Physics 160
Stellar Astrophysics
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Lecture 1
1 October 2013
Lecture 2: Stellar Coordinates, Astrometry & Kinematics
1 October 2013

PRELIMS
• Announcements [5 min]
• CASS seminar [5 min]
• Review [5 min]

MATERIAL [65 min]
• [15 min] Distance scale
• [30 min] Stellar coordinates & the celestial sphere
• [SKIP?] Angular Scale
• [20 min] Astrometry: parallax & proper motion

DEMONSTRATIONS/EXERCIZES
• celestial sphere?
• compass flip

MATERIALS
• Celestial globe (get from demo room)
• NEWS direction sheets
• Burning questions box
Stellar distance scale [10 min]

- Earth-based units are woefully inadequate for stellar distances – nearest star is $4 \times 10^{16}$ m away!
- Light-year is a natural unit – $3 \times 10^8$ m/s $\times \pi \times 10^7$ s $\approx 10^{16}$ m
  - Also forces all stars to be viewed well in the past
- Astronomical unit is the parsec = 3.26 ly = $3 \times 10^{16}$ m => nearest star = 1.3 pc
  - **Question: what is the local density of stars?**
    - Answer: 1 star inside $4\pi/3$ (1 pc)$^3 = 0.25$ pc$^{-3}$ (real answer is 0.14 pc$^{-3}$)
  - **Question: what is the local mass density of stars?**
    - Answer: 1 $M_\odot$ x 0.14 pc$^3 = 0.14$ $M_\odot$pc$^{-3}$ (real answer is $0.076\pm0.015$ $M_\odot$pc$^{-3}$ $\approx 6\times10^{-24}$ g/cm$^3$ $\approx 4$ H atoms/cm$^3$)
- Some scales:
  - Sun is about 8 kpc from center of Galaxy => radius of 10-12 kpc
  - Magellanic clouds 50-70 kpc
  - Andromeda galaxy $\approx 2.5$ Mpc
  - Local group of galaxies $\approx 10$ Mpc across
  - Visible universe? By definition 13.8 billion years => 13.8 Gly $\approx 4$ Gpc (“actual” universe likely much bigger but we haven’t crossed its lightcone yet)

QUESTIONS?

Where are the stars? Coordinates & Celestial Sphere [30 min]

- We map stars like we map the earth – a projected outward sphere [DEMO – CELESTIAL SPHERE]
- Locally: azimuth (east of north) and altitude (above horizon)
  - **QUESTION: why might these not be useful?**
• Answer: local-specific (hard to share with other observers); changes with time (constantly!)

• Equatorial Coords
  
  o Right Ascension & Declination = projection of our earth map on the sky (geocentric)
  
  o Example: $17^h\ 45^m\ 37.2^s\ -28^\circ\ 56'\ 10.2''$
    
      ▪ **WHERE IS THIS?** Center of the Galaxy
      
      ▪ **QUESTION:** what is the Right Ascension and declination of Polaris, the North Star?
        
        ▪ Answer: straight north = $90^\circ$ dec, any RA

      ▪ **QUESTION:** what is the altitude of Polaris?
        
        ▪ Answer: $32.7^\circ$, same as San Diego latitude

  
  o Declination is given in degrees, arcminutes, arcseconds
    
      ▪ Comparison: moon and sun are $\approx0.5^\circ$
      
      ▪ our eye can resolve $1'$
      
      ▪ Typical blur of a star due to seeing is a few arcseconds

      ▪ Best imaging resolution (HST, AO) $\approx0''05$, 1200× better than eye

  
  o RA is given in hours, minutes, seconds – time units
    
      ▪ 24 hours for $360^\circ$ - **why?**
        
        ▪ $x15$ to get back to degrees

      ▪ Looking up, E and W are reversed
        
        ▪ **PROVE IT:** put directions on the walls and have students lie upside down

      ▪ Arbitrary zero point (cf Greenwich) = vernal equinox = position of noon Sun at Spring equinox ($\approx$March 21)

      ▪ **QUESTION** – what is the RA directly overhead at midnight tonite? How about in one month?
• Answer: RA = 0^h – we’re ½ year from spring and midnight is ½ day from noon – flips over today!

- QUESTION: when can you see the center of the galaxy tonight?
  - Answer: just after sunset it will be low in the south-southwest sky (sunset LST = 0^h - 6^h = 18^h)

• Local Sidereal Time
  o measure of what RA is directly overhead at a given time
  o Sidereal time different from Solar time – explain geometry
    ▪ Solar day is noon to noon, sidereal day is from fixed star to fixed star
    ▪ Question – which is longer, a sidereal or solar day? by how much do they differ?
    ▪ Answer: solar day – Earth orbits as well as rotates, and changes orientation with respect to Sun (but not stars!) – longer by 24/360° x 360°/365 dy = 4 min

• Precession and Nutation effects = coordinates must also specify epoch (currently J2000 = Julian calendar year 2000)

• Other coordinate systems
  o Ecliptic
    ▪ aligned with average plane of the planets, used for Solar System, vernal equinox sets 0° longitude
    ▪ QUESTION: how much of a tilt is there between equatorial and ecliptic?
      ▪ Answer: 23.5° = Earth’s axial tilt
      ▪ Transforming - simple matrix rotation
• Trivia: North Solar pole ≈ North Earth pole – this is relevant to how planets formed!
  o Galactic
    ▪ aligned with the average plane of the Galactic disk, center of Galaxy sets 0° longitude
    ▪ useful for stellar population studies
    ▪ Trivia: North Galactic pole not aligned with north earth/solar pole – galaxy doesn’t care what we call “north”!
  o Supergalactic
    ▪ aligned with average “plane” of local group of galaxies
    ▪ used in large-scale galaxy maps
• Organization into constellations
  o 88 across the sky – defined by IAU in 1930s
  o names and mappings are different in different cultures
  o star names are based on assigned constellation and order of brightness: α Orionis is brighter than β Orionis, etc.
    ▪ Note: brightest apparent star is not necessarily most luminous – we’ll discuss this next class

QUESTIONS?

[SKIP?] Angular Scale
• simple ratio of projected size (s) and distance (d)
• \( s = 2d \tan \frac{\Omega}{2} \approx d\Omega \) where angle \( \Omega \) is in radians
• example: can we resolve the space shuttle with our eyes?
  o \( \Omega \approx \frac{s}{d} \approx 60 \text{ m}/350 \text{ km} \approx 1.7 \times 10^{-4} \text{ rad} \approx 35” \)
  o just a bit too small/far
• resolution of circular apertures (eye, telescope)
- based on interference pattern of light passing through aperture (Airy function)
- \( \Omega_{\text{resolve}} \approx 1.22 \frac{\lambda}{\text{diameter}} \approx 0.1''/D(\text{m}) \) in visible
- This (and sensitivity) pushes telescope design to ever larger telescopes

QUESTIONS?

Astrometry: Parallax, Proper Motion & Stellar Kinematics

- Parallax
  - **DEMO: parallax with eye**
  - Sketch parallactic motion
  - Relationship between parsec, arcsec & AU
  - **CALCULATE: what is the parallax of \( \alpha \) Cen?**
    - Answer: \( \frac{1}{1.3} \text{ pc} \approx 0.8'' = \) maximum possible parallax
    - This is impossible to see by eye
    - Tycho argued lack of visible parallax ruled out Copernican model (stars can’t possibly be that far)
  - First parallax credited to Friedrich Bessel in 1838 (huge race)
  - Today parallax measured in space to \( 10^{-3} '' = 1 \text{ kpc} \) (Hipparcos); GAIA satellite will measure to \( 2 \times 10^{-5} '' = 50 \text{ kpc} \) (launch in November)
  - This is the first ladder of the cosmic distance scale

- Proper motion: Stars aren’t actually “fixed in the firmament” – they move on small scales
  - Decomposition of velocity vector
• in “plane of sky” = proper motion
• perpendicular to sky = radial velocity
• Position angle – orientation of $\mu$, going E of N

○ **CALCULATE:** typical relative stellar velocities are of order 10 km/s. Compute the angular motion of a star at 10 pc moving at that speed perpendicular to our line of sight
  - Answer: $\alpha = \frac{s}{d} \Rightarrow \frac{d\alpha}{dt} = \mu = \frac{v_{\text{tan}}}{d} = 1$ km/s/pc $\times (1 \text{ pc}/3\times10^{13} \text{ km}) \times (180^\circ/\pi \text{ radian}) \times (3600 \text{ “}/\text{s}) \times (\pi\times10^7 \text{ s}/\text{yr}) = 0.2”/\text{yr}$
  - Highest $\mu$ star is Barnard’s star: 10”/yr

○ Typical nearby $\mu \approx 0.5”/\text{yr}$ is much too small to “see” with the eye – even monitoring for a decade!

○ Wasn’t until Halley in 1718 noticed a change in the position of a few stars compared to Hipparcos (1850 yr baseline!)

○ Today we can measure motions of m”/yr; GAIA will measure down to 10 $\mu”/\text{yr}$

• Other motions on sky
  - binary orbit
  - other gravitational encounter
  - gravitational lensing (apparent astrometric perturbation – 1919 GR experiment)

• Kinematics
  - combine coordinates, parallax, proper motion and radial velocity and you have 6D position/velocity vector of a star
- important for Galactic stellar kinematics: traces star clusters (co-moving stars) and gravitational potential of Galaxy (e.g., velocity curve)
- Cartesian galactocentric coordinate system has XYZ and UVW tied to Galaxy
- Show some fun orbits
Announcements

• HW #1 online, due Friday 10/4 at 5pm in box outside my office SERF 340

• Discussion Section tomorrow 10/2 at 2pm in WLH 2113 (downstairs)

• Office hour split: Th 10am-11am and Fr 11am-12pm (this week only)

• Burning question box

• Astrophysics Seminar this week: Dr. Amanda Ford (U. Arizona): “The Dynamic Circumgalactic Medium” – We 4-5pm in SERF 340

• “Our Star Will Die Alone” Fr & Sa @ 10:30pm on Galbraith south patio; free preview Th @ 8pm
What is the Circumgalactic Medium?

This is the material that builds up galaxies; 99% Hydrogen
Once inside a galaxy, circumgalactic material (CGM) becomes interstellar material (ISM) and this is the stuff that makes stars

computer simulation of gas flow and accretion on a galaxy
http://www.stsci.edu/~inr/thisweek1/2012/thisweek079.html
The Interstellar Medium is the Source Material for Stars

Most ISM is either translucent or opaque

Some is heated by nearby stars and can be seen in thermal or emission line radiation

Review

• Most of the events related to class (office hours, labs, seminars) happen where? on the 3rd floor of the SERF building
• Is it going to be really easy to get an A in this class? No, you need to get >90%!
• How is gold made? created in supernovae explosions
• How do stars tell us that dark matter exists? gravitational lensing & velocity curves of galaxies
• How do stars tell us that dark energy exists? supernovae distances and redshifts
• What is the mass of the Sun? 1 Solar Mass or 2x10^{30} kg
• How far to the nearest star? 1 AU (The Sun!), then 4.4 lightyears ≈ 1.3 pc ≈ 4x10^{16} m
• What is log_{10}\pi? = 0.5
Distance Scales for Stars

Natural physics units = \( m, kg, s \) (SI)

\( = cm, g, s \) (cgs)

These are woefully inadequate for many astronomical scales.

E.g. 1 Astronomical Unit (AU) = Earth-Sun distance (average)

\( = 1.5 \times 10^{11} \) m

1 light-year (ly) = distance light travels in one year

\( = (3 \times 10^{8} \text{ cm/s})(3.15 \times 10^7 \text{ s}) \)

\( = 9.5 \times 10^{15} \) m

1 parsec (pc) = “standard” cosmic distance unit

\( = 3.1 \times 10^{16} \) m

\( = 3.26 \) ly

Example scales:

Size & Solar System (Sun \rightarrow \text{Kuiper Belt}) \approx 50 \text{ AU}

\( \approx 7.5 \times 10^{11} \) m

\( \approx 2 \times 10^{-4} \) pc

Nearest star (besides Sun) = Prox Centauri = 1.3 pc \approx 4.2 \) ly

\( \approx 4 \times 10^{16} \) m

Radio Galaxy \approx 10,000 \) pc = 10 kpc < natural unit

Nearest large galaxy = Andromeda = 2.5 \times 10^6 \) pc = 2.5 Mpc < natural unit

“Size” of Universe (visible) \approx 8 \times 10^{26} \) 10^{10} \) pc = 10 Gpc
Stellar positions are represented by 2D vector indicating angular position on sky w.r.t. reference system.

1) Altitude - azimuth

\( h \) = altitude above horizon
\( r \) = zenith distance, \( 7 + h = 90^\circ \)
\( A \) = angle East of North

\( 1^\circ = 60' \) (arc minute)
\( 1' = 60'' \) (arc second)

\((A, h)\) is convenient locally but not for stars - "rotation" of sky, daily offset due to Earth's orbit, specific to latitude, longitude of observer.

2) Equatorial coordinates - projection of Earth's lat/long to sky

\( S \) = declination, angle above celestial equator
\( \alpha \) = Right Ascension, angle East along celestial equator from vernal equinox (located in Pisces)

\( \alpha \) measured in degrees or hours:

\( 24^h = 360^\circ \), \( 1^h = 15^\circ \), \( 1^\circ = 15' \)

\((\alpha, S)\) provides "fixed sky" coordinates for stars independent of location on Earth or time - most common coordinate system.

In reality, precession of Earth causes secular change in coordinates which must be accounted for, e.g. equinox B1950, J2000, etc.
(3) Ecliptic Coordinate System - projection of ecliptic plane, useful for Solar System astronomy

\[ \beta = \text{ecliptic latitude} \]

- angle above/below ecliptic plane

\[ \delta = \text{ecliptic longitude} \]

- angle eastward of vernal equinox

Equatorial $\rightarrow$ ecliptic is a simple rotation about x-axis (vernal eq.) by Earth's obliquity (tilt)

\[
\begin{bmatrix}
  x \\
  y \\
  z \\
\end{bmatrix}_{\text{ecliptic}} =
\begin{bmatrix}
  1 & 0 & 0 \\
  0 & \cos \beta & \sin \beta \\
  0 & -\sin \beta & \cos \beta \\
\end{bmatrix}
\begin{bmatrix}
  x \\
  y \\
  z \\
\end{bmatrix}_{\text{equatorial}}
\]

where \( \beta = 23^\circ 43^\prime 21^\prime\prime \) today

(varies due to rotation over 41,000 yr cycle)

(4) Galactic Coordinates - fixed to Milky Way - useful for stellar population astronomy

\( \alpha = 12^h 14m 12^s.5 \)

\( \delta = +27^\circ 48^\prime \) (B1450)

\( \beta = \text{Galactic latitude} \)

- angle north of Galactic plane

\( \ell = \text{Galactic longitude} \)

- angle away from Galactic center in same direction as RA

(\( \alpha, \delta \)) = (12h, 27.4m)

\( \ell, \beta \) = (285.56', 10.2')

\( \ell, \beta \) = Galactic center

(5) Supergalactic - aligned with supergalactic plane
Measuring Angular Separations

You observe two stars in the sky—how far apart are they?

1. Simple approach: treat the sky as locally "flat"

\[ \Delta \equiv (\alpha_2 - \alpha_1)^2 + (\delta_2 - \delta_1)^2 \]

all in same units!

2. Problems with this:

- Sky isn't flat, curved \( \Rightarrow \) 2 points are closer together in angle

\[ d = 2r \tan \frac{\theta}{2} \]

\[ \theta \approx \frac{\theta_0}{12} \] for small \( \theta_0 \)

\[ \theta_0 > \theta_0' \] for larger \( \theta_0 \)

3. Near poles, run into problems

- Smaller width for same \( \Delta \theta \)

4. Careful approach—spherical angles

- Remember that \( \vec{r}_1 \cdot \vec{r}_2 = |\vec{r}_1||\vec{r}_2| \cos \Omega \)

\[ \text{in Cartesian coordinates:} \]

\[ r = \cos \phi \cos \theta \hat{x} + \cos \phi \sin \theta \hat{y} + \sin \phi \hat{z} \]

Solve dot product to derive \( \cos \Omega \).
Angular Size

The angle an object subtends in the sky is directly related to both its physical size and distance.

Formally: \( S = 2\pi r \tan \frac{\theta}{2} \)

Approximate: \( S \approx r\theta \)

\[ \text{measured in radians} \]

E.g. Angular size of space shuttle in orbit

- \( L = 40800 \text{ m} \) (wikipedia)
- Orbit height \( z = 350 \text{ km} \) (Low Earth orbit)

\[ \theta = \frac{60 \text{ m}}{3.5 \times 10^5 \text{ m}} = 1.7 \times 10^{-4} \text{ radians} \]
\[ = 10^{-2} \text{ degrees} \]
\[ = 35'' \]

Typical angular resolutions:

- Eye: 1'
- Meade (4''): 1''
- Hubble telescope: 0.04''
- Keck telescope (10m): 0.01''

\[ \text{in general, } \theta_{\text{resolve}} = \frac{1}{D} \text{ in diameter of telescope} \]

\[ \text{in radians} \]

\[ \text{visible } = 555 \text{ nm} \Rightarrow \theta_{\text{resolve, visible}} \approx 0.1''/D(m) \]
Stellar Parallax

\[ \tan \pi \approx \pi = \frac{r}{D} \Rightarrow D = \frac{r}{\pi} \]

Typical parallaxes are \( < 1'' \approx \frac{1}{3600} \approx 0.0000048 \text{ rad} \)

\( r = 1 \text{ AU} = 1.5 \times 10^{16} \text{ m} \)

\( \pi (\text{''}) = 0.0000048 \text{ rad} \)

\[ D = \frac{3.086 \times 10^{16} \text{ m}}{\pi (\text{''})} \]

or \( D(\text{pc}) = \frac{1}{\pi (\text{''})} \)

Example: in 1838 Bessel measured 61 Cygni: \( \pi = 0.316 \text{''} \)

\[ D = 3.16 \text{ pc} = 10.3 \text{ ly} \]

(True value = 3.48 pc)

1990 Hipparcos: accuracy \( \pm 1 \text{ mas} \Rightarrow \) distances to 1000 pc = 1 kpc

2012 GAIA: accuracy \( \pm 20 \text{ mas} \Rightarrow 50 \text{ kpc} \)

Can also turn around:

\[ r(\text{AU}) = A \pi (\text{''}) D(\text{pc}) \]

binary star at 20 pc

\( = 10 \text{ AU} \)
GAIA Satellite: European Space Astrometry Mission

GAIA is a 5-year space mission that will measure stellar astrometry to a precision of $2 \times 10^{-5}$ arcseconds, and hence distances to 50 kpc.

Launch date is this quarter!

20 November 2013