Part VIII

Supernovae, Gamma-Ray Bursters, and Cosmology

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The Expanding and Accelerating Universe

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Summary. Measuring distances back to a significant portion of the look back time probes the make-up of the Universe, through the effects of different types of matter on the cosmological geometry and expansion. Over the past five years two teams have used type Ia supernovae to trace the expansion of the Universe to a look back time more than 70% of the age of the Universe. These observations show an accelerating Universe which is best explained by a cosmological constant, or other form of dark energy with an equation of state near $w = p/\rho = -1$. There are many possible lurking systematic effects. However, while difficult to completely eliminate, none of these appears large enough to challenge current results. However, as future experiments attempt to better characterize the equation of state of the matter leading to the observed acceleration, these systematic effects will ultimately limit progress.

1 The Cosmological Paradigm

Astronomers use a standard model for understanding the Universe and its evolution. The assumptions of this standard model, that General Relativity is correct, and the Universe is isotropic and homogenous on large scales, are not proven beyond a reasonable doubt - but they are well tested, and they do form the basis of our current understanding of the Universe. If these pillars of our standard model are wrong, then any inferences using this model about the Universe around us may be severely flawed, or irrelevant.

The standard model for describing the global evolution of the Universe is based on two equations that make some simple, and hopefully valid, assumptions. If the universe is isotropic and homogenous on large scales, the Robertson-Walker Metric gives the line element distance between two objects separated in space and time. The dynamic evolution of the Universe needs to be input into the Robertson-Walker Metric by the specification of the scale factor $a(t)$, which gives the radius of curvature of the Universe over time - or more simply, provides the relative size of a piece of space at any time. This description of the dynamics of the Universe is derived from General Relativity, and is known as the Friedman equation.

In cosmology, there are many types of distance, with the luminosity distance, D_L, being the most relevant to supernova observers. D_L is defined as the apparent brightness of an object as a function of its redshift, z. If we

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assume the Universe is composed of a set of matter components, each having a fraction Ω_i of the critical density

$$\Omega_i = \frac{\rho_i}{\rho_{crit}} = \frac{\rho_i}{\frac{3H_0^2}{8\pi G}}, \tag{1}$$

with an equation of state which relates the density ρ_i and pressure p_i as $w_i = p_i/\rho_i$, then D_L is given by the numerically integrable equation,

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

Here we define $S(x) = \sin(x)$, x, or $\sinh(x)$ for closed, flat, and open models respectively, and the curvature parameter κ_0, is defined as $\kappa_0 = \sum_i \Omega_i - 1$.

At low z, D_L scales linearly with redshift, with H_0 serving as the constant of proportionality. In the more distant Universe, D_L depends first order on whether on the rate of acceleration/deceleration (often referred to as q_0), or equivalently, the amount and types of matter that it is made up of. However, by observing objects over a range of high redshift (e.g. $0.3 > z > 1.0$), this degeneracy can be broken, providing a measurement of the absolute fractions of Ω_M and Ω_Λ [15].

To illustrate the effect of cosmological parameters on the luminosity distance, in Fig. 1 we plot a series of models for both Λ and non-Λ Universes. In the Left Panel, Top, the various models show the same linear behavior at $z < 0.1$ with models with the same H_0 indistinguishable to a few percent. By $z = 0.5$, the models with significant Λ are clearly separated, with distances that are significantly further than the zero-Λ universes. Unfortunately, two perfectly reasonable universes, given our knowledge of the local matter density of the Universe ($\Omega_M \sim 0.25$), one with a large cosmological constant, Ω_Λ=0.7, $\Omega_M = 0.3$, and one with no cosmological constant, $\Omega_M = 0.2$, show differences of less than 10%, even to redshifts of $z > 5$. Interestingly, the maximum difference between the two models is at $z \sim 0.8$, not at large z.

Figure 1 illustrates the effect of changing the equation of state of the non $w = 0$ matter component, assuming a flat universe $\Omega_{tot} = 1$. If we are to discriminate a dark energy component that is not a cosmological constant, measurements better than 5% are clearly required, especially since the differences in this diagram include the assumption of flatness, and also fix the value of Ω_M.

2 Type Ia Supernovae as Distance Indicators

SN Ia have been used as extragalactic distance indicators since Kowal first published his Hubble diagram ($\sigma = 0.6$ mag) for SNe I in 1968 [28]. We

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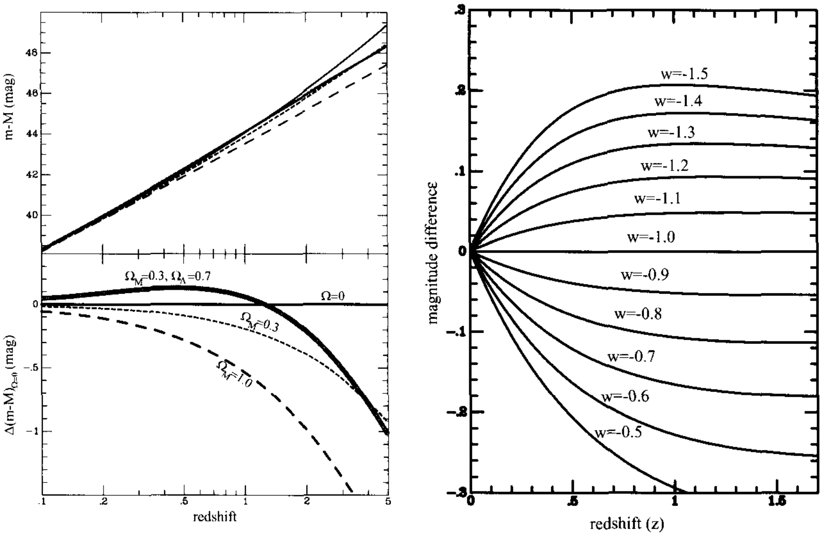

Fig. 1. Left Panel, Top: D_L expressed as distance modulus $(m-M)$ for four relevant cosmological models; $\Omega_M = 0$, $\Omega_\Lambda = 0$ (empty Universe); $\Omega_M = 0.3$, $\Omega_\Lambda = 0$; $\Omega_M = 0.3$, $\Omega_\Lambda = 0.7$; and $\Omega_M = 1.0$, $\Omega_\Lambda = 0$. In the Left Panel, Bottom, the empty universe has been subtracted from the other models to highlight the differences. Right Panel: D_L for a variety of cosmological models containing $\Omega_M = 0.3$ and $\Omega_x = 0.7$ with equation of state w_x. The $w_x = -1$ model has been subtracted off to highlight the differences of the various models.

now recognize that the old SNe I spectroscopic class is comprised of two distinct physical entities: SN Ib/c which are massive stars that undergo core collapse (or in some rare cases might undergo a thermonuclear detonation in their cores) after losing their hydrogen atmospheres, and the SN Ia which are most likely thermonuclear explosions of white dwarfs. In the mid-1980s, it was recognized that studies of the Type I supernova sample had been confused by these similar-appearing supernovae, which were henceforth classified as Type Ib [35, 57, 61] and Type Ic [23]). By the late 1980s/early 1990s, a strong case was being made that the vast majority of the true Type Ia supernovae had strikingly similar lightcurve shapes [5, 29, 30, 31], spectral time series [3, 8, 16, 38], and absolute magnitudes [30, 33]. There were a small minority of clearly peculiar Type Ia supernovae, e.g. SN 1986G [43], SN 1991bg [9, 32], and SN 1991T [9, 44], but these could be identified and "weeded out" by unusual spectral features.

Realizing the subject was generating a large amount of rhetoric despite not having a sizeable well-observed data set, a group of Astronomers based in Chile started the Calan/Tololo Supernova Search in 1990 [17]. This work took the field a dramatic step forward by obtaining a crucial set of high-quality supernova lightcurves and spectra. By targeting a magnitude range that would discover Type Ia supernovae in the redshift range between 0.01 and 0.1, the Calan/Tololo search was able to compare the peak magnitudes of supernovae whose relative distance could be deduced from their Hubble velocities.

The Calan/Tololo Supernova Search observed some 25 fields (out of a total sample of 45 fields) twice a month for over $3\frac{1}{2}$ years with photographic plates or film at the CTIO Curtis Schmidt telescope, and then organized extensive follow-up photometry campaigns primarily on the CTIO 0.9m telescope, and spectroscopic observation on either the CTIO 4m or 1.5m. The search was a major success; it created a sample of 30 new Type Ia supernova lightcurves, most out in the Hubble flow, with an almost unprecedented control of measurement uncertainties [18].

In 1993 Phillips, in anticipation of the results he could see coming in as part of the Calan/Tololo search (he was a member of this team), looked for a relationship between the rate at which the Type Ia supernova's luminosity declines and its absolute magnitude. He found a tight correlation between these parameters using a sample of nearby objects, where he plotted the absolute magnitude of the existing set of nearby SN Ia which had dense photoelectric or CCD coverage, versus the parameter $\Delta m_{15}(B)$, the amount the SN decreased in brightness in the B band over the 15 days following maximum light [45]. For this work, Phillips used a heterogenous mixture of other distance indicators to provide relative distances, and while the general results were accepted by most, skepticism about the scatter and shape of the correlation remained. The Calan/Tololo search presented their first results in 1995 when Hamuy et al. showed a Hubble diagram of 13 objects at $cz > 5000$ km/s that displayed the generic features of the Phillips (1993) relationship [18]. It also demonstrated that the intrinsic dispersion of SN Ia using the $\Delta m_{15}(B)$ method was better than 0.15 mag.

The community more or less settled on the notion that including the effect of light curve shape was important for measuring distances with SN Ia when in 1996 Hamuy et al. showed the scatter in the Hubble diagram dropped from $\sigma \sim 0.38$ mag in B to $\sigma \sim 0.17$ mag for their sample of nearly 30 SN Ia at $cz > 3000$ km/s using the $\Delta m_{15}(B)$ correlation [20] .

Impressed by the success of the $\Delta m_{15}(B)$ parameter, Riess, Press and Kirshner developed the multi-color light curve shape method (MLCS), which parameterizes the shape of SN lightcurves as a function of their absolute magnitude at maximum [47]. This method also included a sophisticated error model, and fitted observations in all colors simultaneously, allowing a color excess to be included. This color excess, which we attribute to intervening dust, enables the extinction to be measured.

Another method that has been used widely in cosmological measurements with SN Ia is the "stretch" method, described by Perlmutter et al. [40, 42]. This method is based on the observation that the entire range of SN Ia lightcurves, at least in the B and V bands, can be represented with a

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simple time-stretching (or shrinking) of a canonical light curve. The coupled stretched B and V light curves serve as a parameterized set of light curve shapes, providing many of the benefits of the MLCS method, but as a much simpler (and constrained) set. This method, as well as recent implementations of $\Delta m_{15}(B)$ [13, 46], and template fitting [56] also allow extinction to be directly incorporated into the SN Ia distance measurement. Other methods that correct for intrinsic luminosity differences or limit the input sample by various criteria have also been proposed to increase the precision of SNe Ia as distance indicators [2, 10, 55, 58], while these latter techniques are not as developed as the $\Delta m_{15}(B)$, MLCS, and stretch methods, they all provide distances that are comparable in precision, roughly $\sigma = 0.18$ mag about the inverse square law, equating to a fundamental precision of SN Ia distance being 6% (0.12 mag), once photometric uncertainties and peculiar velocities are removed.

3 The Measurement of Acceleration by SN Ia

The intrinsic brightness of SN Ia allow them to be discovered to $z > 1.5$. Fig. 1 shows that the differences in luminosity distances due to different cosmological models at this redshift are roughly 0.2 mag. For SN Ia, with a dispersion 0.2 mag, 10 well observed objects should provide a 3σ separation between the various cosmological models. It should be noted that the uncertainty described above in measuring H_0, is not important in measuring other cosmological parameters, because it is only the relative brightness of objects near and far that is being exploited in Eq. 2 - the value of H_0 scales out.

The first distant SN search was started by a Danish team. With significant effort and large amounts of telescope time spread over more than two years, they discovered a single SN Ia in a $z = 0.3$ cluster of galaxies (and one SN II at $z = 0.2$) [22, 34]. The SN Ia was discovered well after maximum light, and was only marginally useful for cosmology itself.

Just before this first discovery in 1988, a search for high-redshift Type Ia supernovae was begun at the Lawrence Berkeley National Laboratory (LBNL) and the Center for Particle Astrophysics, at Berkeley. This search, now known as the Supernova Cosmological Project (SCP), targeted SN at $z > 0.3$. In 1994, the SCP brought on the high-Z SN Ia era, developing the techniques which enabled them to discover 7 SN at $z > 0.3$ in just a few months.

The High-Z SN Search (HZSNS) was conceived at the end of 1994, when this group of astronomers became convinced that it was both possible to discover SN Ia in large numbers at $z > 0.3$ by the efforts of Perlmutter [39], and also use them as precision distance indicators as demonstrated by the Calan/Tololo group [18]. Since 1995, the SCP and HZSNS have both been working feverishly to obtain a significant set of high-redshift SN Ia.

3.1 Discovering SN Ia

Quantitatively, type Ia supernovae are rare events on an astronomer's time scale – they occur in a galaxy like the Milky Way a few times per millennium [6, 36, 37, 56]. With modern instruments on 4 meter-class telescopes, which scan 1/3 of a square degree to $R = 24$ magnitude in less than 10 minutes, it is possible to search a million galaxies to $z < 0.5$ for SN Ia in a single night.

Since SN Ia take approximately 20 days to rise from nothingness to maximum light [49], the three-week separation between "before and after" observations (which equates to 14 rest frame days at $z = 0.5$) is a good filter to catch the supernovae on the rise. The supernovae are not always easily identified as new stars on galaxies - most of the time they are buried in their hosts, and we must use a relatively sophisticated process to identify them. In this process, the imaging data that we take in a night, is aligned with the previous epoch, with the image star profiles matched (through convolution) and scaled between the two epochs to make the two images as identical as possible. The difference between these two images is then searched for new objects which stand out against the static sources that have been largely removed in the differencing process [40, 52]. The dramatic increase in computing power in the 1980s was thus an important element in the development of this search technique, as was the construction of wide-field cameras with ever-larger CCD detectors or mosaics of such detectors.

3.2 Obstacles to Measuring Luminosity Distances at High-Z

As shown above, the distances measured to SN Ia are well characterized at $z < 0.1$, but comparing these objects to their more distant counterparts requires great care. Selection effects can introduce systematic errors as a function of redshift, as can uncertain K-corrections, and an evolution of the SN Ia progenitor population as a function of look-back time. These effects, if they are large and not constrained or corrected with measurements, will limit our ability to accurately measure relative luminosity distances, and have the potential to undermine the potency of high-z SN Ia at measuring cosmology [27, 40, 42, 48, 52, 56].

K-Corrections

As SN are observed at larger and larger redshifts, their light is shifted to longer wavelengths. Since astronomical observations are normally made in fixed bandpasses on Earth, corrections need to be made to account for the differences caused by the spectrum of a SN Ia shifting within these bandpasses. K-correction errors depend critically on several separate uncertainties, including, the accuracy of spectrophotometry of SN; the accuracy of the absolute calibration of the fundamental astronomical standard systems; and using spectrophotometry for appropriate objects to calculate the corrections.

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Extinction

In the nearby Universe we see SN Ia in a variety of environments, and about 10% have significant extinction [21]. Since we can correct for extinction by observing two or more wavelengths, it is possible to remove any first order effects caused by the average extinction properties of SN Ia changing as a function of z. However, second order effects, such as the evolution of the average properties of intervening dust could still introduce systematic errors. This problem can also be addressed by observing distant SN Ia over a decade or so of wavelength, in order to measure the extinction law to individual objects, but this is observationally expensive. An additional problem is the existence of a thin veil of dust around the Milky Way. Measurements from the COBE satellite have measured the relative amount of dust around the Galaxy accurately [51], but there is an uncertainty in the absolute amount of extinction of about 2% or 3% [4]. This uncertainty is not normally a problem; it affects everything in the sky more or less equally. However, as we observe SN at higher and higher redshifts, the light from the objects is shifted to the red, and is less affected by the galactic dust.

Selection Effects

As we discover SN, we are subject to a variety of selection effects, both in our nearby and distant searches. The most significant effect is Malmquist Bias - a selection effect which leads magnitude limited searches finding brighter than average objects near their distance limit; brighter objects can be seen in a larger volume relative to their fainter counterparts. Malmquist bias errors are proportional to the square of the intrinsic dispersion of the distance method, and because SN Ia are such accurate distance indicators, these errors are quite small - approximately 0.04 mag. Monte Carlo simulations can be used to estimate these effects, and to remove them from our data sets [42, 52].

Gravitational Lensing

Several authors have pointed out that the radiation from any object, as it traverses the large scale structure between where it was emitted, and where it is detected, will be weakly lensed as it encounters fluctuations in the gravitational potential [24, 26, 60]. Generally, most light paths go through underdense regions, and objects appear de-magnified. Occasionally the photons from a distant object encounter dense regions, and these lines of sight become magnified. The distribution of observed fluxes for sources is skewed by this process, such that the vast majority of objects appear slightly fainter than the canonical luminosity distance, with the few highly magnified events making the mean of all paths unbiased. Unfortunately, since we do not observe enough objects to capture the entire distribution, unless we know and include the skewed shape of the lensing, a bias will occur. At $z = 0.5$, this

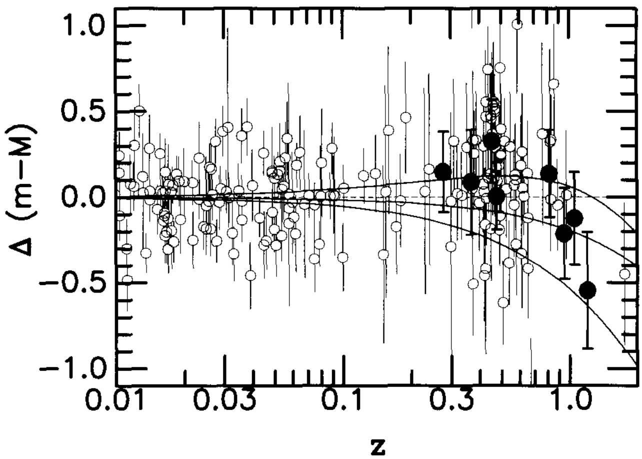

Fig. 2. Data as summarized in Tonry 2003 with points shown in a residual Hubble diagram with respect to an empty universe. In this plot the highlighted points correspond to median values in six redshift bins. From top to bottom the curves show $\Omega_M, \Omega_\Lambda = 0.3, 0.7$, $\Omega_M, \Omega_\Lambda = 0.3, 0.0$, and $\Omega_M, \Omega_\Lambda = 1.0, 0.0$.

lensing is not a significant problem, however, the effect scales roughly as z^2, and by $z = 1.5$, the effect can be as large as 25% [25]. While corrections can be derived by measuring the distortion on background galaxies in the line-of-site region around each SN, at $z > 1$, this problem may be one which ultimately limits the accuracy of luminosity distance measurements, unless a large enough set of SN at each redshift can be used to characterize the lensing distribution and average out the effect.

Evolution

SN Ia are seen to evolve in the nearby Universe. Hamuy et al. plotted the shape of the SN light curves against the type of host galaxy [19]. Early hosts (ones without recent star formation), consistently show light curves which rise and fade more quickly than those objects which occur in late-type hosts (objects with on-going star formation). However, once corrected for light curve shape, the corrected luminosity shows no bias as a function of host type. This empirical investigation provides confidence in using SN Ia over a variety of stellar population ages. It is possible, of course, to devise scenarios where some of the more distant supernovae do not have nearby analogues; therefore, at increasingly higher redshifts it can become important to obtain sufficiently detailed spectroscopic and photometric observations of each distant supernova to recognize and reject such examples that have no nearby analogues.

In principle, it could be possible to use the differences in the spectra and light curves between nearby and distant samples to correct any differences

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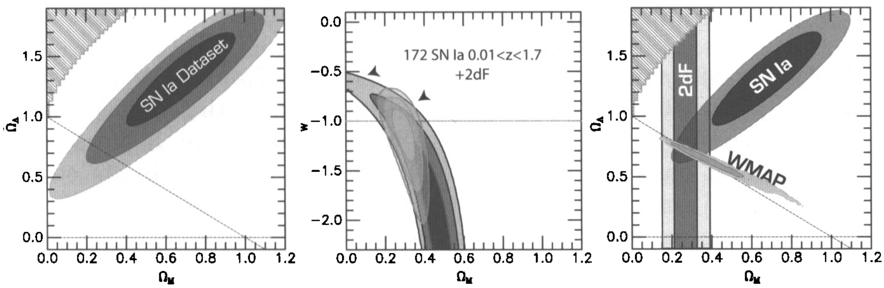

Fig. 3. Left Panel: The joint confidence contours for Ω_M, Ω_Λ using the Tonry et al. compilation of objects. Center Panel: Contours of Ω_M versus w_x from current observational data, where $\Omega_M + \Omega_x = 1$ has been used as a prior overlaid by contours including the current value of Ω_M from the 2dF redshift survey as an additional prior. Right Panel: Contours of Ω_M versus Ω_Λ from three current observational experiments; High-Z SN Ia [56], WMAP [53], and the 2dF redshift survey [59].

in absolute magnitude. Unfortunately theoretical investigations are not yet advanced enough to precisely quantify the effect of these differences on the absolute magnitude. A different empirical approach to handle SN evolution is to divide the supernovae into subsamples of very closely matched events, based on the details of the object's light curve, spectral time series, host galaxy properties, etc. A separate Hubble diagram can then be constructed for each subsample of supernovae, and each will yield an independent measurement of the cosmological parameters [1]. The agreement (or disagreement) between the results from the separate subsamples is an indicator of the total effect of evolution. A simple, first attempt at this kind of test has been performed comparing the results for supernovae found in elliptical host galaxies to supernovae found in late spirals or irregular hosts; the cosmological results from these subsamples were found to agree well [54].

Finally, it is possible to move to higher redshift and see if the SN deviate from the predictions of Eq. 2. At a gross level, we expect an accelerating Universe to be decelerating in the past because the matter density of the Universe increases with redshift, whereas the density of any dark energy leading to acceleration will increase at a slower rate than this (or not at all in the case of a Cosmological Constant). If the observed acceleration is caused by some sort of systematic effect, it is likely to continue to increase (or at least remain steady) with look-back time, rather than disappear like the effects of dark energy. A first comparison has been made with SN 1997ff [14] at $z \sim 1.7$, and it seems consistent with a decelerating Universe at this epoch [50]. More objects are necessary for a definitive answer, and these should be provided by a large program using the Hubble Space Telescope in 2002-3 by Riess and collaborators.

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3.3 High Redshift SN Ia Observations

The SCP in 1997 announced their first results with 7 objects at a redshift around $z = 0.4$ [40]. These objects hinted to a decelerating Universe with a measurement of $\Omega_M = 0.88^{+0.69}_{-0.60}$, but were not definitive. Soon after, a $z \sim 0.8$ object observed with HST [41], and the first five objects of the HZSNS [11, 52] ruled out a $\Omega_M = 1$ universe with greater than 95% significance. These results were again superceded dramatically when both the HZSNS [48] and the SCP [42] announced results that showed not only were the SN observations incompatible with a $\Omega_M = 1$ universe, they were also incompatible with a Universe containing only normal matter. Both samples show that SN are, on average, fainter than what would be expected for even an empty Universe, indicating that the Universe is accelerating. The agreement between the two teams experimental results is spectacular, especially considering the two programs have worked in near complete isolation.

The easiest solution to explain the observed acceleration is to include an additional component of matter with an equation-of-state parameter more negative than $w < -1/3$; the most familiar being the Cosmological constant ($w = -1$). If we assume the universe is composed only of normal matter and a cosmological constant, then with greater than 99.9% confidence, the Universe has a cosmological constant.

Since 1998, many new objects have been added and these can be used to further test past conclusions. Tonry et al. has compiled current data (Fig. 2), and used only the new data to re-measure Ω_M, Ω_Λ, and find, more constrained, but perfectly compatible set of values with the SCP and High-Z 1998/99 results [56]. A similar study has been done with a set of objects observed using the Hubble Space Telescope by Knop et al. which also find concordance between the old data and new observations [27]. The 1998 results were not a statistical fluke, these independent sets of SN Ia still show acceleration. Tonry et al. has compiled all useful data from all sources (both teams) and provides the tightest constraints of SN Ia data so far [56]. These are shown in Fig. 3.

Of course, we do not know the form of dark energy which is leading to the acceleration, and it is worthwhile investigating what other forms of energy are possible second components [12, 42]. Fig. 3 shows the joint confidence contours for Ω_M and w_x (the equation of state of the unknown component causing the acceleration) using the current compiled data set [56]. Because this introduces an extra parameter, we apply the additional constraint that $\Omega_M + \Omega_x = 1$, as indicated by the Cosmic Microwave Background Experiments [7, 53]. The cosmological constant is preferred, but anything with a $w < -0.73$ is acceptable.

Additionally, we can add information about the value of Ω_M, as supplied by recent 2dF redshift survey results [59], as shown in the 2nd panel, where the constraint strengthens to $w < -0.73$ at 95% confidence. As a further test, if we assume a flat Λ universe, and derive Ω_M, independent of other methods, the SN Ia data give $\Omega_M = 0.28 \pm 0.05$, in perfect accord with the 2dF results. These results are essentially identical, both in value and in size of uncertainty, to those obtained from the recent WMAP experiment [53] when they combine their experiment with the 2dF results. Taken in whole, we have three cosmological experiments — SN Ia, Large Scale Structure, and the Cosmic Microwave Background, each probing parameter space in a slightly different way, and each agreeing with each other. Fig. 3 shows that in order for the accelerating Universe to go away, two of these three experiments must both have severe systematic errors, and have these errors conspire in a way to overlap with each other to give a coherent story.

4 The Future

How far can we push the SN measurements? Finding more and more SN allows us to beat down statistical errors to arbitrarily small amounts, but ultimately systematic effects will limit the precision by which SN Ia distances can be applied to measure distances. A careful inspection of Fig. 3 show the best fitting SN Ia cosmology, does not lie on the $\Omega_{tot} = 1$ line, but rather at higher Ω_M, and Ω_Λ. This is because, at a statistical significance of 1.5σ, the SN data show the onset and departure of deceleration (centered around $z = 0.5$) occurs faster than the flat model allows. The total size of the effect is roughly 0.04 mag, which is within the current allowable systematic uncertainties that this data set allows. So while this may be a real effect, it could equally plausibly be a systematic error, or just a statistical fluke.

Our best estimate is that it is possible to control systematic effects from a ground based experiment to a level of 0.03 mag. A carefully controlled ground based experiment of 200 SN will reach this statistical uncertainty in $z = 0.1$ redshift bins, and is achievable in a five year time frame. The Essence project and CFHT Legacy survey are such experiments, and should provide answers over the coming years.

The Supernova/Acceleration Probe (SNAP) collaboration has proposed to launch a dedicated Cosmology satellite - the ultimate SN Ia experiment. This device, will, if funded, scan many square degrees of sky, discovering a thousand SN Ia in a year, and obtain spectra and lightcurves of objects out to $z = 1.8$. Besides the large numbers of objects and their extended redshift range, space also provides the opportunity to control many systematic effects better than from the ground.

With rapidly improving CMB data from interferometers, the satellites MAP and Planck, and balloon based instrumentation planned for the next several years, CMB measurements promise dramatic improvements in precision on many of the cosmological parameters. However, the CMB measurements are relatively insensitive to the dark energy and the epoch of cosmic acceleration. SN Ia are currently the only way to directly study this acceleration epoch with sufficient precision (and control on systematic uncertainties) that we can investigate the properties of the dark energy, and any time-dependence in these properties. This ambitious goal will require complementary and cross-checking measurements of, for example, Ω_M from CMB, weak lensing, and large scale structure. The supernova measurements will also provide a test of the cosmological results independent from these other techniques (since CMB and weak lensing measurements are, of course, not themselves immune to systematic effects). By moving forward simultaneously on these experimental fronts, we have the plausible and exciting possibility of achieving a comprehensive measurement of the fundamental properties of our Universe.

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