

## STELLAR DISTANCES

# A VLBI resolution of the Pleiades distance controversy

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Because of its proximity and its youth, the Pleiades open cluster of stars has been extensively studied and serves as a cornerstone for our understanding of the physical properties of young stars. This role is called into question by the “Pleiades distance controversy,” wherein the cluster distance of  $120.2 \pm 1.5$  parsecs (pc) as measured by the optical space astrometry mission *Hipparcos* is significantly different from the distance of  $133.5 \pm 1.2$  pc derived with other techniques. We present an absolute trigonometric parallax distance measurement to the Pleiades cluster that uses very long baseline radio interferometry (VLBI). This distance of  $136.2 \pm 1.2$  pc is the most accurate and precise yet presented for the cluster and is incompatible with the *Hipparcos* distance determination. Our results cement existing astrophysical models for Pleiades-age stars.

**R**obust physical parameters for stars can only be obtained when an estimate of the distance to the object of interest exists. Trigonometric parallax, which uses the orbit of Earth around the Sun to inform the principle of triangulation, provides the most fundamental distance measurement outside of our solar system. High-precision tests of stellar physical models thus rely heavily on collections of parallax determinations. With reasonable physical models for nearby stars—and some mild assumptions about the homogeneity of classes of astrophysical objects throughout the universe [the Vogt-Russell theorem; see, e.g., (1, 2)]—distance estimates for sources that lie beyond the current limit of trigonometric parallax can be systematically compiled. Such a methodology forms the basis of the cosmic distance ladder that elucidates the structure and evolution of the universe (3).

Clusters of coeval stars yield a solid foundation for tests of stellar physical models. Young open clusters are especially important because their stellar constituents define the “zero-age main sequence,” the curve along which stable, core-hydrogen-burning stars reside in a color-magnitude diagram. Empirical isochrones developed from these young open clusters can be applied to other vastly more distant groups of stars (when brightness measurements of individual stars in the group can be made) to estimate their distance, thus providing structural information for the galaxies

that contain them (4, 5). The Pleiades open cluster of stars is critical for such studies because its relatively young age places many of its stars on the zero-age main sequence. It is the closest cluster to Earth of its age and richness of stars and thus lends itself to highly detailed investigations. One would expect that all astrophysical parameters for such an important sample of stars would be well characterized. However, there still rages an open debate regarding the distance to the Pleiades.

Figure 1 summarizes distances obtained for the Pleiades cluster to date, including the new measurement described here. As can be seen, most measurements are in rough agreement with that produced in this work, with the stark exception of the *Hipparcos* astrometric satellite distances. For a single object near the distance of the Pleiades, *Hipparcos* was not capable of producing a distance measurement with accuracy better than 10%. However, by taking the aggregate of many cluster members, *Hipparcos* was able to achieve a Pleiades parallax with roughly 1% precision (6, 7). In almost any other case, one would simply discard the disagreeable *Hipparcos* cluster distances as bad measurements, but the *Hipparcos* mission represents the most complete astrometric survey of the sky and of the Pleiades cluster to date. It provides a path that is free of stellar physical models to obtaining the cluster distance and combines more than 50 cluster-member distance measurements. Other methods either include at most several cluster members in their distance determination, rely heavily on physical models to obtain a cluster distance (whereas it should be the distance measurement that informs the development of physical models), or result in large uncertainties in the cluster distance.

Although the discrepancy between *Hipparcos* and the average non-*Hipparcos* distance (Fig. 1) amounts to a 10% difference, the resultant changes to physical models needed to obtain agreement with the *Hipparcos* value are quite significant.

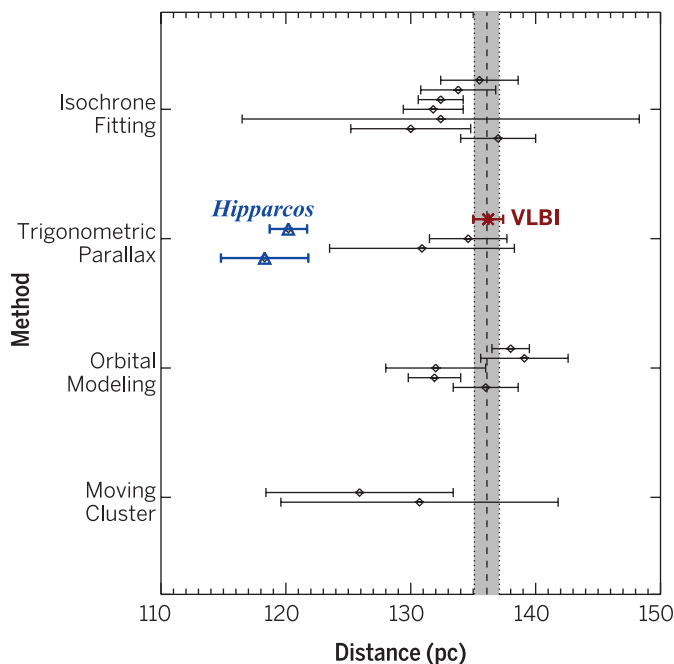
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**Fig. 1. Pleiades cluster distances.**

Summary of Pleiades distances obtained through various methods. The red asterisk with a distance of  $136.2 \pm 1.2$  pc is the new VLBI determination. The blue triangles near 120 pc are from two reductions of the *Hipparcos* data (6, 7). The vertical dashed line with uncertainty range shown by dotted lines and filled in with gray is the cluster distance derived from non-*Hipparcos* trigonometric parallaxes and binary orbits. All plotted errors are  $\pm 1$  SD. References for the distances shown, from top to bottom for each category, are as follows:

isochrone fitting—An *et al.* (4), Percival *et al.* (19), Stello and Nissen (20), Pinsonneault *et al.* (5), Giannuzzi (21), van Leeuwen (22), and Nicolet (23); trigonometric parallax (excluding *Hipparcos* and VLBI)—Soderblom *et al.* (8) and Gatewood *et al.* (10); orbital modeling—Groenewegen *et al.* (11), Southworth *et al.* (24), Zwahlen *et al.* (12), Munari *et al.* (25), and Pan *et al.* (26); moving cluster—Röser and Schilbach (27) and Narayanan and Gould (13).



One such change requires a 20 to 40% increase in the amount of helium (He) that Pleiades stars are composed of (5), a change that throws into question any attempt to systematically apply model isochrones to groups of stars that have not been characterized in great detail, because one typically only has brightness measurements at a few wavelengths. (Making compositional measurements is extremely resource expensive, and He measurements in particular are difficult. He measurements to date suggest that stars formed in the recent Galactic history have similar He abundances.) A more disconcerting explanation invokes different, unknown physics for young stars of roughly Pleiades-age (6), thus challenging our general understanding of the star-formation and evolution process. As a result, the controversy surrounding the distance to the Pleiades has not subsided. On the contrary, it has grown as each side of the debate has exchanged their own views and neither side has backed down (7, 8).

Given the disagreement between parallax measurements using a similar methodology (relative astrometry in the optical wavelengths), we pursued a new approach that could provide an independent view on Pleiades cluster distance measurements made to date. Our approach uses radio astrometry (9), a technique that provides an absolute distance measurement via referencing to an essentially stationary (to within our measurement capabilities) quasistellar object (an actively accreting supermassive black hole in the

distant universe). To achieve sufficient precision (better than 0.0001 seconds of arc) in stellar position measurements, we made observations using an array of widely separated radio antennas that when acting in concert give the resolution of a telescope the size of Earth. The very long baseline interferometry (VLBI) array employed by our study uses the Very Long Baseline Array (VLBA) as its core and additionally incorporates the Robert C. Byrd Green Bank Telescope, the Effelsberg Radio Telescope, and the William E. Gordon Telescope at Arecibo Observatory for enhanced resolution and sensitivity. Four Pleiades star systems were observed with this array over a period of  $\sim 1.5$  years to completely map their parallax motion (tables S1 to S5 and Fig. 2). Model fits to the motion of each star on the plane of the sky produce the desired parallax measurement (Table 1). The measured distances and  $\pm 1$  SD errors for the four systems are  $134.8 \pm 0.5$  pc (HII 174),  $138.4 \pm 1.1$  pc (HII 625),  $135.5 \pm 0.6$  pc (HII 1136), and  $136.6 \pm 0.6$  pc (HII 2147 system). Of note is the  $<1\%$  accuracy for the individual object VLBI distance measurements.

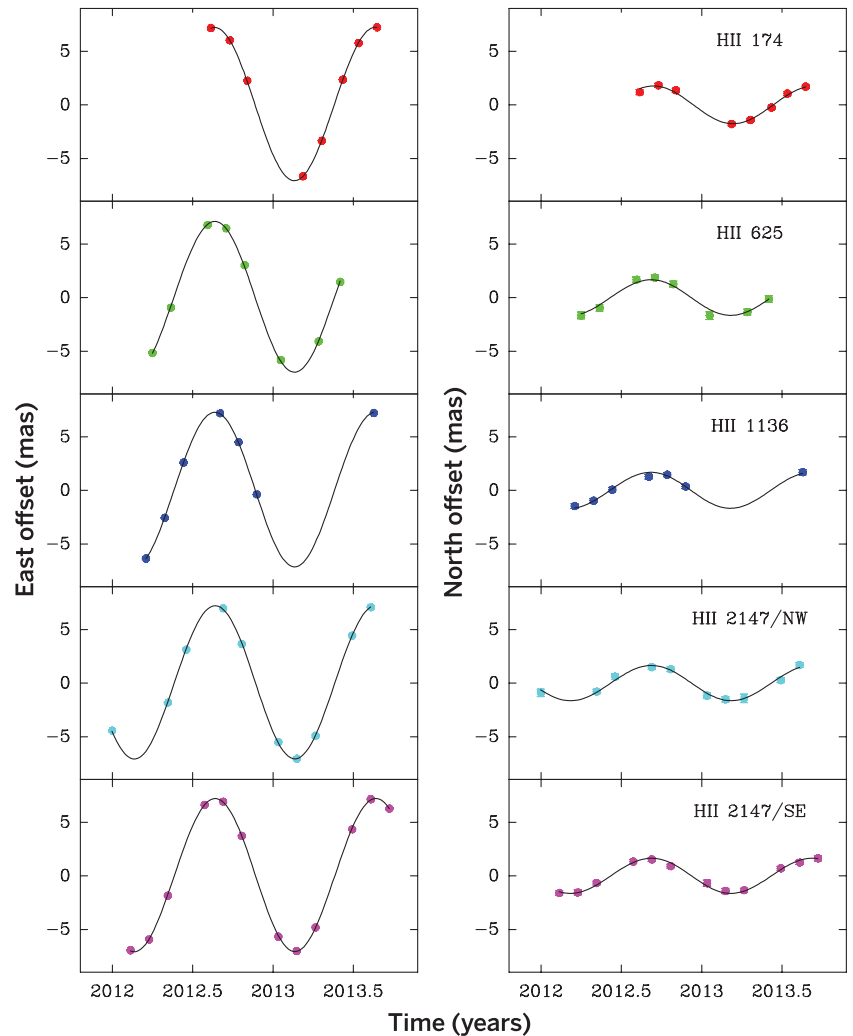
Already evident in each individual stellar distance measurement for our sample is gross disagreement with the *Hipparcos* cluster distance. To derive the cluster absolute parallax, however, one must include with the measurements of the individual stars the additional uncertainty of each star's position with respect to the center of the cluster. We adopt the approach of Soderblom *et al.* (8) of using the  $1-\sigma$

angular dispersion of the cluster as the systematic cluster-depth uncertainty. For an assumed Pleiades distance of 130 pc and cluster dispersion of  $1^\circ$ , we estimate the cluster-depth uncertainty to be 2.3 pc and add this value in quadrature to each object's formal distance uncertainty. This additional error component dominates the final cluster-distance uncertainty. When averaging individual VLBI measured distances to arrive at the final cluster distance, we treat HII 2147 as a single system and use the average of the distance measurements for HII 2147 NE and SW as given above. In this way, we calculate the VLBI-measured Pleiades cluster distance to be  $136.2 \pm 1.2$  pc ( $\pm 1$  SD).

An important aspect of this independent VLBI distance measurement is that it validates previous non-*Hipparcos* parallax and binary orbit distance measurements. As such, we can combine all parallax (including VLBI) and binary orbit distances into a single non-*Hipparcos* cluster distance; this sample includes 17 individual Pleiades star systems. Due to their fitting techniques, which result in coupled individual Pleiades member parallaxes, we treat each of the distance measurements of Soderblom *et al.* (8) and Gatewood *et al.* (10) as a single system measurement similar to the case of HII 2147 above. Each of the VLBI individual parallaxes, the two binary orbit distances (11, 12), and the distances of Soderblom *et al.* (8) and Gatewood *et al.* (10) are combined with a weighted mean. In deriving the combined cluster distance and associated uncertainty, cluster-depth uncertainty is added in quadrature to the uncertainty of each system distance measurement. From this, we obtain a non-*Hipparcos* Pleiades cluster distance of  $136.1 \pm 1.0$  pc (the vertical gray band in Fig. 1; this value is nearly identical to the VLBI-measured cluster distance because the VLBI parallaxes have the smallest uncertainty and hence carry the most weight).

Our results conclusively show that the *Hipparcos*-measured distance to the Pleiades cluster is in error. The general agreement of our distance measurement with those distances obtained by isochrone fitting in Fig. 1 suggests that physical models provide an accurate representation of the properties of Pleiades-age stars and that no unusual compositions or unknown physics lurk within this canonical cluster. Although this is likely a great relief for modelers of stars, it raises further questions into what happened with *Hipparcos*. Whatever error that manifested itself as a significantly skewed distance to the Pleiades cluster remains at large [some have suggested possible explanations; see, e.g., (13, 14)]. The unrecognized nature of such an error is especially dangerous when one considers that *Gaia* (15), the successor to *Hipparcos* and very similar in design, is just now starting its Galaxy-mapping mission. If the unrecognized *Hipparcos* error has crept into the *Gaia* pipeline, how would it manifest itself (if it does)? VLBI distance measurements like those presented here will serve as an important cross-check of the *Gaia* output near its predicted precision limits.

**Fig. 2. VLBI Pleiad parallaxes.** Parallax fits to VLBI position measurements and associated random errors ( $\pm 1$  SD) for five Pleiades stars, including both components of the HII 2147 binary system. For each object, the solid line is the best-fitting astrometric model that includes proper motion and parallax; the proper motion has been removed in the data points to accentuate the parallax motion. For each component of the HII 2147 binary system and for HII 1136, we additionally include acceleration terms in our fit to model short segments of a binary orbit. (The average angular separation between the two stars of the HII 2147 system over the monitoring period reported in tables S4 and S5 is  $\approx 60$  milliarcseconds (mas) or  $\approx 8.2$  astronomical units in projection). The left-hand panel curves and data points show east (right ascension times  $\cos(\text{declination})$ ) angular offsets on the sky of the source position relative to a distant quasar. The right-hand panel curves and data points show north (declination) offsets. Each source is color-coded and labeled in the declination panels.



**Table 1. Fitted astrometric parameters.** For each object in our sample, we conducted astrometric fits to the measured positions to extract stellar parallaxes. Only data taken in 2012–2013 were used for HII 1136 to ensure consistent and readily comparable results. Measured positions are modeled with the sum of a parallax sinusoid (determined by the parallax magnitude,  $\pi$ , and the purely geometrical motion for a given part of the sky induced by Earth's orbit), a reference position at an arbitrarily chosen fixed epoch, and a linear or accelerated proper motion ( $\mu_\alpha \cos \delta$ ,  $\mu_\delta$ ,  $a_\alpha \cos \delta$ , and  $a_\delta$ ). [Acceleration terms account for binary motion when the orbital period is much larger than the time frame over which the system was monitored and have been successfully

used in past attempts to measure system parallaxes; see (16).] This results in five or seven fitted model parameters. During the fitting process, the data are weighted using the quadrature sum of the formal measured fit uncertainties and an additional component that represents systematic uncertainties. A least-squares fitting routine determines the parameters that minimize the sum of the squares of the residuals. This process allows the systematic error component to be adjusted as necessary to obtain a  $\chi^2$  equal to 1 for each of the right ascension and declination data. The fitted proper motions can be compared with the values shown in the second and third columns that were previously determined from optical measurements. All uncertainties are  $\pm 1$  SD.

Source Name	Optical proper motions (17, 18)		Fitted parameters					
	$\mu_\alpha \cos \delta$ (mas year $^{-1}$ )	$\mu_\delta$ (mas year $^{-1}$ )	$\pi$ (mas)	$\mu_\alpha \cos \delta$ (mas year $^{-1}$ )	$\mu_\delta$ (mas year $^{-1}$ )	$a_\alpha \cos \delta$ (mas year $^{-2}$ )	$a_\delta$ (mas year $^{-2}$ )	$\chi^2$
HII 174	$22.0 \pm 2.0$	$-45.7 \pm 2.1$	$7.418 \pm 0.025$	$19.86 \pm 0.05$	$-45.41 \pm 0.16$	—	—	1.018
HII 625	$20.0 \pm 2.0$	$-47.9 \pm 6.9$	$7.223 \pm 0.057$	$19.47 \pm 0.11$	$-44.39 \pm 0.27$	—	—	1.002
HII 1136	$17.3 \pm 0.7$	$-44.8 \pm 1.8$	$7.382 \pm 0.031$	$17.18 \pm 0.05$	$-47.39 \pm 0.24$	$-0.43 \pm 0.16$	$0.6 \pm 0.8$	0.941
HII 2147 NW	$17.1 \pm 1.0$	$-45.4 \pm 0.7$	$7.328 \pm 0.035$	$23.22 \pm 0.05$	$-46.76 \pm 0.16$	$1.73 \pm 0.19$	$-3.9 \pm 0.7$	1.008
HII 2147 SE	$17.1 \pm 1.0$	$-45.4 \pm 0.7$	$7.319 \pm 0.027$	$14.05 \pm 0.04$	$-42.24 \pm 0.11$	$-1.05 \pm 0.18$	$2.0 \pm 0.5$	0.982

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#### SUPPLEMENTARY MATERIALS

[www.sciencemag.org/content/345/6200/1029/suppl/DC1](http://www.sciencemag.org/content/345/6200/1029/suppl/DC1)  
Supplementary Text  
Tables S1 to S5  
References (28–33)

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