

Coping with Type Ia Supernova “Evolution” When Probing the Nature of the Dark Energy

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ABSTRACT

Observations of high-redshift Type Ia supernovae (SNe Ia) have provided strong evidence that the dark energy is real, and making further accurate observations of high-redshift SNe Ia is the most promising way to probe the nature of the dark energy. We discuss one of the concerns about such a project — that of coping with SN Ia evolution. We emphasize that SN Ia evolution differs in an important respect from the kind of evolution that has foiled some past projects in observational cosmology, and we outline empirical strategies that will take it into account. The supporting role of physical models of SNe Ia also is discussed. Our conclusion is that systematic errors due to SN Ia evolution will be small.

Subject headings: cosmology: observations – supernovae: general

1. INTRODUCTION

A strong empirical case, based on using Type Ia supernovae (SNe Ia) to determine the cosmic distance–redshift relation, has been made that the expansion of the universe is accelerating, driven by some kind of “dark energy” such as a cosmological constant or quintessence (Riess et al. 1998; Perlmutter et al. 1999; Riess 2000). The most promising way to probe the nature of the dark energy is to make further observations of SNe Ia to more accurately determine the distance–redshift relation (e.g., Wang & Garnavich 2001). A frequently expressed concern is that SN Ia evolution — a systematic variation in the properties of SNe Ia as a function of redshift — may cause an erroneous distance–redshift relation to be inferred from the data. In this paper (which is intended to be sufficiently free of astronomical jargon to be intelligible to physicists) we are concerned only with this single issue of SN Ia evolution; we do not consider related potential complications such as evolution of interstellar dust. The present discussion is partially motivated by what we see

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as a fairly common misconception that controlling SN Ia evolution will require a thorough understanding of the origin and physics of SNe Ia.

Note that although absolute distances are needed to determine the value of the Hubble constant, probing the nature of the dark energy requires only accurate relative distances.

SNe Ia have a well deserved reputation for observational homogeneity. In particular, at their maximum brightness they have similar luminosities, i.e., they are very good, but not perfect, “standard candles” (Branch & Tammann 1992). Most SNe Ia in the current observational sample have, at the time of maximum brightness, a blue minus visual apparent magnitude difference $B - V$ (a “color index”) near 0.0 (like that of Vega, a hot star of spectral type A0). A small fraction of the SNe Ia are subluminous and redder in color, some being intrinsically weak events and others simply being highly extinguished and reddened by interstellar dust. When the redder events are eliminated by means of an objective color cut that excludes those having $B - V > 0.2$, the observational dispersion in the peak blue-band luminosities is only 25 percent (Phillips et al. 1999). Considering that this value is affected by interstellar extinction and observational errors, the intrinsic luminosity dispersion is about 20 percent (corresponding to 10 percent in distance). By traditional astronomical standards this is an excellent standard candle, and as will be discussed below this is not the best that can be done, even with existing data.

In §2 we emphasize that SN Ia evolution differs in an important respect from the kind of evolution that has defeated some past endeavors in observational cosmology. In §3 we outline two simple empirical strategies for coping with SN Ia evolution. (More sophisticated statistical strategies may, of course, prove to be preferable.) In §4 the supporting role of SN Ia models is discussed. In §5 we conclude that systematic errors in the distance–redshift relation due to SN Ia evolution will be small.

2. SN Ia EVOLUTION IS NOTHING BUT PROGENITOR POPULATION DRIFT

When making counts of the numbers of galaxies per comoving volume element as a function of redshift, or when using the brightest galaxies in clusters as standard candles, coping with evolution is difficult. This is because the counts and the luminosities depend on the time (the age of the universe) and therefore, from our perspective, on the redshift, z . Galaxies and their numbers per volume element evolve continuously with time in a way that cannot be controlled by making observations of nearby galaxies.

SN Ia “evolution” is quite different, and the term can be misleading. A fundamental

distinction between a SN Ia and a galaxy is that the SN Ia is an *event* that doesn’t know the time — it just knows the properties of its immediate progenitor star. Similar progenitors at different times should produce similar SNe Ia.

In nearby galaxies, some 14.5 Gyr after the big bang, a wide range of potential SN Ia progenitors is available: local galaxies contain stellar populations of a variety of ages and metallicities (heavy–element mass fractions). As we look out to high redshift and back in time (e.g., back to when the universe was some 4 Gyr old at $z = 1.7$) we should expect a “progenitor population drift”. For example, if any SNe Ia in nearby galaxies are produced by very old stellar populations, ~ 10 Gyr, they will not have counterparts at high redshift. We also can expect a slow drift toward lower mean metallicity at higher redshift. However, the important point is that there will be a strong overlap in the nature of the immediate SN Ia progenitors at different redshifts. Any event that appears at one redshift but has no counterpart at another can be disregarded, however interesting it may be physically.³ It follows that empirical strategies that are effective at correcting (standardizing) the luminosities of low–redshift SNe Ia should also correct the luminosities of high–redshift SNe Ia and effectively control the progenitor population drift. And, because SNe Ia don’t know what time it is, that’s all the SN Ia evolution there is.

3. EMPIRICAL STRATEGIES FOR COPING WITH EVOLUTION

3.1. Multi–Parameter Luminosity Corrections

As mentioned above, a color–cut sample of SNe Ia has a blue–band luminosity dispersion of 20 percent. In addition, the peak luminosity correlates with the time interval during which the luminosity rises and falls — the width of the light curve. The intrinsic luminosity scatter about the luminosity–width relation is only 10 percent (Phillips et al. 1999), so a single–parameter luminosity correction can give relative distances to 5 percent (here we are disregarding the nuisance of interstellar extinction). Some form of a luminosity–width relation has been used in each of the studies of high–redshift SNe Ia that have established the existence of the dark energy. [Although, because the distributions of the light–curve widths in the low–redshift and high–redshift SN Ia samples are statistically indistinguishable (Perlmutter et al. 1999) — thus providing no evidence for significant evolution out to $z \sim 0.5$ — practically the same answer is obtained when a luminosity–width relation is *not* applied.]

³The recent well observed SN 2000cx (Li et al. 2001) is an example of a very interesting SN Ia that does not yet have a known counterpart.

Two-parameter luminosity corrections have not yet been applied to high-redshift SNe Ia, but they have been introduced for determining the value of the Hubble constant (Tripp & Branch 1999; Parodi et al. 2000). When the light curve width and the $B - V$ color index are used to correct the luminosities of a color-cut sample (Hamuy et al. 1996) of well observed SNe Ia whose relative luminosities are well known, the luminosities are completely corrected to within the quoted observational errors. Actually, the luminosities are corrected to better than that (Tripp 1998), indicating that the observational errors were overestimated. It follows that the two-parameter correction yields relative distances to within about 3 percent or better. From existing data we can't tell how much better.

The multi-parameter luminosity-correction strategy for coping with SN Ia evolution is a straightforward extension of the above: 1) Obtain a great deal of spectroscopic and broad-band photometric data for a large sample of SNe Ia in the Hubble flow⁴, where the relative SN Ia luminosities are well known; 2) Establish multi-parameter luminosity corrections as warranted on statistical grounds, and apply them to SNe Ia at all redshifts. If a two-parameter correction gives relative distances to within 3 percent, it is reasonable to expect that this strategy will do even better.

3.2. Comparing Like with Like

Here the strategy is to have enough good photometric and spectroscopic data on so many SNe Ia, well distributed over redshift, to be able to scrupulously compare only like with like. Then the assumption is just that two events that have the same spectroscopic and photometric properties have the same luminosity. This sensible assumption is supported by SN Ia models (§4). If SNe Ia turn out to be continuously distributed in parameter space, then in the process of quantifying what exactly is meant by “like”, this strategy may become essentially equivalent to the multi-parameter luminosity-correction strategy. But if SNe Ia break up into discrete groups in parameter space this strategy will be distinct, because it will be possible to assign relative distances to events in each group without needing to establish the relative luminosities of events in different groups.

⁴Not so near that galaxy peculiar velocities contribute significantly to the observed redshift and not so far that the distance-redshift relation depends on Ω_m and Ω_Λ .

4. THE SUPPORTING ROLE OF SN Ia MODELS

4.1. The Current Level of Understanding

The exact nature of the immediate progenitors of SNe Ia is not yet firmly established. SNe Ia most likely are produced by carbon–oxygen white dwarfs that accrete matter from non–degenerate binary companion stars until they approach the Chandrasekhar limiting mass of 1.4 solar masses, ignite carbon, undergo thermonuclear instability, and explode (the single–degenerate scenario). It now appears that single degenerate systems should not fail to produce Chandrasekhar–mass SNe Ia (Nomoto et al. 2000; Langer et al. 2000; Branch 2001; Thoroughgood et al. 2001). It is still possible, but perhaps unlikely (Saio & Nomoto 1998), that some SNe Ia are produced by mergers of binary white dwarfs (the double–degenerate scenario).

In the single–degenerate scenario a nuclear burning front propagates outward from the center, burning the inner half of the mass to tightly bound iron–peak isotopes (primarily ^{56}Ni because of the equality of the neutron and proton numbers in ^{12}C and ^{16}O) and most of the outer half to intermediate–mass elements such as silicon, argon, and calcium. The fusion energy unbinds the white dwarf and provides the final kinetic energy. Adiabatic losses cause the ejected matter to cool rapidly, but reheating by the trapped decay products of the radioactive ^{56}Ni (6.2–day half life) and its daughter ^{56}Co (77–day half life) powers the light curve. Nuclear energy explodes the star, radioactivity makes it shine. When SNe Ia are treated as a one–parameter family, the dominant parameter that determines the luminosity is M_{Ni} , the mass of ^{56}Ni that is synthesized in the explosion.

In one dimensional nuclear–hydrodynamical explosion models the velocity of the burning front is parameterized because the flame propagation is inherently three–dimensional. Models in which the velocity always is subsonic are called deflagrations, and those in which the velocity goes from subsonic to supersonic are called delayed detonations. Three–dimensional models are just beginning to appear (Khokhlov 2001; Hillebrandt et al. 2000; Hillebrandt & Niemeyer 2000).

From calculations of spectra and light curves of explosion models (e.g., Nugent et al. 1997; Höflich et al. 1998; Lentz et al. 2001) we have quite a good idea of what a normal SN Ia ejects: about a Chandrasekhar mass, including $M_{\text{Ni}} \simeq 0.6$ solar masses, with a kinetic energy of 10^{51} erg so that the velocity at the boundary between the iron–peak core and the intermediate–mass elements is near 9000 km s^{-1} . Models that have acceptable light curves and spectra include the deflagration model W7 of Nomoto et al. (1984), and the delayed–detonation models DD4 of Woosley (1991) and M36 of Höflich (1995). Models that differ substantially from these have spectra and light curves that are inconsistent with the

observations of normal SNe Ia.

Explosion at the Chandrasekhar mass (in the single degenerate scenario) or at least not very far from it (double degenerate scenario) is a plausible reason for the impressive homogeneity of SNe Ia. The first-order cause of the diversity among SNe Ia is a range in M_{Ni} . This may be due to a range in the white-dwarf carbon-to-oxygen ratio, which in turn may be caused by a range in the initial (main-sequence) mass of the white dwarf progenitors. We know that the diversity among SNe Ia actually is multi-dimensional (Hatano et al. 2000). Other factors that could contribute to the diversity include the white-dwarf mass accretion rate, rotation speed, and magnetic field.

4.2. The Role of Models

Models support the basic assumption of the like-with-like strategy. We can make models that have a variety of luminosities and spectroscopic and photometric properties — most of which aren't consistent with observation because the diversity among model SNe Ia exceeds the diversity among real SNe Ia. *What we don't know how to make are models that have the same spectroscopic and photometric properties but different luminosities.*

At present, models are used to indicate which spectroscopic and photometric observables are likely to be sensitive to the physical conditions of the ejected matter, and therefore may prove useful for making multi-parameter luminosity corrections. As more good data accumulate, the process of choosing the observables will become purely empirical. One reason that spectroscopic observables have seldom been used so far to correct SN Ia luminosities is that most of the SNe Ia with good spectroscopic data are nearer than the Hubble flow, making it difficult to establish tight correlations with luminosity. This situation is expected to improve rapidly in the near future (Nugent & Aldering 2000; Aldering 2000).

Models provide bounds on how much evolution can be expected. For example, model calculations indicate that even decreasing the metallicity all the way to zero cannot provide a substantial shift in the luminosity-width relation (Domínguez et al. 2001). Large evolutionary effects are not plausible.

Models provide reassurance that we are not using tools of which we have no understanding. For example, the luminosity-width correlation is understandable (Khokhlov et al. 1993) in terms of a range in M_{Ni} among SNe Ia. The higher the value of M_{Ni} the higher the luminosity, and the higher the value of M_{Ni} the higher the temperature, the higher the opacity, the longer the photon diffusion time, and the broader the light curve.

The ultimate role of models is to help us learn about SNe Ia. Using SNe Ia to probe the nature of the dark energy does not require SN Ia models. Inferring the physical properties of SNe Ia from the observations obviously does.

5. CONCLUSION

SN Ia evolution is unlike the kind of cosmic evolution that presents such a challenge for some other projects in observational cosmology. SN Ia evolution boils down to a modest amount of progenitor population drift. Because we expect a large overlap between the properties of the immediate progenitors of the SNe Ia at various redshifts, we expect the empirical strategies for making luminosity corrections to nearby SNe Ia to apply generally. Thus SN Ia evolution should be controllable to high accuracy.

Probing the nature of the dark energy with SNe Ia is primarily an empirical venture, just as establishing the existence of the dark energy with SNe Ia was empirical. If our physical understanding of SNe Ia were to change, the existence of the dark energy would remain established nonetheless. Consider the analogy with Cepheid variable stars. We have a well developed theoretical understanding of the Cepheid pulsation mechanism, and detailed models that account for the Cepheid period–luminosity relation (which itself is analogous to the SN Ia luminosity–width relation). Yet when astronomers use Cepheids to measure the Hubble constant (e.g., Parodi et al. 2000; Freedman et al. 2001), they use an empirical period–luminosity relation.

Astronomers do not refrain from scrutinizing the radiation from the cosmic photosphere — the microwave background radiation — on the grounds that *its* progenitor is not known. (What was going on before the Planck time?) Similarly, present uncertainties about the origin and physics of SNe Ia need not deter us from exploiting the radiation from SN Ia photospheres to learn about the nature of the dark energy. SN Ia evolution is unlikely to be the limiting factor in our ability to do so.

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