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Measuring global curvature and cosmic acceleration with supernovae*

Brian P. Schmidt
Research School of Astronomy and Astrophysics, The Australian National University, Mount Stromlo Observatory, Cotter Road, Weston Creek, ACT 2611 Australia

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1. Introduction

Since the dawn of humanity, people have pondered over cosmological questions such as "What is the Universe's past?", "What is the Universe's future?", "How big is the Universe?", and "What is the Universe made of?". Astronomers have slowly made progress towards answering these questions largely thanks to a well-developed paradigm for our Universe which is principally based on two observations, Hubble's observation that the Universe is expanding, and Penzias and Wilson's discovery of the Cosmic Microwave Background; an assumption, the Universe is homogenous and isotropic on large scales; and the theory of General Relativity. Together, these pieces give the standard Big Bang model, from which we can ask additional specific questions like, "How old is the Universe?", "Will the Universe expand forever?", and "What shape is the Universe?".

Since 1994, astronomers have successfully used a type of exploding star, known as a Type Ia supernova, to work towards answering these fundamental questions, tracing out the expansion of the Universe to look-back times exceeding 8 billion years. I will outline the basis of these cosmology experiments, describe the supernovae which we used to trace the expansion, and provide a brief description of the current results from supernovae and from new experiments using other astronomical observations.

2. Global curvature and cosmic acceleration

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

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isotropic and homogenous on large scales, the Robertson-Walker metric,

$$ds^2 = dt^2 - a^2(t)\left[\frac{dr^2}{1-kr^2} + r^2 d\theta^2\right]$$

gives the line element distance (s) between two objects with coordinates r, θ, and time separation, t. The Universe is assumed to have a simple topology such that if it has negative, zero, or positive curvature, k takes the value $\{-1, 0, 1\}$, respectively. These Universes are said, in order, to be open, flat, or closed, although this is not strictly true. It is possible to have closed Universes with non-trivial topology that have either zero or negative curvature. The Robertson-Walker metric also requires the dynamic evolution of the Universe to be given through the evolution of the scale factor $a(t)$, which gives the radius of curvature of the Universe $-$ or more simply put, tracks the relative size of a piece of space over time. This dynamic equation of the Universe is derived from General Relativity, and was first given by Friedman in the equation which we now name after him,

$$H^2 \equiv \left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi G\rho_{tot}}{3} - \frac{k}{a^2}.$$

The expansion rate of the Universe (H), is called the Hubble parameter (or the Hubble constant H_o at the present epoch) and is related to the matter/energy content of the Universe. Let's assume matter/energy is composed of a set of components, each having a fraction Ω_i of the critical density – the density where space is flat. In equation form

$$\Omega_i = \frac{\rho_i}{\rho_{crit}} \equiv \frac{\rho_i}{\left(\frac{3H_0^2}{8\pi G}\right)}.$$

How the density of matter behaves in an expanding Universe is also important, and the equation of state – which relates the density ρ_i and volume V is described as

$$\rho_i \propto V^{-(1+w_i)}.$$

For example w_i takes the value 0 for normal matter. That is, if space doubles in size, its density halves. For photons, which give up energy through stretching in an expanding Universe, the equation of state parameter is $w = +1/3$. Einstein's cosmological constant, whose density is tied to space itself and is invariant in the expansion, has $w = -1$.

Combining the above equations can yield solutions to the global evolution of the Universe (Coles & Lucchine 1995). As experimentalists, what we need are observables, and these are usually described as the classical tests of cosmology. These tests include measuring the brightness of an object as a function of its redshift, z – the amount an object's light has been Doppler shifted by the expansion of the Universe. This is referred to as the luminosity distance D_L, and is given by the numerically integrable equation

$$D_L H_0 = (1+z)\Omega_k^{-\frac{1}{2}} S\left\{\Omega_k^{\frac{1}{2}} \int_0^z dz' \left[\Omega_k (1+z')^2 + \sum_i (1+z')^{3+3w_i}\right]^{-\frac{1}{2}}\right\}.$$

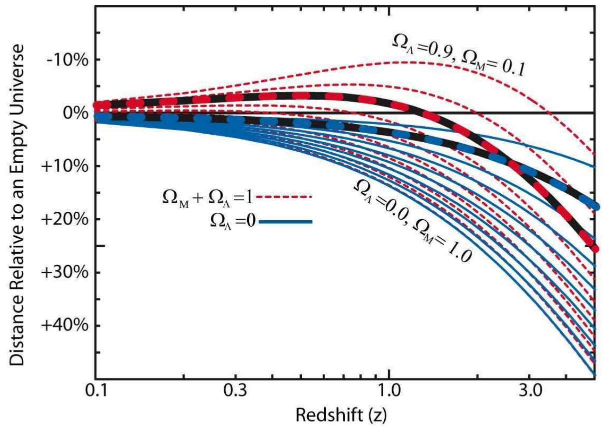

Figure 1. The luminosity distance compared to an empty Universe for flat Universes with cosmological constant (dotted lines), and for Universes with no cosmological constant (solid lines). The flat cosmological constant models are uniformly spaced between $\Omega_\Lambda = 0.9$ and $\Omega_\Lambda = 0$. The $\Omega_\Lambda = 0$ models are uniformly spaced between $\Omega_M = 1.0$ to $\Omega_M = 0.1$. Also shown as heavy lines are $\Omega_\Lambda = 0.7$, $\Omega_M = 0.3$ and $\Omega_\Lambda = 0$, $\Omega_M = 0.2$ models. These two models have their largest difference ($\approx 10\%$) at $z = 0.5$ for redshifts z below 5.

Here c has been set to unity, $S(x) = \sin(x)$, x, or $\sinh(x)$ for closed, flat, and open models respectively, and Ω_k , the curvature parameter, is defined as $\Omega_k \equiv 1 - \sum_i \Omega_i$.

To illustrate the effect of cosmological parameters on the luminosity distance, in Figure 1 we plot a series of models for both Λ and non-Λ Universes. At low z ($z < 0.1$) the various models are indistinguishable to a few per cent, but 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 ($\Omega_M \approx 0.25$), one with a large cosmological constant, $\Omega_\Lambda = 0.7$, $\Omega_M = 0.3$, and one with no cosmological constant, $\Omega_M = 0.2$, show differences less than 10%, even to redshifts of $z > 5$. Interestingly enough, the maximum difference between the two models is at $z \approx 0.5$, not at large z. Figure 1 shows what is required to provide an interesting measurement of cosmological parameters. The object must provide distances accurate to 10% to at least $z > 0.4$. Of the current luminosity distance methods, one stands out as being appropriate – Type Ia supernovae.

3. Using supernovae to measure distances

Supernovae (SN) come in a variety of flavours, and their taxonomy is confusing, and not very informative. They have historically been divided into two types based on their spectra. Type I supernovae have no hydrogen, whereas Type II supernovae have hydrogen. In addition, these two classes have been further divided into sub-classes. The Type I class is made up of the silicon-rich Type Ia, the helium-rich Type Ib, and the objects which have neither silicon nor helium in abundance, Type Ic.

Core Collapse Supernovae: These explosions are the result of massive stars collapsing as iron burning (which is endothermic) commences in their cores. As their pressure support is removed by the fusing iron, their interiors collapse to neutron stars, and a shock wave is thought to be set up by neutrino deposited energy outside of the neutron star region. A massive star that has a massive, intact hydrogen envelope produces a SN II. Other variants are caused by different stages of mass loss. SN Ib represent a massive star which has lost its hydrogen envelope, and SN Ic are objects which have, in addition, lost their helium envelope.

Thermonuclear Explosions: These explosions are the result of the complete nuclear burning of a white dwarf star. The entire star is burned, mainly to ^{56}Ni, but also to intermediate mass elements such as silicon, sulfur. The actual mechanism has long assumed to occur when an approximately 1.4 $M_{\odot}$ (Chandrasekhar Mass) white dwarf accretes mass, and its self-gravity exceeds the pressure support supplied by its electron degenerate gas. As the star begins to collapse, this sphere with considerable latent nuclear energy is ignited, presumably near the core, and the entire star is consumed by a rapidly expanding thermonuclear burning front. Further investigations have shown that this simple picture is not necessarily correct; it may be possible to ignite an explosion in a variety of ways. These include sub-Chandrasekhar explosions initiated by a surface helium detonation which compresses the star's centre to its nuclear flash point, and super-Chandrasekhar explosions involving the merger of two white dwarfs via gravitational radiation.

3.1 Measuring distances with SN Ia

Despite their relative homogeneity compared to their core-collapse siblings, SN Ia are not all the same. Kowal (1968) published the first Hubble diagram for SN Ia in 1968, and this work, which plotted the maximum brightness of the SN versus their observed recession velocity, showed that SN Ia scattered about the Hubble flow with an RMS scatter of about 50%. While not an overwhehming tight relation, this was as good as anything in 1968, and was remarkable given the very poor quality of the observations. Over the next 25 years, many more, and much better observations were acquired, culminating with the Calan-Tololo SN search (Hamuy et al. 1993, 1995, 1996a), which discovered some 50 objects between 1992-1994, and did the first large-scale digital photometric and spectral follow-up of their objects. The resulting 30 object data set has revolutionized our understanding of SN Ia, and definitively showed that SN Ia have a variety of light curves and luminosities. While this initially seemed to indicate the death of using SN Ia as standard candles, Phillips (1993), and later Hamuy et al. (1996b) showed that a

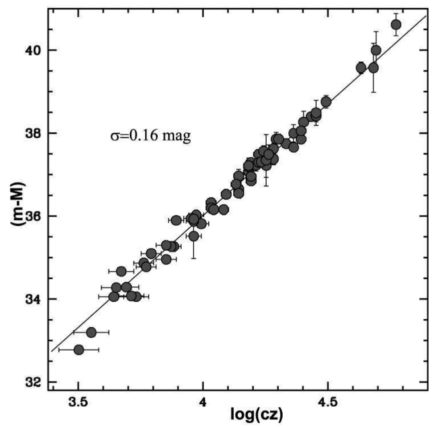

Figure 2. A Hubble diagram of SN Ia with more than 60 objects (Germany et al. 2004). These objects have a dispersion of 0.16 mag (8%), and indicate, once observational uncertainty and peculiar motions are removed, that SN Ia have intrinsic scatter, after correction for light curve shape and extinction of approximately 6%.

SN Ia's light curve shape is correlated with absolute magnitude to a precision of about 7%. These two studies parameterized the light curve shape by the amount the SN fell in brightness in the first 15 days after maximum light in the B band, $\Delta m_{15}(B)$. Enticed by the success of the $\Delta m_{15}(B)$ parameter, Riess, Press & Kirshner (1995, 1996) developed the multi-colour light curve shape method (MLCS), which parameterizes the shape of SN light curves as a function of their absolute magnitude at maximum. This method allows an error model to be created, and fits observations in all colours simultaneously, allowing a colour excess to be included. This colour excess, which we attribute to intervening dust, enables the extinction to be measured if one uses the reddening law derived from our own Milky Way. Phillips et al. (1999) have extended the $\Delta m_{15}(B)$ method to multi-colours, and achieves similar results. While many other implementations of SN Ia light curves shape methods have been developed, it is worthwhile to mention the "stretch" method of Perlmutter et al. (1997). This method is based on the observation that the range of SN Ia light curves, at least in the B and V bands, can be represented with a simple stretching (or shrinking) of a canonical light curve; it too gives similar results to the MLCS and $\Delta m_{15}(B)$ methods.

Figure 2 shows objects compiled by Germany et al. (2004) from all sources between $0.01 < z < 0.2$. The scatter about the Hubble line, 0.16 mag (8%), implies a scatter of about 0.12 mag (6%) per object if observational uncertainty (which is significant in about 1/3 of the objects), were removed. This makes these objects amongst the most precise distance indicators in the quiver of modern astrophysics.

4. Distant SN searches

The decision to undertake distant SN searches was not an epiphany by one person or group. Type Ia have instead been waiting for the appropriate technology to be developed so that they could be unleashed on the problems of measuring cosmological distances. The first successful distant SN search was started by a Danish team (Nørgaard-Nielsen et al. 1998). With much effort and telescope time, they discovered their first object in a $z = 0.3$ Abell cluster. The object was discovered well after maximum light, and was only marginally useful for cosmology itself, but it signalled the birth of the high-z SN field. At this time, a group, now known as the Supernova Cosmological Project (SCP), was formed as part of the Center for Particle Astrophysics, at Berkeley. They uncovered their first SN in 1992 (Perlmutter et al. 1995), but demonstrated that technology had arrived to do large-scale surveys when they discovered 7 objects in a few months in 1994 (Perlmutter et al. 1997). The High-Z SN Search (HZSNS) was born at the end of 1994, when the author became convinced that it was both possible to discover SN Ia in large numbers at $z > 0.3$ by the efforts of Perlmutter et al. (1997), and also use them as precision distance indicators as demonstrated by the Calan/Tololo group (Hamuy et al. 1995). Since 1995, the SCP and HZSNS have been working feverishly to obtain a significant set of SN Ia. The methods of the two teams, while initially different, have converged to a more or less common strategy.

4.1 Discovering SN Ia

Type Ia supernovae are not common objects, they occur in a galaxy like the Milky Way a few times per millennium (Cappellaro et al. 1997). With modern instruments on 4-metre class telescopes, which scan a square degree to R=24$^{\text{th}}$ 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. With this rate of imaging, taken on two nights separated by a month in time, we should expect to discover more than 50 SN Ia in a single night.

Since SN Ia take approximately 20 days to rise from nothingness to maximum light (Riess et al. 1999), observing a piece of sky twice with a one month separation (which equates to 20 rest frame days at $z = 0.5$) will yield objects which are, on average, at maximum light, maximizing the number of objects. The SN 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 (Figure 3). In this process, the imaging data is aligned with the previous epoch, and the image point spread function is matched and scaled between the two epochs to make the two images as identical as possible. The differenced image is then searched for new objects, which stand out against the static sources that have been largely removed in the differencing process (Schmidt et al. 1998).

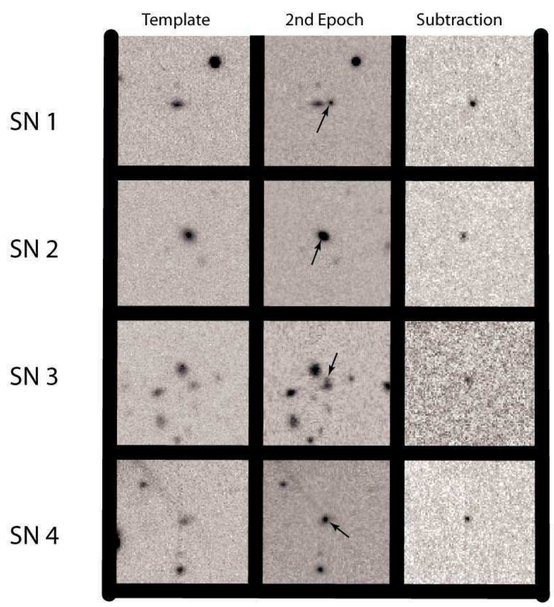

Figure 3. Four SN discovered on one CFHT 8K Mosaic Image. For each object we show the Template image (taken in October 1997), the second epoch image (taken 24 days later), and the difference between the two epochs. This difference removes the non-variable objects, revealing the new SN, even if buried in galaxies as in the case of SN 2.

4.2 The obstacles

Despite the promise of SN Ia to trace the expansion of the Universe to $z > 0.5$, there are many possible effects which could derail this experiment.

4.2.1 *Extinction*

In the nearby Universe we see SN Ia in a variety of environments, and about 10% have significant extinction (Hamuy & Pinto 1999). Since we can correct for extinction by observing the colours of SN Ia, we can remove any first-order effects caused by the average extinction properties of SN Ia changing between $z = 0$ and $z = 0.5$. However, second-order effects, such as the evolution of the intervening dust could still introduce significant errors. Fortunately, technology has advanced to the point where, with 8-metre class telescopes, we can observe distant SN Ia over a sufficiently large baseline of wavelength, that we can investigate the extinction law to individual objects and see if it is changing back in time.

4.2.2 *Selection Effects*

As we discover SN, we suffer from a variety of selection effects, both in our nearby and distant searches. The most significant effect is Malmquist bias – a selection effect which leads brightness limited searches finding brighter than average objects near their sensitivity limit. This bias is caused by the larger volume in which bright objects can be uncovered compared 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 2%. We use Monte Carlo simulations to estimate these effects, and remove their effects from our data sets.

4.2.3 *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. Kim et al. (1996) showed that these effects can be minimized if one does not stick with a single bandpass, but rather if one chooses the closest bandpass to the redshifted rest-frame bandpass. The High-Z SN search took this one step further, designing new bandpasses, specifically made to emulate the $z = 0$ bandpass at several redshifts.

4.2.4 *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 (Kantowski, Vaughan & Branch 1995; Wambsganss et al. 1997; Holz & Wald 1998). On average, most of the paths go through under-dense regions, and objects appear de-magnified. Occasionally they encounter dense regions, and they become magnified. The resulting distribution of the observed flux densities 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 lensing is not a significant problem: if the Universe is flat in normal matter, the large-scale structure can induce a shift of the mode of the distribution by a few per cent. However, the effect scales roughly as z^2, and at $z = 1.5$, the effect can be as large as 25% (Wambsganss et al. 1997). While corrections can be derived by measuring the distortion on background galaxies in the line-of-sight region around each SN, at $z > 1$, this problem may be one which ultimately limits the accuracy of luminosity distance measurements.

4.2.5 *Evolution*

SN Ia are seen to evolve in the nearby Universe. Hamuy et al. (1995) plotted the shape of the SN light curves against the type of host galaxy. Early hosts (ones without recent star formation), consistently show light curves which evolve more quickly than those objects which occur in late-type hosts (objects with on-going star formation). This could be a lethal observation for using SN Ia to measure cosmology if it were not for the observation that once corrected for light curve shape, the corrected luminosity shows no bias as a function of host. So while this empirical investigation provides confidence in using SN Ia over a variety of stellar population ages, devil's advocates can create an infinite number of scenarios where the large redshift SN Ia do not have nearby analogues, and therefore the consistency in the nearby Universe is misleading. While this type of contrived evolution seems unlikely to me, it is difficult to rule out, and this ultimately limits the level of uncertainty at which the community will accept as being reasonable for SN Ia. In addition, theoretical investigations are beginning to help sort out problems, but considerable work still needs to be done (Dominguez et al. 1999; Höflich, Wheeler & Thielemann 1998; Timmes, Brown & Truran 2003).

5. Current results

In 1995, when the two SN searches began in earnest to measure distant objects, the community was divided into 3 groups. The vast majority separated into those who believed the Universe had Ω_M=0.2 (mainly observers) and those who thought $\Omega_M = 1$ (mainly theorists). This dichotomy was set up because observers had taken a census of the gravitational influences in the nearby Universe, and consistently came up with a matter density significantly short of the critical density. Furthermore, measurements of the Hubble constant, coupled with the ages of the oldest stars, consistently demanded a Universe with a low Ω_M so as not to have the Universe younger than the stars in it. On the other hand, theorists could not understand how to solve the problem of the smoothness of the Cosmic Microwave Background (CMB) without something like inflation, and this theory most naturally demands a flat Universe. In addition, there was a heretical group, largely ignored and snickered at, who suggested that the Universe was dominated not by normal matter, but by some other form of energy; this energy allowed the low value of Ω_M, as well as providing theorists with a flat Universe. The difficulty with this solution is that it required positing the existence of some unknown form of matter which had no particular reason for existing.

The SCP (Perlmutter et al. 1997) in 1997 announced their first results with 7 objects at a redshift around $z = 0.4$. These objects pointed towards a $\Omega_M = 1$, but were not

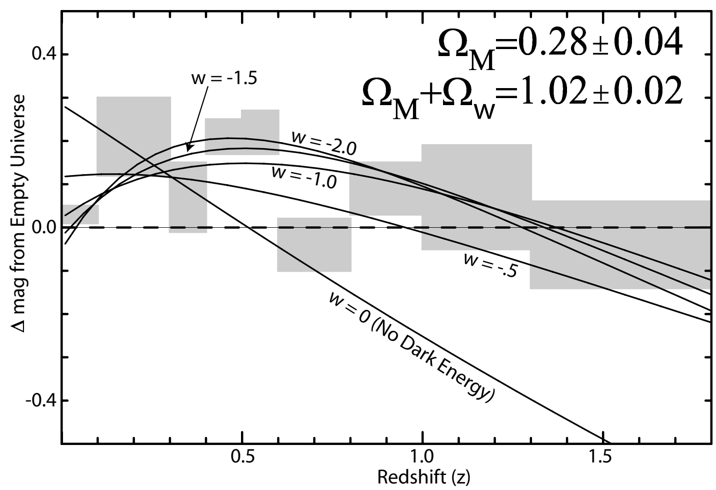

Figure 4. Data as summarized from all sources with points shown in a residual Hubble diagram with respect to an empty Universe. The data have been binned for easier viewing, with 4 values of an equation-of-state parameter overlaid.

definitive, with an additional $z = 0.81$ object observed with the Hubble Space Telescope (Perlmutter et al. 1998) casting doubt on a $\Omega_M = 1$ Universe. The HZSNS followed suit soon after with 5 objects, and these ruled out a $\Omega_M = 1$ Universe with greater than 95% significance (Schmidt et al. 1998; Garnavich et al. 1998). The major results came out only a few months later when both HZSNS (Riess et al. 1998) and SCP (Perlmutter et al. 1999) announced results which showed that not only were the SN observations incompatible with a $\Omega_M = 1$ Universe, they were also incompatible with a matter only low Ω_M Universe. 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 simplest solution to 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 (with $w = -1$). Figure 4 shows the current data from all sources, and Figure 5 (right panel) shows the joint confidence contours for values of Ω_M and Ω_Λ from all SN Ia experiments with published results up to 2004. The SN Ia experiments are in remarkable agreement – with greater than 99.99% confidence, the Universe has a significant cosmological constant.

Another question worthwhile asking is, are other forms of energy acceptable as the second component? Figure 5 shows the joint confidence contours for data from all sources. Because this introduces an extra parameter (and the observations do not have anywhere enough signal to extract 3 parameters), we apply an additional constraint, that the total energy density in Ω_M and Ω_x (the unknown component causing the acceleration) is 1

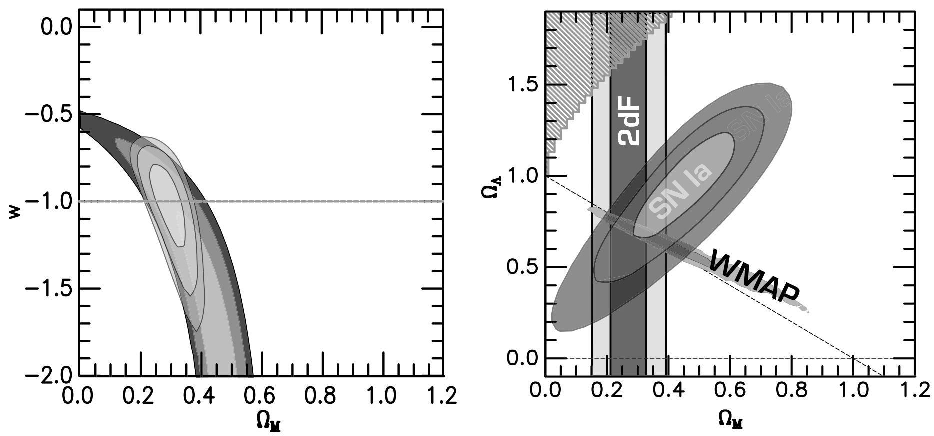

Figure 5. Left Panel: Contours of Ω versus w_x from current SN Ia observational data, where $\Omega + \Omega_x = 1$ has been used as a prior. Also overlaid by contours is the limit including the current value of Ω_M from the 2dF redshift survey as an additional prior. Right Panel: Contours of Ω_M versus Ω_Λ from three current observational experiments; High-Z SN Ia, WMAP, and the 2dF redshift survey

(i.e. the Universe is flat). The Cosmological constant is preferred, but anything within the region $-1.5 < w < -0.73$ is acceptable (Tonry et al. 2003; Riess et al. 2004).

6. Can we believe the SN Ia results?

Taken at face value, the two group's measurements in combination indicate that the Universe must have an unknown matter/energy component with greater than 99.99% statistical confidence, but can we believe this result? Are these conclusions compromised by systematic error? Systematic error is, unfortunately, a difficult thing to estimate. If you know about a source of error, you correct for it, and estimate the statistical error in the correction. But what about things we do not know about?

There is some hope that the conclusion of an accelerating Universe is not tainted by systematic effect based on plausibility. Because the SN Ia have such a small dispersion, even at large redshift, the HZSNS data show that if systematic effects are at play, they affect *every single SN Ia*. Since each object is almost a 2σ measurement of the acceleration, to be reconciled with the nearby sample, every high$-z$ SN must have evolved by twice the observed dispersion of the method, with a spread in the evolution equal to less than the intrinsic dispersion. Since no such effect is seen in the nearby Universe over the entire gambit of galaxies, this would be an extraordinary coincidence. None-the-less, extraordinary claims require extraordinary proof.

The best way to avoid systematic error is to look at other experiments. Since 1998, two other physical experiments have developed to the point where they can also probe cosmological parameters to an interesting accuracy. Large Scale structure measurements, as supplied by recent 2dF redshift survey results (Verde et al. 2002), have measured the density of gravitating matter with high accuracy - $\Omega_M = 0.27 \pm 0.04$. When coupled with measurements of anisotropies in the Cosmic Microwave Background (de Bernardis et al. 2000; Balbi et al. 2000; Spergel et al. 2003), who find the density of all species of matter, $\Omega_M = 1.02 \pm 0.02$, an almost identical conclusion is reached – the Universe is 27% normal matter, and 73% is dark energy. 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. Figure 5 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.

7. 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 Figure 5 shows that 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 about 70%, the SN data show the onset and departure of deceleration (centred around $z = 0.5$) occurs faster than the preferred flat model allows. The total size of the effect is roughly 2% in distance, 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 1 in 3 statistical fluke. Our best estimate is that it is possible to control systematic effects from a ground-based experiment to a level of 1.5% in distance, but this requires better data than what has yet been collected. A carefully controlled ground-based experiment of 200 SN will reach this statistical uncertainty in $z = 0.1$ redshift bins between $0.2 < z < 0.8$, 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) and Destiny collaborations have proposed to launch a dedicated Cosmology satellite - the ultimate SN Ia experiment. This device, will, if funded, scan many square degrees of the sky, discovering a thousand SN Ia in a year, and obtaining spectra and/or light curves 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 WMAP 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. Large Scale Structure measurements and weak-lensing experiments also promise to make measurements of cosmology at unprecedented levels, by watching the growth of structure in the Universe, using literally millions of galaxies to garner the information. So while SN Ia are currently the only way to directly study the acceleration epoch, they will be joined by other methods in the not-too-distant future. By moving forward simultaneously on several experimental fronts, we have the plausible and exciting possibility of achieving a comprehensive measurement of the fundamental properties of our Universe within the next 10−15 years.

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