Practice Problem

Assuming a uniform protogalactic (H and He only) cloud with a virial temperature of $10^6$ K and a density of $0.05 \text{ cm}^{-3}$ (a) estimate the minimum mass that could collapse, (b) what is the velocity dispersion in such a cloud, and (c) what would be its Jean’s radius?
Astronomy 422

Lecture 14: The Extragalactic Distance Scale

Every January, we see this:

Every July, we see this:

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1 AU

(not to scale)
Key concepts:

The extragalactic distance scale:
   Primary methods
   Secondary methods
The Extragalactic Distance Scale

Why do we want to measure distances to galaxies?
The Extragalactic Distance Scale

Why do we want to measure distances to galaxies?

• Want to measure physical size and structure of galaxies

• Want to measure their masses and luminosities

• Mapping 3D large-scale structure of the Universe (more later)

• Cosmology - study expansion of Universe (acceleration, age). We can determine the Hubble constant if we know V and D.
Measuring the Hubble constant

\[ V = H_0 D, \] so if we can measure \( V \) and \( D \) we can find \( H_0 \).
Huchra 2008: Hubble constant versus time.
Hubble constant versus time
Huchra 2008: Hubble constant versus time post-HST.

$70.4 \pm 1.4 \text{ (km/sec)/Mpc.}$
Problem:
Distances are truly vast => almost no direct geometrical method will work for extragalactic objects.

Distance measurements in general are divided into two types of methods: direct and indirect.

- Direct methods (aka primary or absolute methods)
  - radar ranging
  - geometric parallax
  - Disk masers

- Indirect methods (aka secondary methods)
  - Standard candles and rulers (apparent magnitude and apparent angular size depend only on distance).
• If you know luminosity \( L \), measure flux \( F \) and get distance \( D \) from 
\[ D^2 = \frac{L}{4\pi F} \]

• If you know the true metric size \( S \), measure the angular size \( \theta \) and get distance \( D \) from 
\[ D = \frac{S}{\theta} \]

• The accuracy of the resulting \( D \) depends on
  – how good your assumptions about \( L \) and \( S \) are
  – how accurate your measurements are

• Can also use redshift: for objects at cosmological distances (once the Hubble constant is known)

• An important concept is that applicable distance range of different methods overlap, and thus indirect methods can be calibrated using direct methods \( \Rightarrow \) the cosmological distance ladder.
Example Direct Measurements: Radar ranging
Distances within the Solar System can be measured via radar ranging.

Send out pulses at radio frequencies, and measure how long it takes for pulse to go and return. Distance $D = ct/2$. 
Example Direct Measurements: Trigonometric Parallax

Recall the traditional unit of distance is the parsec, defined in terms of the parallax angle $p$.

$$d\text{(parsecs)} = \frac{1}{p\text{('')}}$$

We can measure parallaxes only for stars within a few 100 pc (optical/IR), but there is a good sampling of stars within this range.

In radio we can go out to a few kpc, but only for radio loud objects.
HDE 283572

Proper motion
26.42 milliarcsec/yr
v = 16.9 km/s

Parallax:
7.794 milliarcsec

Distance:
128.3 parsecs

0.5% accuracy

Similar results for Pulsars, Masers, etc.
Example of direct distance measurements: Expanding supernovae.

Measure the angular extent of a supernova's photosphere, \( \theta(t) \).
The angular velocity of the gas is achieved from two measurements over a time interval \( \Delta t \):

\[
\omega = \frac{\Delta \theta}{\Delta t}
\]

If \( d \) is the distance to the supernova (=distance to host galaxy) then

\[
\nu_\theta = \omega d
\]

where \( \nu_\theta \) is the transverse velocity.
Assume that the expansion is spherically symmetric. Then

\[ v_\theta = v_r \]

where \( v_r \) is the radial velocity of the ejecta. This is easy to measure. Then:

\[ d = \frac{v_\theta}{\omega} = \frac{v_r}{\omega} \]

This is useful for only the closest supernovae.
Primary (Local) Distance Indicators

• Trigonometric, secular and statistical parallax

• Moving cluster method
  – proper motions of stellar clusters of significant angular extent

• Main sequence fitting to star clusters
  – Open and globular.
  – Depends on distance to known cluster (usually Hyades)

These gets us distances to galactic clusters, so we can calibrate RR Lyraes and Cepheids.
Secondary Distance Indicators

• Techniques that require local calibration via parallax and MS fitting

• Usually luminous *standard candles*

• Many methods, we will cover some of the most important ones
  – Cepheids and RR Lyraes
  – Planetary Nebula LF, Globular Cluster LF
  – Red Giant Branch tip
  – Surface Brightness Fluctuations
  – Type Ia supernovae
  – Tully-Fisher and D-σ relation.
Cepheids

- Luminous, pulsating, variable stars - evolved high mass stars on the instability strip in the HR diagram

- Obeys a Period-Luminosity relation (Leavitt 1912, SMC Cepheids)

- Brighter Cepheids have longer periods
  - $M = -2.80 \log(P) - 1.43$

Cepheid star in galaxy M100 with Hubble. Brightness varies over a few weeks.
• Pro's:
  • bright, so easily seen in other galaxies
  • pulsation physics fairly well understood
• Con's:
  • relatively rare
  • period depends on metallicity or color

• Found in spirals (Pop I) so extinction corrections required

• Require multiple observations

• Usually calibrated using distance to the LMC and its Cepheids
  – Biggest uncertainty for deriving Hubble constant

• With HST (The $H_0$ key project) Cepheids can be found out to distances of $\sim 25$ Mpc.
RR Lyraes

• Pulsating variable stars, evolved low-mass, low-metallicity stars
  – Pop II indicator, found in globular clusters, galactic halos

• Lower luminosity than Cepheids, $M_V = \text{constant} = 0.75 \pm 0.1$
  – May be a metallicity dependence

• Have periods of 0.4 - 0.6 days, so don't require as much observing to find.

• Pro's:
  – less dust, easy to find

• Con's:
  – fainter (~2 mag fainter than Cepheids), used for Local Group
  – Calibration still uncertain, requires statistical parallaxes for a large sample of nearby Lyraes.
RR Lyrae light curve with period $P=0.5668$ days.
Globular cluster luminosity function.

The *luminosity function* for any sort of object = number of object with luminosity between $M$ and $M+dM$ as a function of $M$.

- GC.s have a characteristic luminosity function which is approximately Gaussian with a well defined peak (empirically) at $M_B \sim -6.5$.

Jacoby et al 1992
• Globular Clusters are a Pop II indicator, no dust!

• Pro's:
  – luminous, easy to find in elliptical galaxies
  – measuring the LF turnover possible out to 200 Mpc

• Con's:
  – Rare in late-type galaxies (Sc's and later)
  – Need deep photometry to detect LF turnover
  – Slight metallicity dependence
  – Not as precise as some other methods, +- 0.3 mag
  – Empirical, the physical basis is not well understood

Method:

Construct apparent luminosity function for the galaxy of interest.
Compare the apparent magnitude of turnover with $M_0 = -6.5$

=> distance modulus.
Planetary Nebula Luminosity function

- Planetary nebula (PN) are evolved, red giant stars which have ejected outer layers of gas
- Strong emission at 5007Å, a forbidden line of oxygen [OIII]
  - easy to find using narrow band filters
[O III] $\lambda 5007$ (on-band) \hspace{1cm} \lambda 5300 (off-band)

O III] $\lambda 5007$ Difference
• Empirically, see a cutoff at $M_{5007} \sim -4.5$ for brightest nebulae.

• Method: Construct PN luminosity function, assume brightest nebulae at $M_{5007} \sim -4.5$

• PN are found in galaxies of all Hubble Types but require a small metallicity correction

• Calibration based on M31 (somewhat uncertain)

• Only useful to $\sim 16$ Mpc (Virgo)

• Physical basis fairly well understood
Ciardullo et al 2002: PN luminosity functions for a few galaxies.

Cutoff magnitude versus metallicity.
Tip of the Red Giant Branch

• In old stellar populations, the brightest stars are red giants
• In I-band, \( M_I = -4.1 \pm 0.1 \) (constant) for the tip of the red giant branch if stars are old and metal poor ([Fe/H]<0.7)
  – Conditions met for dwarf galaxies and galactic halos

• Pro's:
  – relatively bright, precise, many RGB stars available. Extinction problems reduced.

• Con's:
  – Only works out to \( \sim 15 \) Mpc (Virgo) and only for old, metal-poor populations.

• Calibration relies on subdwarf parallaxes from Hipparcos and distances to galactic GCs which are a little uncertain
Varies with $[\text{Fe/H}]$ for metal-rich populations

Based on Vandenberg et al. (2000) models
Surface Brightness Fluctuations for ellipticals

While surface brightness of a galaxy is distance independent, surface brightness *fluctuations* are not.

- Fluctuations for old stellar populations (E's, SO's and bulges) based primarily on the giant stars

- Assume a typical average flux density $<f>$ per star, and N number of stars per pixel
  - Average flux density per pixel $N<f>$, variance per pixel $N<f>^2$
  - $N$ scales as $d^2$, $f$ scales as $d^{-2}$
    ⇒ variance scales as $d^{-2}$
    ⇒ RMS scales as $d^{-1}$

Hence, a galaxy twice as far away appears twice as smooth
• The average flux density <f> can be measured as the ratio of the variance and and the mean flux density per pixel. If we know the average L (or M) => distance

• <M> is roughly the absolute magnitude of a giant star and can be calibrated empirically (using the bulge of M31)

• But there is a color-luminosity relation so
  \[ <M_I> = -1.74 + 4.5 \left( (V-I)_0 - 1.15 \right) \]

• Have to model and remove contamination from foreground stars, background galaxies and globular clusters

• Can be used out to \sim 100 \text{ Mpc} in the IR (NICMOS on the HST)
Nearby Galaxy

\[ \bar{f} \quad \text{Star flux} \quad \bar{f}/9 \]

\[ n \quad \text{Star density} \quad 9n \]

Same Galaxy
Three times the distance

Galaxy star field

Surface Brightness

\[ n\bar{f} \quad n\bar{f} \]

What the CCD sees

Rms fluctuation
(inversely prop. to distance)

\[ \sqrt{n\bar{f}} \quad \sqrt{9n\bar{f}/9} \]

= \frac{1}{3} \sqrt{n\bar{f}}

More CCD pixels

Variance divided by Mean
(Star flux)

\[ \bar{f} = \frac{(rms)^2}{\text{mean}} \quad \bar{f}/9 = \frac{(rms)^2}{\text{mean}} \]

Blurred by atmosphere

Blurred by atmosphere
The Tully-Fisher relation

- Based on global properties of spiral galaxies.
- Recall from ch 25 the relation between the luminosity of a galaxy and the 21-cm linewidth. Also true for other lines.
  - $L \sim V^4$ (exponent varies with wavelength)
  - $M = a \log(W) + b$
  - $W$ the doppler broadened line width, usually measured from the HI 21cm line width, needs to be corrected for inclination. $W_{\text{true}} = W_{\text{obs}} / \sin I$
  - $a+b$ can be found by measuring the TF relation in nearby galaxies with good Cepheid distances
Least scatter is seen in the infrared. Why?

a) Extinction is reduced.

b) Most light is from late-type giant stars.
TF at different distances, Jacoby et al 1992

Local Group

Ursa Major

Virgo
The $D-\sigma$ relation

For ellipticals. Recall the Faber-Jackson relation $\sigma^4 \propto L$ where $\sigma$ is the velocity dispersion. Less scatter appears when \textit{diameter} is plotted against $L$:

\[ D = \text{diameter to mean surface brightness of } 20.75 \text{ mag/arcsec}^2 \]
Novae

Relation between a nova's maximum visual magnitude, $M_{V,\text{max}}$ and the rate at which it dims, $\dot{m}$, usually taken to be the rate it dims 2 magnitudes.

$$M_{V,\text{max}} = -9.96 - 2.31 \log \dot{m}$$

Why? More massive white dwarfs will have smaller radii:

$\Rightarrow$ Greater compression, heating of surface gases
$\Rightarrow$ Smaller accumulated mass will trigger thermonuclear reactions
$\Rightarrow$ less massive surface layers will eject easily, nova declines faster.
Type Ia Supernovae

Recall these are supernovae which occur in close binary system of a white dwarf and a companion star.

If evolving companion dumps enough mass onto a WD near $M_{cs}$, runaway nuclear reactions may be ignited.

Brighter SN rise and decline slower than fainter ones.
Summary from Table 27.1 C&O:

<table>
<thead>
<tr>
<th>Method</th>
<th>Uncertainty (mag)</th>
<th>Distance to Virgo (Mpc)</th>
<th>Range (Mpc)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cepheids</td>
<td>0.16</td>
<td>15-25</td>
<td>29</td>
</tr>
<tr>
<td>Novae</td>
<td>0.4</td>
<td>21.1±3.9</td>
<td>20</td>
</tr>
<tr>
<td>PNLF</td>
<td>0.3</td>
<td>15.4±1.1</td>
<td>50</td>
</tr>
<tr>
<td>GCLF</td>
<td>0.4</td>
<td>18.8±3.8</td>
<td>50</td>
</tr>
<tr>
<td>Surface br fluc</td>
<td>0.3</td>
<td>15.9±0.9</td>
<td>50</td>
</tr>
<tr>
<td>TF</td>
<td>0.4</td>
<td>15.8±1.5</td>
<td>&gt;100</td>
</tr>
<tr>
<td>D-σ</td>
<td>0.5</td>
<td>16.8±2.4</td>
<td>&gt;100</td>
</tr>
<tr>
<td>Type Ia SN</td>
<td>0.10</td>
<td>19.4±5.0</td>
<td>&gt;1000</td>
</tr>
</tbody>
</table>
The Distance Ladder

- Other estimators
  - Gravitationally lensed QSOs
  - Sunyaev-Zel'dovich effect
  - Supernovae
- Tully-Fisher relation/D_n-σ method/Fundamental Plane
- RR-Lyrae stars and Cepheids
- Miscellaneous stellar techniques
- Main-sequence Fitting
- Proper Motions
- Parallax

Distances:
- Alpha Centauri
- Hyades
- Magellanic Clouds
- M31
- M81
- Virgo Cluster
- Coma Cluster

Distance Scale (parsec): 1, 10, 100, 1000, 10^4, 10^5, 10^6, 10^7, 10^8, 10^9, 10^10
Next time:

Exam 2, Thursday, March 10