The distance to the Pleiades: an emblematic Pro-Am project

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A Pro-Am collaboration

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- E. García Melendo (Obs. Esteve Duran)
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- R. Miles, J. Saxton, K. Holland, R. Pickard (VSS, British Astronomical Association)
The Distance of the Pleiades and Nearby Clusters

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Abstract

We have determined the distance to nearby open clusters from the means of Hipparcs parallaxes recomputed from the intermediate data. The first result worth noticing is that Praesepe, Coma Ber, Alpha Persei and Blanco 1 define the same main sequence in spite of their differences in metallicity. The second and more surprising result is that the Pleiades, and probably IC 2391 and 2602, define a sequence about 0.5 mag fainter than the previous one. The mean parallax of the Pleiades is 8.60 mas, corresponding to 116 pc. There is no way to reconcile the trigonometric and photometric distances of the Pleiades. These results contradict the commonly accepted interpretation of the metallicity effects. The results are the same for the UBV, uvby and Geneva photometric systems. The parameter responsible for these differences has not yet been identified, although they could be accounted for by a significant difference in the helium abundance. However there is presently no indication of a much higher helium abundance in nearby young clusters or associations. The present result could be linked to the so-called Hyades anomaly.
Cosmology: $H_0 + \text{acceleration} + ...$

Pathways to Extragalactic Distances
[...] the project of determining the parallax of the Pleiades is not altogether hopeless.

Agnes M. Clerke (1893)

*The Observatory*, 16, 198
I have been in astronomy so long that I don't really believe astronomical distances are much good.
[...] the project of determining the parallax of the Pleiades is not altogether hopeless.

Agnes M. Clerke (1893)
*The Observatory*, 16, 198

I have been in astronomy so long that I don't really believe astronomical distances are much good.

Donald Lynden-Bell (1998)
*IAU Symp* 192, 15
d_{Hipparcos} = 120 (± 3) pc \hspace{1cm} vs \hspace{1cm} d_{CMD} = 135 (± 5) pc

(Mermilliod et al., Robichon et al. 1998)

Very significant difference :

15 pc = -0.3 mag = +1 mas
Hipparcos Venice Conference

\[ d_{\text{Hipparcos}} = 120 (\pm 3) \text{ pc} \quad \text{vs} \quad d_{\text{CMD}} = 135 (\pm 5) \text{ pc} \]

(Mermilliod et al., Robichon et al. 1998)

Very significant difference:

\[ 15 \text{ pc} = -0.3 \text{ mag} = +1 \text{ mas} \]

Increase Y to 0.34 (Belikov et al. 1998) ?
Decrease Z to 0.012 (Castellani et al. 2002) ?
Photometric evidence for \([\text{Fe/H}]=-0.1\text{dex}\) (Grenon 2001)?

[ Error in the ZP limited to 0.1 mas (Arenou/Lindegren) ]
High-resolution spectroscopic metallicities in the Pleiades

<table>
<thead>
<tr>
<th>Reference</th>
<th>[Fe/H]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cayrel et al. 1988</td>
<td>+0.13</td>
</tr>
<tr>
<td>Boesgaard 1989</td>
<td>+0.03</td>
</tr>
<tr>
<td>Cayrel 1990</td>
<td>+0.026</td>
</tr>
<tr>
<td>King et al. 2000</td>
<td>+0.04</td>
</tr>
<tr>
<td>Soderblom et al. 2009</td>
<td>+0.03 (±0.02 ±0.05)</td>
</tr>
<tr>
<td>Schuler et al. 2010</td>
<td>+0.01 (±0.02) (FeI)</td>
</tr>
</tbody>
</table>
# Trigonometric Parallaxes (Selection)

<table>
<thead>
<tr>
<th>Reference</th>
<th>$d$ [pc]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Schouten 1919</td>
<td>27(2)</td>
</tr>
<tr>
<td>Alden 1923</td>
<td>83(15)</td>
</tr>
<tr>
<td>Binnendijk 1946</td>
<td>101(16)</td>
</tr>
<tr>
<td>van Leeuwen 1983</td>
<td>130(5)</td>
</tr>
<tr>
<td>Hipparcos 1998</td>
<td>118(3)</td>
</tr>
<tr>
<td>Gatewood et al. 2000</td>
<td>131(7)</td>
</tr>
<tr>
<td>Makarov 2002</td>
<td>129(3)</td>
</tr>
<tr>
<td>van Leeuwen 2004</td>
<td>125(5)</td>
</tr>
<tr>
<td>Soderblom et al. 2004</td>
<td>135(3)</td>
</tr>
</tbody>
</table>
Van Leeuwen 1999
Über den Zusammenhang
von Helligkeit und Spektraltypus in den Plejaden.
Von Hans Rosenberg.

The first “HR” diagram

Hans Rosenberg (1911)
Ast. Nach. 186, 71
An et al. (2006)
An et al. (2006)

\[
(m - M)_0 = 5.66 \pm 0.01 \text{ (internal)} \pm 0.05 \text{ (systematic)}
\]
Optical (B-V) (V-I) diagrams required implausible [Fe/H]=-0.4

(V-K) (J-K) appear consistent above M(V)=6

Mean distance 134(3) pc
**Question:** how to measure the distance to the Pleiades, independently of trigonometric parallaxes and/or stellar evolution?
**Question:** how to measure the distance to the Pleiades, independently of trigonometric parallaxes and/or stellar evolution?

**Answer:** find a double-lined spectroscopic and eclipsing binary. This yields all orbital and physical parameters!
secondary eclipse detected!
A pro-am investigation of an interesting spectroscopic binary star

The plot shows the secondary minimum of an especially interesting eclipsing binary star which happens to be a member of the Pleiades star cluster. Several BAA members, including John Saxton, Andy Hollis, Karen Holland, Roger Pickard, Kevin West and Graham Salmon, are currently participating in an observing campaign on this star in support of an astronomer at the Cambridge Institute of Astronomy, David Valls-Gabaud (David has also been a member of the BAA since 1979).

The star in question, HD 23642, is a known spectroscopic binary system. Roger Griffin has derived a period for this system of 2.461136 days. Examination of HIPPARCOS data revealed 5 data points which happened to coincide with the expected time of the secondary eclipse. These data suggested the existence of a minimum with a depth of about 0.05 mag. Unfortunately none of the HIPPARCOS data coincided with the expected time of the primary minimum.

David Valls-Gabaud e-mailed the VSS Director, Gary Puyner last October requesting pro-am collaboration in support of a proposed observing campaign to verify possible eclipse phenomena. Gary immediately passed on details to various members of the Association, who could assist by carrying out photoelectric photometry of HD 23642.

primary and secondary eclipses. The depth of the first was found to be about 0.08 mag, and the secondary minimum was 0.05 mag in depth, consistent with the few Hipparcos observations.

Other observers around the world have also begun to monitor this binary system. John Saxton and myself, both in Cheshire, have detected the primary and secondary minima. The figure depicts the results of a CCD observing run made by the author on average of about 15 CCD frames each of 20-sec duration recorded through a small short-focus refractor of 100mm aperture, V-filter and Starlight Xpress SX-2 CCD camera. The standard deviation of differential magnitudes derived from individual CCD frames was 0.010 mag when near mid-eclipse.

John Saxton also carried out PMT-based photometry on the same night confirming the secondary eclipse, which from his data occurred at 21:64 hrs UT. Interestingly, this...
HD23642     HIC 17704     HzI 540     Gaultier 145

SB2 (Pearce 1957, Abt 1958)
Orbital elements : Griffin 1995
Summary of Pro-Am observations

Total: 12382 observations
Summary of Pro-Am observations

Total: 12382 observations
Observations in the same band at different telescopes to assess systematics in photometry

Summary of Pro-Am observations

Total: 12382 observations
there are still systematics in the residuals
Spectroscopy

Espadons at CFHT
Radial velocity orbit

Days

Radial Velocity (km s\(^{-1}\))

Phase

HD 23642
v sin i
v sin i

Espadons

UVES
$\phi_{\text{spec}} = 0.887$

$\phi_{\text{spec}} = 0.370$

SWP and LWP (IUE)
Full spectral energy distribution
Some systematics

- Zero points in radial velocities
- Differential reddening/patchy extinction
- Effet of diffuse light (decreasing with wavelength)
- Effects of assumed/inferred limb darkening
- Effects of inconsistent model atmospheres
Ca II CN CH absorption lines

CO cloud

Richtey et al. (2006)
Megacam image (J.C. Cuillandre, CFHT)
Systematic effects due to diffuse light
Systematic effects due to diffuse light
Systematic effects due to diffuse light
Systematic effects due to diffuse light
Systematic effects on the radii

Model: NextGen

$T_{\text{eff}} = 9800$ K

$\log g = 4.00$
Summary

- Outstanding Pro-Am collaboration
- The distance to the Pleiades is not quite settled yet!
- The 1% precision barrier not broken
- HD 23642 as a fundamental calibrator for SB2+EBs
- Importance of systematics
- Need for more observations, esp. in the IR (K-band)
Tomkin (2005)
Southworth et al. (2004)
Encoding:

<table>
<thead>
<tr>
<th>P(P1)</th>
<th>x = 0.14429628</th>
<th>y = 0.72317247</th>
</tr>
</thead>
<tbody>
<tr>
<td>P(P2)</td>
<td>x = 0.71281369</td>
<td>y = 0.83459991</td>
</tr>
</tbody>
</table>

↓

71281369

↓

83459991

S(P2)  7128136983459991

Breeding:

S(P1)  1442962872317247
S(P2)  7128136983459991

(a) Crossover (gene = 4):

144 2962872317247

↓

712 8136983459991

144 8136983459991

712 2962872317247

S(01)  1448136983459991
S(02)  7122962872317247

(b) Mutation (Offspring = 02, gene = 10):

S(02)  7122962872317247

7122962872317247

7122962872317247

S(02)  7122962878317247

Decoding:

S(02)  7122962878317247

71229628

78317247

↓

↓

P(02)  x = 0.71229628  y = 0.78317247
P(01)  x = 0.14429628  y = 0.83459991
[Fe/H] = 0.0668, $\alpha_{ov} = [0.00 - 0.20]$, $m_V - M_V = [5.60 - 5.70]$, $A = [70 - 100] \times 10^6$ years

<table>
<thead>
<tr>
<th>Star</th>
<th>$\nu$ ((\mu)Hz)</th>
<th>Identification ((n, l, m))</th>
<th>Star</th>
<th>$\nu$ ((\mu)Hz)</th>
<th>Identification ((n, l, m))</th>
</tr>
</thead>
<tbody>
<tr>
<td>V624 Tau</td>
<td>242.9</td>
<td>(1, 0, 0)</td>
<td>V650 Tau</td>
<td>197.2</td>
<td>(1, 1, 1)</td>
</tr>
<tr>
<td>$M = [1.68 - 1.72] M_\odot$</td>
<td>409.0</td>
<td>(3, 1, 1)</td>
<td>$M = [1.84 - 1.88] M_\odot$</td>
<td>292.7</td>
<td>(0, 2, -2), (2, 2, 2)</td>
</tr>
<tr>
<td>$\nu_{rot} = [3 - 5] \mu$Hz</td>
<td>413.5</td>
<td>(3, 1, 0)</td>
<td>$\nu_{rot} = [25 - 28] \mu$Hz</td>
<td>333.1</td>
<td>(3, 1, 1), (3, 2, 2)</td>
</tr>
<tr>
<td>$i = [37^\circ - 67^\circ]$</td>
<td>416.4</td>
<td>(3, 1, -1)</td>
<td>$i = [60^\circ - 70^\circ]$</td>
<td>377.8</td>
<td>(2, 2, -2), (3, 1, 0)</td>
</tr>
<tr>
<td></td>
<td>451.7</td>
<td>(3, 2, -2), (4, 0, 0)</td>
<td></td>
<td>489.4</td>
<td>(4, 1, 0), (4, 1, 1)</td>
</tr>
<tr>
<td></td>
<td>529.1</td>
<td>(4, 2, -1), (4, 2, -2)</td>
<td></td>
<td></td>
<td>(5, 0, 0)</td>
</tr>
<tr>
<td>V534 Tau</td>
<td>234.2</td>
<td>(1, 1, 0)</td>
<td>HD 23628</td>
<td>191.8</td>
<td>(0, 2, 2)</td>
</tr>
<tr>
<td>$M = [1.65 - 1.69] M_\odot$</td>
<td>252.9</td>
<td>(1, 1, 0)</td>
<td>$M = [1.82 - 1.86] M_\odot$</td>
<td>201.7</td>
<td>(1, 1, 1)</td>
</tr>
<tr>
<td>$\nu_{rot} = [14 - 16] \mu$Hz</td>
<td>307.6</td>
<td>(2, 0, 0), (2, 1, 1)</td>
<td>$\nu_{rot} = [24 - 26] \mu$Hz</td>
<td>376.6</td>
<td>(2, 2, -2)</td>
</tr>
<tr>
<td>$i = [59^\circ - 79^\circ]$</td>
<td>377.9</td>
<td>(2, 2-1), (3, 0, 0)</td>
<td>$i = [53^\circ - 59^\circ]$</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>379.0</td>
<td>(3, 1, 1)</td>
<td></td>
<td>448.1</td>
<td>(3, 2, -1), (4, 0, 0)</td>
</tr>
<tr>
<td></td>
<td>525.0</td>
<td>(4, 2, -1)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>V647 Tau</td>
<td>236.6</td>
<td>(1, 1, 1)</td>
<td>HD 23194</td>
<td>533.6</td>
<td>(5, 1, 1), (5, 1, -1)</td>
</tr>
<tr>
<td>$M = [1.68 - 1.72] M_\odot$</td>
<td>304.7</td>
<td>(1, 2, 1)</td>
<td>$M = [1.78 - 1.82] M_\odot$</td>
<td>574.9</td>
<td>(5, 2, 0), (5, 2, 1)</td>
</tr>
<tr>
<td>$\nu_{rot} = 10 - 11 \mu$Hz</td>
<td>315.6</td>
<td>(2, 0, 0), (2, 1, 1)</td>
<td>$\nu_{rot} = [14 - 23] \mu$Hz</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$i = 17^\circ - 18^\circ$</td>
<td>374.4</td>
<td>(2, 2, -1)</td>
<td>$i = 7^\circ - 12^\circ$</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>405.8</td>
<td>(3, 1, 0)</td>
<td></td>
<td>444.1</td>
<td>(3, 2, 0)</td>
</tr>
</tbody>
</table>
Fox Machado et al. (2006)

70-100-130 Ma

$Z=0.020$
Pan et al. (2004) and PTI (96-99) measures

Mark III (89-92) and PTI (96-99) measures

Must assume a mass-luminosity relation to get the distance range 133-137 pc

$d_{\text{Hipparcos}} = 117(14) \text{ pc}$

Pan et al. (2004)
Pan et al. (2004) and PTI (96-99) measures

Mark III (89-92) and PTI (96-99) measures

Must assume a mass-luminosity relation to get the distance range 133-137 pc

$d_{\text{Hipparcos}} = 117^{(14)}$ pc

Somewhat circular argument: requires astrophysical inputs and so gets MS distance

Pan et al. (2004)
Zwahlen et al. (2004)

12 further astrometric measures with MarkIII and NPOI
Disentangling with KOREL
Zwahlen et al. (2004)

No astrophysical assumptions

A purely geometrical measure

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Period [d]</td>
<td>290.984 ± 0.079</td>
<td>$K_1$ (km s$^{-1}$)</td>
<td>26.55 ± 1.41</td>
</tr>
<tr>
<td>$T_0$ [BJD]</td>
<td>2.450 583.0 ± 1.9</td>
<td>$K_2$ (km s$^{-1}$)</td>
<td>36.89 ± 0.22</td>
</tr>
<tr>
<td>$e$</td>
<td>0.2385 ± 0.0063</td>
<td>$q$</td>
<td>0.720 ± 0.036</td>
</tr>
<tr>
<td>$i$ (deg)</td>
<td>107.87 ± 0.49</td>
<td>$a$ (AU)</td>
<td>1.73 ± 0.04</td>
</tr>
<tr>
<td>$\omega$ (deg)</td>
<td>151.9 ± 2.2</td>
<td>$M_1$ ($M_\odot$)</td>
<td>4.74 ± 0.25</td>
</tr>
<tr>
<td>$\Omega$ (deg)</td>
<td>154.0 ± 0.7</td>
<td>$M_2$ ($M_\odot$)</td>
<td>3.42 ± 0.25</td>
</tr>
<tr>
<td>$a''$ (mas)</td>
<td>13.08 ± 0.12</td>
<td>$d$ (pc)</td>
<td>132 ± 4</td>
</tr>
</tbody>
</table>
B(492)     V(432)     5 new radial velocities
Independent analysis of the same data set from Munari et al. (2004)
fixed $q_{\text{spectroscopic}}$ : Monte Carlo around best fit of LC
<table>
<thead>
<tr>
<th>Quantity</th>
<th>M04</th>
<th>S05</th>
</tr>
</thead>
<tbody>
<tr>
<td>$T(A)$ [K]</td>
<td>9671(46)</td>
<td>9750(250)</td>
</tr>
<tr>
<td>$T(B)$ [K]</td>
<td>8023(544)</td>
<td>7600(400)</td>
</tr>
<tr>
<td>$E(B-V)$ [mag]</td>
<td>0.012(4)</td>
<td>0.012(4)</td>
</tr>
<tr>
<td>$d$ [pc]</td>
<td>132(2)</td>
<td>139(3)</td>
</tr>
</tbody>
</table>

$d_{\text{Hipparcos}} = 111(12) \text{ pc}$