Oct 28, 2015

- The extragalactic distance scale
- Characterizing large scale structure

- I am passing back HW #6 (which Dominik graded)
- HW#7 is due; please hand it in.
- HW#8,9,10 will focus on the final projects

There is a handout today
## Astro3303 Final Projects

<table>
<thead>
<tr>
<th>WHO</th>
<th>Facility</th>
<th>Science topic</th>
</tr>
</thead>
<tbody>
<tr>
<td>Paola</td>
<td>JWST</td>
<td>Detecting the first stars and galaxies</td>
</tr>
<tr>
<td>John</td>
<td>LSST</td>
<td>Constraints on dark energy from supernovae</td>
</tr>
<tr>
<td>JiSoo</td>
<td>HERA (e.g. PAPER)</td>
<td>Detecting HI from the “Dark Ages”</td>
</tr>
<tr>
<td>James</td>
<td>eRosita</td>
<td>Obscured active nuclei in galaxies</td>
</tr>
<tr>
<td>Zach</td>
<td>CCAT+ALMA</td>
<td>The history of dust-obscured star formation across cosmic time</td>
</tr>
<tr>
<td>Gabe</td>
<td>TMT/GMT/E-ELT</td>
<td>Resolved stellar population studies in the Virgo cluster</td>
</tr>
<tr>
<td>Sam</td>
<td>ngVLA</td>
<td>Mapping cold, star-forming gas in early galaxies</td>
</tr>
</tbody>
</table>
Early history of the redshift

- Slipher (~1912) noticed that spiral nebulae showed almost predominantly redshifts.
  - By 1925, he had radial velocities for 40 galaxies

- Hubble used the 100-inch telescope on Mt. Wilson to measure distance to 18 galaxies
  - Found linear relation between increasing redshift and increasing distance, now known as Hubble’s law

\[ H_0 \, d = v \sim cz \]

- A major early goal of HST has been to measure \( H_0 \sim 70 \text{ km/s/Mpc} \)

Sometimes use \( H_0 \sim 100 \, h \text{ km/s/Mpc} = (10^{10} \text{ yrs})^{-1} \)
Hubble’s Law

The dominant motion in the Universe is the smooth expansion known as the “Hubble flow”.

Hubble’s Law: \( V_{\text{obs}} = H_0 D \)
where \( H_0 \) is Hubble’s “constant” and \( D \) is distance in Mpc

“redshift” \( z = \frac{\lambda(\text{obs}) - \lambda(\text{rest})}{\lambda(\text{rest})} \)

An object at \( z \) is receding at velocity:

\[ \frac{V}{c} = \frac{(z+1)^2 - 1}{(z+1)^2 + 1} \]

\( \text{Note that as } v \rightarrow c, z > 1 \)
Extragalactic distance scale

What makes a distance indicator good?

- A statistically robust correlation between a cheaply-obtained distance-independent observable and a distance-dependent one
- A broadly accessible distance indicator, bridging across environments and host types.
- A high luminosity distance indicator, capable of being used across volumes containing fair samples of the universe
- Low intrinsic scatter: optimizes prediction and minimizes impact of bias
- Based on well-understood physical processes, which can serve to understand biases and secondary dependences (and astrophysics)?
- Allows secure calibration locally
- Robustness vis-à-vis cosmic evolution of the distance indicator
- Understanding of error on predicted distance: lognormal? absolute?
- Minimally affected by reddening
Measuring extragalactic distances

Primary distance methods:
• Measure distance to some “standard candle” (object whose luminosity you can infer) within the galaxy
• Works for nearest systems (where e.g. we can resolve the individual stars) or, in very special cases, also for distance systems.

Hubble’s Law:
• Observationally “low-cost” (but not exactly “cheap”)
• Measure the redshift => measure the distance
• Need to worry however about orbital motions in groups/clusters (and other similar effects)
Determining distances

• Parallax
  • Good for stars; someday nearest galaxies!

• Method of spectroscopic parallax => “standard Candles”
  • Need to know position of object(s) on H-R diagram
    • “Tip of the Red Giant Branch”
    • Cepheid Period-luminosity relation distances
    • Supernovae Type 1a (SNeIa)
  • Surface brightness fluctuations
  • Luminosity functions => Globular clusters, Planetary nebulae

• Dynamical indicators => Fundamental plane, TF relation (“secondary” methods based on scaling relations

• Geometric indicators => Maser motions (NGC 4258)

• Hubble’s Law
  • Works as long as we understand the “tricks”
  • Observationally “low-cost” (but not exactly “cheap”)
  • Measure the redshift => measure the distance
  • Need to worry however about orbital motions in groups/clusters (and other similar effects)
Local Group Proper Motions

• 1920s van Maanen claimed to see M33 spin!

• Specialist in astrometry, measured positions of HII knots ⇒ rotation with period of 60,000-240,000 yrs

• mas/yr motions ⇒ Spiral nebulae must be nearby (Galactic)

• Hubble argued more distant (extra-galactic)

• van Maanen’s error not found ⇒
  • Lundmark reanalyzed van Maanen’s plates and found smaller motion but in same direction
  • Baade claimed rotation of plate holder when exposure paused due to seeing/cloud variation caused elongation of images
**Micro-arcsec Astrometry with the VLBA**

Fringe spacing:

\[ \theta_f \sim \frac{\lambda}{D} \sim 1 \text{ cm/8000 km} = 250 \, \mu\text{as} \]

Centroid Precision:

\[ 0.5 \frac{\theta_f}{\text{SNR}} \sim 10 \, \mu\text{as} \]

Systematics:

path length errors \( \sim 2 \, \text{cm} \) (~2 \( \lambda \))
shift position by \( \sim 2\theta_f \sim 500 \, \mu\text{as} \)

Relative positions (to QSOs):

\[ \Delta\Theta \sim 1 \, \text{deg} \, (0.02 \, \text{rad}) \]

\[ \text{cancel systematics: } \Delta\Theta*2\theta_f \sim 10 \, \mu\text{as} \]

- Parallax accuracy: \( \sigma_D \sim 10\% \) at 10 kpc => *(can’t do galaxies yet)*
- Proper motion: same techniques, but \( \sigma_\mu \sim T^{-3/2} \)

**M31**

5 H\(_2\)O masers

Just a matter of time!

Extragalactic Proper Motions

• M33/IC133 - M33/19 masers
  VLBA: $\Delta \mu_x = 30 \pm 2$, $\mu_y = 10 \pm 5$ μas/yr
  HI: $\Delta v_x = 106 \pm 20$, $\Delta v_y = 35 \pm 20$ km/s
  $D = 750 \pm 50 \pm 140$ kpc

• Improvements in Rotation Model & 3rd maser source: $\sigma_D < 10\%$ possible

VLBA large program on-going!

“... it’s just a matter of time”

The HST-ACS Virgo Cluster Survey
The ACS Virgo Cluster Survey
Data and Analysis

- Model underlying galaxy
- Identify GC candidates
- Fit with PSF-convolved King models
- Compare with customized control fields
- Select clean sample of GCs in g and z
Globular Cluster Formation Efficiencies

Specific Frequency: number of GCs normalized to $M_V=-15$

$$S_N = N_{GC} \times 10^{0.4(M_V+15)}$$

Purpose: “To investigate whether there is in fact a ‘universal’ and uniform capability for globular cluster formation.” (Harris, van den Bergh 1981)

- Spirals: $S_N \sim 1$
- Ellipticals: $S_N \sim 5$
- Dwarf Ellipticals: $S_N \sim 0-30$
- M87: $S_N \sim 14$

Globular cluster formation efficiency is not constant across galaxy mass and morphology.
A gaussian distribution seems to describe well the LF of globular clusters around many galaxies.

Assume turnover and dispersion same.
Globular cluster LF

e.g. Harris+ 2009 AJ 137, 3314 (WFPC2)

• HST survey of Coma cluster ellipticals

• $S_N$ as high as 12 (really big!)
  • cD NGC 48734 has $> 30,000$ GCs
  • gEs are dominated by red, metal-rich GCs
  • Non-supergiant Ells have many fewer, blue GCs – why?
  • Diversity not understood

Figure 8. Composite luminosity function for the globular clusters in four Coma ellipticals, shown in solid dots with error bars. The composite LF is completeness corrected and background subtracted according to the prescription described in the text. The broken line at bottom is the background LF by itself, for comparison. The GCLF for the Virgo giant M87 is shown for comparison in open starred symbols, shifted by $\Delta V = 4.04$ mag and normalized to the same total GC population brighter than the turnover point (see text). The best-fitting Gaussian function, with turnover level $V^{\text{to}} = 27.71$ and dispersion $\sigma_V = 1.48$, is shown as the solid line. The dashed line gives the best-fit evolved Schechter function model, which has parameters $(\delta - V_c) = 3.2$ and a "cutoff" magnitude $V_c = 24.4$. 
Surface brightness fluctuations

Compare a GC to a distance elliptical: which one appears “granier” in images?

\[ \frac{N_*}{\text{pixel}} \sim d^2 \]
\[ f_* \sim d^{-2} \]

\[ \text{SB} = N_* f_* = \text{constant} \]

But variance \((\sqrt{N f})\) ≠ constant \(\Rightarrow\) \(\sigma = d^{-1}\) (more distant \(\Rightarrow\) smoother)

\[ \frac{\sigma^2}{\mu} = \frac{Nf^2}{Nf} = f \]

Mean flux per \(*\)

So take CCD image of galaxy

Measure mean SB \((\mu)\) as well as pixel-to-pixel variance \(\sigma^2\).

\[ \frac{\sigma^2}{\mu} \Rightarrow \langle f \rangle \Rightarrow \langle m_{\text{app}} \rangle \]

Fluctuation magnitude

Model LF \(\Rightarrow\) distance
Surface brightness fluctuations

\[ \frac{N_*}{\text{pixel}} \sim d^2 \quad \frac{f_*}{d} \sim d^{-2} \]  \[ SB = N_* f_* = \text{const.} \]

But variance \((= \sqrt{N \ f})\) \(\neq\) constant \(\sigma = d^{-1}\) (more distant \(\Rightarrow\) smoother)

Schematic galaxy on right is 2X as far as one on left. Large dots = giant stars; small dots MS stars. Grid represents CCD pixels. Although the mean SB/pix is same for both, the rms fluctuation from pix to pix relative to mean \(\propto d^{-1}\).

Jacoby+ 1992 PASP 104, 599
HST Key Project

Main goal: determine $H_0$ to within 10% by observing Cepheids in nearby galaxies.
Cepheid Variables

- Cepheid variables: Analogs of the star $\delta$ Ceph
- Giant, post-main sequence stars which pulsate due to instabilities.
- As the envelope of the star expands and contracts, the star’s brightness changes.
Cepheid Period-Luminosity Relation

- Henrietta Leavitt discovered a relationship between the period of pulsation and the mean luminosity of the star.

1. Identify the star as a Cepheid variable by studying its spectrum (if possible) and/or by the shape of its lightcurve.

2. Calculate its period.

3. Use the Period-Luminosity relationship to determine the Luminosity.

4. Use the inverse-square law to calculate how far a star of that luminosity would have to be in order to appear as a star of that observed apparent brightness.
Cepheid Variables

- Cepheid variables: Analogs of the star δ Ceph
- Giant, post-main sequence stars which pulsate due to instabilities.

Apparent brightness varies over time in repeated fashion

http://www.astro.lsa.umich.edu/Course/MMSS/Interactive/Ex1.4/lightcur.jpg
Cepheid demo

http://astro.wku.edu/labs/m100/
NGC 4258: maser distance + Cepheids

Composite image:
- **Yellow**: optical
- **Purple**: radio continuum
- **Blue**: X-ray
- **Red**: Spitzer IR

X-ray/radio continuum arms (purple/blue) are offset from the stars/gas/dust arms.

X-ray/radio arms not seen in optical; appear associated with shocked material and the SMBH
NGC 4258

- BVI survey of 2 fields using HST-ACS + 1 previously done with HST-WFPC2
- 281 Cepheids with periods from 4 to 45 days
- Observed 12 separate epochs 12/03 to 1/04

NGC 4258

- Master V-band image of inner field.
- Locations of Cepheids shown (circles)

NGC 4258

- Representative light curves of Cepheids in inner field
  - Blue: B
  - Green: V
  - Red: I

Fig. 3.44 The Seyfert galaxy NGC 4258 contains an accretion disk in its center in which several water masers are embedded. In the *top image*, an artist's impression of the hidden disk and the jet is displayed, together with the line spectrum of the maser sources. Their positions (*center image*) and velocities have been mapped by VLBI observations. From these measurements, the Kepler law for rotation in the gravitational field of a point mass of $M_\bullet \sim 35 \times 10^6 M_\odot$ in the center of this galaxy was verified. The best-fitting model of the central disk is also plotted. The *bottom image* is a 20 cm map showing the large-scale radio structure of the Seyfert galaxy. Credit: *Top*: M. Inoue (National Astronomical Observatory of Japan) & J. Kagaya (Hoshi No Techou). *Center*: Results from several groups, compiled by L. Greenhill, J. Herrnstein und J. Moran at CfA and the National Radio Astronomical Observatory. *Bottom*: C. De Pree, Agnes Scott College.
$\text{H}_2\text{O}$ maser in NGC4258

- Radiospectroscopy and VLBI of $\text{H}_2\text{O}$ molecules reveal a thin disk in Keplerian rotation.
- Rotation and distance yield an enclosed mass of $M \approx 4 \times 10^7 M_\odot$ within 0.3 lightyears.

Miyoshi et al. (1995), Herrnstein et al. (1997), Humphreys et al. (2008)
\[ T^2 = kR^3 \]

\[ v \propto 1/\sqrt{\theta} \]

\[ v \propto \theta \]

Redshifted

Systemic

Blueshifted

\[ u \]

\[ \theta \]
\[ T^2 = kR^3 \]
\[ v \propto 1/\sqrt{\theta} \]
\[ v \propto \theta \]

Redshifted

Blueshifted

Systemic

\[ a = \frac{v_0^2}{r_0} \]
\[ a = G\frac{M_{BH}}{r_0^2} \]
Figure 2. A spectrum of the water-vapor emission from NGC 4258 made with the GBT. Velocity axis (LSR, radio definition) is measured with respect to the rest frequency of 22235.080 MHz. The insets show blowups of the high-velocity red- and blue-shifted portions of the spectrum.
NGC 4258

H$_2$O masers at 22 GHz
VLBA @ 22 GHz

- Angular resolution $\sim 200$ μas (microarcsec)
- Spectral resolution $\sim 1$ km/sec

- Radial velocity (l.o.s.) $= \sqrt{\frac{GM}{R}} \sin \theta$ where $\theta$ is the azimuthal angle in the disk measured from the BH, $R$ is the radial distance from the BH, $M$ is the mass of the BH.

Close to l.o.s., $\sin \theta \sim \frac{b}{R}$, where $b$ is the impact parameter, so $V_z \sim b \sqrt{\frac{GM}{R^3}}$

Figure 4. Cartoon of the maser disk adapted from Greenhill et al. (1995).
NGC 4258

Over time, masers are tracked as they orbit, and eventually disappear from sight. Their velocities increase by about 8 km/s/yr from 430 km/s to 530 km/s; we only see them when their maser emission is beamed along the l.o.s.

Geometric distance:
- Measure their doppler shifts => km/s
- Measure the proper motions of the masers over time => “/year
- Comparison of the angular velocities in the latter measurement with the absolute velocities in km s\(^{-1}\) in the former measurements yields the distance.
The SMBH in NGC 4258

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Recessional velocity</td>
<td>$1080 \pm 2$ km/s</td>
</tr>
<tr>
<td>Angular distance</td>
<td>-4.4 mas</td>
</tr>
<tr>
<td>Acceleration</td>
<td>10 km/s per year</td>
</tr>
<tr>
<td>Radius of inner region</td>
<td>0.13 pc</td>
</tr>
<tr>
<td>Distance</td>
<td>7.4 Mpc</td>
</tr>
<tr>
<td>Mass inside inner radius</td>
<td>$3.6 \times 10^7 , M_\odot$</td>
</tr>
<tr>
<td>Bulge mass</td>
<td>$1.1 \times 10^{10} , M_\odot$</td>
</tr>
</tbody>
</table>
NGC 4258

- BVI period-luminosity relations for the brighter Cepheids in the inner field
- Lower right shows period-luminosity relation adopted using combination of methods and extinction

They use the maser distance (next) and the P-L relation for LMC to get Hubble constant

The method of “spectroscopic parallax”

1. Observe the star’s apparent brightness.

2. Observe the star’s spectrum; determine its spectral class and luminosity class.

3. Place the star on the H-R diagram; estimate its luminosity.

4. Use luminosity and apparent brightness to get distance.

Good for normal stars, clusters of stars, some very nearly galaxies (tip of the red giant branch)
1. Assume that the stars at the tip of the red giant branch always have the same luminosity.

2. Observe their apparent brightness.
Distances to far off galaxies: SNeIa

- 1998 and 1999:
  Two independent teams studying exploding stars in very distant galaxies found that the galaxies are further away than predicted!
Distant SNeIa

Host Galaxies of Distant Supernovae

HST04Sas  HST04Yow  HST04Zwi  HST05Lan  HST05Str

NASA, ESA, and A. Riess (STScI)

STScI-PRC06-52
SNeIa
Using SNe to determine distances

• **What measurements would you make?**
  • Observe the supernova suddenly brighten, then fade over time.
  • Identify it as a SN of Type Ia from its “light curve” (how it brightens and fades) and probably from taking spectra (which shows heavy elements like chromium, aluminum, etc).

• **What assumptions would you need to invoke?**
  • That all SN of Type Ia have the same luminosity when they are at their maximum apparent brightness, i.e. that SNeIa are “standard candles”.

• **So, if we observe a supernova’s light curve and apparent brightness, we can derive its distance.**

• **Then we can compare that distance to the distance we expect from its redshift and Hubble’s law => any differences tell us about the geometry of the universe.**
Determining distances from SNe

• What measurements would you make?
  • Observe the supernova suddenly brighten, then fade over time.
  • Identify it as a SN of Type Ia from its “light curve” (how it brightens and fades) and probably from taking spectra (which shows heavy elements like chromium, aluminum, etc).

• What assumptions would you need to invoke?
  • That all SN of Type Ia have the same luminosity when they are at their maximum apparent brightness.
  • That you can properly account for dust obscuration within the galaxy in which the SN resides.

• How do you derive the distance to a galaxy with a SNeIa?
  • Now we have: luminosity and apparent brightness.

\[
\text{Apparent brightness} \propto \frac{\text{Luminosity}}{(\text{Distance})^2} \quad \Rightarrow \text{distance}
\]
Using SNe Ia as standard candles

Velocity = c X z

- Identify a set of objects whose luminosity is taken to be constant: “standard candles”
- Then plot their apparent brightness versus their redshift
- => Determine “Hubble’s Law” over large distances

NOTE: for small z, 

\[ c \times z \approx \text{recessional velocity} \]

\[ c \times z = H(t) \times \text{Distance} \]

“Hubble parameter” units: (km/s)/Mpc
Distance to the LMC

\[ DM = 5 \times \log(\text{Dist}) - 5. \]

\[ = 18.5 \]

So

\[ \text{Dist} = 50 \text{ kpc} \]

Clementini et al. 2003
The Millennium Simulation project:
http://www.mpa-garching.mpg.de/galform/virgo/millennium/
Large Scale Structure

Formation of Structure

Galaxies are not distributed randomly in space.

If one galaxy has comoving coordinate, $x$, then the probability of finding another galaxy in the vicinity of $x$ is not random. They are Correlated.

Courtesy of Michael Blanton.
Different models yield different structure

Simulations of Structure Formation

$\Lambda$CDM: $\Omega_m=0.3$, $\Omega_\Lambda=0.7$

SCDM, $\tau$CDM: $\Omega_m=1$, $\Omega_\Lambda=0$
(they have different $\Gamma$'s).

$\Omega$CDM: $\Omega_m=0.3$, $\Omega_\Lambda=0.0$

From the Virgo Consortium Simulations
The Power Spectrum

An alternative and equivalent description of the statistical properties of Large Scale Structure is the **Power Spectrum, \( P(k) \).** This describes the amplitude of structure on scales of length \( L = 2\pi/k \).

Our density fluctuations can be decomposed into the sum of plane waves.

\[
\delta(x) = \sum a_k \cos(\text{\( x \text{k} \))
\]

Power spectrum is the Fourier transform of the correlation function:

\[
P(k) = 2\pi \int_0^\infty dr \ r^2 \frac{\sin kr}{kr} \xi(r)
\]