SUPERNOVA SCIENCE (SNE)

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Abstract. Type Ia supernovae provide evidence for an accelerating universe, an extraordinary result which has amazing implications for physics. Understanding the properties of the vacuum energy which gives rise to the acceleration may finally give us some handle on how to go beyond the "Standard Model" of particle physics and learn experimentally about grand unification, supersymmetry, and the nature of Nature. The equation of state of the dark energy is the key observable, and SNIa observations are probably the only direct way to measure this. This ratio of pressure to density could be constant, but particle theorists believe that the vacuum energy could also be the result of an evolving scalar field which would reveal its temporal change with a change in the equation of state with redshift. Pan-STARRS offers the possibility of making a definitive measurement of this using 0.5 Pan-STARRS-years of time, ideally carried out within the first two years of operation.

1 Introduction

Careful measurements and calibration of distant Type 1a supernovae constitute a powerful tool for the determination of cosmological parameters. Most importantly, recent SNIa measurements have revealed evidence for a significantly positive cosmological constant (c.f. Tonry et al. 2003; Figure 1). The best indications are that this cosmological constant cannot be explained away as an artifact of systematic bias (e.g. grey extinction or Malmquist bias in the supernova sample).

The measured deviation from a linear velocity-distance relation is nevertheless very small, and large samples of SNIa are needed to beat down random errors of measurement, and to ensure that we are not being deceived by some unsuspected systematic, either observational or physical. More interesting is the question of what causes the vacuum energy which gives rise to the acceleration. It may be that it "just is" a cosmological constant, but particle theorists believe that it is more natural to think that this could be the result of an evolving scalar field. If so, SNIa observations are probably the only way to learn about the effective equation of this dark energy and its time evolution.

The sensitivity, wide-field imaging capabilities, and potentially rapid cadence of Pan STARRS provide an excellent platform for an improved study of the Hubble diagram using SNIa, and for learning about the properties of dark energy.

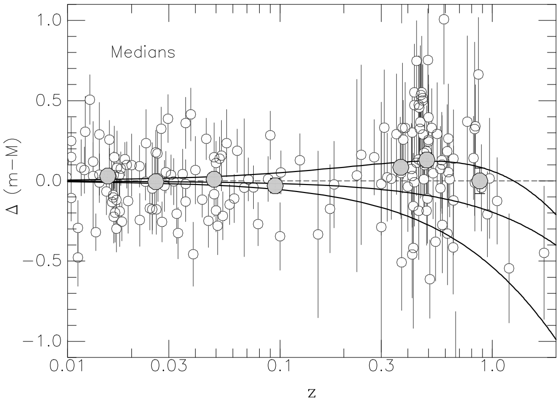

Fig. 1. Hubble diagram computed from supernovae in the redshift range $z \approx 0$ to $z > 1$, relative to an empty universe. The darker symbols show medians of the extant data in redshift bins. From Tonry et al. 2003.

2 Scientific Questions

Using Type 1a supernovae as cosmological probes, we will measure w(z) to ~10% between $0 \leq z \leq 1$ for confrontation with models of scalar fields as dark energy. The distances to individual SNIa are each accurate to ~ 0.25 mag. We can average ~50 supernovae per redshift bin to improve the statistical accuracy of the measurement and expect that the result will still not be dominated by systematics. The form of $w(z)$ in the redshift range $0 \leq z \leq 1$ remains uncertain. The total amplitude is expected to be ~0.1 mag (Figure 2). These deviations can be characterized by a minimum of three well-measured redshift points, with $1\sigma \sim 0.25/50^{1/2} \sim 0.04$ mag uncertainty at each. Therefore we must measure 3×50 SNIa to distinguish $w(z)$ models to 2σ and we need approximately 10 times as many to reach a 5σ measurement.

3 Survey Requirements

3.1 Filters

Supernovae are best behaved as standard candles in the rest frame B and V, so to match these filters over a range of redshift, we need a wide range of observer's filters: $BVRIZ$ or $grizY$.

3.2 Depth

The peak of the supernova luminosity function is listed in Table 1 as AB magnitudes as a function of redshift.

Scaling from similar CCDs and filters presently in use at the UH-2.2m, we list the AB sensitivities of a 1.8-m Pan-STARRS telescope with a 25% obstruction

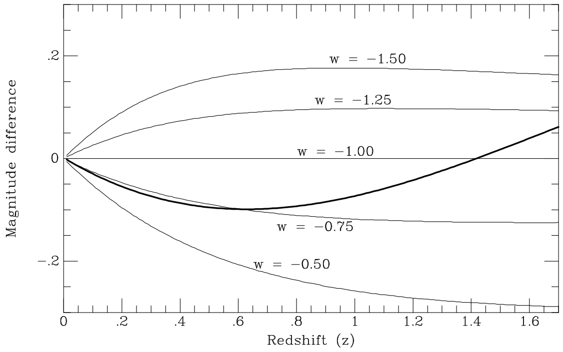

Fig. 2. Hubble diagram for various possible constant values of the equation of state parameter w (light lines), and a example of a time-varying w(z) (heavy line). The asymptotic value as $z \to \infty$ will be known fairly well by 2006 from HST observations of SNIa and the CMB.

Table 1. AB Magnitudes

z	B	V	R	I	Z	J
0.05	17.2	17.4	17.5	18.3	18.3	18.6
0.10	18.8	18.9	19.0	19.6	19.8	20.2
0.20	20.6	20.3	20.4	20.8	21.3	21.9
0.30	21.8	21.1	21.2	21.4	21.8	22.5
0.40	22.9	21.9	21.8	22.0	22.2	22.9
0.50	23.9	22.6	22.3	22.5	22.5	23.2
0.70	25.4	24.0	23.2	23.1	23.2	23.9
1.00	26.6	26.0	24.8	23.9	23.9	24.1

by the secondary to have (m_1 is the magnitude which will produce $1e^-$ per second; μ is the sky brightness per square arcsecond) in Table 2.

Table 2. AB Sensitivities

	B	V	R	I	Z
m_1	24.5	24.8	24.9	25.1	23.9
μ	21.8	21.1	20.7	19.9	19.0

The SNIa luminosity function has a width of about 1 mag, but we also need to follow an SNIa for at least one magnitude below peak in order to determine its decline rate and hence luminosity. In order to reach the systematic noise floor, we require reasonable accuracy (0.05 mag per data point) at 1 magnitude below the magnitudes in the filters (rest frame B and V) listed in Table 3.

Roughly speaking an accuracy of 0.05 mag at $m_R = 23.3$ is required at $z = 0.5$, where the strongest leverage on $w(z)$ is found, 0.05 mag at $m_I = 24.1$, and 0.05 mag at $m_Z = 24.2$ at higher redshifts. Assuming 0.6" seeing and the

Table 3. Redshift vs. Magnitude

z	B	V	R	I	Z	J
0.05	17.2	17.4	—	—	—	—
0.20	—	20.3	20.4	—	—	—
0.50	—	—	22.3	22.5	—	—
0.70	—	—	—	23.1	23.2	—
1.00	—	—	—	—	23.9	24.1

formula

$$S/N = \frac{1}{\pi^{1/2}\mathrm{psf}}\; 10^{-0.2(2m-\mu-m_1)}\; t^{1/2}$$

these correspond to exposure times of approximately 1200 sec in R, 2.4 hours in I, and 20 hours in Z. We hope that our detectors will be significantly better in the red than the present ones (a factor of 2 at Z), and there are four telescopes, so the I observation might require 1600 seconds and the Z observation might be nominally 2.5 hours on the full Pan-STARRS array. In fact we would probably back off on our signal-to-noise requirement for Z band, particularly in light of the time dilation at higher redshift which gives us more observations of an explosion at a given observer's cadence. Nevertheless, the requirements for a supernova survey are that B, V, and R require very modest exposure times for each epoch (at most 300 sec on four telescopes), but I and particularly Z will want as much time as is consistent with sky coverage. The overall observation time on a single field at a single epoch will probably be about 1 hour.

3.3 Sky Coverage and Cadence

There are two strategies for observing SNIa. The first is to simply find them and follow them in a pointed, narrow field strategy using other facilities. For this we generally prefer two observations separated by about 1 month. Shorter that this and the difference image will often lose flux from a rising SNIa, and longer means that we pick up more false alarms from AGN and variable stars. The more interesting option is to use Pan-STARRS to continuously follow the SNIa, automatically getting light curves and colors for extinction and photometric redshifts. The natural timescale for a SNIa explosion is about 20 days FWHM between the rise and fall of the light curve. In order to sample this well, we prefer to have observations approximately every 4 days. Two days is a wasteful sampling, and ten days will cause many SNIa observations to be inadequately sampled, particularly given the exigencies of weather.

In this mode, the first and last month of observations on a given field are less productive of SNIa because we lose enough of the rise or fall of the light curve that we cannot determine a good distance. Therefore the efficiency of detection on a given field is approximately $(N-1)/N$, where N is the number of months spent on it. We therefore prefer to observe at high galactic latitude, with a range in RA in order to follow a given field for as many months as possible.

Figure 3 shows results on the rates from Tonry et al. 2003, which would be appropriate for a Pan-STARRS survey with $I < 24$.

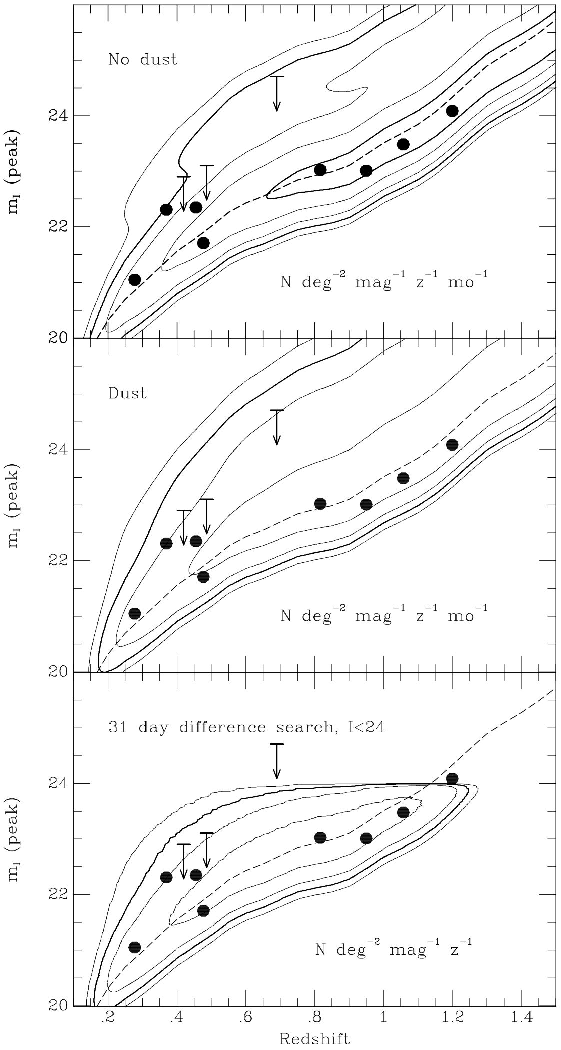

Fig. 3. Distribution of SNIa occurrence as a function of peak I magnitude and redshift. Contours of predicted rates are drawn with heavy contours at 1 and 10, and light contours at intervening intervals of 2 and 5. The ridge line of an unreddened "normal" SNIa is drawn as a dashed line. The upper panel shows the distribution based on the SNIa luminosity function if there were no reddening; the middle panel shows the effect of convolving with the model extinction distribution; and the bottom panel shows the expected distribution for our search parameters. Points are SNIa observed during the Fall 1999 campaign.

Figure 4 shows the cumulative number of SNIa found by Tonry et al. 2003, again appropriate for one month's worth of a Pan-STARRS survey with $I < 24$. We therefore expect something like 4–5 SNIa per degree per month from a survey to $I < 24$. In Pan-STARRS units, if we spend 1 hour for each pointing, the cadence calls for 7 visits per month, and each pointing nets us 7 square degrees, so 1 hour of Pan-STARRS time corresponds to 1 square degree-month of search time. Since we probably would use a 1 hour observation time on each field, we would not reach our desired S/N in all filters, so a number like ≈ 3 SNIa per degree-month is probably more realistic. Therefore if we observe about 150 deg^2 for 12 months, we will net about

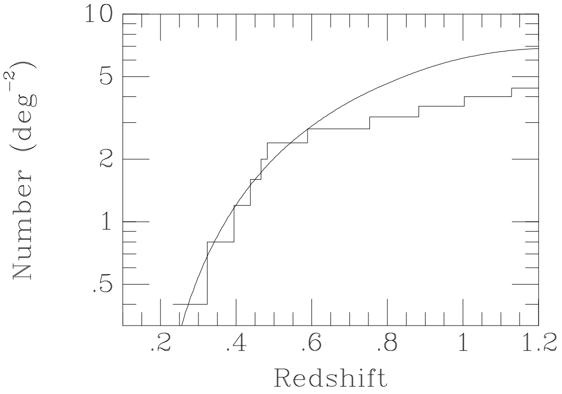

Fig. 4. Cumulative number of SNIa discovery is shown as a function of redshift. The histogram are the SNIa observed by Tonry et al.; the curve is the prediction of what we should have seen given a flux limit of $I < 24$ and a 31 day difference search.

- 5000 SNIa
- 1000 SNIa in early-type hosts (good for photo-z and low dust)
- 10000 SNII

This would take about 1800 hours of Pan-STARRS time, which is roughly 200 nights or 0.5 Pan-STARRS years. A survey of this scale is required to meet the requirements mentioned above, since we naturally find far more SNIa at higher redshifts because there is more volume, but we need good signal to noise at low redshifts as well in order to constrain $w(z)$. In addition, we are unlikely to be able to make use of all of these SNIa since it is very unlikely that we will be able to get spectra of every one.

3.4 Astrometry

We require only that the astrometry be good enough to reject known variable stars and AGN from the Pan-STARRS database, i.e. 0.5 arcsec.

3.5 Image Quality and Sky Brightness

The signal to noise formula above can be used to determine for given conditions how long the integration must be to meet the objective of S/N=20 at $m_I = 24$. In practice the signal to noise degrades very rapidly with worsening image quality or bright sky, so effectively we need a psf FWHM of better than 0.8 arcsec, and a reasonably dark sky. We will want to carry right through bright time, but observations taken when the moon is up and especially near the moon are likely to be of much lower quality.

3.6 Photometric Accuracy

We cannot accept systematics which will compromise photometry at $\delta m = 0.04$, therefore we require that the photometric zero points be good to at least 0.02 mag.

3.7 Follow Up Strategy

We will try to dispense with spectroscopic followup for SNIa in early-type galaxies because the photometric redshifts of the hosts and SNIa should be good enough to get the redshifts we need. The majority of SNIa (80%) will occur in late-type galaxies and will have some amount of dust extinction, so spectroscopic follow up is needed to most accurately characterize the supernovae and to determine precise redshifts. The SDSS or WIYN telescope and spectrograph which uses fiber positioner (e.g. Hydra at WIYN) would be suitable for this purpose.

3.8 Relation to Other Surveys

The main competition is expected from the ESSENCE project underway on the CTIO 4-m telescope and the Wide Synoptic component of the Megaprime Survey on the 3.6-m CFHT. The latter will accumulate about 1 hour in SDSS filters over 170 sq deg and a "deep" component which will accumulate about 66 hours in riz over 4 sq deg. ESSENCE and Megaprime Wide Synoptic should detect $\sim$200 and 50 SNIa, respectively. This is enough to make useful statements about the value of a constant equation of state w, but will not provide any constraint on its time evolution.

References

1. Tonry. et al. (2003). In preparation.