Type Ia Supernovae, Dust, and Cosmology

Brian Schmidt
in collaboration with
Joerg Fischera

Wednesday, 5 May 2010
From the 1930s, the basic Paradigm for Understanding the Global Properties of the Universe was in place

- **Theory of Gravity**
  - General Relativity
- **Assumption**
  - Universe is homogenous and isotropic
\[ D_L = \sqrt{\frac{L}{4\pi F}}, \quad D_A \equiv \frac{l}{\theta} \]

the flux an observer sees of an object at redshift \( z \)

\[ D_L = D_A (1 + z)^2 = \frac{c}{H_0} (1 + z) \kappa_0^{-1/2} S \left( \kappa_0^{1/2} \int_0^z dz' \left[ \sum_i \Omega_i (1 + z')^{3 + 3w_i} - \kappa_0 (1 + z')^2 \right]^{-1/2} \right) \]

\[ \kappa_0 = \left( \Omega_{tot} = \sum_i \Omega_i \right) - 1 \]

\[ S(x) = \begin{cases} \sin(x) & k = 1 \\ x & k = 0 \\ \sinh(x) & k = -1 \end{cases} \]

Brightness or size of object depends exclusively on what is in the Universe - How much and its equation of state.
\[ D_L = \sqrt{\frac{L}{4\pi F}}, \quad D_A \equiv \frac{l}{\theta} \]

the flux an observer sees of an object at redshift \( z \)

\[
D_L = D_A (1+z)^2 = \frac{c}{H_0} (1+z) \kappa_0^{-1/2} S \left\{ \kappa_0^{1/2} \int_0^z dz' \left[ \sum_i \Omega_i (1+z')^{3+3w} - \kappa_0 (1+z')^2 \right]^{-1/2} \right\}
\]

\[
\kappa_0 = \left( \Omega_{tot} = \sum_i \Omega_i \right) - 1
\]

\[
S(x) = \begin{cases} 
\sin(x) & k = 1 \\
x & k = 0 \\
\sinh(x) & k = -1 
\end{cases}
\]

Brightness or size of object depends exclusively on what is in the Universe - How much and its equation of state.
\[ D_L = \sqrt{\frac{L}{4\pi F}}, \quad D_A \equiv \frac{l}{\theta} \]

the flux an observer sees of an object at redshift \( z \)

\[ D_L = D_A (1 + z)^2 = \frac{c}{H_0} (1 + z)^{1/2} S \left[ \kappa_0^{1/2} \int_0^z d z' \left[ \sum_i \Omega_i (1 + z')^{3 + 3w_i} - \kappa_0 (1 + z')^2 \right]^{-1/2} \right] \]

\[ \kappa_0 = \left( \Omega_{tot} = \sum_i \Omega_i \right) - 1 \]

\[ S(x) = \begin{cases} 
\sin(x) & k = 1 \\
x & k = 0 \\
\sinh(x) & k = -1 
\end{cases} \]

Brightness or size of object depends exclusively on what is in the Universe - How much and its equation of state.
\[ D_L = \sqrt{\frac{L}{4\pi F}}, \quad D_A \equiv \frac{l}{\theta} \]

the flux an observer sees of an object at redshift \( z \)

\[ D_L = D_A(1 + z)^2 = \frac{c}{H_0} (1 + z) \kappa_0^{-1/2} S \left[ \kappa_0^{1/2} \int_0^z dz' \left[ \sum_i \Omega_i (1 + z')^{3 + 3w_i} - \kappa_0 (1 + z')^2 \right]^{-1/2} \right] \]

\[ \kappa_0 = \left( \Omega_{tot} = \sum_i \Omega_i \right) - 1 \]

\[ S(x) = \begin{cases} 
\sin(x) & k = 1 \\
x & k = 0 \\
\sinh(x) & k = -1 
\end{cases} \]

Brightness or size of object depends exclusively on what is in the Universe - How much and its equation of state.
Model Content of Universe by the Equation of State of the different forms of Matter/Energy

$$w_i \equiv \frac{P_i}{\rho_i} \quad \rho_i \propto (\text{Volume})^{-(1+w_i)} \propto a^{-(1+w_i)} \propto (1 + z)^{3(1+w_i)}$$

e.g.,

- $w=0$ for normal matter
- $w=1/3$ for photons
- $w=-1$ for Cosmological Constant

$$\rho \propto V^{-1}$$
$$\rho \propto V^{-4/3}$$
$$\rho \propto V^{0}$$

Wednesday, 5 May 2010
Model Content of Universe by the Equation of State of the different forms of Matter/Energy

\[ w_i \equiv \frac{P_i}{\rho_i} \]
\[ \rho_i \propto (\text{Volume})^{-(1+w_i)} \propto a^{-3(1+w_i)} \propto (1+z)^{3(1+w_i)} \]

e.g.,
\[ w=0 \text{ for normal matter} \]
\[ w=1/3 \text{ for photons} \]
\[ w=-1 \text{ for Cosmological Constant} \]
Type Ia Supernovae, Dust , and Cosmology

Wednesday, 5 May 2010
Type Ia Supernovae
Refining Type Ia Distances

Mark Phillips (1993)
How fast a Supernova Fades is related to its intrinsic brightness.
Proof is really that it works...

102 SN at 0.01 < z < 0.2
Hamuy et al. 1995
Riess et al. 1998
Riess et al. 1999
Germany et al. 2002
Jha et al. 2002

dm15, MLCS, stretch, SALT, Sifto, C-magic...
Type Ia Supernovae, Dust, and Cosmology

Discovery of Accelerating Universe
Riess et al. (1998)
Perlmutter et al. (1999)

Riess et al. 1998
Perlmutter et al. 1999

\[ \Omega_M = 0.3, \Omega_\Lambda = 0.7 \]
\[ \Omega_M = 0.3, \Omega_\Lambda = 0.0 \]
\[ \Omega_M = 1.0, \Omega_\Lambda = 0.0 \]
Type Ia Supernovae, Dust, and Cosmology
By 2001

Getting Rid of Dark Energy required 2 out of 3 major experiments to be wrong.
By 2001
Getting Rid of Dark Energy required 2 out of 3 major experiments to be wrong
By 2001
Getting Rid of Dark Energy required 2 out of 3 major experiments to be wrong
By 2001

Getting Rid of Dark Energy required 2 out of 3 major experiments to be wrong
By 2001

Getting Rid of Dark Energy required 2 out of 3 major experiments to be wrong

Wednesday, 5 May 2010
What is Dark Energy?
What is Dark Energy?

One possibility is that the Universe is permeated by an energy density, constant in time and uniform in space.

Such a “cosmological constant” (Lambda: $\Lambda$) was originally postulated by Einstein, but later rejected when the expansion of the Universe was first detected.

General arguments from the scale of particle interactions, however, suggest that if $\Lambda$ is not zero, it should be very large, larger by a truly enormous factor than what is measured.

If dark energy is due to a cosmological constant, its ratio of pressure to energy density (its equation of state) is $w = P/\rho = -1$ at all times. This is testable!
What is the Dark Energy?

Another possibility is that the dark energy is some kind of dynamical fluid, not previously known to physics, but similar to what is postulated to have caused inflation.

In this case the equation of state of the fluid would likely not be constant, but would vary with time.

Unfortunately these theories offer infinite flexibility, can reproduce any observation we make, and can spend much of their time looking like a Cosmological
What is the Dark Energy?

Another possibility is that the dark energy is some kind of dynamical fluid, not previously known to physics, but similar to what is postulated to have caused inflation.

In this case the equation of state of the fluid would likely not be constant, but would vary with time.

Unfortunately these theories offer infinite flexibility, can reproduce any observation we make, and can spend much of their time looking like a Cosmological
What is the Dark Energy?

Another possibility is that the dark energy is some kind of dynamical fluid, not previously known to physics, but similar to what is postulated to have caused inflation.

In this case the equation of state of the fluid would likely not be constant, but would vary with time.

Unfortunately these theories offer infinite flexibility, can reproduce any observation we make, and can spend much of their time looking like a Cosmological...
An alternative explanation of the accelerating expansion of the Universe is that general relativity or the standard cosmological model (homogeneity) is incorrect.

General Relativity is well measured in the strong-field regime through pulsars, but also in various Solar system and Earth-based experiments. These leave a little wiggle-room for modifications of GR.
An alternative explanation of the accelerating expansion of the Universe is that general relativity or the standard cosmological model (homogeneity) is incorrect.

General Relativity is well measured in the strong-field regime through pulsars, but also in various Solar system and Earth-based experiments. These leave a little wiggle-room for modifications of GR.
Type Ia Supernovae, Dust, and Cosmology

Nearby Sample+

- SNLS (Astier et al.)
- Essence (Wood-Vasey et al.)
- Higher-Z (Riess et al.)
- SDSSII (Kessler et al.)

$w \sim -1. \pm 0.1 \pm 0.2$

Kessler et al. '09

Research School of Astronomy and Astrophysics
Australian National University

Ken Freeman's Conference 2010
Brian Schmidt & Joerg Fischera

Wednesday, 5 May 2010
All constrained simultaneously

Komatsu et al 08

$\omega$, $\omega_w$, $\omega_M$, $\omega_K$
Type Ia Supernovae, Dust, and Cosmology

SNLS 3rd-year Preliminary Results

Sullivan et al. in prep

Wednesday, 5 May 2010
Everybody has Dirty Laundry...
The Devil in the details of fitting distances

There are exist many methods of fitting distances to SN Ia presently.

Everyone more or less agrees that SN Ia Luminosity

• Depends on light curve shape (faster is dimmer)
• Depends on colour (redder is dimmer)
• Depends on extinction in MilkyWay + Host (redder and fainter)
• Seems to depend on Host Galaxy Mass (Kelly et al. ’09, Sullivan et al. ’10)
The luminosity fitters that are being used for Cosmology (SALT2 –Guy et al. MLCS2k2 Jha et al)

• Both fit the shape of the light curve,
• deal with colour information differently

MLCS2k2 (Essence) corrects for host galaxy extinction and SN Ia colour–luminosity separately.

• Empirically modelling SN Ia colour–luminosity information,
• Applying a prior on Extinction–reddening relationship.
SALT (SNLS) empirically corrects for colour of SNIa, combining effects of host galaxy extinction and luminosity–colour relationship of SN Ia into one parameter.

- Uses Schlegel et al. Dust Maps to correct for Milky Way extinction
- Measures Shape and Colour of Light curve
- Empirically corrects the entire sample with a linear colour and shape coefficient.
Comparing light-curve fitters

MLCS2k2 and SALT2 give tightly correlated light curve parameters!

Small (few percent) differences arise in converting these parameters to distances.

from Mark Sullivan

Conley et al. (2007, in prep)
**On the face of it...MLCS2k2 treatment seems the way to go...**

If the intrinsic colour–luminosity relationship does not exactly mimic the extinction law, if average extinction amount of two samples is different, (or the extinction law changes), there will be a systematic bias.

However, finding the intrinsic colour–luminosity relationship for SN Ia is non-trivial.

It seems likely that in flux–limited surveys **SN-colour relationship dominates over dust!**
How we treat dust affects Cosmological Measurements

• Using the two approaches affects Cosmological measurement at the $w \geq \pm 0.1$ level.

• How to correct...

• IR data (Hard - Sky is Bright/Space is expensive!)

• Understand extinction/colour better in the nearby Universe
**Hubble Bubble?**

- MLCS2k2 paper (Jha 2007)

- $3\sigma$ decrease in Hubble constant at $\approx 7400$ km/sec – local value of $H_0$ high; distant SNe too faint

- Local void in mass density?
Hubble Bubble
Not seen with SALT method
The Hubble Bubble and Dust

Conley et al. (2007)

Hubble Bubble
Not seen with SALT method
“Bubble” significance versus colour coefficient

Conley et al. (2007)

Observed: $\beta \sim 2$

Standard Dust: $\beta \sim 4.1$

Conley et al. (2007)
Kessler et al ’09
SN Ia empirical relationships depend on Galaxy Mass or specific Star Formation Rate.

Sullivan et al 2010
SkyMapper

- 1.35m telescope with 5.7 sq degree imager (~14s readout time)
- All Southern Sky Survey (2pi steradians) 6 colours 6 epochs
- 1000 sq-degrees continually covered in poor seeing will find 1000 SN Ia at z<0.1 over 5yrs
- Commissioning, ongoing
Location of SN Ia

- Distribution of Type Ia SNe is poorly constrained
Location of SN Ia

- Distribution of Type Ia SNe is poorly constrained
Location of SN Ia

- Distribution of Type Ia SNe is poorly constrained
Location of SN Ia

- Distribution of Type Ia SNe is poorly constrained
- Two different kinds? SN Ia associated with:
  - young stellar population (small scale height).
  - old stellar population (large scale height),

Different probabilities for SNe to explode in the thin dusty disc.
Location of SN Ia

- Distribution of Type Ia SNe is poorly constrained
- Two different kinds? SN Ia associated with:
  - young stellar population (small scale height).
  - old stellar population (large scale height),

Different probabilities for SNe to explode in the thin dusty disc.

The relative abundance probably varies with redshift.
• Structure assumed to be isotropic.
• Density distribution is log-normal.
• Structure is a simple power law in Fourier space.
• Because of self-gravity massive density enhancements will become stable.

Joerg Fischera 2004
The Model

Dust scattered light from interstellar clouds

Joerg Fischera
Cloud Model

Spherical, isothermal, and in pressure equilibrium with the ambient medium.

- Problem scales with cloud temperature:
  ➡ 50 K or 100 K.

- Extinction determines pressure/density profile.

- $A_V$ varied from 0.1 to 3.0:
  ➡ Flat density profile.

Pressure/Density Profile

$n_H = \frac{c}{r^2}$

$p_{\text{ext}} / k = 2 \times 10^4 \text{K/cm}^3$
The Mean Optical Properties of ISM Dust
Dust Model of Weingartner & Draine 2001

- in optical/UV high dust albedo
- in optical/UV strong forward scattering (high g-parameter)
Light-echo of a light flash (Kernal function)

Model restrictions:
- based on single scattering events
- model is axial symmetric

Kernal function is given by the integral over the scattering surface (all scattering events with same delay-time $\tau$).

$$K_{\lambda}(\tau) = c \int \frac{dR}{2R} n_H(R(\tau)) C_{\text{sca}}(\lambda) \Phi_{\lambda}(\vartheta_{\text{sca}}(R(\tau))) e^{-\tau_1(\lambda)} e^{-\tau_2(\lambda)}$$

- hydrogen density
- scattering cross section
- scattering phase function
- extinction

Wednesday, 5 May 2010
The SN Light Echo

$A_v = 0.25$
$T_d = 100 \text{ K}$
$R_d = 0.43 \text{ pc}$
• Clouds are centered in the line of sight to the source.
• Cloud distances are varied from $1 \, R_{cl}$ to $32 \, R_{cl}$. 

The SN Light Echo
For short delay times (10 days) and small cloud distances clouds are well illuminated by the SN light.
Model calculation
Model calculation

$A_T = 0.5 \quad \text{day}: 0.0$
$D_{cl} = 2.0 \quad R_{cl}$
$T_{cl} = 50 \text{ K}$
$R_{cl} = 0.41 \text{ pc}$
$z = 0.0$

![Graph with model calculation]
Effect on the Distance Modulus ($z=0$)

Curves are labelled with the cloud distance (in radii).
Effect on the Distance Modulus \((z=0)\)

- Scattered light leads to an overestimate of the actual distance.

Curves are labelled with the cloud distance (in radii).
Effect on the Distance Modulus (z=0)

- Scattered light leads to an overestimate of the actual distance.
- Effect is small:
  - at large cloud distances and
  - for low extinction values.

Curves are labelled with the cloud distance (in radii).
‘Galaxy Model’
(the thin dusty disc)

interstellar clouds  infinite slab (sources)

• Clouds have all the same size (extinction $A_V$).
• Clouds are randomly distributed.
• Clouds fill a certain volume of the ISM (filling factor $f_f$).

Assume extinction through intercloud medium is negligible.
The Mean Offset in Distance Modulus

For SNe well mixed with the dusty disc:

The mean distance offset is in the regime of several percent.

Mean offset in distance modulus for three values of cloud extinction.
Conclusions
Conclusions

- SN Experiments march on, severely hampered by Dust. But still, they remain Cosmology’s most precise method of probing Cosmic Acceleration.

- Light Echoes from Nearby Clouds can affect SN Distance by several percent, and this effect could be expected to increase with redshift.

- IR SN light curves will lower dust systematics by factor of 5, but observationally, extremely expensive.

- Future improvements will be slow, removing systematic effects from larger and better datasets.

- BAOs, Weak Lensing, ... or possibly someone’s good idea...
Thank You Ken for Being Forever Young
If the Universe is Homogenous and Isotropic
the Universe is Accelerating!

- Expand the Robertson-Walker Metric and see how $D(1+z,q_0)$...

Supernova Data is good enough now to show the acceleration independent of assuming General Relativity.

$q(z) = \frac{-(\ddot{a}/a)}{\dot{a}^2}$

Daly et al. 2008

Wednesday, 5 May 2010
Dark Energy ?

Wednesday, 5 May 2010
only if the Universe is not homogenous or isotropic – Robertson Walker Metric invalid.

Occam’s Razor does not favour us living in the center of a spherical under-density whose size and radial fall-off is matched to the acceleration.
only if the Universe is not homogenous or isotropic – Robertson Walker Metric invalid.

Occam’s Razor does not favour us living in the center of a spherical under-density whose size and radial fall-off is matched to the acceleration.

Theoretical Discussion on whether or not the growth of structure can kink the metric in such a way to mimic the effects of Dark Energy. This is the only way out I can see - But controversial!