13. The distance to the Pleiades

Measuring distances across the vast scale of our Galaxy and beyond has long been a central problem in astronomy. Only for objects within a few tens of parsecs has direct distance determination, through parallax measurements, been possible from the ground.

Beyond that, too far away for distances to be determined directly, estimates have had to rely on a distance scale 'ladder', constructed from a sequence of indirect and often uncertain measurements relating the closest objects to increasingly distant ones.

Open clusters have long been a crucial step in this sequence of distance estimates.

Open clusters are groups of several hundred stars that were formed from the same giant molecular cloud and have roughly the same age. They are still being formed in our own Galaxy, at an estimated rate of one every few thousand years.

More than a thousand have been discovered within our Galaxy, and many more are thought to exist. A few, such as the Hyades (at about 45 pc), the Pleiades (at about 130 pc), and the Alpha Persei cluster (at about 175 pc), are visible with the naked eye.

Open clusters are key objects in the study of stellar evolution. Because the cluster members are of similar age and chemical composition, their properties (such as distance, age, metallicity, extinction, and velocity) are more easily determined than they are for isolated stars.

Although loosely bound by mutual gravitational attraction when they formed, open clusters slowly disperse as gas (and therefore mass) is stripped by the radiation pressure of their hot young stars. They are further disrupted by close encounters with other cluster stars, and other external structures, as they orbit the Galaxy. Open clusters may survive as recognisable clumps for a few hundred million years, with the most massive clusters surviving for a few billion years.

As stars slowly escape the gravitational field of the cluster, many will still be moving through space on a roughly similar path around the Galaxy, in what is known as a moving cluster or moving group.

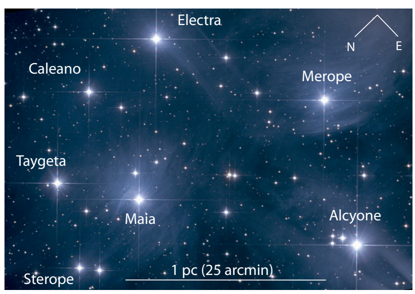
Distances to the nearest open clusters, notably the Hyades and the Pleiades, have long been used to calibrate the distances to others more remote, notably by matching their main sequences on the Hertzsprung–Russell diagram. And clusters containing luminous Cepheid variables can be used to calibrate the Cepheid period–luminosity relationship, allowing them to be used as standard candles out to more distant galaxies in the Local Group.

Determining the distances to these clusters has its own long history. For the Hyades this gathered pace with the work of Lewis Boss (1908) whose opened his study with the words: *'The phenomenon of neighbouring stars moving athwart the sky with motions of the same order of magnitude and in sensibly parallel directions has been noticed many years ago. It has been demonstrated that the greater part of the stars in the Pleiades are moving in this manner.'* And over the next 30 years, other big names tackled the problem, including Jacobus Kapteyn, Willem de Sitter, Henry Plummer, and Ejnar Hertzsprung.

Fast forward 60 years (and dozens of papers), and Hipparcos allowed the distance to the Hyades to be established more securely, with the cluster centre being estimated at around 46 parsec (Perryman et al., 1998).

The Pleiades, in the constellation Taurus, has been recognised as a group of stars since antiquity, and has long played an important role in establishing the distance scale.

The cluster contains more than 1000 members, with a total mass of about 800 solar masses. Its light is dominated by young, hot blue stars, some dozen of which can be seen with the naked eye. The cluster has a 'core radius' of about 2–3 pc, and a 'tidal radius' of about 13 pc .



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Until the Hipparcos measurements of its trigonometric parallax were published, various alternative and somewhat less-direct methods had all converged on a Pleiades distance of about 130–135 pc.

But, in 1999, the results from Hipparcos yielded an unexpected result. The technique that should have provided the most accurate results to date, viz. measuring stellar parallaxes from space, gave a mean distance of only 118 pc, 7% 'shorter' than the previous consensus.

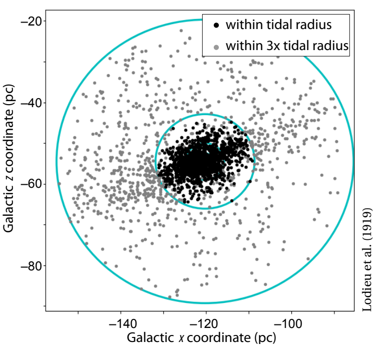
Later work, amongst them optical interferometric observations of the binary star Atlas, main-sequence fitting in the infrared, Hubble Space Telescope Fine Guidance Sensor observations, VLBI observations, and others, consistently argued that the Hipparcos distance for the Pleiades must be erroneous.

But the problem did not disappear: a detailed re-analysis of the Hipparcos data a decade later led to only a small revision, from 118 to 120 pc (van Leeuwen, 2009).

What do the Gaia results have to say on the subject? The first Data Release, DR1 in 2016, included the Tycho–Gaia Astrometric Solution (TGAS), a subset of about 2 million stars incorporating the Hipparcos and Tycho-2 positions centred at 1991.25. Their parallaxes for 152 Pleiades members gave a mean distance of 133.7 ± 0.6 pc, agreeing with other non-Hipparcos values of the cluster distance (van Leeuwen, 2017).

And their results for 19 open clusters, ranging from the Hyades (at just under 47 pc) to IC2422 (at nearly 440 pc) gives a good agreement with a similar study using the Hipparcos data – with the one exception of the Pleiades cluster, which remains unexplained.

The same prescription was used by Abramson (2018) to estimate the cluster's distance using the new Gaia DR2 data. From 1594 cluster stars, an order of magnitude more than available for the DR1 analysis, he derived a mean distance of 136.2 ± 5.0 pc.



Stars escaping from the Pleiades

A more rigorous treatment of cluster members in DR2 allowed Lodieu et al. (2019) to identify 1248 members, yielding a mean distance of 135.15 ± 0.43 pc. They estimated the cluster's age, of 132 ± 26 Myr, from its single white dwarf LB 1497. And they detected a stream of stars escaping from the cluster, extending up to 40 pc from its centre.

A separate analysis of DR2 found 1454 cluster members, and a mean distance of 136.0 ± 0.1 pc (Gao 2019).

Recent Pleiades distances (Hipparcos and Gaia highlighted)

Year	Distance (pc)	Technique	First author
1999	118.3 ± 3.5	Hipparcos	van Leeuwen
2004	132.0 ± 4.0	binary star (Atlas)	Zwaalen
2005	133.8 ± 3.0	infrared main-sequence	Percival
2005	134.6 ± 3.1	HST–FGS	Soderblom
2007	122.2 ± 2.0	Hipparcos re-reduction	van Leeuwen
2009	120.2 ± 1.9	Hipparcos re-reduction	van Leeuwen
2014	136.2 ± 1.2	VLBI	Melis
2017	133.7 ± 0.6	Gaia Data Release 1	van Leeuwen
2018	136.2 ± 5.0	Gaia Data Release 2	Abramson
2019	135.2 ± 0.4	Gaia Data Release 2	Lodieu
2019	136.0 ± 0.1	Gaia Data Release 2	Gao

Taken together, it is now clear that all methods, whether ground- or space-based, converge on one agreed mean distance to the Pleiades cluster, of about 136 pc, with the collective exception of the various Hipparcos estimates, which placed it significantly, but erroneously, some 10–15 pc nearer.

The papers cited here have much more to say about the Pleiades cluster than just its distance. Gaia reveals, for the first time, the cluster's depth, allowing each star to be be pinpointed in space with respect to its centre. It allows us to recognise stars that are slowly escaping from the cluster, gradually merging into the background population over millions of year. And it clarifies its age and stellar content from its Hertzsprung–Russell diagram.

While the Pleiades distance provided, by far, the largest controversy in the Hipparcos results, and while it remains an important problem to resolve, I will make a couple of observations.

At 135 pc distance, the mean parallax of the Pleiades stars is around 7.4 mas. Hoping to establish the distance with a 10% error was always going to be at the limit of the Hipparcos measurement accuracies. Compounding the problem, the stars are also much closer together on the sky than the satellite was ever designed to probe.

The Hipparcos distance of the Pleiades was an 'outlier' compared to the other cluster distances. And even before Gaia, the cosmic distance ladder could be weighted to other nearby clusters where a better consensus existed.

Today, the Gaia parallaxes have been pushed to such great distances that the Hyades and Pleiades, for many decades key steps in unravelling the cosmological distance scale, are no longer relevant in this endeavour – a century of ingenuity and experimental perseverance have been consigned, at a stroke, to historical curiosity.

Open clusters will remain of great importance for dynamical and evolutionary studies of stellar systems, and it would be good to see the Hipparcos parallax of the Pleiades more definitively resolved. Meanwhile, it has surely made its final appearance in the lengthy and proud history of the distance scale in astronomy.