Advancing the Physics of Cosmic Distances
Proceedings IAU Symposium No. 289, 2012
Richard de Grijs, ed.

doi:10.1017/S1743921312021114

Toward a VLBI resolution of the Pleiades distance controversy

Carl Melis,[1] **M. J. Reid,**[2] **A. J. Mioduszewski,**[3] **J. R. Stauffer,**[4] **and G. C. Bower**[5]

[1]Center for Astrophysics and Space Sciences, University of California, San Diego,
CA 92093–0424, USA
email: `cmelis@ucsd.edu`

[2]Harvard–Smithsonian Center for Astrophysics, 60 Garden Street, Cambridge, MA 02138, USA

[3]National Radio Astronomy Observatory, Array Operations Center, 1003 Lopezville Road,
Socorro, NM 87801, USA

[4]Spitzer Science Center (SSC), 1200 E. California Blvd., California Institute of Technology,
Pasadena, CA 91125, USA

[5]Astronomy Department and Radio Astronomy Laboratory, University of California, Berkeley,
CA 94720, USA

Abstract. The Pleiades is the best-studied open cluster in the sky. It is one of the primary open clusters used to define the 'zero-age main sequence,' and hence it serves as a cornerstone for programs which use main-sequence fitting to derive distances. This role is called into question by the 'Pleiades distance controversy:' the distance to the Pleiades from *Hipparcos* of approximately 120 pc is significantly different from the distance of 133 pc derived using other techniques. To resolve this issue, we plan to use Very Long Baseline Interferometry to derive a new, independent trigonometric parallax distance to the Pleiades. In these proceedings we present our observational program and report some preliminary results.

Keywords. techniques: interferometric, astrometry, stars: distances, open clusters and associations: individual (Pleiades), distance scale

---

1. Introduction

Because of its proximity and its youth, the Pleiades open cluster has been the subject of extensive observational and theoretical work throughout the 20th Century. It remains so in the 21st Century, with almost 100 refereed journal papers having 'Pleiades' in the title since 2000. Thanks to the wealth of existing knowledge, the Pleiades cluster stars are often used as templates with which to define the properties of other young stars (e.g., the Pleiades' lithium abundance versus color is used to define the locus for pre-main-sequence stars; the Pleiades' $v \sin i$ distribution is often compared to that for other clusters when discussing the evolution of angular momentum on the main sequence; the first brown dwarf in an open cluster was a Pleiades member; and the Pleiades now has the best-defined substellar locus of any open cluster). One would expect that all critical astrophysical parameters for such an important sample of stars would be well characterized. However, there still remains an open debate regarding the distance to the Pleiades.

Currently there are two main camps. On one side is the *Hipparcos* team (van Leeuwen & Hansen Ruiz 1997; van Leeuwen 2007) who state that their satellite's trigonometric parallaxes put the Pleiades at a distance of 118.3±3.5 pc and, more recently, 122.2±1.9 pc (van Leeuwen & Hansen Ruiz 1997; van Leeuwen 2007). On the other side are various

Table 1. Pleiades parallaxes (updated from Soderblom *et al.* 2005)

Method	π_{abs} (mas)	D (pc)	$m - M$ (mag)	Ref.
Hipparcos all-sky	8.45±0.25	118.3±3.5	5.37±0.06	2
Hipparcos new reduction	8.18±0.13	122.2±1.9	5.44±0.03	7
Main-sequence fitting	7.58±0.14	131.9±2.4	5.60±0.04	1
Allegheny Observatory parallaxes	7.64±0.43	130.9±7.4	5.59±0.11	3
Interferometric orbit	7.41±0.11	135.0±2.0	5.65±0.03	4
Dynamical parallax	7.58±0.11	131.9±3.0	5.60±0.05	5
HST FGS parallax of 3 Pleiads	7.43±0.17	134.6±3.1	5.65±0.05	6

References: 1, Pinsonneault *et al.* (1998); 2, van Leeuwen (1999); 3, Gatewood *et al.* (2000); 4, Pan *et al.* (2004); 5, Munari *et al.* (2004); 6, Soderblom *et al.* (2005); 7, van Leeuwen (2007).

ground-based and *Hubble Space Telescope (HST)*-based teams employing methods from main-sequence fitting to dynamical parallax determinations using binary stars (see Table 1). These teams, whose work can be theory-dependent or rely on a small sample of stars, offer a distance of 133 ± 0.9 pc (see Table 1 for a summary of Pleiades distances). Outside the *Hipparcos* community, the most often cited physical mechanism to explain the *Hipparcos* distance to the Pleiades is that there are unmodeled correlations in the *Hipparcos* data on angular scales of $\sim 1°$, which can (under some circumstances) bias distance estimates (Narayanan & Gould 1999)

Although what is listed above amounts to a 10% difference in the distance, the resultant discrepancies as propogated into the Pleiades Hertzsprung–Russell diagram, and the necessary revisions of physical models to obtain agreement with the *Hipparcos* result, are quite significant. The *Hipparcos* result, if correct, means that stars in the Pleiades are of order ∼0.2 magnitudes fainter than otherwise similar field stars. According to Soderblom *et al.* (2005):

> “This large discrepancy has forced a careful re-examination of the assumptions and input parameters of the stellar models, as well as a thorough study of the *Hipparcos* data itself and potential errors in it. The controversy has not been fully resolved in that builders of star models find that the changes in physics or input parameters needed to account for the *Hipparcos* distance are too radical to be reasonable, whereas the *Hipparcos* team has resolutely defended the *Hipparcos* result.”

The final comment regarding the *Hipparcos* team has held true, despite the recent ‘new’ reduction of the *Hipparcos* raw data (van Leeuwen 2007). As stated by van Leeuwen:

> “The new *Hipparcos* reduction results largely confirm the earlier results, including what has been referred to as errors in the published data: the parallaxes of the Pleiades... The new reduction leaves little, if any, room for an explanation of these differences as due to errors in the *Hipparcos* data.”

What can be done to reach a resolution regarding the distance to the Pleiades? Do models fall short of describing the *Hipparcos* Pleiades main sequence because of important, albeit overlooked, additional physics? Van Leeuwen (1999) considered whether plausible errors in the assumed helium or metal abundance of the Pleiades could explain the distance discrepancy, but concluded that this seemed very unlikely. The difference is instead ascribed to some unspecified, age-related property that causes young stars to be underluminous relative to current theoretical models (van Leeuwen 1999). Or does *Hipparcos* contain a systematic or instrumental error that has yet to be characterized? A clear resolution to the Pleiades distance problem requires a new approach that is free of the limitations of previous optical astrometric measurements. Such a technique is radio interferometric astrometry as afforded by Very Long Baseline Interferometry (VLBI). The highly accurate radio reference frame combined with the exquisite precision of VLBI astrometric measurements (e.g., Loinard *et al.* 2007, 2008; Reid *et al.* 2009) can be used to settle the Pleiades distance debate.

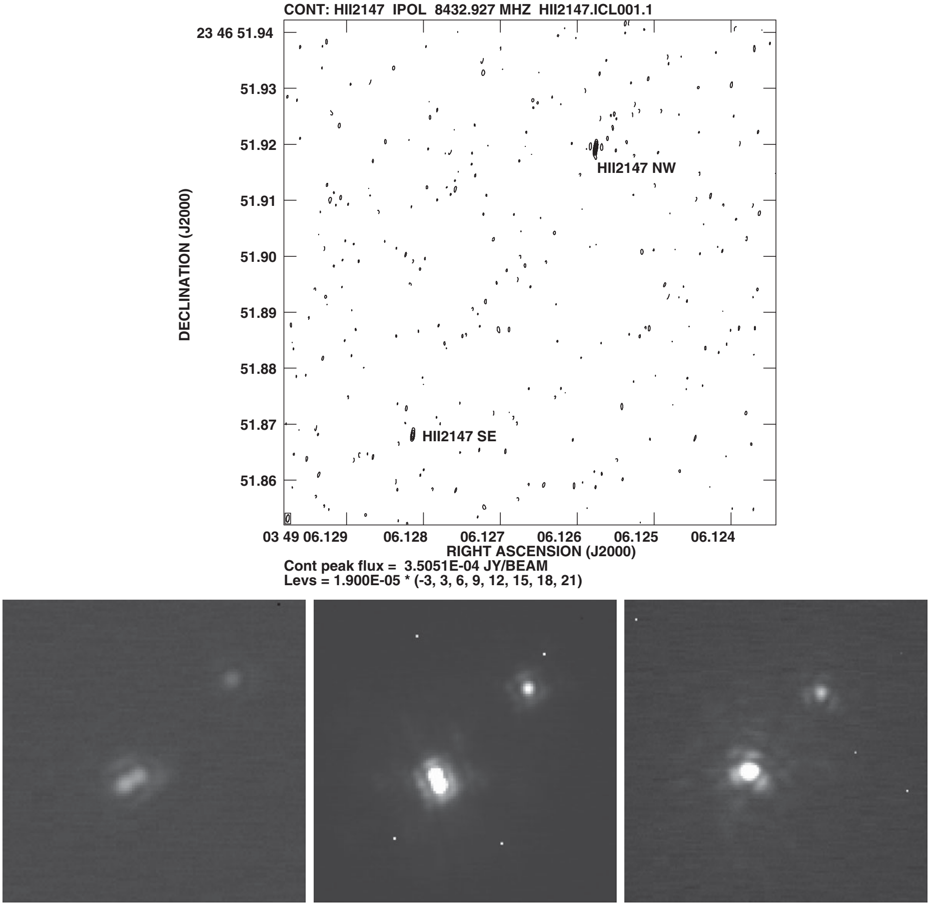

Figure 1. (top) Epoch 05 May 2012 VLBI image of the binary HII 2147 system. Both components are clearly detected. The projected separation between the binary components is 50 mas or roughly 6 AU. (bottom) Three epochs of *Keck II*/NIRC2-NGSAO imaging of HII 3197. The system is resolved into a triple and significant orbital motion of the close pair is seen from 2006 (left) to 2011 (middle) and 2012 (right). North is up and East is left in each image. The separation between the close pair and the tertiary is ≈0.6″.

2. NRAO Key Science Project

Using the full High Sensitivity Array (*HSA*: Very Long Baseline Array, Green Bank, Effelsberg, and Arecibo antennas), we are conducting a large (≈900 hr) program to determine the most accurate trigonometric parallax to the Pleaides cluster and hence resolve the 'Pleiades distance controversy.'

Of course, one needs radio sources with sufficient flux to enable VLBI measurements. Previous studies of the Pleiades at radio wavelengths have proven largely unsuccessful (e.g., Bastian *et al.* 1988; Lim & White 1995; and references therein). Pleiades members

Table 2. *VLA*-detected Pleiads

Star	$\log(L_X)$ (ergs s^{-1})	$(B-V)$ (mag)	$v \sin i$ (km s^{-1})	Radio program	Flux (μJy)	Binary?
HII 174	30.19	0.81	28	AM978,*JVLA*	90–120	Y
HII 253	30.46	0.64	37	AL361	90	N
HII 314	30.28	0.60	38	*JVLA*	115	N
HII 625	30.19	0.78	94	LW95,*JVLA*	110–160	Y
HII 1136	30.14	0.72	75	LW95,AL361	110–930	Y
HII 1883	29.67	0.99	140	LW95	50-100	N
HII 2147	30.5	0.76	27	AM978	130–180	Y
HII 2244	29.99	0.99	45	*JVLA*	60	N
HII 3197	30.14	1.03	33	AM978	90	Y
PELS75	30.1	0.91	56	*JVLA*	150	Y

X-ray data taken from Stauffer *et al.* (1994) and Micela *et al.* (1996, 1999). LW95 = Lim & White (1995). The binary column indicates whether any hint of binarity is noted in literature studies of the Pleiades (e.g., Mermilliod *et al.* 1992; Bouvier *et al.* 1997; and references therein).

have only been detected in a deep survey carried out by Lim & White (1995). However, the lesson learned through the study of Lim & White is that some Pleiads have quasi-steady radio luminosities on the order of 2×10^{15} ergs Hz^{-1} s^{-1}. Such luminosities equate to flux levels on the order of ∼0.2 mJy. Capitalizing on these previous observations, and with the eventual goal of a VLBI survey in mind, we attempted deep Very Large Array (*VLA*) observations of the brightest X-ray-emitting Pleiads. Our *VLA* sample targeted ultra-fast rotators (UFRs) that have X-ray luminosities on the order of $\log(L_X) \sim 30$ [ergs s^{-1}]. UFRs are known to exhibit enhanced coronal activity and are often detectable non-thermal radio emitters. Note that this target-selection strategy did not take into account whether or not sources were suspected members of binary systems. That is to say, our input *VLA* target catalog was unbiased with respect to binarity and included roughly equal numbers of (believed) single and binary stars. We designed our *VLA* experiment to test the quasi-steady flux level of known radio-emitting Pleiads, aiming for rms flux levels of ∼ 16 μJy $beam^{-1}$. Our program was successful (Table 2), with a ∼50% detection rate when we reached our sensitivity threshold. The flux levels we measure are on the order of ∼50–100 μJy.

The HSA is capable of detecting the elevated flux levels (≈100 μJy) and will be able to obtain even deeper detections (≈30–50 μJy) once 2 Gbps sampling, the phased Jansky *VLA* (*JVLA*), and the VLBA C-band receiver upgrades are complete.

2.1. *Project Path*

Our VLBI observational strategy includes nine total epochs of positional measurements for 10 Pleiads. Five target sources are being monitored with the HSA and will continue to be monitored until early 2013; after that time, five new sources will be monitored for roughly one year. This strategy is driven by two considerations: target binarity and cluster-depth issues.

Binarity

Through astrometric monitoring and literature searches, we have determined that most (if not all) of our VLBI target sources reside in binary systems. This preference for binary systems was not explicit in our source selection procedure; our targets were selected based solely on bright radio emission detected in preliminary *VLA* surveys. There is mounting evidence that radio-bright stars tend to reside within binary systems, so it is unlikely that there is a population of radio-loud targets in single systems.

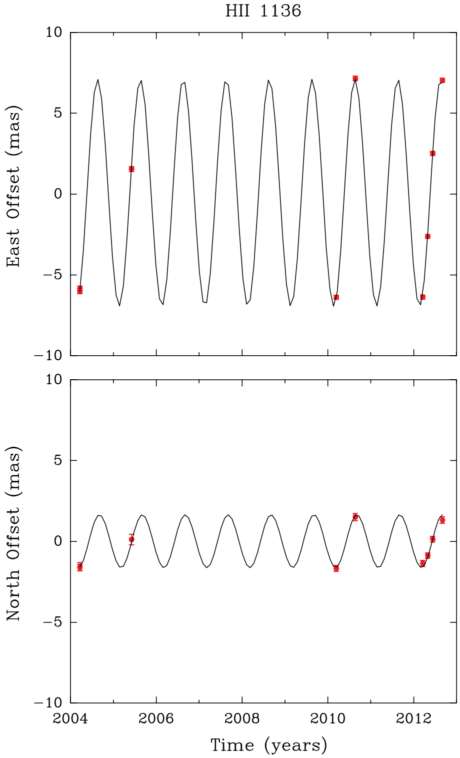

Figure 2. Astrometric model for Pleiad HII 1136 that includes proper motion, parallax, and orbital acceleration from an unseen binary companion. The top-panel curve and data points show right ascension angular offsets on the sky of the source position relative to an arbitrary reference position. The bottom-panel curve and data points show declination offsets. Proper motion has been removed in the data points to accentuate the parallax motion. The fit allows for acceleration as might come from a widely separated (orbital period greater than 10 yr) stellar companion. However, the fitted accelerations are small and do not change the parallax.

In some special cases, suspicions of binarity are confirmed by detection of light emitted by the binary component (e.g., Fig. 1). To properly determine the parallax motion of any astrometric binaries requires complete mapping of the binary system's orbital motion. To do this requires ≈9 astrometric measurements spaced over one year. Such a data set (18 measurements taking R.A. and Dec as independent parameters) will allow us to decouple parallax and proper motion (5 model parameters) from orbital motion (7 model parameters). Longer-period (>1 yr) systems, despite having incomplete orbital-period information, may still have an accurate parallax determined by the inclusion of acceleration terms in place of complete orbital fits. Such a strategy was successfully implemented by Loinard *et al.* (2007) in their determination of the parallax of the T Tau binary system with the VLBA.

Cluster Depth

The sample size of Pleiades objects is necessary to decouple cluster-depth issues from individual cluster member parallax measurements. In the new reduction of the *Hipparcos* data, van Leeuwen (2007) raises an important issue when discussing the *HST* parallax measurements of three low-mass cluster members by Soderblom *et al.* (2005). To derive the cluster's absolute parallax, one must include with the measurements of the individual stars the additional uncertainty of the star's position with respect to the cluster center.

It is thus of the utmost importance to have enough members to average out positionally dependent effects like the (unknown) distance between the target source and the true cluster center. A rough estimate of this uncertainty can be made (with simplifications) as follows: the half-mass radius of the Pleiades is 1.9 pc (Raboud & Mermilliod 1998). With 10 targets, and if the uncertainties are dominated by the physical depth of the cluster, our final distance uncertainty would be of order $1.9/\sqrt{10}$, or $\sim$0.6 pc.

3. Preliminary Results

One star in particular in the Lim & White sample exhibited a radio flare that peaked at a flux density of $\sim$1 mJy. This star, HII 1136, became the subject of VLBI pilot surveys to determine the feasibility of a full-scale Pleiades parallax program. We have now amassed VLBI detections for this system spanning almost 10 years. With these data we attempt a preliminary parallax fit. Two automated least-squares fits are performed (for fit details see, e.g., Reid *et al.* 2009; and references therein): one fit only allows parallax and proper motion as free parameters, while in the other fit we also allow for a constant acceleration term, the likes of which would be obtained if the HII 1136 system was composed of a long-orbital-period (>10 yr) binary.

The preliminary fit for the case of a constant acceleration term is shown in Fig. 2. Note that the addition of the constant acceleration term, although resulting in lower rms residuals, does not affect the parallax obtained. For this particular system we obtain a parallax of $\approx$7.2 mas. Such a distance is slightly farther away than the non-*Hipparcos* distances reported in Table 1. It could be the case that HII 1136 is on the far side of the cluster, since it lies within the cluster tidal radius regardless of which cluster distance is assumed.

References

Bastian, T. S., Dulk, G. A., & Slee, O. B. 1988, *AJ*, 95, 794

Bouvier, J., Rigaut, F., & Nadeau, D. 1997, *A&A*, 323, 139

Gatewood, G., de Jonge, J. K., & Han, I. 2000, *ApJ*, 533, 938

Lim, J. & White, S. M. 1995, *ApJ*, 453, 207

Loinard, L., Torres, R. M., Mioduszewski, A. J., & Rodríguez, L. F. 2008, *ApJ*, 675, L29

Loinard, L., *et al.* 2007, *ApJ*, 671, 546

Mermilliod, J.-C., Rosvick, J. M., Duquennoy, A., & Mayor, M. 1992, *A&A*, 265, 513

Micela, G., Sciortino, S., Kashyap, V., Harnden Jr., F. R., & Rosner, R. 1996, *ApJS*, 102, 75

Micela, G., *et al.* 1999, *A&A*, 341, 751

Munari, U., Dallaporta, S., Siviero, A., Soubiran, C., Fiorucci, M., & Girard, P. 2004, *A&A*, 418, L31

Narayanan, V. K. & Gould, A. 1999, *ApJ*, 523, 328

Pan, X., Shao, M., & Kulkarni, S. R. 2004, *Nature*, 427, 326

Pinsonneault, M. H., Stauffer, J., Soderblom, D. R., King, J. R., & Hanson, R. B. 1998, *ApJ*, 504, 170

Raboud, D. & Mermilliod, J.-C. 1998, *A&A*, 329, 101

Reid, M. J., *et al.* 2009, *ApJ*, 700, 137

Soderblom, D. R., Nelan, E., Benedict, G. F., McArthur, B., Ramirez, I., Spiesman, W., & Jones, B. F. 2005, *AJ*, 129, 1616

Stauffer, J. R., Caillault, J.-P., Gagne, M., Prosser, C. F., & Hartmann, L. W. 1994, *ApJS*, 91, 625

van Leeuwen, F. 1999, *A&A*, 341, L71

van Leeuwen, F. 2007, *A&A*, 474, 653

van Leeuwen, F. & Hansen Ruiz, C. S. 1997, in: *Hipparcos – Venice '97*, (Bonnet, R.M., Høg, E., Bernacca, P.L., *et al.*, eds), ESA-SP, 402, 689