SN Ia Cosmology and Deep Imaging Surveys

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Dark Energy & Measurement of Cosmological Parameters

The nature of dark energy is a premier astrophysical challenge in the coming decade, perhaps the next century. Constraining dark energy is frequently expressed in terms of cosmological parameters. In particular, the Dark Energy Task Force (DETF) has proposed a figure of merit *FoM* for DE studies consisting of the inverse of the area of the 95% confidence contour for two parameters describing the DE equation of state: its equation of state now (w_0) and its derivative (w_a, where $w(z) = w_0+w_a(1-a)$ and $a = (1+z)^{-1}$), expressed as $FoM=1/[6.17\pi\ (\sigma^2_{w0}\sigma^2_{wa}-\sigma^2_{w0wa})^{1/2}]$, with standard deviations σ in measuring the equation of state parameters (Wang 2008). A simple cosmological constant is uniquely parameterized by $w_0 = -1$ and $w_a = 0$, while alternatively proposed models can be distinguished according to w_0 and w_a (Caldwell & Linder 2005).

In order to constrain w_0 and w_a, we need to perform cosmological surveys, which tend to produce elongated ellipses in the (w_0, w_a), or other parameter pairs we might consider e.g., (Ω_{de}, w_0). To localize the allowed (w_0, w_a) value, we need two survey techniques to provide measurements with quasi-orthogonal error ellipses intersecting in the (w_0, w_a) plane. To check this, one needs a third quasi-orthogonal (non-parallel) technique. To prevent an unfortunate alignment of systematic errors producing an erroneous intersection (or to "break the tie" if three intersection points result from a wayward ellipse), one needs a fourth technique.

Several methods are developed, including weak lensing (WL), baryon acoustic oscillations (BAO), SNe Ia, and various measures of the growth of clustering. SNe Ia make up the best proven, powerful technique (Albrecht 2006). It is often assumed that SN Ia systematic errors in photometry will improve sufficiently for DETF Stage IV projects (such as LSST or JDEM) to succeed; they must be under ~2% photometric in the SN Ia standard candle (SC) relation (Linder & Huterer 2003). Systematic errors might be larger than this now (Tonry 2004), but no planned program is able to bring these under control at the Stage IV level with confidence established by any cross-check or verification stratagem. Indeed, Stage III or Stage IV projects tend to sample SN Ia light curves about twice per week, sufficient to measure the "stretch" parameters that relate lightcurve duration to maximum luminosity (and ^{56}Ni mass); none establish a dataset at much higher cadence or data quality, as might be required to find higher-order corrections to the SC relation and further refine SNe Ia as cosmological probes at the Stage IV level. In this work we discuss how SN Ia SC systematics might be improved in principle, and how a survey might be designed to sufficiently probe variations in the SC relation which might lead to a systematic error in SN Ia surveys used to measure cosmological parameters.

Systematic Effects in Type Ia Supernova Standard Candle Photometry

Elaborating on the Δm_{15} relation (Phillips 1993), many groups have advanced SN Ia SC refinements (Reiss et al. 1996, 1997, Perlmutter et al. 1997, 1999, Wang et al. 2003, Wang et al. 2005). Currently the scatter is about 14% in luminosity (7% in distance; using MLCS2k2, for example: Jha, Riess & Kirshner 2007). While we hope to improve this scatter (and will discuss this below), the pressing requirement is to reduce systematic errors to the few percent level or less in luminosity.

Foley et al. (2007) review the status of the SN Ia SC relation and argue on the basis of spectroscopic consistency between high and low redshift samples that photometric systematic errors are not worse than ~10%. This level of accuracy would suffice, if true, to verify the existence of dark energy, but would be several times too large to allow w_a measurement better than order unity. As Riess & Livio (2006) point out for current checks of systematic errors, absence of evidence is not evidence of absence; they propose observing luminosity evolution as a function of parameters such as metallicity or progenitor age, using SN Ia at $1.5 < z < 3$ and a large program on the *Hubble* and *Webb* space telescopes.

Here we propose a more direct and sensitive test of SN Ia SC systematic effects (below), but first we must discuss a bit more the nature of these systematics. There are many variables that might affect SN Ia luminosity, some tied to observables that might provide a correction, some purely stochastic, to be suppressed by $\sqrt{N}$ statistics, and some more insidious. These have been reviewed by various authors e.g., Podsiadlowski et al. 2008. One can imagine, for instance: ^{56}Ni mass, single or double-degenerate progenitors, progenitor age (or evolutionary track), metallicity, progenitor compositional structure e.g., C/O variation with radius, amount of rotational support of density structure, magnetic field strength, density structure depending on progenitor mass before accretion, convective structure in the deflagration front, viewing angle, ejection asymmetries, circumstellar interactions, varying extinction laws, or cosmological noise due to weak lensing magnification variation or peculiar motions (or redshift errors). Some of these are more likely to increase the scatter in the SC relation, others will have systematic bias effects, some will do both. Only the ^{56}Ni mass effect is well understood, although the progenitor age (or population) effect is becoming more evident. Some of these effects have been modeled, but accounts of their significance vary.

Cases are found of super-Chandrasekhar mass explosions, roughly doubling the luminosity e.g., SNLS-03D3bb (Howell et al. 2006). If these are due to double white dwarf mergers, they will be easy to reject from SC samples. Still, this is a worrisome discovery if the higher mass is more of a continuous tail to the Chandrasekhar norm. Recent evidence points to a relation of Δm_{15} to galaxy morphology (Altavilla et al. 2004, Della Valle et al. 2005) and there appears to be bimodality in progenitor age (~1 Gy vs. a few Gy: Mannucci et al. 2006), which is reflected in the Δm_{15} relation (Hamuy et al. 1996, van den Bergh et al. 2005). These effects are sufficiently well known to SN observers but become much more difficult to distinguish at higher redshift where host galaxies are more ellusive e.g., Foley et al. (2007).

Several complicating effects not widely known might easily affect the scatter or centroid luminosity of SNe Ia. For instance, Patat (2005) shows that light echoes can easily introduce several percent changes into the luminosity L, particularly on the decreasing side of the maximum light pulse, and will reduce L while increasing Δm_{15} in a stochastic manner depending on the distribution of surrounding material. The presence of echoes can easily be teased out by anomalous behavior in bluer bands versus redder multiband photometry. A second effect which seems evident in the data is the "blue bump" revealed by CMAGIC analysis (Wang et al. 2005) near maximum light. This feature easily adds almost 10% to L in some bands and appears correlated with L, so should be suspected as an observable parameter that might reduce the scatter (or improve systematics) in the SC relation.

It is evident that we should study SNe in the near infrared in order to reduce the effects of

systematic errors (Wood-Vasey et al. 2008 and references therein). This does not imply, however, that the near infrared is optimal or adequate for studying systematic errors. Rather, we can develop the most leverage on systematic effects by studying rest optical and near-ultraviolet (at shorter wavelengths the luminosity is becoming prohibitively low for intermediate or high redshift studies). Furthermore, essentially all planned surveys of large numbers of SNe Ia (more than a few hundred) sample their light curve adequately to measure a stretch parameter e.g., Δm_{15}, but no more. It seems likely that if more detail is to be derived regarding the effects of observable parameters on the SN Ia SC relation, a denser cadence in light curve measurements is required, in several photometric bands, likely along with information from spectroscopy.

There is no guarantee that SNe Ia are standard candles at the level needed to measure (w_0, w_a) for DETF Stage IV; this must be demonstrated empirically. Furthermore, to assure that a SC relation is safe to use at some level of photometric accuracy, it must be demonstrated at some higher level of accuracy (presumably a factor of two or so better). Systematic errors frequently lurk just below the level at which they have been eliminated. Even if SNe Ia are standard candles in principle, there are associated issues that must progress far beyond the current state of the art if DETF Stage IV goals are to be achieved. For instance, establishing the photometric zero-point at a level better than a few percent for several photometric bands will be a challenge. Proposals by Stubbs et al. (2007) and Kaiser et al. (2005) can plausibly accomplish this. Furthermore, photometric consistency at the level of 1% or 2% will require the construction and verification of special filter bandpass systems designed to transform over redshift in rigorously determinable fashion, especially for SNe Ia. Several other such factors must be overcome.

We argue here for a program targeted at fixing the SNe themselves, to establish whether or not SNe Ia can ever serve as standard candles, regardless of the photometric accuracy used to observe them. We argue that such a program if successful would justify the ensuing requirement of superb photometric calibration, and would serve as a guide for Stage IV projects that intend to use the SN Ia SC program as a cosmological probe. It would also likely elucidate details of the SN Ia process itself. The kernel of this idea is that more detailed photometric lightcurve data is likely to uncover subclasses of SNe Ia (or at least observable parameters that can be used to rank SC behavior into distinct groups). Presumably, the detailed SC relation for each of these SN Ia subcategories will differ, but two or more SC relations can be compared to establish that they are at least proportional over a range of redshifts. With three or more subcategory SC relations, deviants from the consensus behavior of the several SC relations could be rejected. If several subcategories of SNe Ia follow the same SC relation (up to a multiplicative constant), further confidence is justified in using SNe Ia as standard candles for cosmological probes. (This general approach is recommended by other SN Ia cosmology groups e.g., Hicken et al. 2009, p. 38.) If such subcategories exist but are not probed by this level of detail in Stage IV survey data, the admixture of differing fractions of these subcategories over redshift will produce an apparent luminosity evolution effect that will not be resolved by Stage IV, leading to errors in cosmological parameter estimation.

An excellent approach to obtaining this sample would be to observe many SNe, with spectroscopy and high-cadence multiband lightcurves, over sufficiently narrow redshifts interval so that evolution is insignificant and cosmological models can be used to compute reliable luminosity distances to bring the SNe all to a common effective distance, so as to measure the SC relation directly at a given redshift. In a sense we are turning a slice of the Universe into an

analog of a Magellanic Cloud, recalling Cepheid variable period-luminosity relations. Assuming that we know the cosmological densities for matter and dark energy (Ω_m and Ω_{de}) to within 0.03, and need to calculate relative luminosities over this redshift slice to within 1%, we cannot allow the slice to grow much larger than $\Delta z \approx 0.1$.

Deep, Wide Surveys for Type Ia Supernovae

These are demanding requirements, since performing this survey requires thousands of SNe to be relatively sure of resolving subclasses. We need to perform this at significant redshift in order to detect any evolution, and to overcome the limited volume element at low redshift. At $z \approx 0.5$, we are discussing SNe of magnitudes $r \approx 24$. To acquire roughly nightly multiband imaging to this magnitude calls for 8m-class telescopes, and a wide field (or very long survey) to collect enough SNe to define new SN sub-populations. Essentially no Stage IV projects plan such an approach. Such a survey might be possible on the Large Synoptic Survey Telescope (LSST), but would require a dedicated survey of years in duration, which would supplant much of the emphasis on wide-angle weak lensing and searches for transients. In this respect the LSST is largely complementary to what we suggest below. To our knowledge no other survey concept has been proposed capable of addressing this problem.

We have developed a concept for a powerful but economical instrument ideal for this task, which can acquire $>10^5$ high-quality SN Ia lightcurves, with nightly, multiband photometry at high S/N, with spectroscopy. We propose ALPACA (Advanced Liquid-mirror Probe of Astrophysics, Cosmology & Asteroids: http://www.astro.ubc.ca/lmt/alpaca/), an 8-meter, wide-field, zenith-pointing telescope that will survey roughly half of its ~1000 deg^2 field every night, in five bands, down to about $r = 24.5$ (at 10 σ) every night. This will be a dedicated instrument, tuned to provide this demanding SN Ia sample, but churning out powerful datasets for other dark energy studies (including BAO and WL surveys: Corasaniti et al. 2006), plus a wealth of other astrophysics from high-redshift quasars to near-Earth asteroids. This survey is envisioned for a minimum three-year run that could begin within four years and inform Stage IV projects as how to best to incorporate SNe Ia into mastering the understanding of dark energy.

The design of such a survey and telescope can be made relatively simple and inexpensive. SNe Ia are ubiquitous, so we are free to pick those passing overhead. For both phases of the projects, tracking these objects electronically by drift scanning, rather than using a mechanical mount, greatly simplifies the telescope's mechanical structure. By pointing only at the zenith, the telescope enclosure likewise has minimal requirements. The imager needs no shutter or filter wheel, again minimizing costs and enhancing reliability. This simple mode of observation and analysis will produce large savings in data reduction and analysis costs. A further cost savings (of order $5 million) can be realized by using the recently developed technology of liquid-mirror telescope primaries, which we will describe below.

The great strength of ALPACA, then, is the simplicity of the telescope, instrumentation, and data products. The telescope has very few moving parts (with the exception of the rotating primary mirror). Furthermore, all detectors deliver data from the sky with 100% duty cycle as long as weather and sky conditions permit, eliminating usual interruptions for hardware

reconfiguration or telescope repointing. The data read out continuously in drift scan mode (similar to the enormously successful Sloan Digital Sky Survey - SDSS); software to handle such data has already been highly developed. This leads to a simple means for analyzing the data which is much more straightforward than more conventional schemes, and greatly simplifies the effort and expense of producing the final data products.

We have constructed a 6-meter liquid-mirror telescope (the LZT: Large Zenith Telescope: http://www.astro.ubc.ca/lmt/lzt/ & Hickson et al. 2007), for less than US $1 million. The LZT has already delivered seeing-limited imaging (best FWHM ≈ 1.3 arcsec at a relatively poor site; see Hickson & Racine 2007). This has been accomplished by several retrofitted upgrades that we would build into a next-generation telescope; together these serve to suppress several varieties of waves in the liquid mirror surface that would otherwise degrade optical imaging.

The plans for the ALPACA project consist of a prototype stage (Proto-ALPACA) to incorporate the LZT technology into a telescope at a quality astronomical site. When seeing-limited performance is demonstrated here, the telescope can be upgraded to wide field with the imaging focal plane and data system expanded to that of the ALPACA survey. We have already passed the ALPACA idea through a conceptual design review (CoDR), producing a fairly detailed version of the Proto-ALPACA design. Including 30% cost contingency and three years of operations, we estimated the Proto-ALPACA phase of the project to cost $8 million. This CoDR was conducted by optical designer Lynn Seppala (Livermore), astronomer Robert Williams (STScI) and astronomer/telescope technologist Jacques Beckers (Washington). Additional review was performed by Robert Kirshner (Harvard) and Donald York (Chicago). The recommendation of the CoDR panel to the university administrations was that the ALPACA project in its various phases should proceed, and that it offered an exciting and unique role in cosmology and astrophysics in general, for surprisingly low cost. The project at this point will proceed to the Preliminary Design phase (PD), which would include the detailed design and cost estimate of the wide-field corrector, 3-degree imaging camera, data system and software (estimated roughly as $25 million more, assuming the final telescope uses a liquid, not a glass primary mirror). We have also conducted a seeing measurement campaign using three different seeing monitors at the Cerro Tololo Inter-American Observatory, and have chosen a prime site.

A quick overview of the current ALPACA design is in order. The ALPACA 8-m primary mirror will rotate on a massive air bearing like the LZT's. Like the LZT, the ALPACA mirror will employ technology to prevent turbulent interaction with the moving air. The telescope will incorporate a two-mirror reflective corrector (one spherical). For wide-field ALPACA there will also be a central obscuration of ~30%, for a total ~40% loss. The system will have a field of view of ~3 degrees, and total throughput of ~40%. Imaging quality error budgeting will respect the median site seeing of 0.7 arcsec, so imaging performance is expected to remain well sub-arcsecond.

Proto-ALPACA is the testbed for the metamorphosed ALPACA, to eliminate bugs before we deal with ~2 TBytes of nightly data. The analysis of imaging data from the ALPACA program will be straightforward: each CCD will always observe the same portion of sky (0.13 degree wide by 310 degree long), in the same filter band, and always at the lowest possible atmospheric extinction. (We will first set up calibration fields using the same CCDs and filters on a smaller telescope.) Data analysis is simplified by requiring that each specialized processor always deals

with data from the same CCD. Biasing and flatfielding for driftscan data are 1-D operations (which are handled by modifying open-source code PHOTO written for the SDSS, including other operations such as scattered light correction). Next we will compare the CCD image to a single reference image to find variable or moving sources, using image subtraction pipeline code like those we have already developed e.g., Alves et al. (2004). Our tests on LZT data show image subtraction to be remarkably simple and fast, leaving no significant residuals for even bright, non-variable objects. All of these operations will be handled by one processor, then fed to a second processor for source-finding in the subtracted residual image, and hence to source cataloging. With roughly 200 detectors in the wide-field ALPACA, the number of processors is an order of magnitude more than for SDSS, but the operations are remarkably similar, in fact somewhat simpler in terms of cross-correlation between individual fields seen by each detector.

Figure 1 shows results from a conservative exposure-time calculation of the signal and noise likely to be delivered by ALPACA for SNe Ia at various redshifts ($z = 0.25, 0.5, 0.75$ and 1). The stretch parameter can be computed easily for all of these, and for redshifts $z < 0.7$ the quality of these light curves is comparable to the best published light curves even for $z \approx 0$. The sample of SNe Ia for which such data can be delivered is conservatively 20,000 per year, primarily for redshifts $0.2 < z < 0.7$, which should be sufficient for a detailed study of SNe Ia subpopulations. For this sample, one can measure the flux in at least four bands for at least ten epochs over the maximum light pulse of each SN, at $>10\ \sigma$. This is more than enough to measure stretch parameters, and will allow higher order moments of the lightcurve shape.

As part of the ALPACA PD, we are investigating ways in which SN spectroscopy could also be achieved with the survey telescope. We are studying options for a "drift scanning spectrograph" which could provide the required redshifts to determine the luminosity of the SN Ia sample (or a large subsample thereof). We do not yet have a design to present for this capability, however.

Regardless of whether ALPACA is implemented, and whether it incorporates liquid mirror technology, some survey of this kind must be performed to justify the more intensive use of SNe Ia as standard candles at the DETF Stage IV level. Otherwise, the danger exists that systematic errors in the SN Ia SC relation will creep into the final determination of dark energy parameters. There are no options more capable than ALPACA in addressing this problem.

Technology Development

NASA is now considering a large, liquid-mirror telescope for easily deployed use on the Moon (Angel et al. 2006, Borra et al. 2007). LZT and ALPACA would serve as precursor test beds for this technology that could deliver ~10 picoJy sensitivities in the near-to-mid IR, perhaps in the most cost-effective way. Furthermore, liquid mirror apertures might be combined interferometrically to cost-effectively achieve milliarcsecond imaging and ~100 picoJy sensitivities in the near-IR from Earth (see http://www.astro.ubc.ca/lmt/lama/).

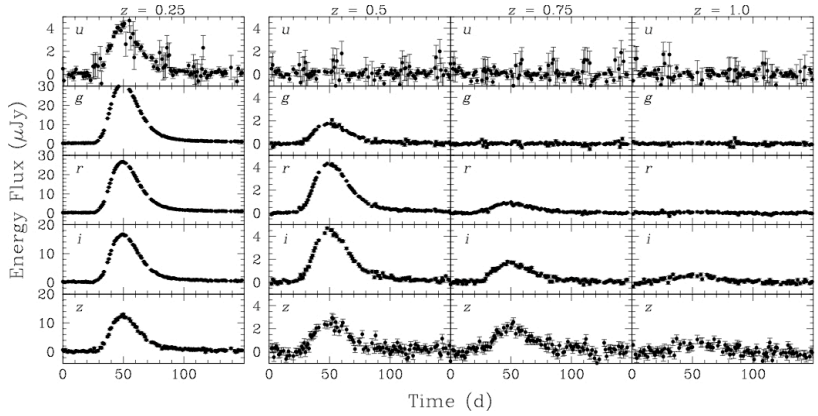

Figure 1: Examples of simulated ALPACA survey observations of SNe of redshift z = 0.25, 0.5, 0.75, 1.0. Maximum light occurs at day 50, and the closest SNe have fluxes extending off the plot.

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