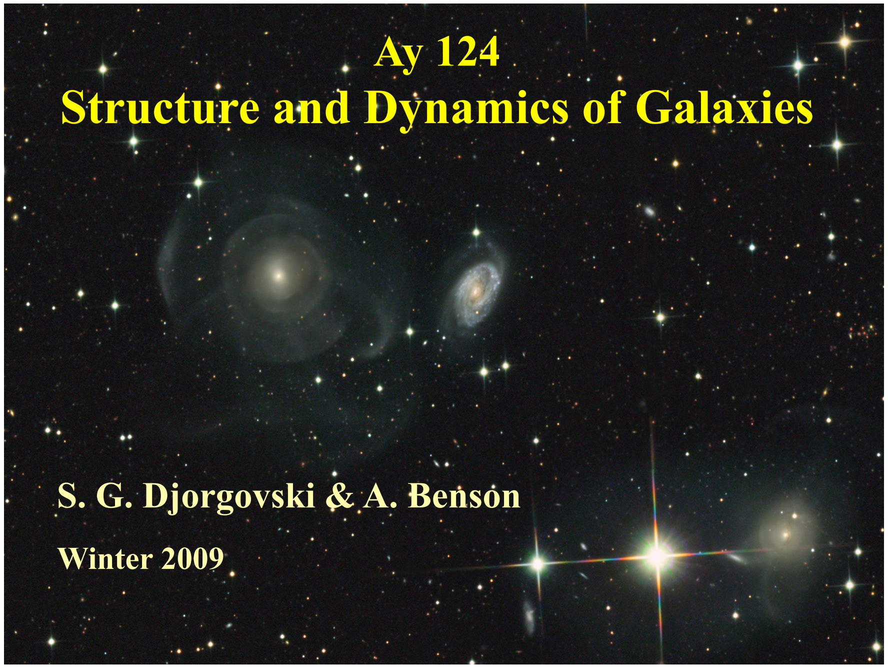


Ay 124
Structure and Dynamics of Galaxies

S. G. Djorgovski & A. Benson

Winter 2009

Class Logistics

- All info, lecture notes, useful links, homeworks, exams, announcements, etc., will be on the class webpage:

  http://www.astro.caltech.edu/~george/ay124/
- Textbook:
  - Binney & Merrifield, "*Galactic Astronomy*" (BM)
  - With some chapters from Binney & Tremaine, "*Galactic Dynamics*" (BT)
- Please read ahead, and ask questions during the class!

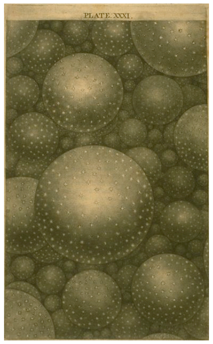
Today's lecture:

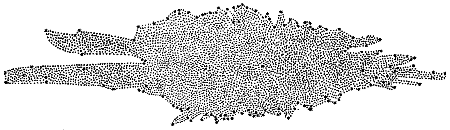
- Some history (BT 1)
- Common units, coordinates, astrometry (BT 2.1)
- Measuring distances to stars and clusters (BT 2.2)

The Discovery of Galaxies

18th Century:

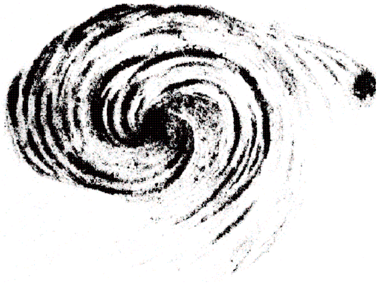
- The first catalogs of "nebulae": Charles Messier, William Herschel
- The pioneers of "island universes": Thomas Wright, Immanuel Kant





Herschel's sketch of the Galaxy, from his star counts

Lord Rosse's sketch of M51



19th and Early 20th Centuries:

- More catalogs, first spectra, but no physical understanding

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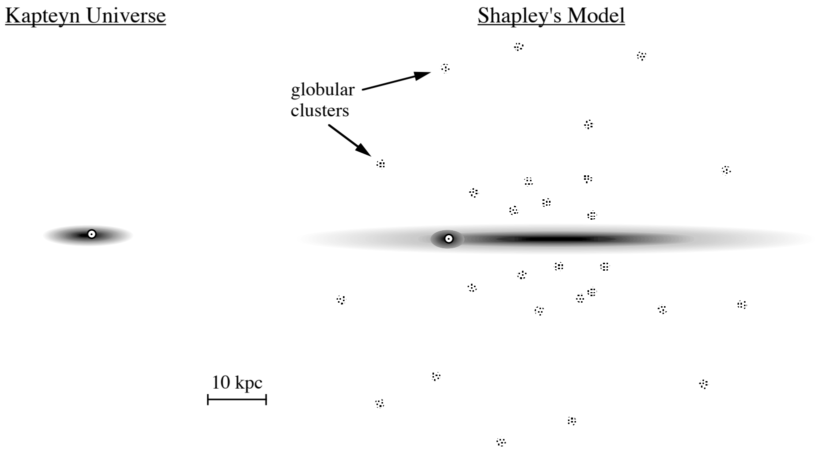
Expanding the Scale of the Galaxy

Discovery of the interstellar extinction circa ~ 1920's (Trumpler, Shapley) greatly expanded the scale of the Milky Way, and displaced the Sun from its center



The Shapley-Curtis Debate

on the nature of faint nebulae (= galaxies)

At the meeting of the National Academy of Sciences in Washington on 26 April 1920, Harlow Shapley of Mount Wilson and Heber D. Curtis of Lick Observatory gave talks under the title "The Scale of the Universe"

☚ Shapley argued that the nebulae are parts of our own Galaxy, the only one

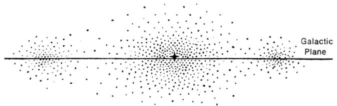
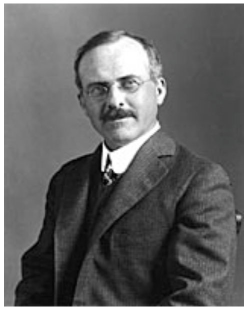


FIG. 3—Arthur Eddington's (1912) galaxy placed the Sun's position 60 LY above the center of the galactic plane.

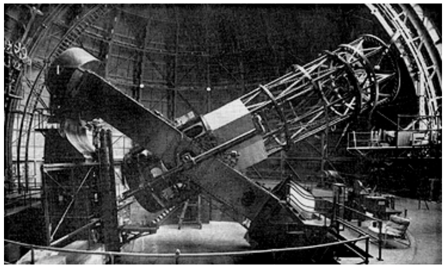


Curtis ☛
thought that these are other galaxies, just like ours

The Resolution: Nebulae are Extragalactic

- In 1923 Hubble resolved Cepheids in M31 (Andromeda)
- A profound shift in the understanding of the scale of the universe

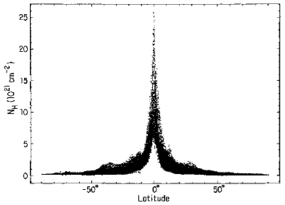
Edwin Hubble

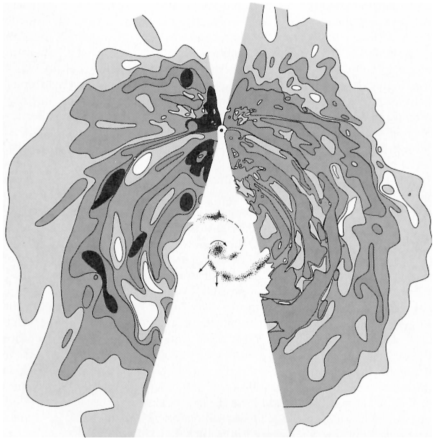


The Mt. Wilson 100-inch

Mapping the Milky Way and Its Kinematics

The development of radio astronomy after the WW2, and the discovery of the 21 cm line of H I, enabled the mapping of the Milky Way independent of the optical extinction.

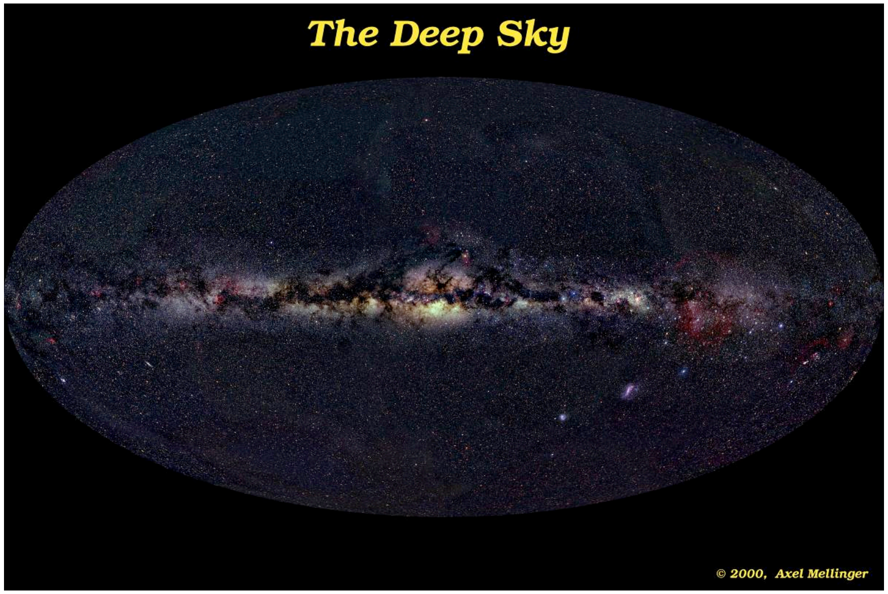




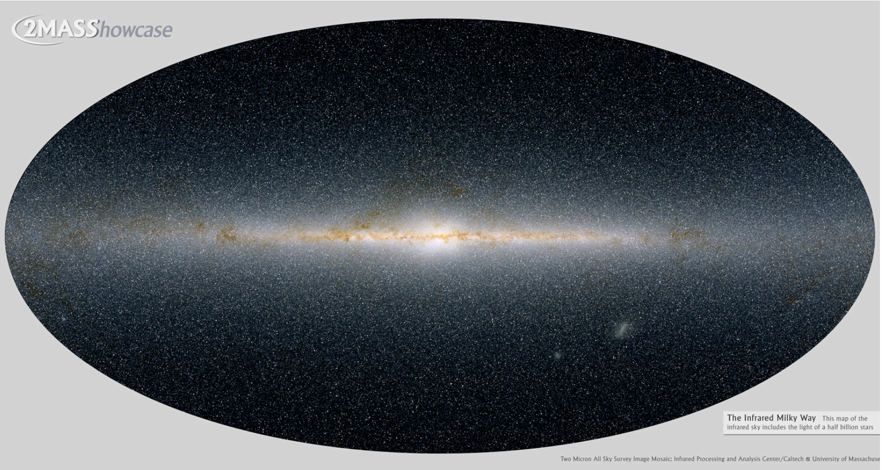
At the same time, that opened the possibility of the measurements of the global kinematics (e.g., rotation) of the Milky Way (Oort et al. 1958).

Until then, only the ~ local kinematic of stars could be measured.

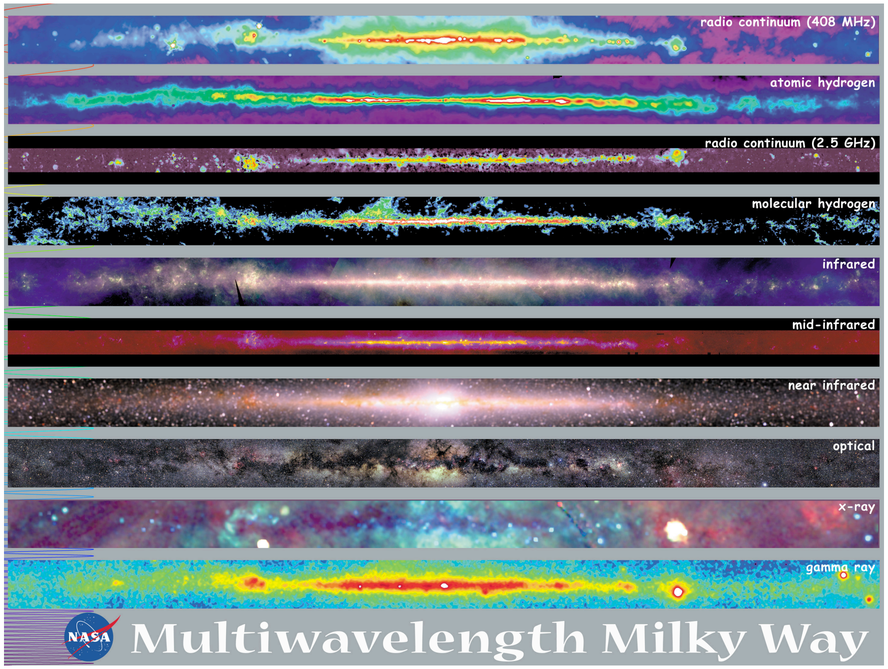
The Milky Way in Visible Light



The Milky Way from 2MASS



And it is a barred galaxy!



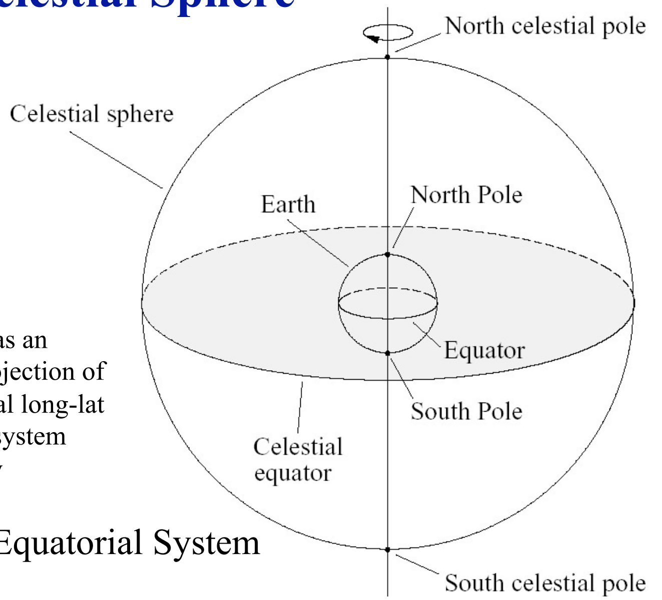
The Fundamental Goals and Methods

- Understand the physics and the origins of galaxies and their subsystems (structural, dynamical, compositional), as well as other types of stellar systems (e.g., star clusters)
- Stellar dynamics is an essential tool
- Consider galaxies in the 6-dimensional phase space of positions and velocities
  - For stars, measure the 2 positions on the sky, plus distances from parallaxes and other methods (XYZ)
  - Get the velocity components from proper motions + distances (v_ϑ, v_φ), and radial velocities (v_r)
  - For gas, measure the sky positions and radial velocities directly, but infer the other components using a global Galaxy rotation model
  - Spectroscopy also provides chemical abundances, ages for the stars, physical state of the ISM
- Use stars or gas as test particles to probe the gravitational potential

Some Commonly Used Units

- Distance:
  - Astronomical unit: the distance from the Earth to the Sun, $1 \text{ au} = 1.496 \times 10^{13}$ cm
  - Light year: $c \times 1$ yr, $1 \text{ ly} = 9.463 \times 10^{17}$ cm
  - Parsec: the distance from which 1 au subtends an angle of 1 arcsec, $1 \text{ pc} = 3.086 \times 10^{18} \text{ cm} = 3.26 \text{ ly} = 206{,}264.8$ au
- Angle:
  - Usually in "hex", e.g., $12^{\circ}\, 34'\, 56.78''$, or 12.5824389 deg, except for RA, which is usually given in *time* units, e.g., $12^{h}\, 34^{m}\, 56.789^{s}$. Note that $\Delta\alpha\,[\text{deg}] = \Delta\alpha\,[\text{h}] \times 15 \cos\delta$
- Mass and Luminosity:
  - Solar mass: $1\, M_{\odot} = 1.989 \times 10^{33}$ g
  - Solar luminosity: $1\, L_{\odot} = 3.826 \times 10^{33}$ erg/s

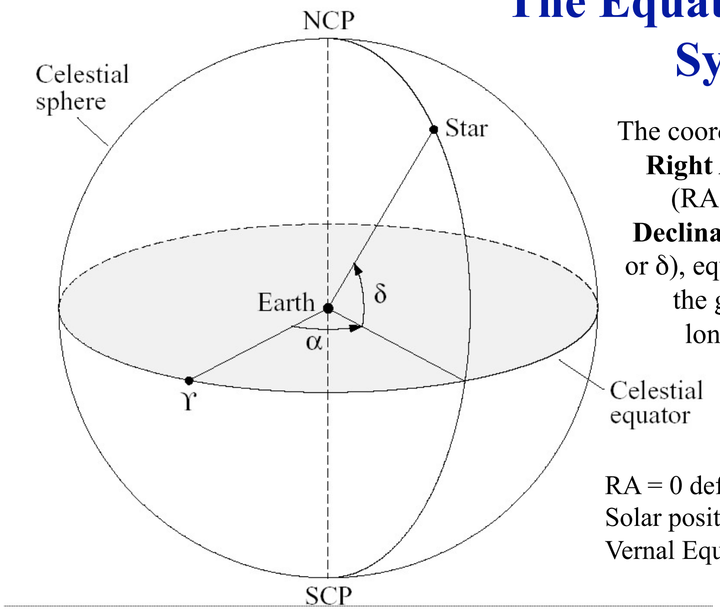
The Celestial Sphere



Think of it as an outward projection of the terrestrial long-lat coordinate system onto the sky

→ the Equatorial System

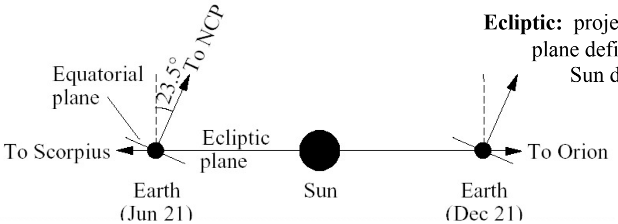
The Equatorial System



The coordinates are **Right Ascension** (RA, or α) and **Declination** (Dec, or δ), equivalent to the georgaphic longitude and latitude

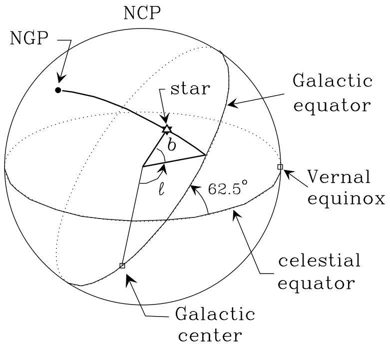
RA = 0 defined by the Solar position at the Vernal Equinox

Other Common Celestial Coordinate Systems

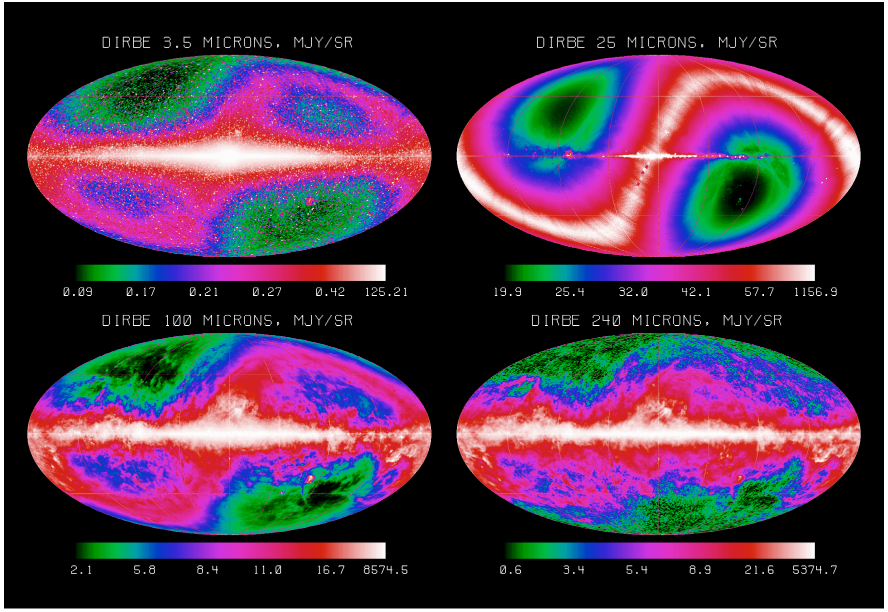


Ecliptic: projection of the Earth's orbit plane defines the Ecliptic Equator. Sun defines the longitude = 0.

Galactic: Projection of the mean Galactic plane is close to the agreed-upon (!) Galactic Equator; longitude = 0 is close, but not quite at the Galactic center. (α,δ) → (l,b)



COBE DIRBE Galactic Sky



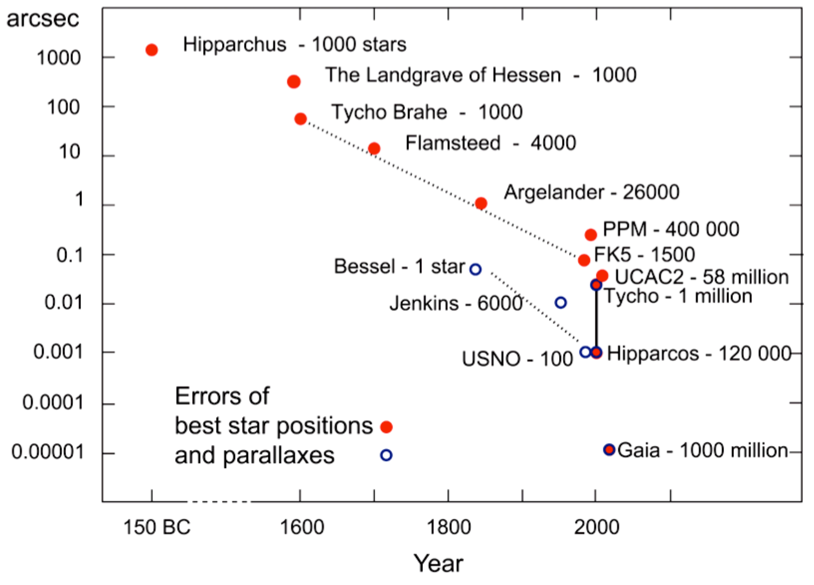
Astrometry

- Deals with (precise) positions, angular proper motions, and parallaxes of celestial sources
- Could be ***wide-angle*** (e.g., for reference systems) or ***narrow-angle*** (e.g., precision parallaxes, stellar wobbles, etc.)
- Reference coordinate systems (typically equatorial) are defined by a grid of stellar positions; the basic one is the International Celestial Reference System (ICRS), as embodied by the Fifth Fundamental Catalogue (FK5)
- USNO is a handy place to get catalogs and other info:

  http://ad.usno.navy.mil/star/
- See also the *Hipparcos* mission website:

  http://www.rssd.esa.int/HIPPARCOS

The Evolution of Astrometric Accuracy



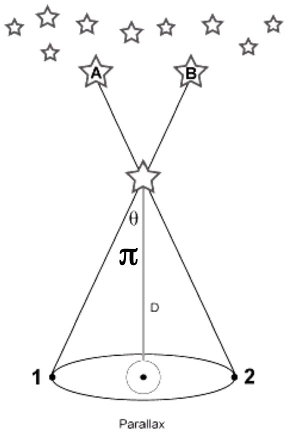
Some Astrometric Catalogs

Name	*Date*	*Nstars*	*σ(p)(mas)*	*σ pm(mas/yr)*
SAO	**1966**	**260 000**	**1000**	**10**
ACRS	**1991**	**320 000**	**200**	**5**
PPM	**1991**	**469 000**	**200**	**4**
HIPPARCOS	**1997**	**120 000**	**0.8**	**0.9**
Tycho1	**1997**	**1 060 000**	**40**	**40**
ACT	**1997**	**989 000**	**40**	**~2.5**
TYCHO-2	**1999**	**2 500 000**	**25**	**~2.5**
UCAC-2	**2003**	**48 330 000**	**22-70**	**1-6**

Distances and Parallaxes

- Distances are necessary in order to convert apparent, measured quantities into absolute, physical ones (e.g., luminosity, size, mass…)
- Stellar parallax is ***the only*** direct way of measuring distances in astronomy! Nearly everything else provides relative distances and requires a basic calibration
- Small-angle formula applies:

  D [pc] = **1** / π [arcsec]
- Limited by the available astrometric accuracy (~ 1 mas, i.e., D < 1 kpc or so, now)



How Far Can We Measure Parallaxes?

Since nearest stars are > 1 pc away, and ground-based telescopes have a resolution of ~1 arcsec, might seem impossible to measure π (and thus D) to any useful precision. Actually, it can be done :

1838: Bessel measured $\pi = 0.316$ arcsec for star 61 Cyg (modern value $\pi = 0.29$ arcsec)
Current ground-based: best errors of ~ 0.001 arcsec
Hipparcos satellite: measured ~10^5 bright stars with errors also of ~0.001 arcsec
GAIA satellite: will measure positions of ~10^9 stars with an accuracy of micro-arcsecs - this is a reasonable fraction of *all* the stars in the Milky Way!

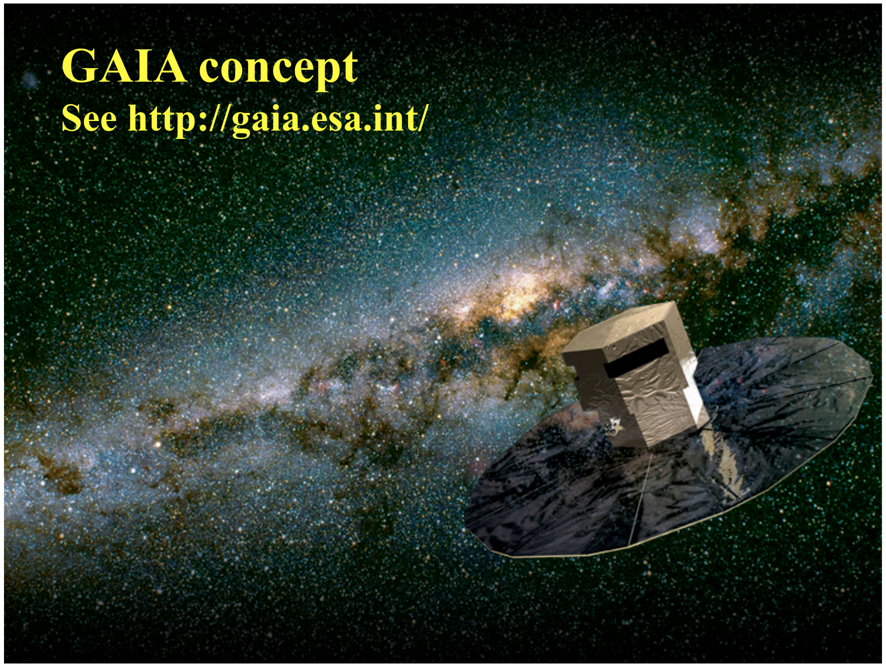
Currently: measure D accurately to ~ a few × 100 pc

Parallax Programs

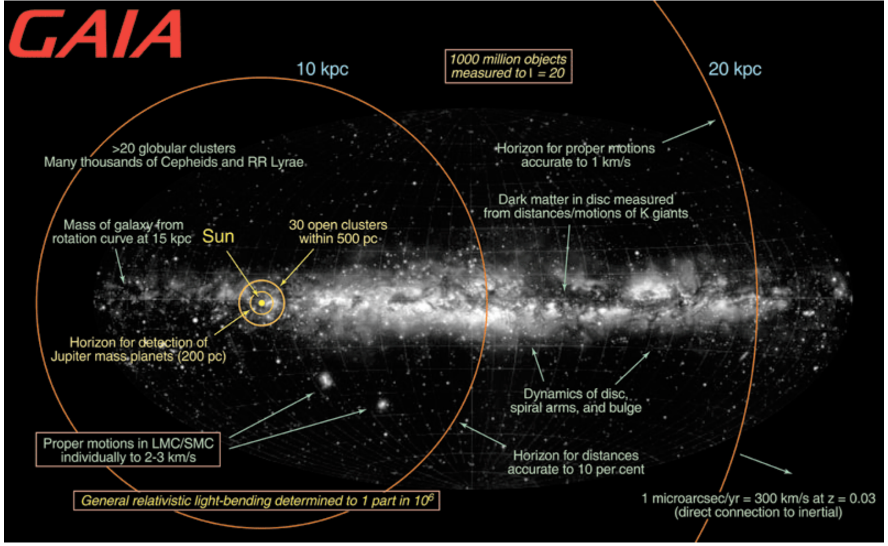
Catalog	**Date**	**#stars**	**σ(mas)**	**Comments**
YPC	1995	8112	±15 mas	Cat. of all π through 1995
USNO pg	To 1992	~1000	±2.5 mas	Photographic parallaxes
USNO ccd	From '92	~150	±0.5 mas	CCD parallaxes
Nstars & GB	Current	100?	± 2 mas	Southern π programs
Hipparcos	1997	10^5	±1 mas	First modern survey
HST FGS	1995-2010?	100?	±0.5 mas	A few important stars
SIM	2016?	10^3	±4 μas	Critical targets & exoplanets
Gaia	2016?	10^9	±10μas	"Ultimate" modern survey

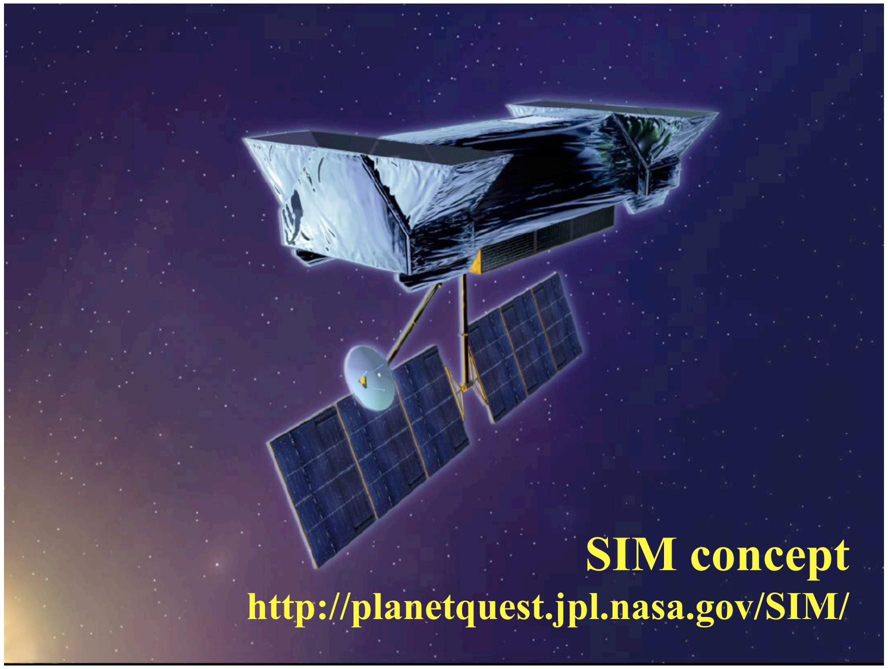
GAIA concept

See http://gaia.esa.int/



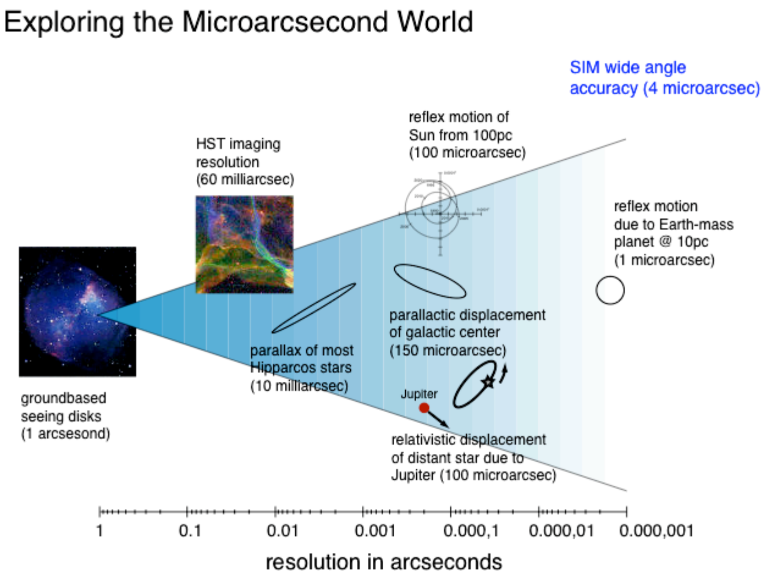
Scientific Goals of the GAIA Mission





SIM concept

http://planetquest.jpl.nasa.gov/SIM/



Exploring the Microarcsecond World

Astrometry in Practice

- Typically telescopes do not point better than to a few arcsec; so one points to a nearby star with precisely known coordinates, zeroes the telescope system, and does a small, "blind" offset to a target
- For imaging observations, one often uses positions of the stars in the frame, which have known positions (usually to a ~ 0.2 arcsec accuracy, e.g., from the ***USNO-B*** catalog), measures their XY positions in the image, and solves for the XY ⇆ RA,Dec transformation
- These transformation can be encoded in the image headers using the ***World Coordinate System (WCS)*** standard

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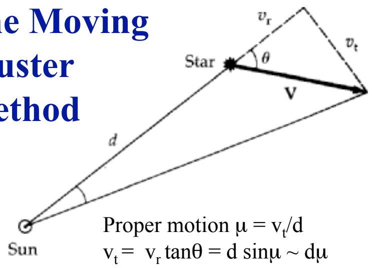
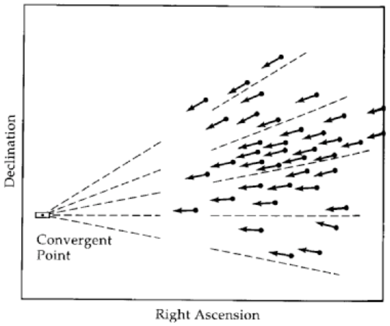
Moving Cluster Method

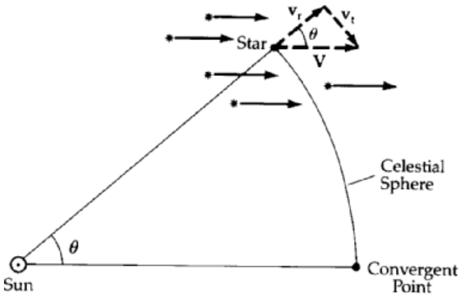
- A geometrical method, with some assumptions
- Nearby clusters of appreciable angular extent (e.g., Hyades) have stellar proper motions which converge to a point in the sky parallel to cluster's mean motion relative to the sun
- This gives the angle between our line of sight and the cluster's motion – what fraction of the motion is tangential (proper motion) and what fraction is radial
- Allows us to calibrate the magnitudes of the stars in the cluster; this calibrates the H-R diagram main sequence
- Can get distances out to the Hyades & Pleiades, young open star clusters, nearly Solar metallicity
- D(Hyades) = 46 ± 2 pc, and from Hipparcos parallaxes D = 46.3 ± 0.3 pc

The Moving Cluster Method



Proper motion $\mu = v_t/d$
$v_t = v_r \tan\theta = d \sin\mu \sim d\mu$





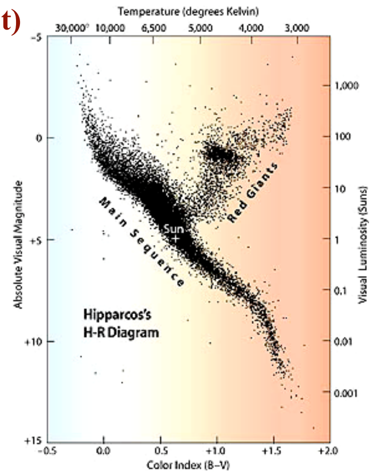
$v_t = 4.74\ \mu\ d = (4.74\ \mu) / p$ (km/s)
where p is parallax in arcsec
and μ is proper motion in arcsec/yr

Thus,
$d = (\langle v_r \rangle \tan\theta) / (4.74 \langle\mu\rangle)$
$p = (4.74 \langle\mu\rangle) / (\langle v_r \rangle \tan\theta)$

Main Sequence Fitting for Star Clusters

Luminosity (distance dependent) vs.
Temp. or color (distance independent)

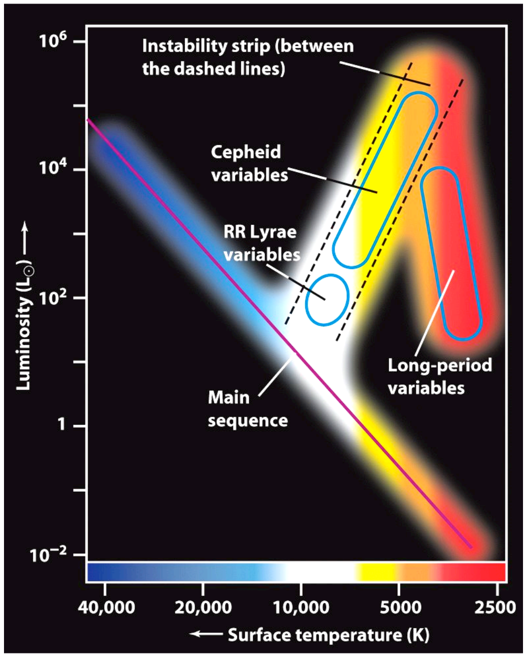
- Can measure distance to star clusters (open or globular) by fitting their main sequence of a cluster with a known distance (e.g., Hyades)
- The apparent magnitudes difference gives the ratio of distances, as long as we know reddening!
- There are no parallaxes to GCs (no nearby globulars) so we use parallaxes to nearby subdwarfs (metal-poor main sequence stars)



Hipparcos H-R diagram

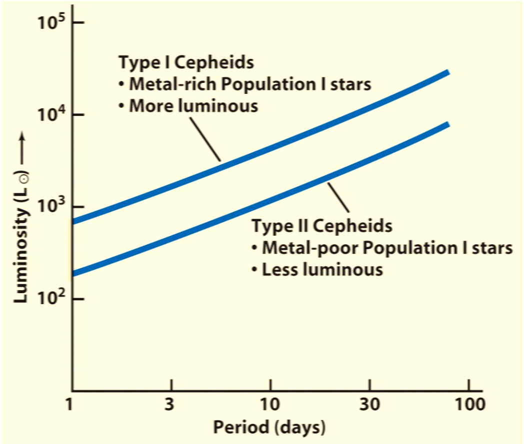
Pulsating Variables

- Cepheids are high-mass, Pop. I stars
- RR Lyrae are low-mass, metal-poor stars, often found in globulars
- Long-period variables (e.g., Miras) pulsate in a fashion that is less well understood
- All obey empirical period-luminosity rel's which can be calibrated to yield distances



Population I *vs.* Population II

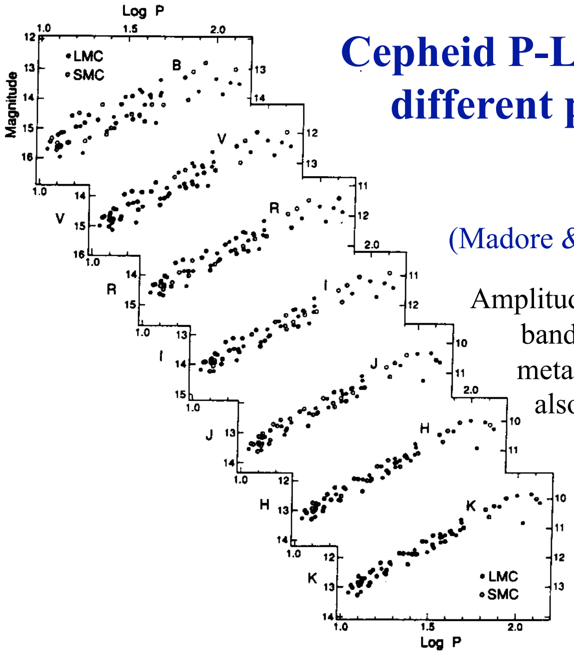
The first major revision in the distance scale was Walter Baade's realization that there are different stellar population - and their most common pulsating variables (classical Cepheids vs. RR Lyrae stars) have vastly different luminosities at the same pulsation periods



Cepheids

- Luminous (M ~ -4 to -7 mag), pulsating variables, evolved high-mass stars on the instability strip in the H-R diagram
- Shown by Henrietta Leavitt in 1912 to obey a period-luminosity relation (P-L) from her sample of Cepheids in the SMC: brighter Cepheids have longer periods than fainter ones
- **Advantages:** Cepheids are bright, so are easily seen in other galaxies, the physics of stellar pulsation is well understood
- **Disadvantages:** They are relatively rare, their period depends (how much is still controversial) on their metallicity or color (P-L-Z or P-L-C) relation; multiple epoch observations are required; found in spirals (Pop I), so extinction corrections are necessary
- P-L relation usually calibrated using the distance to the LMC and now using Hipparcos parallaxes. *This is the biggest uncertainty now remaining in deriving the H_0!*
- With HST we can observe to distances out to ~25 Mpc

Cepheid P-L Relation in different photometric bandpasses



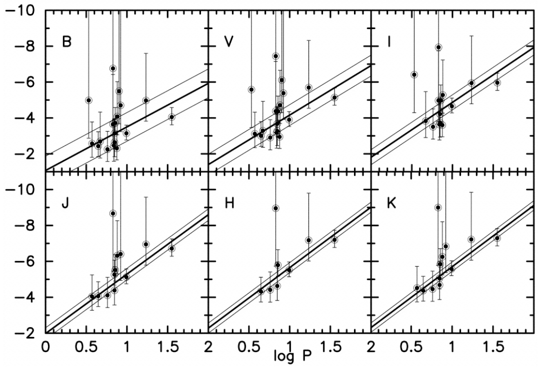
(Madore & Freedman 1998)

Amplitudes are larger in bluer bands, but extinction and metallicity corrections are also larger; redder bands may be better overall

Hipparcos Calibration of the Cepheid Period-Luminosity Relation

P-L relations for Cepheids with measured parallaxes, in different photometric bands

(from Freedman & Madore)



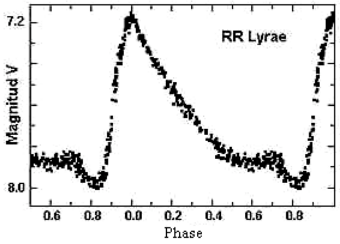
Typical fits give: $\langle M_V \rangle = -2.76 \log P - 1.45$

$\langle M_I \rangle = -2.96 \log P - 1.88$

… with the estimated errors in the range of **~ 5% - 20%**

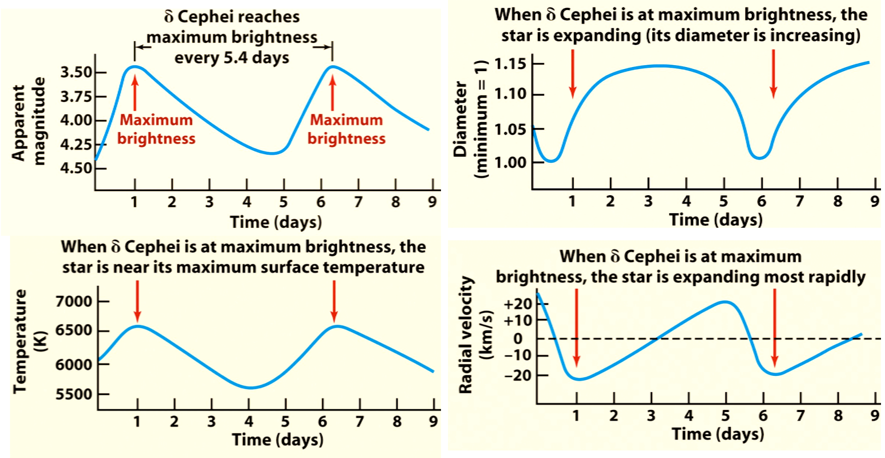
RR Lyrae Stars

- Pulsating variables, evolved old, low mass, low metallicity stars
  - Pop II indicator, found in globular clusters, galactic halos
- Lower luminosity than Cepheids, M_V ~ 0.75 +/- 0.1
  - There may be a metallicity dependence
- Have periods of 0.4 – 0.6 days, so don't require as much observing to find or monitor
- **Advantages:** less dust, easy to find
- **Disadvantages:** fainter (2 mag fainter than Cepheids). Used for Local Group galaxies only. The calibration is still uncertain (uses globular cluster distances from their main sequence fitting; or from Magellanic Clouds clusters, assuming that we know their distances)



Physical Parameters of Pulsating Variables

Star's diameter, temperature (and thus luminosity) pulsate, and obviously the velocity of the photosphere must also change



Baade-Wesselink Method

Consider a pulsating star at minimum, with a measured temperature T_1 and observed flux f_1 with radius R_1, then:

$$f_1 = \frac{4\pi R_1^2 \sigma T_1^4}{4\pi D^2}$$

Similarly at maximum, with a measured temperature T_2 and observed flux f_2 with radius R_2:

$$f_2 = \frac{4\pi R_2^2 \sigma T_2^4}{4\pi D^2}$$

Note: T_1 , T_2 , f_1 , f_2 are directly observable! Just need the radius…

So, from spectroscopic observations we can get the photospheric velocity $v(t)$, from this we can determine the change in radius, ΔR:

$$R_2 = R_1 + \Delta R = R_1 + \int_{t_1}^{t_2} v(t)\, dt$$

➞ **3 equations, 3 unknowns, solve for R_1, R_2, and D!**

Difficulties lie in modeling the effects of the stellar atmospheres, and deriving the true radial velocity from what we observe.

Summary of the Key Ideas

- This is a field with a venerable history – and it remains one of the most vibrant areas of modern astrophysics
- We map the structure and kinematics of Galaxian subsystems using a combination of positional and spectroscopic measurements, and interpret them using stellar dynamics
- Astrometry provides some of the most fundamental data we need; *GAIA* is the key forthcoming mission
- Parallaxes are the only direct, model-independent way of measuring distances; everything else is statistical, model-dependent, or empirical, requiring basic calibrations
- Other popular methods for determining distances to stars and clusters include: pulsating variables (e.g., Cepheids, RR Lyrae), main sequence fitting, the moving cluster method