Supernovae Reveal An Accelerating Universe (A Science Adventure Story)

“If the Lord Almighty had consulted me before embarking on creation thus, I should have recommended something simpler.” —King Alfonso X
MODELS OF EXPANDING UNIVERSE – early 1990’s

Heavy ($\Omega_M > 1$)  Lightweight ($\Omega_M < 1$)

Measuring deceleration “weighs” Universe, ultimate fate!
Type Ia Supernovae, (imperfect) Standard Candles

Type Ia Supernovae

An explosion resulting from the thermonuclear detonation of a White Dwarf Star.

Bright = near  
faint = far

but not all the same…

faint & red = not so far!

Thesis: Multicolor Light Curve Shape (MLCS) Method

- Distinguish faint=far vs faint=intrinsically dim vs faint=dusty
- All ages, covariance, galaxy sims to improve dust measure
- For missing data: Snapshot method (1998)
CfA I Survey: A Northern Collection of SNe Ia; Expansion

1.2m Mt. Hopkins, 1200+ observations, 4 colors, 22 SN Ia, 1993-1996

-6 days

Maximum

+26 days

+47 days

+102 days

22 SNe Ia CfA I+MLCS:
Riess et al 1996, 1999

log redshift

log distance
In 1994 the High-z Team was formed: “To Measure the Cosmic Deceleration of the Universe with Type Ia Supernovae”

To measure changes in the expansion rate, we sought the highest-redshift, most distant supernovae to compare to their nearby brethren we had already collected.
• Fall of 1996 went to Berkeley (nearby, nearly in SCP group)
• Observing for High-z at Keck with A. Filippenko, improving algorithms, reducing High-z supernova data (SN 95ao, 95ap, 96E, 96R, 96T, 96U)

High Redshift Supernovae—hard work!

<table>
<thead>
<tr>
<th>Before</th>
<th>After</th>
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<td>SN Ia 1972E at 10 million light years</td>
<td>SN Ia 1996E at 6.6 billion light years</td>
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I have been picked to lead analysis of all data (16 SNe) to date.

"Eureka Moment" came when calculating the mass of Universe implied by the deceleration \( (q_0>0) \) of our supernovae, assuming no cosmological constant \( (\Omega_\Lambda = 0) \).

\[
q_0 = \frac{\Omega_M}{2} - \Omega_\Lambda
\]

Adam’s Lab book, Key Page, Fall 1997:

**Negative Mass?**

Actually the first indication of the discovery!

This negative sign means a negative deceleration \( (q_0<0) \) which means acceleration!

\[
\Omega_M = -0.36 \pm 0.16
\]

This negative sign represents 70% of Universe!
Days later … What does this mean? There cannot be negative mass, but would Einstein’s Cosmological Constant explain this acceleration?

Odds are…

After cross-checks, time to tell the team!

Yes!!! At least 99.73% sure something like Einstein’s Cosmological Constant is needed!
The Team is Excited, Worried (over 4 continents, email)...

A. Filippenko, Berkeley, CA, 1/10/1998 10:11am: “Adam showed me fantastic plots before he left for his wedding. Our data imply a non-zero cosmological constant! Who knows? This might be the right answer.”

B. Leibundgut, Garching, Germany, 1/11/1998: 4:19am “Concerning a cosmological constant I’d like to ask Adam or anybody else in the group, if they feel prepared enough to defend the answer. There is no but how confident are we in this result? I find it very perplexing…”

R. Kirshner, Santa Barbara, CA, 1/12/1998 10:18am: “I am worried. In your heart you know [the cosmological constant] is wrong, though your head tells you that you don’t care and you’re just reporting the observations; it would be silly to say ‘we MUST have a nonzero [cosmological constant]’ only to retract it next year.”

M. Phillips, Chile, 1/12/1998, 04:56 am: “As serious and responsible scientists (ha!), we all know that it is FAR TOO EARLY to be reaching firm conclusions about the value of the cosmological constant”

J. Tonry, Hawaii, 1/12/1998, 11:40 am: “who remembers the detection of the magnetic monopole and other gaffs? on the other hand, we should not be shy about getting our results out ..”

A. Filippenko 1/12/1998, 12:02 pm: “If we are wrong in the end, then so be it. At least we ran in the race.”

A. Riess, Berkeley, CA 1/12/1998 6:36pm: “The results are very surprising, shocking even. I have avoided telling anyone about them because I wanted to do some cross checks (I have) and I wanted to get further into writing the results up. The data require a nonzero cosmological constant! Approach these results not with your heart or head but with your eyes. We are observers after all!”

A. Clocchiatti, Chile 1/13/1998 07:30pm: “If Einstein made a mistake with the cosmological constant—Why couldn’t we?”

N. Suntzeff, Chile 1/13/1998 1:47pm: “I really encourage you [Adam] to work your butt off on this. We need to be careful—if you are really sure that the [cosmological constant] is not zero—my god, get it out! I mean this seriously—you probably never will have another scientific result that is more exciting come your way in your lifetime.”
SNe Ia near and far indicate acceleration equating to ~70% dark energy in Universe!
Steady dimming from grey dust or evolution instead? Test: brighter at $z>1$ (i.e., prior deceleration)?

Alternative Explanations for faint=far supernovae

- **Faint=far**
  - Universe accelerating
- **Faint=grey dust, not far**
  - Grey dust
  - Not accelerating

Present past

\[ \rho_M = \frac{\rho_{M,0}}{(1 + z)^3} \]

\[ \rho_\Lambda = \rho_{\Lambda,0} \]

HZT: Riess et al. 1998

SCP: Perlmutter et al. 1999
Telescope sensitivity improves, we see farther...

Sensitivity Improvement over the Eye

- Photographic & electronic detection
- Telescopes alone
- Electronic
- Hubble Space Telescope

Year of observations

- Galileo
- Huygens eyepiece
- Slow f ratios
- Short’s 21.5”
- Herschell’s 48”
- Rosse’s 72”
- Mount Wilson 100”
- Mount Palomar 200”
- Soviet 6-m
- Hubble Space Telescope

SN 1997cj

Ground-Based 0.7”

Hubble Space Telescope
A First Glimpse at Decelerating Universe...2001

SN la 1997ff, $z=1.7$

**Discovery:**
The Hubble Deep Field, WFPC2, 1997 (Gilliland & Phillips).

**Rediscovery:**
Light Curve Measured from *Serendipitous* Observations and timing of the NICMOS Near-Infrared Deep Field; (Riess et al 2001)

Results supported accelerating-interpretation of high-$z$ SNe Ia, but with only one object conclusion not very robust.
Hubble gets new camera, can measure SNe Ia at $z>1$, 2002

- In 2002 Astronauts install ACS
- From 2002-2007 the *Higher-z* Team measured 23 new SNe Ia at $z>1$
Not just supernovae require “dark energy”…
1. Expansion recently began Accelerating

2. Galaxy potentials are being pried apart; passing photons gain energy

3. Difference between $\Omega_{\text{tot}}=1$ critical density, $\Omega_M=0.3$ sub-critical is 0.7


5. Change in Absolute Scale of Universe, $z=1000-0$, (WMAP+$H_0=74 \pm 3$), 2009

1998: SNe Ia

2003: CMB & LSS,M/L,BAO,lensing

2003: late-time ISW Effect

2003: X-rays
Why is the Universe Accelerating?

1. Static Vacuum Energy, (the cosmological constant)
   A constant energy of empty space, expected in QM, consequence in GR--repulsive gravity, now $\Omega_{DE} \geq \Omega_M$ (but the coincidence problem & the $10^{120}$ problem)

2. Dynamical dark energy
   A field with energy pervades space, changes with time (e.g., “inflation-lite”)

3. Modification to GR—long range
   Maybe GR fails at long range, modification as scale approaches present horizon

Tests of all 3: is DE strength constant, evolving, scale-dependent?
New studies to help understand dark energy
• Already increased precision in measuring $H_0$ (3.5%)
• A search for SNe at 1.5$<z<$2.3, already found a few so far…
Dark Energy

25%

Gas 4%

25%

Stars 0.5%

70%

Planets 0.05%

Planets+Stars+Gas
Why is Dark Energy (cause of acceleration) so important?

- Its 70% of the Universe and we don’t understand it!
- It will determine the fate (origin) of the Universe
- Touches the central pillars of modern physics (QM, GR, String) It’s a clue and embarrassment, $10^{120}$. It is likely to lead to something interesting…
We discovered accelerating expansion and dark energy in 1998. More distant supernovae seen with the Hubble Telescope test alternatives, confirm acceleration is real.

Understanding dark energy lies in the critical path to understanding gravity, the fate and the origin of the Universe.
• In 1992 I graduated MIT, summer at LLNL on MACHO project

• Fall, 1992: to Harvard (met Brian, fellow grad student), thesis on improving distances to Type Ia Supernovae with R. Kirshner.
  (Began working with Brian and High-z Team on high-z SNe Ia, 1994)
Discovering the most distant supernovae with Hubble, 2002

Step 1: Detection at $m_I > 25$, ACS

Step 2: Winnowing
SN Ia are red in UV

Step 3: Identification, redshift
ACS grism spectrum
Ground has never measured redshift this high

Step 4: Follow-up, near-IR
Light Curve
NICMOS
Peak and shape yields distance
Higher-z Team

Discovery

Follow-up

EXTENDING SNE IA TO 1.5 < z < 2.3 WITH WFC3-IR

Most distant, spec. confirmed SN Ia
Why does the Vacuum Accelerate the Universe?

Newton: $\rho > 0$

Einstein: $\rho + 3p > 0$

Einstein: $\rho - 3p < 0$

QM: vacuum zp energy, do work to expand U, so $p<0$, but At present vacuum 120 Orders of magnitude off!
Nearby SN Ia, SN 1994D, seen by HS

The End
Present and Future Studies of Dark Energy

The Goal: To measure if dark energy evolving & if General Relativity (Einstein’s theory) works on large-scales.

- US Decadal Survey Picks, WFIRST, NASA to build for ~2020+ launch
- ESA selects EUCLID ~2019 launch
- Ground-based Plans: LSST, Big Boss, Subaru, etc. 2015-2025

WFIRST-Wide Field InfraRed Survey Telescope
1.5m, wide angle, Dark Energy via 3 methods