Supernovae and Cosmology

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Outline

- Supernovae as cosmological distance indicators
- Cosmological parameters
- Measurement of acceleration
- Why is the Universe accelerating?
- Summary and conclusions

Type II Supernovae as Distance Indicators

- Massive stars have wide range of luminosities and sizes
  - Probably bad as standard candles for distance measurements
- Fairly simple in terms of radiative transport though
  - SNe II can be modeled well enough to measure distances
  - 10% accuracy with expanding photosphere method
- However, SNe Ia are more precise and easier to measure
  - SNe II will never replace SNe Ia for cosmological measurements
  - Good independent method of confirming SN Ia results

Type Ia Supernovae as Standard Candles

- SNe Ia have been used as extragalactic distance indicators since 1968
  - Wasn't recognized that SNe I are actually two different phenomena
  - SNe Ib/c are massive stars $\rightarrow$ core collapse after losing H atmosphere
  - SNe Ia are themonuclear explosions on white dwarfs
- Late 1980's–early 1990's: recognized distinctions of SNe
  - Most SNe Ia have extremely similar light curve shapes, spectral time series, and absolute magnitudes
  - Those that differ are easily identified and removed

Type Ia Supernovae as Standard Candles

- Branch & Tammann (1992)
  - Intrinsic disperson in B and V maxima were < 0.25 mag (though probably even smaller)
  - "The best standard candles known so far"
- Calan/Tololo Supernova Search began in 1990 ($3\frac{1}{2}$ years long)
  - Obtained high quality SN light curves and spectra for $0.01 < z < 0.1$
  - Compared peak magnitudes to relative distances (deduced from Hubble velocities)
  - Contributed 30 new SN Ia light curves to catalog with unprecedented control of measurement uncertainties

Type Ia Supernovae as Standard Candles

- CTSS data analysis by Phillips (1993)
  - Found tight correlation between rate of luminosity decline and absolute magnitude
  - Found strong correlation between M and $\triangle m_{15}(B)$ (amount B decreases over 15 days): further improved distance accuracy
- Other methods to correct extinction, intrinsic luminosity differences, etc. also improved precision

Cosmological Parameters

- Assuming Universe is homogeneous and isotropic, line element given by Robertson-Walker metric
  - $ds^2 = -dt^2 + a^2(t)[\frac{dr^2}{1-kr^2} + r^2 d\Omega^2]$ $(c \equiv 1)$
  - $k = -1, 0, 1 \leftrightarrow$ open, flat, closed Universe
  - dynamical evolution contained in scale factor $a(t)$
- Description of dynamics of the Universe given by Friedmann equation
  - $H^2 \equiv (\frac{\dot{a}}{a})^2 = \frac{8\pi G\rho}{3} - \frac{k}{a^2}$ (H = Hubble parameter)
  - The density that results in flat Universe is $\rho_c(t) = \frac{3H^2(t)}{8\pi G}$
  - Density of each species usually given in terms of density parameter $\Omega_i(t) \equiv \frac{\rho_i(t)}{\rho_c(t)}$

Cosmological Parameters

- Equation of state parameter given by $w_i \equiv \frac{p_i}{\rho_i}$
  - Usually $w_i \geq -1$ for matter and scalar fields
  - $w_i = 0$ for normal matter and CDM, $\frac{1}{3}$ for photons, and -1 for cosmological constant
- Luminosity distance d_L is the distance actually measured
  - Defined such that flux $F = \frac{L}{4\pi d_L^2}$
  - $d_L = \frac{cz}{H_0}[1 + \frac{1}{2}(1 - q_0)z + \cdots]$, where the deceleration parameter $q_0 = \frac{1}{2}\sum_i \Omega_i(1 + 3w_i)$
  - Note that d_L depends on q_0 and hence on mass/energy composition
  - For decelerating Universe ($q_0 > 0$), d_L is smaller than for accelerating Universe ($q_0 < 0$) for a given z

Cosmological Parameters

- If only forms of mass/energy are Ω_M and Ω_Λ, then $q_0 = \frac{\Omega_M}{2} - \Omega_\Lambda$
  - To discern dark energy component, measurements of $< 5\%$ precision needed (*see figure*)
  - Discriminating between different dark energy models with time varying EOS's require even better accuracy
- Recent results $\Rightarrow \Omega_\Lambda = 0.7$ and $\Omega_M = 0.3$
  - Consistent with WMAP results ($\Omega_{total} = 1.0, \Omega_\Lambda = 0.73, \Omega_M = 0.27$)
  - Imply matter is secondary to dark energy in the (accelerating) expansion of the Universe (*see figure*)

Measuring the Hubble Constant

- Schmidt et al. (1994), using 16 SNe II, estimated $H_0 = 73 \pm 6 \pm 7$ using EPM
  - Independent of other rungs of extragalactic distance latter, like Cepheids (which calibrate SNe Ia)
  - 2 methods (SNe II and Cepheids) agree to within 5% for distance measurements
  - Provide confidence in both methods

Measuring the Hubble Constant

- Current sample of > 100 nearby SNe Ia define Hubble diagram slope to 1% for $0 < z < 0.1$ (*see figure*)
  - Cepheids calibrate SNe Ia $\rightarrow$ major limitation for measuring H_0
  - $H_0 = 66 \pm 3 \pm 7$ from Jha (2003)
  - $H_0 = 76 \pm 3 \pm 8$ from Freedman et al. (2001)
  - Differences due to different methods, not errors in SNe Ia data from HST Cepheid distance measurements
- Best current estimate: $H_0 = 70 \pm 10$
- Future works lies with Cepheid calibrators or other distance indicators, not with SNe

Measurement of Acceleration

- Since SNe Ia are so intrinsically luminous, can currently be detected to $z > 1.5$
  - SNe II can be detected only to $z \approx 0.5$
- However, SNe Ia are relatively rare
  - Happen in galaxies like MW only a few times per 1000 years
  - Method used requires large block of observing time
  - Obtaining observing time not usually feasible until recently

Measurement of Acceleration: Research Teams

- Supernova Cosmology Project (SCP)
  - Led by Saul Perlmutter of the LBNL
  - Formed in 1988 to use high z SNe Ia to determine q_0
  - Large international team of physicists and some astronomers
- High–z Supernova Search Team (HZSNS)
  - Formed in 1994 by Brian P. Schmidt and Nick Suntzeff
  - Motivated by Phillips' SNe Ia calibration relation, success of SCP, and importance of measuring q_0
  - International team of mostly astronomers

Measurement of Acceleration

- Both SCP and HZSNS data $\Rightarrow$ SNe are fainter than expected
  - Agreement of 2 teams' results is extremely good
  - At $z \approx 0.5$, SNe are ~ 0.28 mag dimmer ($\sim 14\%$ farther) than if $\Omega_M = 0.3$, $\Omega_\Lambda = 0$
  - Implies Universe is accelerating
- Simplest explanation is that additional component of matter with $w_i < -\frac{1}{3}$ exists (recall $q_0 = \frac{1}{2}\sum_i \Omega_i(1+3w_i)$)
  - $\Omega_\Lambda \neq 0$ works ($w_\Lambda = -1$)
  - 99.9% confidence that Universe has a nonzero Λ or other form of dark energy

Measurement of Acceleration: Systematic Errors

- K correction
  - SNe Ia observed at high $z \Rightarrow$ large wavelength shifts
  - Obervations made with fixed band passes, so corrections must be made
  - If obervations done well, error can be minimal
- Selection effects
  - Malmquist bias: volume of observed bright objects $>$ volume of observed dim objects
  - Since SNe Ia are such accurate distance indicators, effect is small (~ 0.01 mag)

Measurement of Acceleration: Systematic Errors

- Extinction
  - 1^{st} order effects from changing average extinction can be corrected by observing multiple wavelengths
  - 2^{nd} order effects, such as evolution of intervening dust, more difficult to handle
  - Also, thin dust veil around MW: absolute amount of extinction uncertain $\rightarrow$ systematic error ~ 0.06 mag
- Evolution of SNe Ia
  - SNe Ia in early–type galaxies show light curves with faster rise and fall times than in late–type hosts
  - After data are corrected for light curve shape, luminosity shows no host galaxy type bias

Measurement of Acceleration: Systematic Errors

- Gravitational lensing
  - Light travels through lower density region: demagnification
  - Light travels through higher density region: magnification (uncommon)
  - Process usually makes most objects fainter
  - Distortions in measurements quite difficult to determine
  - May be the effect that most severly limits accuracy of distance measurements

Why is the Universe Accelerating?

- Are astronomers misinterpreting the data?
  - Precision of observations and such close agreement between SCP and HZSNS make this unlikely
  - Need to make drastic and improbable assumptions to make other plausible interpretation of data
- Is general relativity incorrect?
  - For assumption of homogeneous, isotropic, accelerating Universe, GR requires dark energy source
  - GR extremely sucessful in classical experimental tests and prediction of gravitational waves
  - Alternatives to GR constrained by observations
  - Possible but unlikely that GR is wrong

Why is the Universe Accelerating?

- Is dark energy dynamical?
  - If GR is correct, dark energy density must diminish slowly with expansion
  - Friedmann equation $\Rightarrow \dot{a}^2 \propto a^2\rho + constant$, so ρ_{DE} must fall off slower than a^{-2}
  - $\rho_M \propto a^{-3}$ and $\rho_{rad} \propto a^{-4}$, so they won't work
  - ρ_Λ is constant (vacuum energy)
  - But data $\Rightarrow$ smoothly distributed sources of dark energy that vary slowly with time

Why is the Universe Accelerating?

- Is the Universe's current state just a coincidence?
  - Easiest explanation of accelerating Universe is a constant vacuum energy
  - $\frac{\rho_\Lambda}{\rho_M} \propto a^3$ and the Universe has expanded by a factor of $\sim 10^{32}$ since Planck time, but $\frac{\rho_{\Lambda,0}}{\rho_{M,0}} \sim 1$!
  - For comparison, $\frac{\rho_M}{\rho_{rad}} \propto a$ and $\frac{\rho_{M,0}}{\rho_{rad,0}} \sim 6000$
  - Are we at a very special time in the evolution of the Universe? (*see figure*)
- Have we experienced environmental selection?
  - Maybe vacuum energy is different in other regions of Universe
  - Maybe our region is "just right" for life

Future Plans

- More SN Ia measurements
  - Will reduce statistical errors, but systematic errors will remain
  - At best, systematic errors can be reduced to ~ 0.03 mag
- Supernova/Acceleration Probe (SNAP) collaboration proposed to launch cosmology satellite
  - Will scan > 1000 SNe Ia per year out to $z \approx 1.7$
  - Space–based observations $\rightarrow$ better control of many systematic effects
  - First studies of time dependence of EOS w_i

Summary and Conclusions

- SNe Ia are reliable cosmological distance indicators
  - However, systematic errors limit accuracy
- SNe data $\Rightarrow$ expansion of Universe is accelerating
- Accelerating Universe creates unresolved issues for theoretical physics and cosmology
- Next step: SNAP