ASTRONOMY 5500. GALACTIC ASTRONOMY

Assignment 1. Astrometry **Due Date: September 30, 2015.**

1. Visit the web site for open clusters at www.univie.ac.at/webda/navigation.html and download *UBV* observations for stars in the open cluster NGC 2281 (RA2000, DEC2000 = 06:48:17, +41:04:42). Use a $U-B$ versus $B-V$ colour-colour diagram to estimate the reddening of NGC 2281 stars, then a V versus $B-V$ colour-magnitude diagram to establish the distance to the cluster with its uncertainty. Now establish a distance to the cluster using *Hipparcos* parallaxes for cluster stars (http://vizier.u-strasbg.fr/viz-bin/VizieR-3). Which method is more precise? Which is more accurate?

2. Proper motions are important for many reasons: establishing space motions of stars, determining membership probabilities for cluster stars, estimating the masses of star clusters, and calibrating the open cluster distance scale via the moving cluster method. The *Hipparcos* mission was a boon for use of the moving cluster method, since the satellite measured proper motions for stars with very high precision. However, accuracy was another question, given that the satellite observed stars for only about 7 years. Why is that a problem for measuring accurate proper motions? How, then, did *Hipparcos* measure proper motions for stars?

3. The table below summarizes a variety of distance estimates for the Pleiades star cluster, using a number of different methodologies. The two by van Leeuwen that stand out are from *Hipparcos* parallax measures.

m-M	*d*(pc)	Source
5.56 ±0.03	129.4 ±1.8	Turner (1979)
5.57 ±0.08	130.0 ±4.8	van Leeuwen (1983)
5.60 ±0.04	131.8 ±2.4	Vandenberg & Poll (1989)
5.60 ±0.16	131.8 ±9.7	O'Dell et al. (1994)
5.60 ±0.05	131.8 ±3.1	Pinsonneault et al. (1998)
5.32 ±0.06	115.9 ±3.2	van Leeuwen & Ruiz (1997)
5.37 ±0.07	118.6 ±3.8	van Leeuwen (1999)
5.58 ±0.18	130.6 ±10.8	Narayan & Gould (1999)
5.59 ±0.12	130.9 ±7.4	Gatewood & de Jonge (2000)
5.61 ±0.03	132.4 ±1.9	Stello & Nissen (2001)
5.58 ±0.03	130.6 ±1.8	Turner & Burke (2002)
5.57 ±0.06	129.0 ±3.3	Makarov (2002)
5.65 ±0.03	135.0 ±2.0	Pan, Shao & Kulkarni (2004)

The study by Makarov (2002) is interesting, since it uses data from the *Hipparcos* online database to establish a different solution that appears to be well matched to other independent estimates. Read through Makarov's paper with the goal of understanding its methodology, which was heavily criticized by van Leeuwen. Are you convinced or not? Explain.

4. Prior to the *Hipparcos* mission the U.S. Naval Observatory had a program to measure parallaxes for nearby stars that matched the precision reached by *Hipparcos*. However, it is not possible to confirm the accuracy of the two sets of parallaxes since the two independent programs measured quite different stars. In fact, the two samples are essentially mutually exclusive. Explain.

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Assignment 2. Spectroscopy, Moving Clusters **Due Date: October 21, 2015.**

References:. Böhm-Vitense 1981, ARAA, 19, 295; Buser & Kurucz 1979, A&A, 70, 555; Soderblom & Mayor, AJ, 105, 226, 1993; Upton 1970, AJ, 75, 1097.

1. The prominent absorption lines of neutral helium in spectra of B-type dwarf stars originate from the $n = 2\ ^3$P (triplet P) level of He I, reaching maximum strength at spectral type B2. Use the Boltzmann and Saha relations to determine the corresponding temperature at which He I lines reach maximum strength, which is presumably close to the effective temperature T_{eff} for B2 V stars. Include a graphical plot of log $N_2/N_{\rm total}$ versus T to confirm your results.

Input data needed:
Excitation potential of $n = 2\ ^3$P level relative to ground state = 20.96 eV.
$u(T)$ = 1 for He I. $u(T)$ = 2 for He II. $u(T)$ = 1 for He III.
Ionization potential for He I = 24.58 eV. Ionization potential for He II = 54.40 eV.
Statistical weights of He I energy levels: Ground State (^{1}S), g = 1; $n = 2$ level (^{3}P), g = 9.
log P_e (dynes cm^{-2}) = –3.5 + 1.5 log T (for hot main-sequence stars).
Boltzmann and Saha equations:

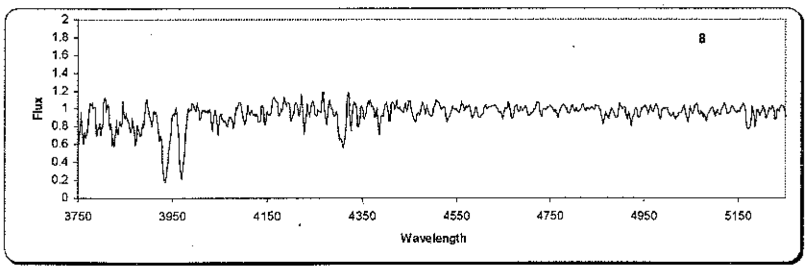
$$\log\frac{N_{\rm excited\ level}}{N_{\rm total}} = -\theta\chi_{\rm excitation} + \log\frac{g_{excited\ level}}{u(T)} .$$

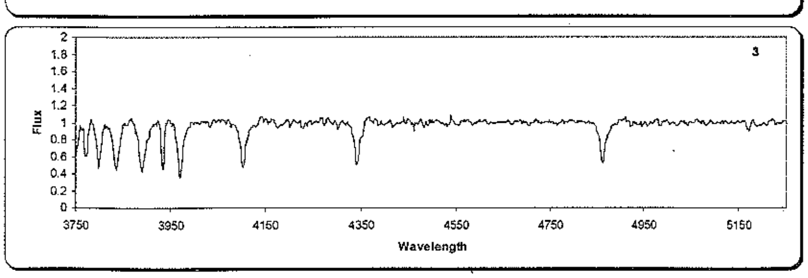
$$\log\frac{N_{\rm ionization\ state}}{N_{\rm next\ lower\ state}} = -\theta I_{\rm ionization} + 2.5\log T - \log P_{\rm electron} - 0.4772 + \log\frac{2u_{\rm ionization\ state}(T)}{u_{\rm next\ lower\ state}(T)} .$$

Spectral lines are formed at higher layers in stellar atmospheres than where the stellar continuum is formed, so spectral lines may yield slightly lower temperatures than the true effective temperatures of the same stars. Compare your results with those of Böhm-Vitense and Buser & Kurucz to see how well they agree (B2 V stars are dwarfs with colours of $B–V$ = –0.24). Is one of the scales the "hot scale" and the other the "cool scale"? If so, which is which? Find another source to see how it compares with your result.

Derive MK spectral types for the two stars at right. An on-line source of stellar spectra can be found at:

http://nedwww.ipac.caltech.edu/level5/Gray/frames.html





2. **The Ursa Major Moving Cluster**

The Ursa Major cluster consists of a small number of stars, including β, γ, δ, and ε UMa, centred on ζ UMa. A more extensive list of members is given below (a more comprehensive listing is given by Soderblom & Mayor 1993) with spectroscopic, photometric, and radial velocity data for the stars. The purpose of the exercise is to examine the usefulness of the Ursa Major cluster as a distance calibrator, which requires a number of tests on the available data for cluster stars.

HD	BD	Sp.Type	V	$B–V$	$U–B$	V_R
87696	+35° 2110	A7 V	4.48	0.18	0.08	–17.2
91480	+57° 1277	F1 V	5. 16	0.33	–0.02	–10.4
95418	+57° 1302	A0 IV-Vm	2.38	–0.01	–0.03	–12.0
103287	+54° 1475	A0 Vn	2.44	0.00	0.01	–12.6
106591	+57° 1363	A2 Vn	3.31	0.08	0.07	–13.4
109011	+55° 1536	K2 V	8.11	0.95	...	–13.1
109647	+52° 1638	K0	8.53	0.94	...	–9.0
110463	+56° 1618	K3 V	8.29	0.95	...	–9.7
111456	+61° 1320	F5 V	5.85	0.46	–0.04	–12.0
112185	+56° 1627	A0 IVp	1.79	–0.02	0.01	–9.3
*113139	+57° 1408	F2 V	4.94	0.36	0.01	–9.8
115043	+57° 1425	G1 V	6.84	0.60	0.09	–8.5
116656	+55° 1598	A1 Vp	2.27	0.02	0.01	–5.6
116657	+55° 1598	A1 IV-Vm	3.95	0.14	0.09	–9.3
116842	+55° 1603	A5V	4.01	0.16	0.08	–8.9
125451	+13° 2782	F6 V	5.41	0.38	–0.03	–3.0
139006	+27° 2512	B9.5 IV	2.23	–0.02	–0.02	+1.7
150706	+80° 0519	G3 V	7.06	0.62	0.06	–16.8
155674A	+54° 1861	K8 V	8.87	1.16	1.08	+3.0
155674B	+54° 1862	K8 V	9.34	1.26	1.21	–0.9

* Binary. Separation = 1.5 arcsec, $\Delta m = 3.6$.

a. Examine the trigonometric parallaxes for the cluster stars listed in the *HIPPARCOS* Catalogue. Calculate the weighted mean for the group and the associated standard error, and determine the resulting best estimate for the distance to the cluster with its associated uncertainty ($\Delta d/d = \Delta\pi/\pi$). That value is the best estimate for the cluster distance obtainable from parallax data.

b. Construct a colour-magnitude diagram (V vs $B–V$) for cluster stars (correct the V magnitude of HD 113139 for contamination by its companion) and find the best distance to the cluster (and its associated uncertainty) from zero-age main-sequence (ZAMS) fitting, *i.e.* by performing a sliding fit to the data, using the instructor's ZAMS (do it analytically if you prefer). Ursa Major cluster stars are close enough to the Sun to be unaffected by interstellar reddening, but evolutionary effects are important for bright cluster members. Find $V–M_V$ and $\Delta(V–M_V)$ from a fit to the standard ZAMS, and calculate the corresponding distance and uncertainty [$\Delta d/d = \Delta(V–M_V)/(5 \log_{10}e)$]. That is the best estimate for the cluster distance obtainable from ZAMS fitting.

c. Try to establish how the proper motions of cluster stars appear in the sky, and whether or not they differe from field stars in the same directions and the expected motion of the cluster if it simply reflected the Sun's motion through space. It should be apparent that members of the Ursa Major cluster can be identified very reliably from their proper motions.
Question. What property of their space motions distinguishes members of the Ursa Major cluster from surrounding field stars?

d, Upton (AJ, 75, 1097, 1970) describes a robust version of the moving-cluster method that uses radial velocity data and proper-motion gradients to determine distances to moving clusters. A major step in the procedure involves converting the positional proper motion and radial velocity data from a spherical co-ordinate grid to a Cartesian co-ordinate grid. Upton describes details of the procedure, which is best done with computer software. Is it a simple matter to apply the procedure to the Ursa Major moving cluster? Explain. The cluster distance in this method follows from $d = -V_R/(4.74\ \mu$ gradient), for d in parsecs, V_R in km/s, and the μ gradient in arcsec/yr/radian. The uncertainty estimate follows from $(\Delta d/d)^2 = (\Delta V_R/V_R)^2 + (\Delta\mu$ gradient/μ gradient$)^2$. In your notes An estimated distance of 24.16 ±1.85 pc is derived in your notes, weighted towards the RA component. Use this value in what follows.

e. Make a table comparing the results from parts a, b and d. Do the various estimates agree to within their uncertainties? The moving-cluster method has certain restrictions for reasonable use. Are any of the restrictions applicable to the Ursa Major cluster? Do you think that the Ursa Major cluster offers any advantages over the Hyades cluster for calibrating the ZAMS?

f. The ZAMS calibration used in this exercise is tied to a Hyades distance modulus of about 3.20. Do your results for the Ursa Major cluster provide any evidence of a need to revise the value either upwards or downwards? Remember to take into consideration the uncertainty estimates on the derived distances in your reasoning for this question.

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Assignment 3. Abundances, Galactic rotation **Due Date: November 18, 2015.**

Globular Cluster Metallicity. References: http://venus.mporzio.astro.it/~marco/gc/

1. Examine how reliably one can establish metallicity for a globular cluster using a parameter such as the slope of the red giant branch. Use the on-line catalogue to check a variety of different Galactic globular clusters. In each case measure the slope of the red giant branch and find the cited metallicity [Fe/H]. For the slope of the red giant branch, measure it from where the horizontal branch intersects the red giant branch to a point on the red giant branch with an intrinsic colour of $(B–V)_0 = 1.40$, using the cluster colour-magnitude diagram. Note that the listed database provides most such information, including the brightness of stars on the horizontal branch.

Once you have collected sufficient data, plot the slope of the red giant branch S versus metallicity [Fe/H] to see if a correlation appears. Keep adding clusters until you are certain that there either *is* or *is not* a correlation. If there is a correlation, what are its limitations? Is there another parameter that one might use from a cluster colour-magnitude diagram that would serve the same purpose?

2. Transform the equations of solar motion from ones involving α, δ, and v_R to ones involving l, b, and v_R (see the general rectangular co-ordinate system, Fig. 5–5, adopted in Mihalas and Routly, for example). Use the equations to solve for the solar motion (U, V, W, or Π, Θ, Z) relative to the select group of 20 Mira variables tabulated below. Discuss the likely population type (Population I, Population II, mixed, thin disk, thick disk, halo, etc.) for this sample of Mira variables on the basis of the resulting solar motion.

Star	l	b	v_R	**Star**	l	b	v_R
SS Aql	47°.01	–4°.18	–17	CE Gem	195°.20	+2°.16	+71
RX Lyr	63°.03	+13°.78	–146	XY Gem	200°.11	+23°.60	+138
TZ Peg	64°.81	–20°.92	–13	Y Ori	208°.58	–17°.42	+64
SZ Vul	65°.75	–10°.72	–97	VV CMi	216°.73	+14°.96	+78
AN Cyg	76°.50	–6°.66	–77	TZ Pup	229°.08	+2°.32	+73
AT Lac	96°.30	–7°.96	–194	ST Crv	284°.06	+47°.72	+72
DL Peg	101°.38	–44°.56	–34	V Crv	299°.25	+45°.15	+189
BP And	105°.37	–9°.08	–88	T Com	325°.61	+85°.69	+15
AI And	107°.59	–11°.12	–91	V Scl	336°.63	–74°.96	+47
T Tri	138°.08	–26°.93	–110	W Lib	350°.87	+30°.82	+22

3. Suppose that the Sun is located in a fixed Galactic feature such as a bar for which the angular velocity of rotation is constant as a function of distance from the Galactic centre, i.e. $\omega(R) = K$. Determine the expected values for Oort's constants A and B in such a situation, and describe how the radial velocities of other bar members would vary as a function of Galactic longitude.

4. Derive an estimate for Oort's constant A using open cluster distances and radial velocities. Remember that cluster radial velocities must first be corrected to the dynamical LSR, and that the full relationship for radial velocity resulting from Galactic rotation must be used, namely:

$$v_R(\text{LSR}) = A d \sin 2l \cos^2 b \ .$$

The necessary data can be found on-line at http://www.astro.iag.usp.br/~wilton/. Use as many clusters as you like, although keep in mind that a few of the nearby clusters (Hyades, Mel 111, etc.) give anomalous results in this type of analysis, and are best excluded. Try separating the cluster sample into smaller sections, based upon distances, *e.g.* < 1 kpc and distances > 1 kpc and > 2 kpc, and possibly age (e.g., $> 250 \times 10^6$ years, turnoffs later than B5, for clusters that have orbited the Galactic centre at least once) in order to eliminate any possible bias resulting from the fact that the equation for Oort's constants are approximations for nearby objects. Discuss your results. You will also find that the easiest way to derive A for your samples is to find the best-fitting slope in a plot of $v_R(\text{LSR})/d \cos^2 b$ versus $\sin 2l$. That will make it easier to derive the uncertainties in your estimates for A, as well as to detect anomalous data points. Do young clusters (turnoff points earlier than B5) give different result from older clusters (turnoff points later than B5)? Compare your estimate of A with other published estimates.