AS1001: Galaxies and Cosmology

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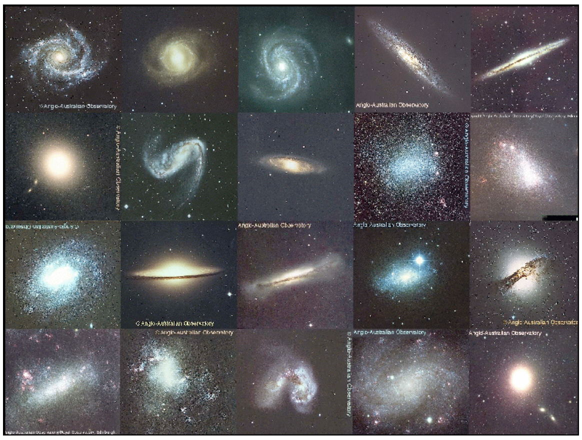
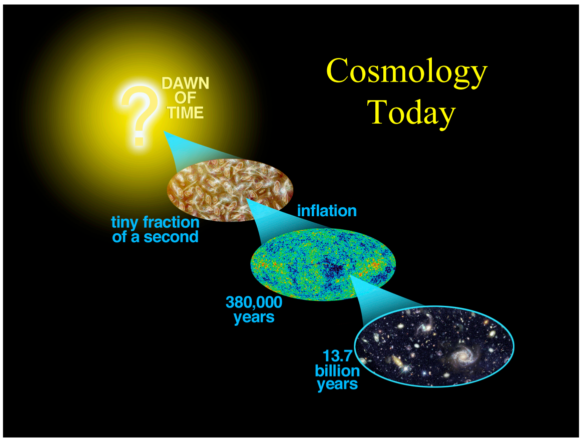
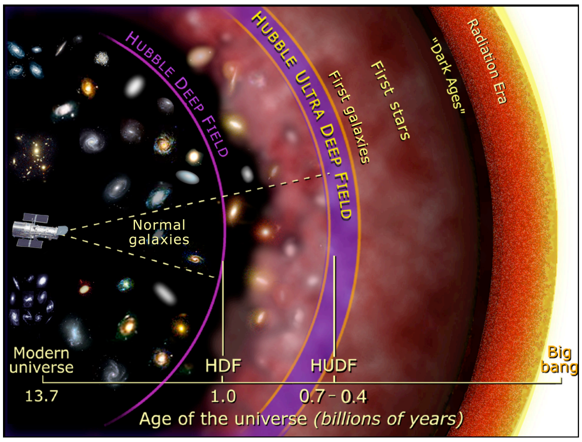
http://www-star.st-and.ac.uk/~kdh1/eg/eg.html

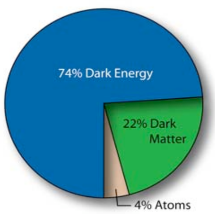
Text: Kutner **Astronomy:A Physical Perspective**
Chapters 17 - 21







Current Mysteries



Dark Matter ?
Holds Galaxies together

Dark Energy ?
Drives Cosmic Acceleration.

Modified Gravity ?
General Relativity wrong ?

Course Outline

- Galaxies (distances, components, spectra)
- Evidence for Dark Matter
- Black Holes & Quasars
- Development of Cosmology
- Hubble’s Law & Expansion of the Universe
- The Hot Big Bang
- Hot Topics (e.g. Dark Energy)

What's in the exam?

- Two questions on this course:
  (answer at least one)
- Descriptive and numeric parts
- All equations (except Hubble's Law) are also in Stars & Elementary Astrophysics
- Lecture notes contain all information needed for the exam. Use book chapters for more details, background, and problem sets

Lecture 1: Distances to Galaxies

- How do we measure distances to galaxies?
- Standard Candles (e.g. Cepheid variables)
- Distance Modulus equation
- Example questions

A Brief History

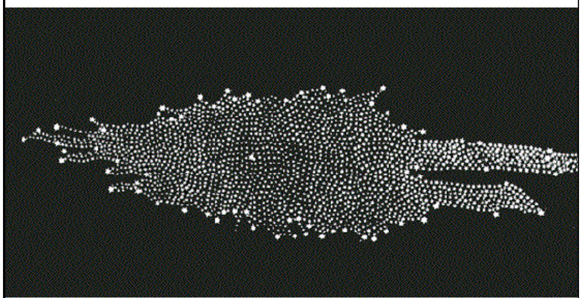
- 1611: Galileo supports Copernicus (Planets orbit Sun, not Earth)

  COPERNICAN COSMOLOGY
- 1742: Maupertius identifies "nebulae"
- 1784: Messier catalogue (103 fuzzy objects)
- 1864: Huggins: first spectrum for a nebula
- 1908: Leavitt: Cepheids in LMC
- 1924: Hubble: Cepheids in Andromeda

  MODERN COSMOLOGY
- 1929: Hubble discovers the expansion of the local universe
- 1929: Einstein's General Relativity
- 1948: Gamov predicts background radiation from "Big Bang"
- 1965: Penzias & Wilson discover Cosmic Microwave Background

  BIG BANG THEORY ADOPTED
- 1975: Computers: Big-Bang Nucleosynthesis (75% H, 25% He)
- 1985: Observations confirm BBN predictions
- 1992… CMB observatories: COBE, WMAP, Planck

1860: Herchsel's view of the Galaxy



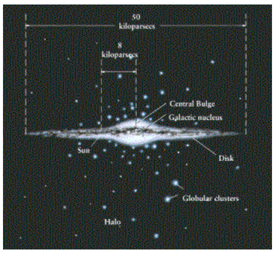
Based on star counts in different directions along the Milky Way. (Absorption by interstellar dust was not yet known).

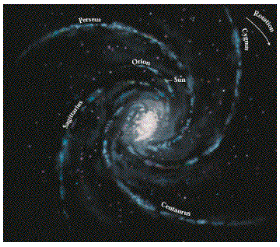
Mapping the Galaxy by counting stars

Dust obscures the centre:

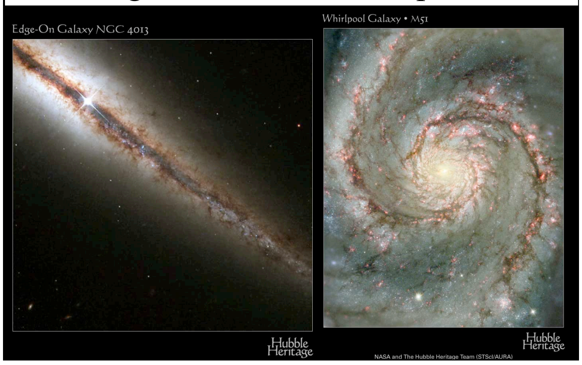
Our Galaxy

- Bulge, disk, globular clusters, spiral arms
- Stars move through the spiral arms.
- Diameter ~ 50 kpc; Sun ~ 8 kpc from centre

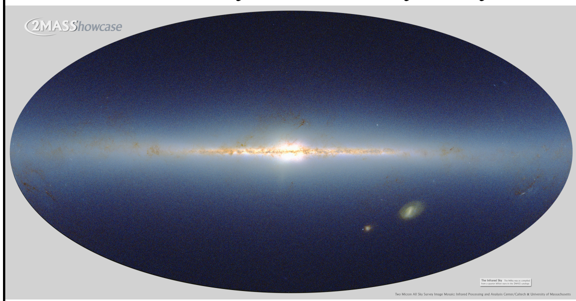




Edge-on and Face-on Spirals



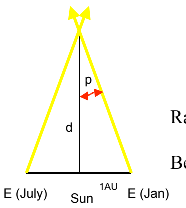
Our Galaxy: The Milky Way



Infrared observations let us see through (most of) the dust.

Measuring Distances to Stars

- Parallax: 2 measurements, 6 months apart



$d\,(\mathrm{pc}) = 1/p('')$

1 AU ~ 8 light minutes.
1 pc ~ 3.2 light years.

Range: limited by atmospheric effects to ~100 parsecs
Better results from space:
Hipparcos: ~300 pc
GAIA (2012): ~3 kpc

- Extragalactic distances: angles are very small so need another measuring technique

Standard Candles

$f = \dfrac{L}{4\pi d^2}$ and $m_1 - m_2 = -2.5 \log f_1 / f_2$

- Luminosity (energy/time) => absolute magnitude M
- Flux (energy/time/area) => apparent magnitude m
- **Distance Modulus:** $m - M = 5 \log_{10}(d/\mathrm{pc}) - 5$
- $M = m$ for $d = 10$ pc
- If we had lightbulbs of known wattage (**blue=500W**, **green=250W**, **red=100W**) we could measure a flux and find the distance.
- Astronomy: We need sources with known luminosity … **Standard Candles**.

Magnitudes: Apparent vs Absolute

Apparent magnitude: gives the observed **Flux** **(Watts m^{-2})**

Sun: m_V = -26.0 mag (V => "visible" light)
Faintest naked-eye stars: +6 mag
Andromeda galaxy: +3.5 mag
Faintest known galaxies: +28 mag

Absolute magnitude: gives the **Luminosity (Watts).**

Sun: M_V = +5.6 mag
Milky Way: -19.5 mag (Andromeda is similar)
Bright Quasars: -24.0 mag

Absolute magnitude = apparent magnitude at d = 10 pc.

Distance Modulus: $m - M = 5 \log_{10}(d/\mathrm{pc}) - 5$

NEVER ADD MAGNITUDES (meaningless) ADD FLUXES

If Galaxy A = -20 mag , Galaxy B = -21 mag
Total mag from both objects = -2.5 log($10^{-(-20)/2.5} + 10^{-(-21)/2.5}$) = ?

How Many Stars in a Galaxy ?

$L_G = N_* L_*$ $N_* = L_G / L_* = (100)^{(\Delta M/5)}$

Compare absolute magnitudes:

Sun: M_V = +5.6 Milky Way: M_V = -19.5

ΔM = (+5.6) - (-19.5) = 25.1 mag

5 mags is flux ratio 100 = 10^2

25 (= 5 x 5) mags is flux ratio $(100)^5 = 10^{10}$

Roughly 10^{10} stars in a bright spiral Galaxy.

In general: flux ratio is $(100)^{(\Delta M/5)} = 10^{(\Delta M/2.5)}$

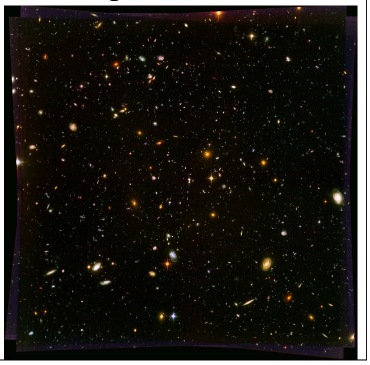
Hubble Deep Field:

At faint magnitudes, we see **thousands of Galaxies for every star** !

~10^{10} galaxies in the visible Universe

~10^{10} stars per galaxy

~10^{20} stars in the visible Universe

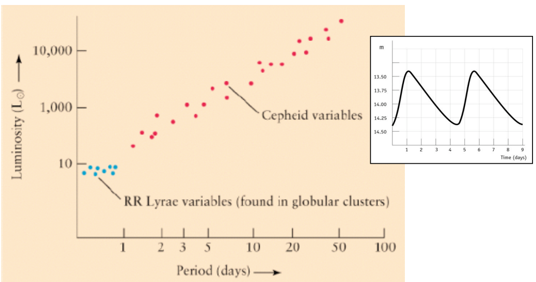


Cepheid Variable Stars as Standard Candles

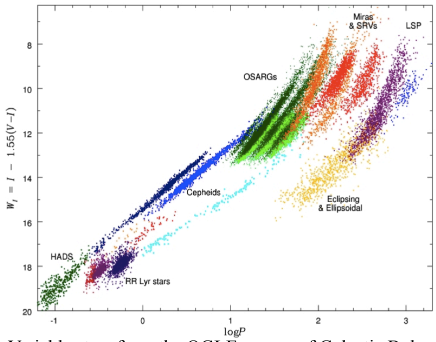
- Well studied pulsating stars (physics understood)
- Very bright (M_V ~ -2)
- Pulsate regularly (~ few days)
- Pulsation period P increases with luminosity L
- P-L relation is calibrated using Cepheids in star clusters of known distance
- (e.g. Cepheids in the Hyades cluster, whose distance is known from parallax)

The Period-Luminosity Relation for Cepheids

Henrietta Leavitt (Harvard, 1912)



Best Modern P-L Relation



Variable stars from the OGLE survey of Galactic Bulge

Distances from Cepheids

$$\log_{10} P + 0.394\ M_V = -0.657$$

DAYS Abs. V Mag. (from Hyades)

Once this Equation has been calibrated (as above) we can use it to measure distances to other clusters.

STRATEGY: Observe a star cluster
Find Cepheids (via light curves)
Measure P
Measure apparent mag m_V (e.g. at peak)
Calculate Mv (from P-L relation above)
Calculate distance ($m - M = 5\log_{10}(d/\mathrm{pc}) - 5$)

Example: Cepheid Distances

- A Cepheid is observed to pulsate with a period of 2.5 days. It has an apparent magnitude m_V = 18.6 mag at peak. How far away is it ?

USE: $\log_{10} P + 0.394\ M_V = -0.657$

REARRANGE: $M_V = \dfrac{-0.657 - \log_{10}(P)}{0.394}$

EVALUATE: $M_V = -2.68$ mag

USE: $m - M = 5\log_{10}(d) - 5 = 18.6 - (-2.68) = 21.28$ mag

REARRANGE: $d = 10^{(m-M+5)/5} = 10^{5.25}\,\mathrm{pc}$

EVALUATE: $d = 0.18$ Mpc

The Distance to Andromeda

- Andromeda (M31) is 0.9 Mpc away.

What would be the apparent magnitude of a 3 day Cepheid ?

AS BEFORE: $M_V = \dfrac{-0.657 - \log_{10}(P)}{0.394}$

$M_V = -2.88$ mag

$m = -2.88 + 5\log_{10}(9\times 10^5) - 5$

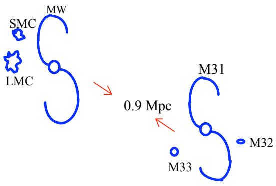
$m = 21.9$ mag

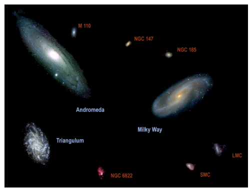
Hubble needed a large telescope to find the M31 Cepheids: 100'' Telescope on Mt Wilson

Local Group Trivia

- ~ 60 galaxies from Mv = -21 to Mv = -6 within 2 Mpc radius
- MW + M31 dominate the light and mass
- M31 is approaching us at about 85 km/s
- Collision expected in ~10 billion years !
- LG will eventually merge to form one giant elliptical galaxy
- LG is falling into the Virgo galaxy cluster

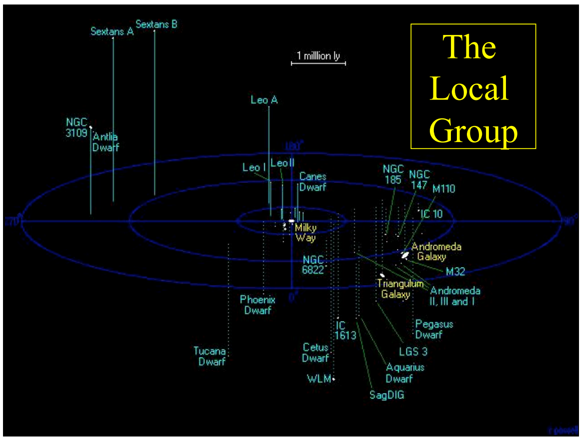
The Local Group



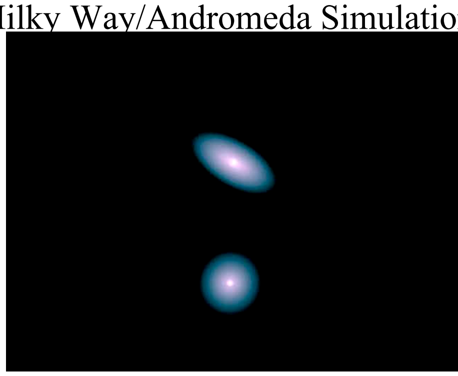


2	Giant Spirals (MW and M31)
1	Small Spiral (M33)
1	Compact Elliptical (M32)
	Irregulars (LMC & SMC)
~60	Dwarf Ellipticals
	Dwarf Irregulars

GRAVITATIONALLY BOUND, COLLISION INEVITABLE!

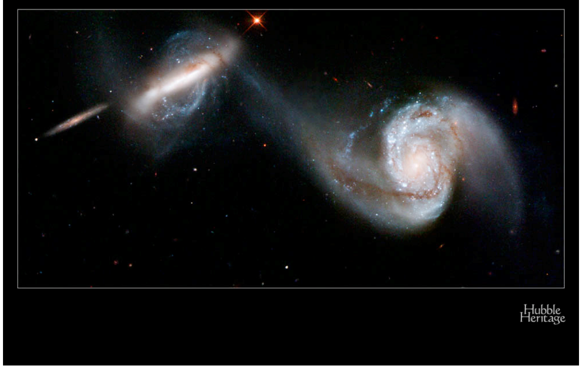


Milky Way/Andromeda Simulation

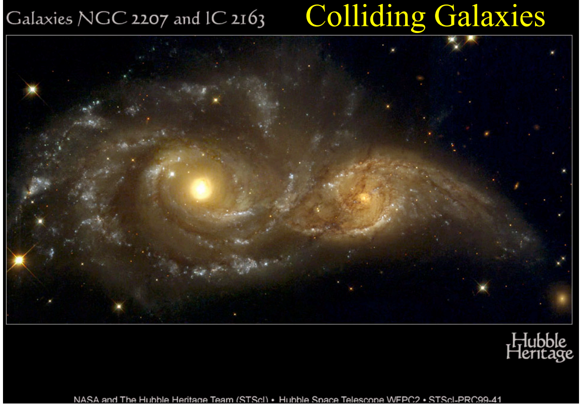


John Dubinski: www.cita.utoronto.ca/~dubinski

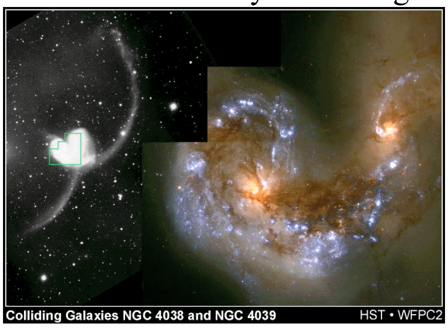
Colliding Galaxies



Colliding Galaxies



The Antennae Galaxy: mid-merger



Rapid burst of new star formation triggered by the collision.