Understanding Dark Energy with the SuperNova Acceleration Probe (SNAP)

BNL
June 28\textsuperscript{th}, 2006

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University of Michigan
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- Dark Energy & The Accelerating Universe
- The Observational Tool: SNe Ia
- SuperNova / Acceleration Probe (SNAP)
- NIR Instrumentation
- Science Reach
The Cosmological Constant

In 1917, Einstein put a cosmological constant (Vacuum Energy) into his equations of General Relativity to allow for a static universe. This constant energy density is:

\[ R_{\mu\nu} - \frac{1}{2} g_{\mu\nu} R - \Lambda g_{\mu\nu} = -8\pi G T_{\mu\nu} \]

- By tuning the current value of \( \Lambda \), attractive gravity due to matter density (and vacuum energy density) and the repulsive effect of the negative pressure can be made to just balance.
- Danger! Runaway solution if \( \Lambda \) is large and positive!
Hubble’s Law

Hubble combined his knowledge of galaxy redshifts with an estimate of the distance to these galaxies: The more distant a galaxy, the faster the galaxy ‘moves away’ from us: \( v = H_0 D \)

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What is the nature of matter and energy at its most fundamental level?
(What is the universe made of?)

What is the evolution and destiny of the universe and how is it affected by the fundamental interactions of energy, matter, time and space?
(Is the universe infinite? Will it last forever?)
Destiny

Traditional philosophy of General Relativity (in absence of a cosmological constant): **Geometry ⇒ Destiny**

Geometry determined by the density parameter $\Omega = \frac{\rho_{TOT}}{\rho_{crit}}$

$$\rho_{crit} \equiv \frac{3H_0^2}{8\pi G} = 1.9h^2 \times 10^{-29} \text{ g / cm}^3$$

$\Omega > 1$ Positively curved space
⇒ Closed universe will eventually recollapse.

$\Omega < 1$ Negatively curved space
⇒ Open universe will expand forever.

$\Omega = 1$ No curvature
⇒ Flat universe expands asymptotically to rest.
Dynamics of $\Omega = \Omega_M + \Omega_\Lambda$ Universes

Geometry $\Rightarrow$ Destiny … Only true for a universe made entirely of “stuff” that dilutes with expansion (e.g. matter with $\rho$, $p > 0$)

Vacuum energy does not change as the universe expands; this implies increase in total energy ($p < 0$) accelerating the expansion of the universe.
A Startling Discovery

Using type Ia supernovae the Supernova Cosmology Project and the High-Z Supernova team constructed a Hubble diagram out to $z = 1$.

Both teams made the startling discovery that the expansion of the universe is accelerating.
A Revolution in Cosmology

Constraints in the $\Omega_M-\Omega_\Lambda$ plane as measured by the Supernova Cosmology Project.
A Revolution in Cosmology

- Weak lensing mass census
- Large scale structure measurements $\Omega_M = 0.3$

Perlmutter et al. 1999
A Revolution in Cosmology

- Weak lensing mass census
- Large scale structure measurements $\Omega_M = 0.3$

Flat universe
$\Omega_{\text{total}} = 1.02 +/- 0.02$

Baryon Density
$\Omega_B = 0.044 +/- 0.004$

WMAP
A Revolution in Cosmology

“Standard Cosmology” $\Omega_{DE} \sim 0.7$, $\Omega_M \sim 0.3$
for a flat universe

- Weak lensing mass census
- Large scale structure measurements $\Omega_M = 0.3$

Flat universe
$\Omega_{total} = 1.02 +/- 0.02$
Baryon Density
$\Omega_B = 0.044 +/- 0.004$

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What is the nature of dark energy?

We now know that dark energy exists

- The dominant component of our universe
- Dark energy does not fit in current physics theory
- New theories propose a number of alternative physics explanations, each with different expansion history we can measure.

Two theories of dark energy:

- Cosmological constant or vacuum energy, constant over time
- Dynamical scalar field → “Quintessence”
The Observational Tool: SNe Ia

C/O white dwarf accretes mass of a companion star leading to a thermonuclear explosion near the Chandrasekhar limit (1.4 $M_\odot$)

- Explosion follows consistent pattern with nearly the same peak intensity
- Extremely bright event – observable on cosmological distance scales

- Spectrum and brightness evolve with time
- Peak Magnitude is a ‘standard candle’ to measure distance

$$ Flux \propto \frac{1}{d^2} $$

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The SNAP Satellite
A ‘simple’ dedicated experiment to study the dark energy

- Essentially no moving parts
- 2 meter aperture telescope: sensitive to light from distant SN
- Focal plane instrumented with > 600 million pixels over ~ 1 square degree: efficiently measures large number of supernovae
- Integral field optical and IR spectroscopy 350 – 1700nm: detailed analysis of each SN
The SNAP Collaboration

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Instrument Concept

Baffled Sun Shade

Solar Array, ‘Sun Side’

3-mirror anastigmat
2-meter Telescope

Spacecraft Bus

Instrument Suite

Solar Array, ‘Dark Side’

Instrument Radiator
Fixed filters atop the sensors

** SNAP redshifted B-band filter set **

- $z=0$
- $z=0.15$
- $z=0.32$
- $z=0.52$
- $z=0.75$
- $z=1.01$
- $z=1.31$
- $z=1.65$
- $z=2.05$

Field before slicing

** Integral Field Spectrograph **

- Field optics (slit mirrors S3)
- Pseudo-slit
- Slicing mirror (S1)

Pupil mirrors (S2)

From telescope and fore-optics

Spectrograph

D = 56.6 cm (13.0 mrad)
0.7 square degrees!
High-Resistivity CCDs for SNAP

• New kind of Charged Coupled Device (CCD) developed at LBNL.
• Better overall response than more costly “thinned” devices in use.
• High-purity “radiation detector” silicon has better radiation tolerance for space applications.
• The CCD’s can be abutted on all four sides enabling very large mosaic arrays.
Hybridized 1.7 \(\mu\m\) cutoff HgCdTe Detectors

- Ongoing R&D effort with Rockwell Scientific and Raytheon Vision Systems to produce high QE, low noise 2Kx2K detectors
- CMOS readout bump bonded to HgCdTe diode
- Non-destructive readout – cosmic ray rejection, reduce read noise
- CdTe substrate will be removed – proton induced luminescence
UM NIR Laboratory

- Dewar #1
- Readout electronics
- Dewar #2
- Power supply and temp. controller
- Calibrated Flat-field Illuminator
- ESD safe environment
- Spot-o-Matic
- RSC 2k x 2k, 1.7 µm HgCdTe
Dark Current, Noise and Multiple Sampling

- Low dark current < 0.1e-/pixel/sec @ 140K (passively cooled focal plane temperature)
- Read Noise ~ 25e- dominates for 300s exposure
- Multiple sampling is used to reduce the read noise to < 10e-
Conversion Gain Measurement

Gain is measured with 3 techniques

Variance estimated using:
- moment analysis
- gaussian fit
- IPC corrected

Agreement between Gaussian and standard variance methods confirms that outliers have been properly masked.

Ignoring correlated noise over-estimates the gain by ~ 20%.

(for this device)
Capacitive Coupling - Autocorrelation

→ Cap. coupling occurs in mux and bump bond region

Average Correlation to neighboring pixels ~ 4% (Nodal capacitance 32.2 fF 38.6 fF w/o IPC)

Average Correlation to neighboring pixels ~ 1% (rows), 0.5% (columns)
Nodal capacitance 75.1 fF

Average Correlation to neighboring pixels ~ 2.5% (rows), 1% (columns)
Nodal capacitance 77.7 fF

trace topology in multiplexer

before epoxy underfill
correlation increases by ~ 2x

Precision NIR Photometry

QE Measurement (5% absolute achieved; 2% goal)

Micron-size NIR point projection system uncovers sub-pixel structure

Raytheon HgCdTe

HgCdTe with AR coating
HgCdTe no AR coating

Liquid light-guide
Narrow Bandpass Filter
Pinhole
NIR Tube Lens

σ ~ 1.8 %
“De-convolution” – Understanding Intra-pixel Response

start with square PRF (18 µm)
convolve with PSF (1.4 µm)
add charge diffusion (1.7±.02 µm)
add capacitive coupling (2.2 ±.1%)
compare to data

let’s fit also the pixel width:
  square PRF (17.8 ± .1 µm)
  PSF (1.4 µm)
  charge diffusion (1.7 ± .02 µm)
  capacitive coupling (2.4 ± .1%)
  published value: 2.2 ± .1%

“Sub-pixel Response Measurements of Near-Infrared Sensors,” *in preparation*
Simulations
Simulated Detector Performance

$z = 1.7$ supernova Ia

Detector parameters measured in the lab are used to simulate light curves.
Simulated Detector Performance

$z = 1.7$ supernova Ia

Detector parameters measured in the lab are used to simulate light curves

Light curve fits $\rightarrow$ parameter errors vs. detector noise

$\%$ error on peak flux, $QE = 95\%$

Simulated Detector Performance

Detector parameters measured in the lab are used to simulate light curves

Light curve fits $\rightarrow$ parameter errors vs. detector noise

Multi-band light curve fits $\rightarrow$ error on SNe peak magnitude

Magnitude error for z=1.7 SNe (type Ia dispersion 0.12-0.15 mag)

Data Sheets to Cosmological Parameters

Images
- Lightcurve & Peak Brightness

Spectra
- Redshift & SN Properties

Data Sheets for each SN

Instrument

Observed Data

Mission Plan

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Data Sheets to Cosmological Parameters

$\Omega_M$ and $\Omega_\Lambda$
Dark Energy Properties  
($w_0$ and $w'$)

Data Analysis Physics

Calibration Plan, External SN Obs.  
Priors, External Cosmology
Simulated SNAP data

Current ground-based data compared with binned simulated SNAP data and a sample of Dark Energy models.

Each SNAP point represents ~50-supernova bin

magnitude difference from a flat, $\Omega_\Lambda = 0.7$ model

based on Weller & Albrecht (2001)
Understanding Dark Energy

Based on Weller & Albrecht (2001)
Conclusions

Dark energy is the dominant fundamental constituent of our Universe, yet we know very little about it.

SNAP will test theories of dark energy and show how the expansion rate has varied over the history of the Universe.

A vigorous R&D program, supported by the DoE is underway, leading to an expected launch early in the next decade.
SN “Tomography”

At every moment in the explosion event, each individual supernova is sending a rich stream of information about its internal physical state.
**Calibrated Standard Candles**

Brightness not quite standard, but correlated with light curve timescale

Intrinsically brighter SNe last longer.

Peak-magnitude dispersion of 0.25 – 0.3 magnitudes

~0.15 magnitude dispersion

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**Kim, et al. (1997)**
Why go to high redshifts?

- Dark energy can be detected at low redshift (SCP, High-z). To determine what it is, and not just that it is, requires measurements over both the acceleration and deceleration epochs.
- This long reach breaks essential degeneracies which low redshift data alone cannot.

SNAP will

- probe the variability of $w$, providing an essential clue to the nature of DE.
- measure $w_0$ precisely to determine whether it is a cosmological constant.

$z_{\text{max}}=1.7$

$z_{\text{max}}=0.7$
NIR available only in space

Crucial near-infrared observations are impossible from the ground

- Sky is very bright in NIR, about 500x brighter at 1.5\( \mu \)m, like observing the sky in Manhattan
- Sky is not transparent in NIR, absorption due to H\(_2\)O molecular absorption bands is very strong and extremely variable
Rest frame B and V shift to NIR

Simulated SNAP observations of high redshift SNe
This can’t be done on the ground!

Simulated 8m telescope ground based observations of high redshift SNe

Optical Bands

NIR Bands

Rest frame B

Rest frame V

Z = 0.8

Z = 1.2

Z = 1.6

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