321 L/T dwarfs, of which 10 are later than L7. This represented 45% of known L/T dwarfs with $G < 20.3$ mag. They also estimated the Gaia magnitude of previously known objects, predicting that 1010 L and 58 T objects would have $G < 21.5$, with 543 L and 10 T having $G < 20.3$.

With Gaia DR2, Reylé (2018) identified 3050 later than M7, 647 L, and 16 T dwarfs, being 61% of known objects with $G < 21.5$ and 74% with $G < 20.3$. Smart et al. (2019) identified 695 M8–T6 objects with accurate parallaxes and proper motions, finding that 100 are in 47 multiple systems, of which 20 were new. Their sample formed the training set for the ultra-cool dwarfs data processing work package (ESP–UCD; see essay #89).

Scholtz (2020) found a further 50 new ultra-cool candidates within 20 pc, objects with relatively small proper motions and low tangential velocities, and concentrated towards the Galactic plane. They include three M7–M8, five M8.5–M9.5, four L0–L1, and seven L4.5–L6.5.

Marocco et al. (2020) identified a further 10 new ultra-cool dwarfs in seven wide binaries, including an L1+L2 system with a projected separation of 959 au.

Best et al. (2021) constructed a volume-limited sample of 369 L0–T8 dwarfs out to 25 pc, defined exclusively by parallaxes, thereby providing the most precise space densities for such objects to date.

With Gaia DR3, came the inclusion of the mean low-resolution B_P/R_P spectra for 220 million sources (Vallenari et al., 2022). With this, Creevey et al. (2022) started with a catalogue of 94 000 ultra-cool candidates, from which they constructed a high-quality sample of 31 000 objects, deriving radii, luminosities, and bolometric fluxes using the Gaia parallaxes combined with infrared (mostly 2MASS and WISE) photometry.

FOR BROWN DWARFS in binary systems, and in view of the progressive and iterative nature of the data analysis, in particular regarding the astrometric solutions for binary and multiple systems, it will clearly be some years before Gaia's full discovery potential is realised, even though more than 9 years of data has already been acquired. But numerous insights are becoming available.

In their wide-ranging paper on stellar multiplicity based on Gaia DR3, Arenou et al. (2022) made a first analysis of the occurrence of ultra-cool dwarf binaries (comprising both very low-mass stars and brown dwarfs) and sub-stellar companions to main sequence stars (comprising both brown dwarfs and planets).

For the former, they examined the orbital solutions for the Gaia 'ultra-cool dwarf sample' defined by Smart et al. (2019). Emphasising that around 75% of that sample are fainter than the $G < 19$ cut-off adopted for processing with the non-single star pipeline, they found (targeted) orbital solutions only for previously known orbital systems. They obtained 13 such orbits, of which only 5 have $G < 19$. Three have previously published astrometric orbit solutions, for which the Gaia results are in reasonable agreement.

For the sub-stellar companions, Arenou et al. (2022) confirmed that the Gaia DR3 astrometric performance reaches the sensitivity to detect substellar companions around a statistically significant number of stars, providing measurements of their three-dimensional orbital architectures and true masses for the first time.

They identified 1843 brown dwarfs (and 72 exoplanets) in their catalogue of companion masses. Only 10 of the brown dwarf companions were already known (from ground-based radial velocity exoplanet surveys). Their Table 11 provides a comparison of periods and eccentricities from Gaia and from the literature, along with the estimates of the minimum mass (from radial velocities) and true mass (from the Gaia astrometry).

Selecting HD 77065 b as a favourable (but tolerably representative!) example, estimates from radial velocity work are $P = 119.113 \pm 0.003$ d, $e = 0.694 \pm 0.0004$, and $M \sin i = 41 \pm 2 M_J$ (Wilson et al., 2016). The corresponding Gaia DR3 values are $P = 119.1 \pm 0.2$ d, $e = 0.70 \pm 0.04$, and with the measured inclination $i = 42 \pm 3^\circ$ yielding a true mass $M = 64.2 \pm 5.1 M_J$. The semi-major axis of the Gaia astrometric orbit is $a_0 = 1.04 \pm 0.07$ milli-arcsec.

More can be said about the Gaia DR3 results at the transition between brown dwarfs and exoplanets, $\sim 13 M_J$, and deeper insights will follow in the future...

BROWN DWARFS are numerous and ubiquitous, with estimates suggesting that our own Galaxy contains some 25–100 billion (Mužić et al., 2017). They are faint (and physically complex) objects, for which Gaia is nonetheless contributing much new knowledge.

Their lifetimes are remarkable too. Due to their slow hydrogen fusion, they are expected to remain convective over most of their lives, surviving for many times the current age of the Universe, with the lowest masses persisting for *trillions* of years (Adams et al., 2005).

BUT LET me finish with a curious phenomenon that has been predicted, and which Gaia may be able to test, which is that brown dwarfs more massive than the hydrogen-burning limit may well exist (Salpeter, 1992).

To form such an 'overmassive' brown dwarf, mass must be added sufficiently slowly to a 'traditional' brown dwarf – but one old (and cool) enough to prevent their cores from igniting when they cross the H-burning limit. Two different possible formation scenarios have recently been suggested, by Forbes & Loeb (2019), and by Majidi et al. (2022). The latter authors detail how future Gaia data releases might demonstrate their existence!