Planetary Nebula

Planetary Nebula Luminosity Function is Universal (Jacoby & Ciardullo)

Advantages:
• Reasonable Physical Understanding
• Works all galaxy types
• Precise (0.15 mag)

Disadvantages:
• Only to $cz<2000$ km/s
• Moderately observationally expensive

Tully–Fisher

Velocity of Galaxy Rotation and Luminosity correlated.

Advantages:
• Observationally inexpensive at low $z$
• Useful nearby (M31) and to $z~0.1$

Disadvantages:
• Moderately Poor Physical Understanding
• Moderately poor precision (0.35 mag)

Sunyaev–Zeldovich

Photons scatter off of Hot electrons in clusters. $\int N_e d\Omega = \frac{N_e(T)}{D_L^2}$

X-Ray emission proportional to $N_e^2$. Model X-ray emission ~ (spherical Isothermal sphere), eliminate $N_e$, measure $T$, and solve for distance.

Advantages:
• Physical method
• Works to $z>1$
• Can be done to large numbers of objects

Disadvantages:
• Substructure
• Asphericity makes imprecise

Surface Brightness

Poisson fluctuation of stars cause lumpiness inversely proportional to distance. Assumes stars causing fluctuations are same brightness (Horizontal Branch stars)

Advantages:
• Precise (0.13 mag)
• Can be done to many galaxies

Disadvantages:
• Only to $cz<8000$ km/s
• Sensitive to Colour, metallicity and Dust
**Supernova Taxonomy**

**Core Collapse**
- II-P: normal 10-30 Solar Mass Star
- II-L: massive star with extended envelope?
- IIn: massive star with dense CSM?
- IIb: massive star with thin H envelope
- Ib: massive star with He envelope
- Ic: massive star without H or He envelope

**Thermonuclear Detonations**
- Ia: white dwarf explosion.

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**The Expanding Photosphere Method**

SN II-P Radiate as modified Blackbodies

\[ \theta_{\mu} = \frac{R_{\mu}}{D} \left( \frac{f_0}{\sqrt{\pi} \Delta(T)} \right) \]

They freely expand

\[ R_{\mu} = v_{\mu} \left( t - t_0 \right) + R_0 \]

\( t = D \left( \frac{0}{1} \right) + t_0 \) (v measured from absorption lines)

\[ t_1, v_1, \Delta_T \]

\[ t_2, v_2, \Delta_T \]

\[ t_3, v_3, \Delta_T \]

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**Type Ia Supernovae**

Somewhere in China, May 1st, 1006…
X-Ray Image of SN 1006

Sun Earth (10 billion years)
Type Ia SN as 
Standard Candles

A Most Useful Way of Parameterizing SNe Ia is by 
the Shape of their Light Curve


Thesis, Saurabh Jha, Harvard University

Reddening from Dust

Wavelength (Angstroms)
What Causes the Diversity?

a. Progenitors have different mass.
b. Progenitors have different age or metallicity.
c. Explosion has different mechanism.
d. all of the above.
e. none of the above.

Distance Method Score Card

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<th>Distance Method</th>
<th>Target</th>
<th>Physical Basis</th>
<th>Comment</th>
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Cepheid Variable Star in Galaxy M100

HST-WFPC2

Hubble Diagram for Cepheids (flow-corrected)
H$_0$=74$^{+8/-8}$ km s$^{-1}$ Mpc$^{-1}$ for $\Omega_m=0.3$ and $\Omega_L=0.7$.

Unfortunately, a more recent analysis (Kochanek and Schechter 2003) gets $H_0=48^{+3/-3}$.

S-Z: 38 clusters
Calstrom et al. find $60 \pm 3 \pm 18$ km s$^{-1}$ Mpc$^{-1}$
For lambda Cosmology

2dF Redshift Survey + WMAP (CMB)
$72 \pm 4$ km/s/Mpc
Spergel et al. 2003
Assumes Universe is Flat and Made up of normal matter + Cosmological Constant.
In Synthesis: Evidence is that $H_0 = 70$ km/s/Mpc

Given uncertainties in the
• Cepheid Distance Scale
• Distance to LMC

But concordance with the physical distances
• Lensing
• S-Z
• SN II
• 2df+CMB

A good bet that $60 < H_0 < 80$ km/s/Mpc, but don’t Expect to win any money...