NMSU ASTRONOMY CUME 439, 25 January 2020 **Jon Holtzman**

This cume is partly motivated by and will ask about material discussed in the research note "The Distance to the Pleiades According to Gaia DR2", by Abramson (2018).

A 75 percent grade will guarantee a pass.

Gravitational constant $G = 6.67 \times 10^{-8} cm^3 g^{-1} s^{-2}$, mass of sun $M_{sun} = 2 \times 10^{33} g$, speed of light $c = 3 \times 10^{10} cm/s$, $1pc = 3.086 \times 10^{18} cm$, $1au = 1.496 \times 10^{13} cm$

1. (9 points) Parallax, magnitudes, etc.

   (a) Make a sketch of the parallactic motion of a star in the Pleiades over the course of a full year. Is this the same for all stars on the celestial sphere? Explain.

   Answer should recognize that the observed parallax signature is an ellipse on the sky, with eccentricity related to ecliptic latitude. Pleiades is near the ecliptic, so parallactic motion for Pleiades should be close to a line.

   (b) Starting with the inverse square law, *derive* the expression relating absolute magnitude, apparent magnitude, and parallax.

$$F = \frac{L}{4\pi d^2}$$
$$m = -2.5 \log L + 2.5 \log 4\pi d^2 + C$$
$$M = -2.5 \log L + 2.5 \log 4\pi 10^2 + C$$
$$m - M = 5 \log \frac{d}{10} = 5 \log d - 5 = 5 log 1/\pi - 5 = -5 log \pi - 5$$

   (c) Derive an expression relating apparent magnitude, parallax, and luminosity in units of the solar luminosity (L_{sun}), in terms of the solar absolute magnitude, M_{sun}.

$$M - M_{sun} = -2.5 \log L/L_{sun}$$
$$m + 5 \log \pi + 5 - M_{sun} = -2.5 \log L/L_{sun}$$
$$L/L_{sun} = 10^{-0.4(m + 5 \log \pi + 5 - M_{sun})}$$

2. (6 points) Proper motion

   (a) Derive the expression between the proper motion in arcsec/year and the tangential velocity in km/s.

   If μ is the proper motion in arcsec/year, proper motion in radians/s is $\mu/206265/(3.15e7)$ radians/sec. At large distance, $\mu \sim x/d$, so in km/s, given the distance, d:

   $v_T(km/s) = \mu(radians/s)d(km) = 3.086e13(km/pc)/206265(arcsec/radian)/3.15e7(sec/year)\mu(arcs$

   (b) Using what you know about kinematics of stars in the solar neighborhood, what is a typical proper motion for nearby stars?

   Adopting a typical velocity dispersion of 50 km/s (perhaps too high), get $10/d$ arcsec/year.

3. (9 points) Uncertainties

   (a) Derive an expression for the uncertainty in the absolute magnitude of an object given an uncertainty in the parallax, σ_π, and an uncertainty in the apparent magnitude of σ_m.

$$m - M = -5 \log \pi - 5$$

   Using error propagation formula:

$$\sigma_M = \sqrt{\sigma_m^2 + (5 \log e \frac{\sigma_\pi}{\pi})^2} = \sqrt{\sigma_m^2 + (2.171 \frac{\sigma_\pi}{\pi})^2}$$

   (b) GAIA results lead to negative parallaxes for some objects. How can this be? What can you say about such objects?

   For small parallaxes, the uncertainty in the measurement can give a negative parallax. This would occur where the uncertainty is large relative to the parallax, i.e., for distant stars (or very faint stars).

   (c) By end of mission, GAIA expects to obtain typical parallax uncertainties of 24 μas and 540 μas, for stars of apparent magnitude 15 and 20, respectively. To what distances will GAIA be able to measure distances with an accuracy of 20% at these two apparent magnitudes?

   $1/(5 * 24e - 6) = 8.33$ *kpc and* $1/(5 * 370e - 6)$ *kpc*

4. (12 points) Pleiades

   (a) Based on information in the article, estimate the physical size of the Pleiades.

   If spread in parallax is 0.45 mas, that is fractional spread $0.45/7.34 = 0.06$, *so* $.06 * 136 = 8.33$ *pc*

   (b) Based on information in the article, estimate a rough mass for the Pleiades.

   Article suggests there are several thousand stars, assuming there is a standard IMF, these are mostly lower mass, so estimate of order 10^3 *solar masses.*

   (c) What is an order-of-magnitude estimate for the internal velocity dispersion in the Pleiades?

$$\sigma \sim \sqrt{\frac{GM}{R}} = 0.75 km/s$$

   (d) The authors consider stars with a proper motion less than 6 mas/yr from the cluster value. What motivates this choice?

   6 mas/yr corresponds to 3.8 km/s. Want stars within a few sigma of the velocity dispersion. Could be motivated by expected velocity dispersion or else by motivated by observational distribution of proper motions (peak against a background).

5. (12 points) Galactic rotation

(a) If you measured parallaxes and proper motions of stars in the solar neighborhood, and averaged them as a function of galactic longitude, what would the relation between tangential velocity and longitude look like? Explain.

In principle, varies as $\cos 2l$ *because of projection. In practice, hard to see (so question discounted!)*

(b) If you looked at a Galactic longitude of 30 degrees in HI 21-cm emission, qualitatively describe how the radial velocity of the gas would vary with distance.

At small distance, see gas with small radial velocity because of projection; as distance increases, the RV increases until tangent point, then decreases.

(c) How can 21-cm observations be used to measure the rotation curve of the inner Milky Way?

Look at various galactic longitudes, find maximum velocity, and assign to galactocentric radius of tangent point.

(d) What does a flat rotation curve imply about the distribution of mass in spiral galaxies, quantitatively?

$$v^2 \propto M/R$$

so if v *is constant, then* $M(R) \propto R$

The Distance to the Pleiades According to *Gaia* DR2

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open clusters and associations: individual (Pleiades) ; parallaxes; stars: distances

We present a calculation of the distance to the Pleiades star cluster based on data from *Gaia* DR2, showing that it finally settles the discrepancy between the values derived from *Hipparcos* and other distance determinations.

The distance to the Pleiades is an important astronomical parameter for a number of reasons. On the one hand, they are one of the closest star clusters and their young main sequence stars provide an important testbed for stellar evolution models. On the other, they are so close that measuring their distance by direct geometrical methods provides a good calibration of one of the rungs of the cosmic distance ladder. As such, they become a solid benchmark to develop empirical isochrones to be used in much more distant clusters, even extragalactic ones. *Hipparcos* was the first instrument able to directly measure the Pleiades' trigonometric parallax, and the publication of its catalog initiated a controversy, since it gave a distance around 120 pc, which was in tension with previous estimations (van Leeuwen 1999). Successive reassessments of the *Hipparcos* data alleviated to some extent this tension, but not entirely. In 2005 a measurement of 3 stars of the Pleiades carried out with the *Hubble Space Telescope* gave a distance of 133.5 pc (Soderblom et al. 2005). More recently, a very accurate measurement of the parallax by Very Large Baseline Interferometry provided a value of 136.2 pc (Melis et al. 2014), confirming that the *Hipparcos* value was indeed too small, most surely due to systematic errors at the small spatial scales of the tight cluster.

The recent publication of the *Gaia* DR2 catalog comes to finally close the controversy. The case of the Pleiades was indeed presented as an example in one of the publications associated with the release of the *Gaia* DR1 catalog (Gaia Collaboration et al. 2016). Using the preliminary values of 164 stars belonging to the cluster they found a distance of 134 pc, thus confirming the anomaly of the value of *Hipparcos*. Using the same method presented there we offer below a calculation of the distance to the Pleiades based on *Gaia* DR2.

Following Gaia Collaboration et al. (2016), we downloaded all the sources within a field centered in the Pleiades, $\alpha = 56\overset{\circ}{.}75$, $\delta = 24\overset{\circ}{.}12$, with a radius of 5°. This produced 699,860 records, of which 598,622 have a parallax value. This set was then subject to a filter in proper motion, keeping those sources satisfying the following criterion:

$$\sqrt{(p_\alpha - 20.5)^2 + (p_\delta + 45.5)^2} < 6\ \mathrm{mas\,yr}^{-1}.$$

This produced 1876 records. This criterion is probably very restrictive, since we had to manually add Merope, for which it gives 6.76 mas yr^{-1}. There are probably more members in the cluster, but this is the criterion used in Gaia Collaboration et al. (2016). Figure 1 shows a histogram of their parallaxes. The peak corresponding to the Pleiades clearly stands out at about 7 mas, together with a number of field stars. With an additional filter in parallax, keeping those in the interval $5 < \varpi < 9.5$, we get 1594 stars, an order of magnitude more than those used in Gaia Collaboration et al. (2016).

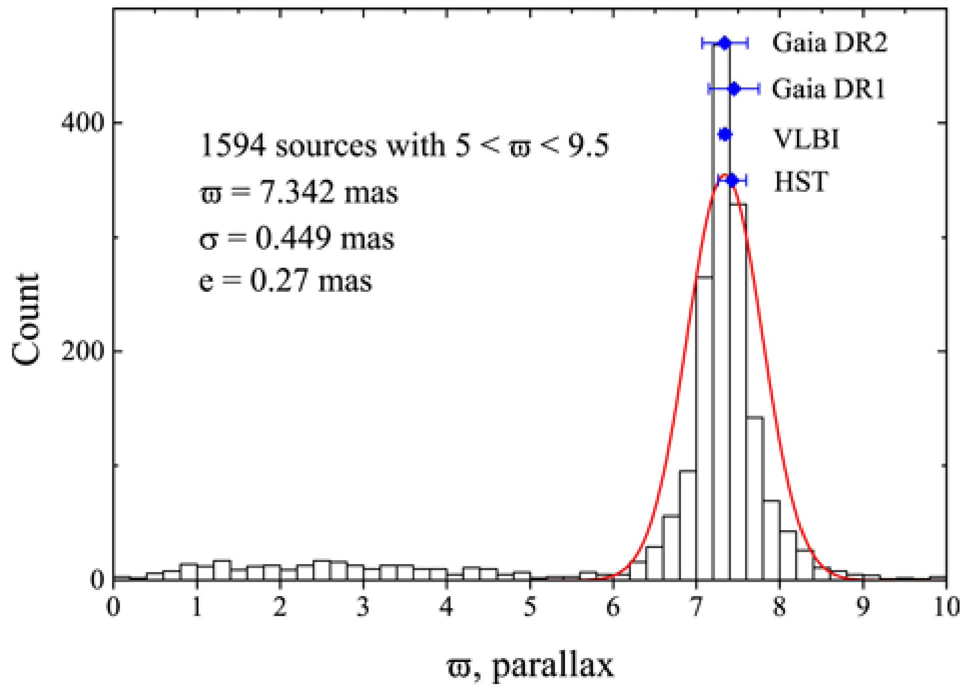

Figure 1. Histogram of the parallaxes of the sources of *Gaia* DR2 in the field of the Pleiades, and with similar proper motion. A Gaussian with the mean and standard deviation of the subset with $5 < \varpi < 9.5$ is also shown, as well as parallax values corresponding to this work and three previous ones.

The mean parallax of this set is 7.34 mas, with a standard deviation of 0.45 mas. A Gaussian with this parameters is also shown in Figure 1. The Pleiades are so close that this deviation cannot be taken as a measurement error at face value, but rather as a statistical characterization of the distribution of the stars of the cluster around its center. To obtain an estimation of the error we used the mean square error of the individual measurements, , where ϵ_i is the error of each measured parallax according to *Gaia* DR2. Finally we obtain a value of 7.34 ± 0.27 mas, which corresponds to a distance of 136.2 ± 5.0 pc.

A more sophisticated calculation would require an account of the systematic error, but Luri et al. (2018) explicitly says that "unfortunately, there is no simple recipe to account for the systematic errors." For the specific case of stellar clusters, Bailer-Jones (2017) suggests the use of a model of the distribution of stars in the cluster to infer the distance to its center. The present analysis could serve as a first step in this direction, since the spatial distribution of the stars is very well resolved. In addition, Luri et al. (2018) recommends to perform a

Bayesian analysis of the errors taking into account also magnitude and color. Such refinements lie beyond the scope of the present note and will eventually be presented elsewhere.

This work has made use of data from the European Space Agency (ESA) mission *Gaia* (www.cosmos.esa.int/gaia), processed by the *Gaia* Data Processing and Analysis Consortium (DPAC, www.cosmos.esa.int/web/gaia/dpac/consortium). Funding for the DPAC has been provided by national institutions, in particular the institutions participating in the *Gaia* Multilateral Agreement.

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