CORRELATED ERRORS IN HIPPARCOS PARALLAXES TOWARD THE PLEIADES AND THE HYADES

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ABSTRACT

We show that the errors in the Hipparcos parallaxes toward the Pleiades and the Hyades open clusters are spatially correlated over angular scales of 2"–3", with an amplitude of up to 2 mas. This correlation is stronger than expected based on the analysis of the Hipparcos catalog. We predict the parallaxes of individual cluster members, \( \pi_{\text{pm}} \), from their Hipparcos proper motions, assuming that all the cluster members move with the same space velocity. We compare these parallaxes with their Hipparcos parallaxes, \( \pi_{\text{H}} \), and find that there are significant spatial correlations in the latter quantity. We derive a distance modulus to the Pleiades of 5.58 ± 0.18 mag from the gradient in the radial velocities of the Pleiades members in the direction parallel to the proper motion of the cluster. This value, derived using a geometric method, agrees very well with the distance modulus of 5.60 ± 0.04 mag determined using the main-sequence fitting technique, compared with the value of 5.33 ± 0.06 mag inferred from the average of the Hipparcos parallaxes of the Pleiades members. We show that the difference between the main-sequence fitting distance and the Hipparcos parallax distance can arise from spatially correlated errors in the Hipparcos parallaxes of individual Pleiades members. Although the Hipparcos parallax errors toward the Hyades are spatially correlated in a manner similar to those of the Pleiades, the center of the Hyades is located on a node of this spatial structure. Therefore, the parallax errors cancel out when the average distance is estimated, leading to a mean Hyades distance modulus that agrees with the pre-Hipparcos value. We speculate that these spatial correlations are also responsible for the discrepant distances that are inferred using the mean Hipparcos parallaxes to some open clusters, although an agreement between the mean Hipparcos parallax distance and the main-sequence fitting distance to other clusters does not necessarily preclude spatially correlated Hipparcos parallax errors. Finally, we note that our conclusions are based on a purely geometric method and do not rely on any models of stellar isochrones.

Subject headings: astrometry — open clusters and associations: individual (Pleiades, Hyades) — stars: distances

1. INTRODUCTION

Trigonometric parallax is a fundamental method for measuring distances to astronomical objects and is the first rung of the cosmic distance ladder. It is a purely geometric technique, without the need for any ill-understood empirical correlations between two physical quantities, one of which is dependent on the distance and the other independent of distance. The Hipparcos Space Astrometry Mission (ESA 1997) has derived accurate absolute trigonometric parallaxes for about 120,000 stars distributed all over the sky and has produced the largest homogeneous all-sky astrometric catalog to date. The global systematic errors in the Hipparcos parallaxes are estimated to be ≤0.1 mas, while the random errors in parallaxes of individual stars are typically on the order of 1 mas (Arenou et al. 1995; Arenou, Mignard, & Palasi 1997; Lindegren 1995). However, the mean Hipparcos parallax distances to some open clusters are different from their distances inferred using other techniques (Mermilliod et al. 1997b; Robichon et al. 1997; van Leeuwen & Ruiz 1997), suggesting that the true systematic errors may be an order of magnitude larger, at least on small angular scales (Pinsonneault et al. 1998, hereafter PSSKH98). In this paper, we estimate the level of the systematic errors in the Hipparcos parallaxes toward the Pleiades and the Hyades clusters by comparing for each of the cluster members, its Hipparcos parallax distance with its relative distance inferred from its Hipparcos proper motion, assuming that all the cluster members move with the same bulk velocity. We first determine the distance to the Pleiades cluster using a variant of the moving cluster method and then present the evidence for spatial correlations in the Hipparcos parallaxes toward both the Pleiades and the Hyades.

The distances to the Hyades and the Pleiades are fundamental quantities in establishing the absolute level of the main-sequence in the H-R diagram and, hence, in estimating the distances to open clusters using the main-sequence fitting technique. Thereby, they provide the first calibration points in the extragalactic distance scale. Hence, it is imperative that these distances are firmly established using techniques that require minimal assumptions. While the Hipparcos astrometric catalog provides straightforward distance estimates to these clusters from the mean of the parallaxes of the cluster members, there are surprising differences between the mean Hipparcos parallax distances and the distances estimated using other techniques for some open clusters, including the Pleiades (Mermilliod et al. 1997b; Robichon et al. 1997). In particular, the distance modulus to the Pleiades derived using the mean of the Hipparcos parallaxes is almost 0.3 mag smaller than that derived using the main-sequence fitting technique (van Leeuwen & Ruiz 1997), while there is no such discrepancy for the Hyades (Perryman et al. 1998; PSSKH98). A confirmation of this 15% shorter distance to the Pleiades from the Hipparcos parallaxes has serious implications for our understanding of stellar evolution. For example, if the Pleiades stars are in fact 0.3 mag fainter than they were previously thought to be,
there must be a population of subluminous zero-age main-
sequence field stars in the solar neighborhood that has so
far escaped detection (Soderblom et al. 1998).

The difference in the distance estimates using the Hip-
parcos parallaxes and using the main-sequence fitting
method are much larger than what would be expected from
incorrect metallicities, and this has led to an active search
for alternate explanations. These alternatives range from
the “Hyades anomaly” (Crawford 1975) arising from a low
helium abundance of the Hyades (Stromgren, Olsen, &
Gustafsson 1982), which therefore affects the relative dis-
tance between the Hyades and the Pleiades, to the “fourth
parameter” effect, which states that a fourth parameter is
required, in addition to the age, the metallicity, and the
helium abundance, to adequately describe solar-type stars
(Alexander 1986; Nissen 1988; see Mermilliod et al. 1997b
for a review of explanations invoking all these different
effects). PSSK98 showed that an impossibly large helium
abundance ($Y = 0.37$) is required for the Pleiades stars to
reconcile the shorter value of the Pleiades distance inferred
from the Hipparcos parallaxes with the main-sequence
fitting distance and proposed a simpler explanation that
there are spatial correlations in the Hipparcos parallax
errors on small angular scales. All these drastic conse-
quences of a shorter distance to the Pleiades mean that we
need to check independently if the Hipparcos parallaxes
toward this cluster are free from any systematic errors,
before invoking alternate explanations for the “failure” of
the main-sequence fitting technique.

Here, we compare the Hipparcos parallax distances to the
members of the Pleiades and the Hyades clusters with their
distances computed using the moving cluster method. This
method assumes that all the cluster members move with the
same space velocity and that the velocity structure of the
cluster is not significantly affected by rotation. Under this
assumption, we can predict the distance (and hence the
parallaxes) to each of the individual cluster members if we
know the common space velocity of the cluster. We use a
variant of the moving cluster method, the radial velocity
gradient method, to compute the distance to the Pleiades
using simple geometrical considerations. We use this
distance to estimate the common space velocity of all the
Pleiades members and then predict the parallaxes of indi-
vidual Pleiades members. We then compare these parall-
exes with the Hipparcos parallaxes of the same stars. This
enables us to test the accuracy of the Hipparcos parallaxes
on small scales, in a manner that is independent of any
stellar isochrones. We extend this analysis to the Hyades
cluster using the common cluster space velocity determined
by Narayanan & Gould (1999, hereafter NG99). The prin-
cipal result of this paper is that the Hipparcos parallaxes
toward both the clusters are correlated with position on
scales of about 3°, with an amplitude of about 1–2 mas.
While it is well known that the errors in the Hipparcos
parallaxes are correlated over small angular scales (Lindegren
1988, 1989; Lindegren, Froeschle, & Mignard 1997; Arenou
1997; van Leeuwen & Evans 1998), we find that
the correlation is probably stronger than previous
estimates.

The outline of this paper is as follows. We explain the
different variants of the moving cluster method in § 2. We
describe our selection of Pleiades cluster members from the
Hipparcos catalog and our estimate of the average proper
motion of the cluster in § 3. In § 4, we derive the distance to
the Pleiades from the gradient in the radial velocities of its
members, in the direction parallel to the proper motion of the
cluster. We compare this distance with the mean Hip-
parcos parallax distance and give our estimates of the sys-
tematic errors in Hipparcos parallaxes toward the Pleiades
in § 5. In § 6, we show that the same type of systematic
errors are also present in theHipparcos parallaxes toward
the Hyades. We present our conclusions in § 7. This is the
second paper in the series in which we compare the Hip-
parcos parallaxes of open clusters with independent
distances derived using geometrical techniques, the first be-
ing a check of the Hipparcos systematics toward the
Hyades (NG99). We note that we will drop the usual conver-
sion factor $A_e = 4.74047$ km yr $^{-1}$ from all our equations for
the sake of clarity, leaving it to the reader to include it in
the appropriate equations. This is equivalent to adopting the
units of AU yr $^{-1}$ for the velocities, although we will still
quote the numerical values of the velocities in km s $^{-1}$.

2. MOVING CLUSTER METHODS

The fundamental requirement for using the moving
cluster method to estimate the distance to a stellar cluster is
that all the stars in the cluster have the same space velocity
($V$) to within the velocity dispersion of the cluster. The three
observables of the cluster members, namely, their radial
velocities ($V_r$), their proper motion vectors ($\mu$), and their
angular separations ($\theta$) from a suitably defined cluster
center, are to a good approximation related by

$$V_T = V - V_r \hat{r},$$

$$\mu = \frac{V}{d},$$

$$\delta V_T = -V_r \theta,$$

$$\delta \mu_\perp = -\left(\frac{V}{d}\right) \theta_\perp,$$

$$\delta \mu_\parallel = -\left(\frac{V}{d}\right) \theta_\parallel - \frac{d \delta d}{d},$$

and

$$\delta V_r = (\theta \cdot \mu) d = \theta_\parallel \mu_\parallel d = \theta_\parallel V_T,$$

where $V_T$ is the transverse velocity of the cluster member in
the plane of the sky, $V_T = |V_T|$, the subscript $\perp$($\parallel$) for the
quantities $\mu$ and $\theta$ refers to the components of the respective
vectors perpendicular (parallel) to the proper motion
vector, and $\delta x$ is the difference in quantity $x$ ($x = V_T, \mu_\perp, \mu_\parallel, d$) between the individual member star and its
average value at the centroid of the cluster sample. Equa-
tions (1)–(6) assume that $|\theta| \ll 1$ (the small angle ap-
proximation), that $(\delta d/d) \ll 1$, that the velocity dispersion
of the cluster is small compared to its mean space velocity,
and that the velocity structure of the cluster is not signifi-
cantly affected by rotation, expansion, shear, etc. Equations
(4), (5), and (6) give three independent measures of the
distance to the cluster center, and we can derive a more ac-
curate distance to the cluster by taking their weighted average.
This can be effectively accomplished using the statistical
parallax formalism, as explained by NG99.

The two variants of the moving cluster method that are
currently in use depending on the nature of the available
data are the following.
1. The convergent-point method.—The proper motions of the individual cluster members are used to derive a convergent point on the sky. This information is combined with the average radial velocity of the cluster center to derive its distance using equation (4). This method has been successfully applied to the Hyades cluster for a very long time (Boss 1908; Schwan 1991; Perryman et al. 1998). Moreover, if there is independent information from high-precision photometry about the relative distances between individual cluster members, equation (5) can also be used to derive a more precise estimate of the cluster distance (NG99).

2. The radial velocity gradient method.—The radial velocities of the individual cluster members can be used to measure the gradient in the radial velocity across the face of the cluster, in the direction parallel to the proper motion of the cluster. This can be combined with an estimate of the average cluster proper motion, to derive the cluster distance using equation (6). This technique was first used by Thackeray (1967) to derive the convergent point of the Scorpio-Centaurus association. It has since been applied to determine the distance to the Hyades cluster (Detweiler et al. 1984; Gunn et al. 1988) and to determine the convergent point of the Pleiades cluster by assuming a distance (Rosvick, Mermilliod, & Mayor 1992a).

The three equations (4), (5), and (6) yield independent measures of the distance to the cluster with relative weights $W_i = N(d_i/\sigma_i)^2$, where $d_i$ and $\sigma_i, (i = 1, 2, 3)$ are the three distances and distance errors and $N_i$ is the number of stars used to estimate the cluster distance by method $i$. These weights are approximately given by

$$W_1 = N\left(\frac{\langle \theta \cdot V \rangle^2}{(d\sigma)^2 + \sigma_{clus}^2}\right),$$

$$W_2 = N\left(\frac{\langle \theta \cdot V \rangle^2}{(d\sigma)^2 + \sigma_{clus}^2 + (d\mu)^2}\right),$$

and

$$W_3 = N\left(\frac{\langle \theta \cdot V \rangle^2}{\sigma_i^2 + \sigma_{clus}^2}\right),$$

where $\sigma_i$ and $\sigma_\mu$ are the errors in the radial velocities and the proper motion, respectively, $\sigma_\mu$ is the uncertainty in the relative distance to individual cluster members, and $\sigma_{clus}$ is the velocity dispersion of the cluster. The weight $W_1$ corresponds to the classical convergent-point moving cluster method using individual proper motions (eq. [4]), while $W_2$ corresponds to the extension of this method using photometry to estimate the relative distances between the cluster members (eq. [5]). The weight $W_3$ corresponds to the radial velocity gradient method described by equation (6).

For the purpose of illustration, we assume that for the Pleiades cluster, $\sigma_{clus} = 0.7 \text{ km s}^{-1}$, $d\mu = 0.9 \text{ km s}^{-1}$, $\sigma_\mu = 0.3 \text{ km s}^{-1}$, $\sigma_\mu = 0.9 \text{ km s}^{-1}$, $\langle \theta \cdot V \rangle = \langle \theta \rangle = \langle \theta \rangle = \langle \theta \rangle$, $V_c = (1/5)V_p = 6 \text{ km s}^{-1}$, and $N_3 = 2N_2 = 2N_1 = 140$. This leads to $W_1$: $W_2$: $W_3 = 0.009:0.005:1.0$, which shows that 99% of the information about the Pleiades cluster distance is in equation (6), i.e., in the radial velocity gradient method. We will therefore use only the radial velocity gradient method in this paper. This is in sharp contrast to the situation for the Hyades where the relative weights are in the ratio 1:0.33:0.50, and hence most of the distance information is in the classical convergent point method as extended by NG99.

3. MEMBERSHIP AND AVERAGE PROPER MOTION

The procedure for determining the distance to the Pleiades from the radial velocity gradient (eq. [6]) requires an accurate estimate of the average proper motion of the cluster center in an inertial frame. In this section, we explain our procedure for selecting Pleiades members from the Hipparcos catalog and our estimate of the location and the average proper motion of the centroid of these members.

3.1. Cluster Membership

We begin by selecting all the stars from the Hipparcos catalog that are within $10^\circ$ of an approximate center of the Pleiades cluster and whose proper motions are consistent with them being Pleiades members. We assume an average radial velocity at the cluster center of $5 \text{ km s}^{-1}$, an average proper motion of $\mu_p = 20 \text{ mas yr}^{-1}$, $\mu_p = -45 \text{ mas yr}^{-1}$, an average distance of $d = 132 \text{ pc}$ and an isotropic cluster velocity dispersion of $\sigma_{clus} = 0.8 \text{ km s}^{-1}$. These values are only representative of the true values and are as such only approximately correct, although we find that the final list of cluster members is not very sensitive to these values. For each star $i$, we predict its proper motion $\mu_{pred,i}$ using equations (1) and (2) and compute the quantity $\chi_i^2$, defined as

$$\chi_i^2 = \langle \Delta \mu_i \mid C^{-1} \mid \Delta \mu_i \rangle,$$

where $\Delta \mu_i = (\mu_{\text{Hip},i} - \mu_{\text{pred},i})$, $\mu_{\text{Hip},i}$ is its Hipparcos proper motion, and where we have employed Dirac notation,

$$\langle X \mid \theta \mid Z \rangle = \sum_i X_i \theta_{ij} Z_j.$$ The covariance matrix $C_i$ is the sum of three terms: (1) the covariance matrix of the Hipparcos proper motion; (2) the isotropic velocity dispersion tensor of the cluster divided by the square of the mean distance of the cluster, $(\sigma_{clus}/d)^2$; and (3) a matrix of the form $\theta^2(\mu'_{\text{pred},i}, \mu_{\text{Hip},i})$ where we adopt $\theta_{ij} = (d/d) = 6\%$. The third term accounts for a finite depth of the Pleiades cluster along the radial direction and allows a Pleiades member to be located either in front of or behind the assumed fiducial distance $d$. We select all the stars with $\chi_i^2 \leq 9$ (corresponding to 3 $\sigma$) to be candidate Pleiades members. This procedure selects a total of 81 Pleiades candidates from the Hipparcos catalog. These include all but 12 of the 74 Pleiades candidate stars in the Hipparcos Input Catalog. The proper motions of these 12 stars (with Hipparcos identifications HIP 16119, 17026, 17684, 17749, 17832, 18018, 18046, 18106, 18149, 18201, 18748, and 19496) differ widely from the average proper motion of the Pleiades, and they are therefore most likely to be nonmembers.

We predict the parallax of each of these Pleiades candidates using its Hipparcos proper motion and the average space velocity of the cluster as

$$\pi_{pm,i} = \frac{\langle V \rangle_{i} \cdot C^{-1} \cdot \mu_{\text{Hip},i}}{\langle V \rangle_{i} \cdot C^{-1} \cdot \langle V \rangle_{i}},$$

where $(V)_{i} = V - \langle \hat{V} \rangle$, $(V)_{i}$ is the transverse velocity of the cluster in the plane of the sky at the position of the star $i$, and the covariance matrix $C_i$ is the sum of the velocity dispersion tensor of the cluster divided by the square of the mean distance to the cluster and the covariance matrix of the Hipparcos proper motion of star $i$. The error in $\pi_{pm,i}$ is...
equal to \( \langle (V_i)_h | C^{-1}_h | (V_j)_h \rangle^{1/2} \). We use this parallax and the \( V_j \) magnitude from Tycho photometry to estimate the absolute magnitude (and the associated error) of each of these Pleiades candidates.

Figure 1 shows the color-magnitude diagram (CMD) of all these Pleiades candidates. There is an easily identifiable main sequence in the color range \( 0 < (B-V)_j < 0.9 \), and there are a few stars that clearly lie either above or below this sequence even after accounting for their magnitude errors. We adopt a color-magnitude relation

\[
M_V = 4 + 5.57[(B-V)_j - 0.5] \quad (13)
\]

in the color range \( 0 < (B-V)_j < 0.9 \) and accept all the stars that lie within 0.4 mag of this line as Pleiades members. The observed color-magnitude relation is quite steep for \( (B-V)_j < 0 \) and does not show an unambiguous main sequence. Therefore, we assume that all the stars with \( (B-V)_j \leq 0 \) are Pleiades members. We also reject one star (HIP 16431) whose error in proper motion is greater than 4 mas yr\(^{-1}\). This algorithm selects a total of 65 stars as Pleiades members from the \textit{Hipparcos} catalog. These members are shown as filled circles in Figure 1, while the nonmembers and plausible binary systems are represented by the open circles. To summarize our selection of Pleiades members, we first select a total of 81 candidates from the \textit{Hipparcos} catalog whose proper motions are consistent with them being Pleiades members. We predict their parallaxes from their \textit{Hipparcos} proper motions assuming that they have the same space velocity as the centroid of the Pleiades. We then enforce a photometric cut where we accept as Pleiades members only those 65 candidates that lie close to the Pleiades main-sequence in the color-magnitude diagram.

![Color-magnitude diagram of all the stars in the Hipparcos catalog whose individual proper motions are consistent with them being Pleiades members. The filled circles show the stars used to derive the average proper motion of the Pleiades, while the open circles represent nonmembers and plausible binaries. The colors and apparent magnitudes \((B-V)_j\) and \(V_j\) are taken from Tycho photometry.](image)

3.2. Average Proper Motion

We estimate the centroid and the average proper motion of the Pleiades cluster using all the 65 Pleiades members identified from the \textit{Hipparcos} catalog in § 3.1. We compute the average proper motion at the cluster center as the mean of all the individual proper motions of the Pleiades members weighted inversely by their covariance matrices. The covariance matrix of each star is the sum of the covariance matrix of the \textit{Hipparcos} proper motions, the diagonal velocity dispersion tensor divided by the square of the mean distance of the cluster \((\sigma_{\text{clus}}/d)^2\) and a term arising from the distance “dispersion” \((\sigma_d)^2 \mu \cdot \mu\) to account for the nonzero depth of the Pleiades cluster. The observed dispersion in the proper motions of the cluster members in the direction perpendicular to the proper-motion vector includes contributions from only the velocity dispersion term and the errors in the \textit{Hipparcos} proper motions, while the observed dispersion parallel to the proper motion vector includes, in addition, a contribution from the dispersion in the distances to individual Pleiades members. Therefore, we estimate the dispersion in the proper motions from the difference between the observed and the \textit{Hipparcos} proper-motion covariance matrices in the perpendicular direction and derive the distance dispersion as the difference between the observed covariance matrices in the parallel and the perpendicular directions.

We find that the equatorial coordinate of the centroid of all the 65 Pleiades members is \( \alpha = 03^h46^m20^s, \delta = 23^\circ37'00" \) (2000). The average proper motion of the cluster at this location is \( \mu_x = 19.79 \pm 0.27 \) mas yr\(^{-1}\), \( \mu_y = -45.39 \pm 0.29 \) mas yr\(^{-1}\), and the correlation coefficient is \(-0.87\). Our estimate of the average proper motion of the Pleiades agrees well with the estimate of \( \mu_x = 19.67 \pm 0.24 \) mas yr\(^{-1}\), \( \mu_y = -45.55 \pm 0.19 \) mas yr\(^{-1}\) by van Leeuwen & Ruiz (1997). We repeat the entire cluster-membership determination from the \textit{Hipparcos} catalog stars using this improved estimate of the average cluster proper motion and find that the membership does not change, showing that our selection of Pleiades members is not very sensitive to the initial values we have assumed for the average cluster proper motion. Therefore, we will use these values for the average proper motion of the Pleiades cluster in the remainder of this paper.

In our solution for the average proper motion of the Pleiades, the dispersion in the proper motions is \( \sigma_d = 1.63 \pm 0.38 \) mas yr\(^{-1}\). Assuming a distance to the Pleiades of \( d = 130.7 \) pc (as we will find below), this dispersion in the proper motion corresponds to a velocity dispersion of \( 1.00 \pm 0.24 \) km s\(^{-1}\), in reasonable agreement with the value of \( 0.69 \pm 0.05 \) km s\(^{-1}\) we infer in § 4.2 from the radial velocities of the Pleiades members. Similarly, we find a value of the distance dispersion of \( \sigma_d = 1.37 \pm 0.74 \) mas yr\(^{-1}\) from the proper motions, corresponding to a depth of \( \sigma_d = (2.77 \pm 1.49)\% \), which in angular scales is \( \theta_d = 1.59 \pm 0.85 \). This is also in agreement with the angular dispersion of the 65 cluster members in the directions perpendicular and parallel to the average proper motion of the cluster, namely, \( \theta_d = 1.74 \pm 0.15 \) and \( \theta_d = 2.03 \pm 0.18 \). Thus, the estimates of the cluster velocity dispersion from both the proper motions and the radial velocities (which we will estimate in § 4.2) are consistent with each other. Similarly, the radial extent of the cluster that we infer from the proper motions is also comparable to the angular extent of the 65
members of the Pleiades cluster. We also find that 64 of the 65 Pleiades members are located within 6.2 of the centroid of the cluster.

4. RADIAL VELOCITY GRADIENT AND CLUSTER DISTANCE

We compute the distance to the Pleiades from the radial velocity gradient method using the average proper motion derived in the previous section and the individual radial velocities of Pleiades members. We now describe our selection of the Pleiades members with radial velocities and our estimate of the distance to the cluster from its gradient in the direction parallel to the average proper motion of the cluster.

4.1. Radial Velocity Sample

The Pleiades candidates in the Hipparcos catalog are mostly bright, early-type stars with large rotational velocities. Hence, it is difficult to measure their radial velocities from their spectra, and the radial velocity surveys of Pleiades stars have been almost entirely limited to faint, late-type stars (later than the spectral type F). Therefore, we select another list of fainter Pleiades members from the literature with measured radial velocities.

Our principal source of radial velocities is the radial velocity survey of the core and the corona stars in the Pleiades using the CORAVEL radial velocity scanner (Rosvick, Mermilliod, & Mayor 1992a, 1992b; Mermilliod, Bratschi, & Mayor 1997a; Raboud & Mermilliod 1998). These three data sets contain the radial velocity data for, respectively, stars in the Pleiades corona selected on the basis of their proper motions and Walraven photometry by van Leeuwen, Alphenaar, & Brand (1986), stars in the outer regions of the cluster selected on the basis of their proper motions by Artymukhina & Kalinina (1970), and stars in the inner region of the Pleiades in the Hertzsprung catalog (Hertzsprung 1947). The radial velocities quoted in the three sources are the raw values measured from the spectra of these stars (J. C. Mermilliod 1998, private communication). In practice, however, the measured radial velocities might include contributions from nonastrometric sources such as convective and gravitational line shifts, atmospheric pulsations etc. (Dravins, Larsson, & Nordlund 1986; Nadeau 1988). The measured radial velocities must be corrected for all these effects to estimate the true astrometric radial velocities of the stars. However, these corrections are likely to be smaller than 1 km s\(^{-1}\); therefore, we do not correct for these effects. Further, it is possible that the three different sources of radial velocities have different zero points, although this is unlikely to be a major problem for our sample of radial velocity stars as all the radial velocities are measured using the same instrument. We note here that our estimate of the distance to the Pleiades using the radial velocity gradient method using the average proper motion derived in §3.2 for a sample of stars whose centroid is at \( \alpha = 03^h46^m20^s, \delta = 23^\circ37^\prime0 \) (2000), we must use the same direction for \( \mathbf{n} \) in the present analysis, even though this is not the centroid of the radial velocity.

We use equation (14) to estimate the distance to the Pleiades \((d)\) from the radial velocities of all the Pleiades candidates selected in §4.1 and the average cluster proper motion derived in §3.2. For each Pleiades candidate star \( i \), we predict its radial velocity \( V_{r,i,\text{pred}} \) at this cluster distance and compute a quantity \( \chi^2 \), defined as

\[
\chi^2 = \sum_{i=1}^{N} \frac{(V_{r,i} - V_{r,i,\text{pred}})^2}{\sigma_{r,i}^2},
\]

where \( \sigma_{r,i} \) is the sum in quadrature of the errors in the observed radial velocity of star \( i \) and the velocity dispersion of the cluster \( \sigma_{\text{clus}} \) and \( N \) is the number of Pleiades candidates. We adjust the value of \( \sigma_{\text{clus}} \) so that the total value of \( \chi^2 \) is equal to \((N-2)\), and reject as nonmembers all the stars whose individual contributions to \( \chi^2 \) is greater than 9 (corresponding to a 3 \( \sigma \) outlier). We repeat this procedure with the reduced list of candidates until there are no stars whose individual contributions to \( \chi^2 \) are greater than 9.

We adopt as Pleiades members all the 141 of the 154 candidate stars that remain after the last iteration and derive a distance to the Pleiades of \( d = 130.7 \pm 11.1 \) pc, a velocity dispersion of \( \sigma_{\text{clus}} = 0.69 \pm 0.05 \) km s\(^{-1}\), and a radial velocity of the centroid of the cluster of \( V_r = 5.74 \pm 0.07 \) km s\(^{-1}\). The total \( \chi^2 \) at the end of the last iteration is 139 for a total of 141 stars, corresponding to 139 degrees of freedom. The distribution of individual contributions to \( \chi^2 \) is around the cut-off value of 9 are 6.1, 6.4, 8.0, 10.1, 12.2, 12.6, 25.4, 25.5, 49.9, and 60.6, where we include the first three stars with the values less than 9 as Pleiades members. The individual contributions to \( \chi^2 \) are not distributed as the square of a Gaussian function, and there is a clear break in the distribution around 13, although there is no clear break in the individual \( \chi^2 \) values at 9. The three stars with individual \( \chi^2 \) in the range \( 9 < \chi^2 < 12 \) are plausible members,
While the stars with $\chi^2 > 20$ are most likely to be binary systems or nonmembers. We find that if we include these three plausible members, the cluster distance is $d = 132.9 \pm 12.4$ pc, the new velocity dispersion is $\sigma_{\text{disp}} = 0.80 \pm 0.07$ km s$^{-1}$, and the radial velocity of the centroid of the cluster is $V_r = 5.80 \pm 0.08$ km s$^{-1}$. The total $\chi^2$ is 142 for a total of 144 stars, corresponding to 142 degrees of freedom. This shows that our estimate of the cluster distance is not very sensitive to the uncertainty in the cluster membership, and yields values around $d = 130$ pc as long as we reject the extreme outliers.

Figure 2 shows the radial velocity difference $[V_{r,i} - \langle \bar{V}_r \rangle_{n \cdot n_i}]$ for all the Pleiades candidates as a function of the quantity $(\mu \cdot n_i)$. The filled circles show the Pleiades members that are used to fit for the cluster distance, while the open circles represent the stars that are rejected as nonmembers by our algorithm. The solid line shows our best fit to equation (14), and its slope is our estimate for the distance to the Pleiades. We repeat here that the radial velocity gradient method is a geometrical method, which relies on the assumption that the velocity structure of the Pleiades is not significantly affected by rotation.

5. COMPARISON WITH HIPPARCOS PARALLAXES

The distance to the Pleiades from the radial velocity gradient method corresponds to a distance modulus of $(m - M) = 5.58 \pm 0.18$ mag. This value agrees very well with the "classical" estimates of the Pleiades distance modulus using main-sequence fitting techniques (Vandenberg & Bridges 1984; Eggen 1986; Vandenberg & Poll 1989; PSSKH98), all of which cluster around 5.60 mag. The discrepancy between the main-sequence fitting distance and the mean Hipparcos parallax distance to the Pleiades could arise for one of two reasons.

1. The Hipparcos parallaxes of the Pleiades members are systematically in error and are larger on average than their true parallaxes.

2. The isochrones that are used to derive the cluster distance in the main-sequence fitting technique are all systematically too bright, leading to a larger distance for the Pleiades.

The theoretical isochrones are calibrated on the Sun using accurate helioseismological data, and they are mostly used in a differential manner to derive the relative distances to clusters. Furthermore, the distances to other open clusters (e.g., the Hyades and α Per) using the same set of theoretical models are consistent with the Hipparcos parallax distances (PSSKH98). Finally, only explanation (1) can account for the marginal discrepancy between the mean Hipparcos parallax distance to the Pleiades and the distance derived using the radial velocity gradient method in § 4. The distance modulus to the Pleiades using the rotational modulation stars is also $5.60 \pm 0.16$ mag (O’Dell, Hendry, & Cameron 1994), marginally larger than the mean Hipparcos parallax value and in very good agreement with the values from both the main-sequence fitting and the radial velocity gradient techniques. This consistency between the different independent methods of estimating the distance to the Pleiades, all of which converge on a value of about 5.60 mag, strongly suggests that there may be systematic errors in the Hipparcos parallaxes toward the Pleiades. We now extend our analysis to examine the spatial structure of these errors.

Figure 3 shows the difference between $\pi_{\text{Hip}}$, the Hipparcos parallaxes, and $\pi_{\text{pm}}$, the parallaxes predicted using Hipparcos proper motions assuming that the members have a common space velocity, as a function of their angular distance from the centroid of the cluster $(|\theta|)$, for the 65 Pleiades members that are selected from the Hipparcos
catalog using the procedure described in § 3.1. The error bars show the quadrature sum of the errors in \( \pi_{\text{Hip}} \) and the errors in \( \pi_{\text{pm}} \). It is immediately obvious from this figure that the \textit{Hipparcos} parallaxes are systematically larger than the parallaxes predicted assuming common cluster motion, by up to 2 mas, for all the stars that are located within 1° of the centroid of the cluster. The scatter in the values of \( (\pi_{\text{Hip}} - \pi_{\text{pm}}) \) increases for \( |\theta| > 1° \), although it is clear that there is still a systematic deviation from zero up to about \( |\theta| = 2° \).

Figure 4 shows the contours of the difference between the \textit{Hipparcos} parallaxes \( (\pi_{\text{Hip}})_{\text{pm}} \), smoothed on scales of \( \theta = 1° \) and the similarly smoothed parallaxes predicted from the \textit{Hipparcos} proper motions assuming a common space velocity for all the cluster members \( (\pi_{\text{pm}})_{\text{pm}} \), in an \( 8° \times 8° \) region about the centroid of the Pleiades cluster. Solid contours correspond to \( (\pi_{\text{Hip}} - \pi_{\text{pm}}) \geq 0 \), while dashed contours correspond to \( (\pi_{\text{Hip}} - \pi_{\text{pm}}) < 0 \). The light contours range from \(-1.8 \) mas to \(+2 \) mas in steps of \( 0.1 \) mas, while the heavy contours range from \(-1 \) mas to \(+2 \) mas in steps of \( 1 \) mas. The filled circles show the positions of the individual Pleiades members. We find this smoothed parallax difference field by computing the quantity \( (\pi_{\text{Hip}} - \pi_{\text{pm}}) \) for each of the 65 Pleiades members and convolving this difference with a Gaussian filter \( \exp \left( -\theta^2 / (2\theta^2) / \sigma^2 \right) \), where \( \sigma^2 = \sigma^2_{\text{Hip}} + \sigma^2_{\text{pm}} \). The weighting by the inverse of the square of the error ensures that the stars with noisy estimates of the parallax difference are naturally given low weights when computing the smoothed parallax difference field. This figure clearly shows that the \textit{Hipparcos} parallaxes \( \pi_{\text{Hip}} \) are systematically larger than \( \pi_{\text{pm}} \) by up to 2 mas, throughout the inner \( 6° \times 6° \) region around the centroid of the Pleiades. Since very few of our 65 cluster members are located outside the inner \( 4° \times 6° \) region, the smoothed field values (the signal) outside this region comes primarily from the stars in the inner region and therefore contains very little independent information about the spatial structure of the systematic errors. Hence, we restrict our quantitative analysis of this parallax difference field of the Pleiades to the inner \( 4° \times 6° \) region (shown by the dashed box in Fig. 4) in the remainder of this paper.

The spatial structure seen in Figure 4 can arise from spatially correlated systematic errors in (1) the \textit{Hipparcos} parallaxes \( \pi_{\text{Hip}} \), (2) the parallaxes predicted from the \textit{Hipparcos} proper motions assuming a common space velocity for all the cluster members \( \pi_{\text{pm}} \), or (3) both of these parallaxes. Of these three possibilities, (1) will be true if there are as yet uncorrected spatial correlations in the \textit{Hipparcos} parallax errors on angular scales of a few degrees, while (2) will be the main source of error if the velocity field of the Pleiades is dominated by substantial substructures that invalidate the assumption of a common space velocity for all the cluster members. In principle, it is also possible that the structure arises from spatially correlated errors in the \textit{Hipparcos} proper motions. Indeed, if there are spatially correlated errors in \textit{Hipparcos} parallaxes, it is reasonable to expect similar effects in the \textit{Hipparcos} proper motions. However, the structures seen in Figure 4 are of the same size \( (~1 \) mas) as \( \sigma_{\text{Hip}} \), the statistical errors in \( \pi_{\text{Hip}} \). The statistical errors in \( \pi_{\text{pm}} \) arising from \( \sigma_{\text{pm}} \), the errors in the \textit{Hipparcos} proper motions, are smaller than this by a factor \( (\sigma_{\text{pm}} / \sigma_{\text{Hip}}) \approx \frac{1}{2} \). Hence, one does not a priori expect correlations among the \textit{Hipparcos} proper-motion errors to have a noticeable effect. Nevertheless, the tests that we carry out below would automatically detect this unexpected effect if it were present.

To check which of the three alternatives is correct, we plot the quantities \( (\pi_{\text{Hip}} - \langle \pi_{\text{Hip}} \rangle) \) and \( (\pi_{\text{pm}} - \langle \pi_{\text{pm}} \rangle) \), in Figures 5 and 6, respectively, in the same format as in Figure 4. Here, \( \langle \pi_{\text{Hip}} \rangle = 8.52 \pm 0.15 \) mas and \( \langle \pi_{\text{pm}} \rangle = 7.63 \pm 0.03 \) mas are the average values, computed using the 65 Pleiades members, of the \textit{Hipparcos} parallaxes and the parallaxes predicted assuming a common space velocity for all the cluster members. The structures in Figure 5 closely resemble those in Figure 4 except for a shift of the zero point caused by the adoption of \( \langle \pi_{\text{Hip}} \rangle \) as the Pleiades cluster parallax. In Figure 6, on the other hand, the inner \( 4° \times 4° \) region around the cluster center is remarkably smooth and close to zero, and there are no contours (either positive or negative) other than the one corresponding to \( (\pi_{\text{pm}} - \langle \pi_{\text{pm}} \rangle) = 0 \). This shows that the structures in \( \pi_{\text{pm}} \) arising from the errors in the \textit{Hipparcos} proper motions are quite small compared to the structures arising from the correlations in the \textit{Hipparcos} parallaxes.

It is clear from Figures 5 and 6 that the spatial structure in Figure 4 arises primarily from the spatial structure in the \textit{Hipparcos} parallaxes. The parallaxes in the entire region southeast of the centroid of the cluster are systematically too large by up to 2 mas, while there are no regions inside the inner \( 4° \times 6° \) region where the parallax difference is less than \(-0.5 \) mas. It is clear from Figure 4 that an average of the \textit{Hipparcos} parallaxes of stars lying in this region will be systematically larger, leading to an underestimate of the distance to the Pleiades. We note here that the spatial structure seen in the \( (\pi_{\text{Hip}} - \pi_{\text{pm}}) \) field in Figure 4 is independent
of our distance scale to the Pleiades itself. Thus, if our estimate of the Pleiades space velocity is wrong, so that all of our estimates of \( \pi_{\text{pm}} \) are systematically in error, the absolute levels of the contours will change, while the spatial structure itself will remain the same. A one-dimensional analog of our Figure 5 is Figure 20 of PSSKH98, which plots the Hipparcos parallaxes of individual Pleiades members as a function of their angular distance from the cluster center.

We see from the spatial structure in the smoothed field \( (\pi_{\text{hip}} - \pi_{\text{pm}}) \), in Figure 4 that the Hipparcos parallax errors are correlated with position on angular scales of about 3\(^{\circ}\), with an amplitude of up to 2 mas. This is much larger than the upper limit of 0.1 mas to the error in the global zero point of the Hipparcos parallaxes (Arenou et al. 1995, 1997), which, however, is valid only on large angular scales. Our estimate of the systematic errors demonstrates that they could be an order of magnitude larger than this on small angular scales, as was already suggested by PKSSH98.

Even before the launch of the Hipparcos satellite, it was anticipated that the errors in the Hipparcos parallaxes would be correlated over angular scales of a few degrees (Hoyer et al. 1981; Lindegren 1988, 1989). The analysis of the Hipparcos parallaxes showed that the parallax errors are indeed strongly correlated on small scales, although the correlation becomes negligible for angular separations greater than about 4\(^{\circ}\) (Lindegren et al. 1997; Arenou 1997; van Leeuwen & Evans 1998). An empirical fit to this correlation is given by the function (Lindegren et al. 1997)

\[
R(\theta) = R(0) \exp \left( -0.14 \theta - 1.04 \theta^2 + 0.41 \theta^3 - 0.06 \theta^4 \right),
\]

(16)

where the angular separation, \( \theta \), is measured in degrees, and \( R(0) = 0.59 \). We now estimate how likely it is to get a parallax difference map \( (\pi_{\text{hip}} - \pi_{\text{pm}}) \) with the severe fluctuations seen in Figure 4 if the errors in \( \pi_{\text{hip}} \) are correlated according to equation (16).

Figure 7 shows the normalized distribution of the fluctuation amplitude, \( A \), in the quantity \( \langle \pi_{\text{hip}} - \pi_{\text{pm}} \rangle \), if the errors in Hipparcos parallaxes are correlated over small angular scales as described by equation (16). We define \( A \) as

\[
A = \left[ \langle \pi_{\text{hip}} - \pi_{\text{pm}} \rangle^2 - \langle \pi_{\text{hip}} - \pi_{\text{pm}} \rangle_s^2 \right]^{1/2}.
\]

We compute this distribution of \( A \) from an ensemble of 5000 Monte Carlo realizations of the parallax differences \( (\pi_{\text{hip}} - \pi_{\text{pm}}) \). At each Monte Carlo experiment, we assign a value of \( \langle \pi_{\text{hip}} - \pi_{\text{pm}} \rangle \) to each of the 65 members that is drawn from a Gaussian distribution whose variance is \( \sigma^2_{\text{tot},i} = \sigma^2_{\text{pm},i} + \sigma^2_{\text{pm},i} \) and whose correlation with the other stars is described by equation (16). We then compute \( A \) using only the values of the smoothed parallax difference field within the inner \( 4^\circ \times 6^\circ \) region of the centroid of the cluster. The arrow in Figure 7 shows the value of the observed fluctuation amplitude in the same region, \( A_{\text{obs}} = 0.47 \) mas, for the field shown in Figure 4. The probability of obtaining a fluctuation amplitude greater than the observed value is \( P(A > A_{\text{obs}}) = 17.7\% \), if the errors in the Hipparcos parallaxes are correlated according to equation (16).

There is a small but finite probability that the fluctuation amplitude of the smoothed parallax differences \( (\pi_{\text{hip}} - \pi_{\text{pm}}) \) toward the Pleiades is as high as that seen in Figure 4. However, the modest probability of 17.7\% suggests that there might be angular correlations in the Hipparcos parallax errors over and the above the correlation...
in the same region, mas, for the field shown in Fig. 4. The arrow shows the observed fluctuation amplitude \( p \) described by eq. (16). The distribution of the Pleiades members is described by a Gaussian function whose variance is about the center of the Pleiades cluster. This distribution is componentally correlated over angular scales of a few degrees, beyond what is expected from the analysis of the entire Hipparcos parallax errors toward the Hyades open cluster.

6. SYSTEMATIC ERRORS TOWARD HYADES

The analysis in the previous section shows that the Hipparcos parallax errors toward the Pleiades cluster are spatially correlated over angular scales of a few degrees, beyond what is expected from the analysis of the entire Hipparcos catalog. We now check to see if these extra angular correlations are also present in the Hipparcos parallax errors toward the Hyades. If we do find extra correlations toward the Hyades, it is possible that these correlations are generic features of the Hipparcos parallax errors all over the sky. We describe our selection of Hyades members from the Hipparcos catalog in § 6.1 and analyze the systematics of their Hipparcos parallax errors in § 6.2.

6.1. Hyades Membership

We start by selecting a sample of stars from the Hipparcos catalog that are likely to be Hyades members based on their Hipparcos proper motions, using the procedure described in § 3.1. We assume that the centroid of the Hyades cluster is at a distance of 46.5 pc toward the direction \( \alpha = 04^h 26^m 32^s, \delta = 17° 13' 3" \) (2000), the velocity dispersion of the cluster is \( \sigma_{\text{clus}} = 320 \text{ m s}^{-1} \), and the bulk velocity of the cluster in equatorial coordinates is \( (V_\ell, V_\phi, V_z) = (-5.41, 45.45, 5.74) \text{ km s}^{-1} \), as determined by NG99 using the statistical parallax algorithm. For each star that is within 30° of this direction, we form the quantity \( \chi_0^2 \) as defined in equation (10) and select the stars whose \( \chi_0^2 \) is less than 9 to be Hyades candidates. We adopt a value of the distance dispersion \( \theta_d \equiv (\delta d / d) = 15\% \) to account for the finite depth of the cluster. This procedure selects a total of 204 Hyades candidates from the Hipparcos catalog. We use equation (12) to predict the parallaxes (and the associated errors) of these Hyades candidates from their Hipparcos proper motions, assuming that all the cluster members move with the same space velocity. We estimate the absolute magnitudes of these stars using the parallaxes derived in this manner and their apparent \( V_j \) magnitudes from Tycho photometry.

Figure 8 shows the color-magnitude diagram of these Hyades candidates. We have plotted only the 197 candidates whose absolute magnitude errors are less than 1 mag. The parallax to each star is estimated from its Hipparcos photometry. The solid line in the figure shows this relation. We assume that all the stars that lie within a finite width of these relations as Hyades members. Our color-magnitude relation for the Hyades is

\[
M_V = \begin{cases} 
2.72 + 7.14[(B-V)_j - 0.35], & \text{if } 0.1 < (B-V)_j < 0.6, \\
6.44 + 4.84[(B-V)_j - 1.00], & \text{if } 0.6 < (B-V)_j < 1.5.
\end{cases}
\]

The solid line in the figure shows this relation. We assume that all the stars that lie within 0.4 mag of the blue CMD range have a steeper slope and a larger width compared to that in the color range 0.6 < (B-V)_j < 1.5. The larger width on the blue side probably arises from unidentified binary systems. Accordingly, we fit different color-magnitude relations in each of these color ranges and select all the Hyades candidates that lie within a finite width of these relations as Hyades members. Our color-magnitude relation for the Hyades is

\[
M_V = \begin{cases} 
2.72 + 7.14[(B-V)_j - 0.35], & \text{if } 0.1 < (B-V)_j < 0.6, \\
6.44 + 4.84[(B-V)_j - 1.00], & \text{if } 0.6 < (B-V)_j < 1.5.
\end{cases}
\]
shows that the Pleiades. have also plotted (but do not show) the quantities a few degrees, with an amplitude of about 1°È 

The dashed box shows the inner 6° region about the centroid of the Hyades cluster. This figure for the Hyades is analogous to Figure 4 for the Pleiades. We find this smoothed parallax difference field using the 132 Hyades members, in the same manner as described in § 5 for the Pleiades.

The smoothed parallax difference field in Figure 9 clearly shows that the Hipparcos parallaxes toward the Hyades are also spatially correlated over angular scales of a few degrees, with an amplitude of about 1–2 mas. We have also plotted (but do not show) the quantities (π_{Hip} – <π_{Hip}>)_s and (π_{pm} – <π_{pm}>)_s for the Hyades, in a manner similar to Figures 5 and 6 for the Pleiades. Once again, we find that the spatial structure in Figure 9 arises from the structure in the Hipparcos parallaxes toward the Hyades and is not due to the structure in (π_{pm})_s. However, unlike the Hipparcos parallaxes toward the Pleiades, which were all too large in the entire inner 4° × 6° region, the Hipparcos parallaxes toward the Hyades are systematically larger in some regions [e.g., a region of 2° × 2° centered on (Δx, Δδ) = (+3°, −1°)] and systematically smaller in other regions [e.g., a region of 2° × 2° centered on (Δx, Δδ) = (−1°, 1.5°)]. Hence, the average value of the parallax difference is close to zero, when it is computed using all the Hyades members that lie in different regions. This, combined with the large angular size of the Hyades cluster, can explain why the main-sequence fitting distance to the Hyades agrees with the average of the Hipparcos parallaxes of its members (PSSK98), although there are significant spatial correlations in the Hipparcos parallax errors of the individual Hyades members.

Figure 10 shows the normalized distribution of the fluctuation amplitude, A, in the quantity (π_{Hip} – π_{pm})_i, if the errors in Hipparcos parallaxes are correlated according to equation (16). We compute this distribution in the same manner as described for the Pleiades cluster. We compute the fluctuation amplitude only within the inner 6° × 8° region (dashed box, Fig. 9) around the centroid of the Hyades. The arrow in Figure 10 shows the value of the observed fluctuation amplitude in the same region, A_{obs} = 0.62 mas, for the field shown in Figure 9. The probability of obtaining a fluctuation amplitude greater than the observed value is P(A > A_{obs}) = 9.1%.

We see that there is only a modest probability of obtaining a fluctuation amplitude that is as large as the observed value. This is similar to the case of the Pleiades, although the probability in the case of the Hyades is almost a factor of two smaller than that for the Pleiades. The joint prob-

![Fig. 9.—Contours of the difference between the Hipparcos parallaxes (π_{Hip})_s, smoothed on a scale of θ = 1° and the similarly smoothed parallaxes predicted from the Hipparcos proper motions assuming a common space velocity for all the cluster members (π_{pm})_s, in an 8° × 8° region about the centroid of the Hyades cluster. Solid contours correspond to (π_{Hip} – <π_{Hip}>)_s ≥ 0, while dashed contours correspond to (π_{Hip} – π_{pm})_s < 0. The light contours range from −1.4 mas to +1.4 mas in steps of 0.1 mas, while the heavy contours range from −1 mas to +1 mas in steps of 1 mas. The filled circles show the positions of the individual Hyades members. The dashed box shows the inner 6° × 8° region about the centroid of the Hyades cluster.](image)

![Fig. 10.—Normalized distribution of the fluctuation amplitude, A, in the difference between the smoothed Hipparcos parallaxes (π_{Hip})_s and the parallaxes predicted from Hipparcos proper motions assuming a common space velocity for all the Hyades members (π_{pm})_s, in a 6° × 8° region about the center of the Hyades cluster. This distribution is computed assuming that the parallax differences for each of the i = 1, 2,...132 Hyades members are distributed as a Gaussian function whose variance is σ^2_{i,i} = σ^2_{Hip} + σ^2_{pm} and whose correlation with the other stars is described by eq. (16). The arrow shows the observed fluctuation amplitude in the same region, A_{obs} = 0.62 mas, for the field shown in Fig. 9.](image)
ability of obtaining the observed fluctuation amplitudes for both the Pleiades and the Hyades is only about 1.6%, if the smoothed parallax differences of the Pleiades and the Hyades clusters are independent random processes. This supports our speculation that there might be stronger angular correlations in the \textit{Hipparcos} parallax errors, beyond the model described by equation (16).

7. CONCLUSIONS

The \textit{Hipparcos} mission has derived absolute trigonometric parallaxes to about 120,000 stars distributed all over the sky. It is the largest homogeneous all-sky source of absolute parallaxes to date and can potentially influence many parallaxes to about 120,000 stars distributed all over the sky. It is clear from the above conclusions that it is necessary to adopt a cautious approach when averaging the \textit{Hipparcos} parallaxes over small angular scales. In particular, it is necessary to quantify the effect of spatial correlations in the parallaxes when dealing with a distribution of stars that are separated by a few degrees. Thus, for example, it has been found that when \textit{Hipparcos} parallaxes are used to estimate the absolute magnitudes of stars in open clusters, such disparate open clusters as Praesepe, Coma Ber, α Per and Blanco I define the same main sequence despite their widely different metallicities, with [Fe/H] ranging from −0.07 dex for Coma Ber to about +0.23 dex for Blanco I (Mermilliod et al. 1997b; Robichon et al. 1997). Our analysis shows that such an effect could arise from spatially correlated \textit{Hipparcos} parallaxes of the cluster members, of the type seen toward the Pleiades and the Hyades clusters. Thus, a metal-rich cluster whose \textit{Hipparcos} parallaxes are all systematically larger than the true values can have the same apparent main sequence as a metal-poor cluster whose systematic errors in different regions of the cluster cancel out on an average. The discrepancy between the distances inferred from the average \textit{Hipparcos} parallax and that inferred from the main-sequence fitting technique for other open clusters (e.g., for Coma Ber, PSSKH98) could also arise from correlated parallax errors that do not cancel out on average, similar to the situation in the Pleiades. On the other hand, as we showed for the Hyades, an agreement between these two distance measurements does not necessarily preclude stronger spatial correlations in the \textit{Hipparcos} parallaxes.

Our work shows that there are strong spatial correlations in the errors of the parallaxes in the \textit{Hipparcos} catalog. We note that this is not necessarily in conflict with the upper limit of 0.1 mas to the error in the global zero point of the \textit{Hipparcos} parallaxes over the full sky (Arenou et al. 1995, 1997). The global tests have very little power to probe for systematic errors on smaller scales. Finally, we note that, given the sparse average density of about 3 stars arcsec$^{-2}$ in the \textit{Hipparcos} catalog, the open clusters with a large local concentration of stars may be the only regions where we can test the small-scale systematics in the \textit{Hipparcos} catalog.

After the completion of this work, we became aware of the work of van Leeuwen (1999), who has suggested the existence of an age-luminosity relation for main-sequence stars, in strong contradiction with the standard theory of stellar evolution. Alternatively, if the small-angle correlations in the \textit{Hipparcos} parallaxes toward the Pleiades and the Hyades that we found in this paper are a generic feature of \textit{Hipparcos} parallaxes, then this proposed age-luminosity relation could be an artifact arising from an inadequate

4. The probabilities of obtaining the observed fluctuation amplitudes, $A_{\text{obs}}$, in the smoothed parallax difference field ($\pi_{\text{Hip}} - \pi_{\text{Hip}}$, are small for both the Pleiades and the Hyades (17.7% and 9.1%, respectively), if the angular correlations in the \textit{Hipparcos} parallax errors are described by equation (16). This suggests that there are almost certainly stronger spatial correlations in the \textit{Hipparcos} parallax errors beyond what is modeled by equation (16). Since we see these stronger correlations in \textit{Hipparcos} parallax errors toward both the Pleiades and the Hyades, we suggest that this may be a generic feature of the \textit{Hipparcos} parallax errors all over the sky.
treatment of these correlations. A more detailed discussion of this issue is beyond the scope of this paper and will be addressed in the ongoing work of Pinsonneault et al. (1999).

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