A Century of Supernovae

Peter Garnavich
Physics Departement, University of Notre Dame, Notre Dame, IN 46556; pgarnavi@nd.edu

Invited review paper, received June 28, 2012

Abstract The concept of "supernova," a class of exploding stars more than 100 times the luminosity of an ordinary nova, was introduced almost eighty years ago. Over that time the physics of supernovae has matured into a rich field of study with the identification of several types of explosions and models to explain many of the observations. While there has not been a supernova visible in our Galaxy in over 300 years, only twenty-five years ago a naked-eye supernova, SN 1987A, was intensively studied in a companion galaxy to the Milky Way. Type Ia supernovae have proven to be a reliable way to estimate cosmological distances and these standardizable "candles" have greatly improved the estimate of the local expansion rate of the universe. Pushed to great distances these supernovae have demonstrated that the universe is accelerating, a discovery recognized with the 2011 Nobel Prize in physics.

1. Introduction

The founding of the AAVSO predates the concept of "supernova" by twenty years. New stars, or novae, had been seen through the centuries and introduced to western science by Tycho's and Kepler's observations, but the differentiation between the luminosities of ordinary novae and supernovae required the development of a extragalactic distance scale in the late 1920s and early 1930s (Baade and Zwicky 1934). Hubble had recognized a class of particularly luminous events he referred to as "exceptional novae" (Hubble 1929), but for a new age of "supermarkets" and comic books featuring "Superman," it was Baade and Zwicky's "super-nova" that caught the imagination of the public (Koenig 2005).

Supernovae are stellar explosions that completely disrupt their progenitor star while classical novae result from the thermonuclear fusion on the surface of a compact stellar remnant such as a white dwarf. Novae leave their binary star system intact to nova again another day, decades or millennia down the road. Supernovae yield high velocity gas, luminous energy, and sometimes a neutron star or a black hole. The creation of a neutron star was one of Zwicky's early explanations for the power of these explosions (Baade and Zwicky 1934) although the neutron had been discovered less than two years earlier.

Supernovae were clearly more energetic than novae, based on the new extragalactic distance scale of the 1930s. The absolute magnitude (the apparent magnitude of a star if it were placed 10 parsecs (32.6 light-years) from the Earth) of supernovae range from –16 to –19 while the brightest novae reached –10 magnitude. Searches for intermediate luminosity events have been recently made possible with new, wide-field instrumentation (Kasliwal 2011). Gamma-ray astrophysics and wide-field optical searches have also identified classes of explosions more luminous than supernovae—“hypernovae” (Iwamoto *et al.* 2000; Garnavich *et al.* 2010). Hypernovae have absolute magnitudes of –20 to –21 but their explosion mechanisms are uncertain and their origins appear diverse.

Supernovae and their cousins are important to the ecology of galaxies and the universe. These stellar explosions inject energy into the interstellar gas that triggers star formation. The heavy elements synthesized in supernovae have polluted the pristine hydrogen and helium from the Big Bang, allowing the formation of planets (and people). Supernovae have also become valuable tools for the study of cosmology and have led to the discovery of the accelerating universe and “dark energy” (Reiss *et al.* 1998; Perlmutter *et al.* 1999).

2. Searching for supernovae

In the late 1930s Baade and Zwicky teamed up with Johnson and Minkowski to begin the world’s first systematic search for supernovae (Baade and Zwicky 1938) using a Schmidt telescope on Palomar Mountain. They soon discovered one of the three brightest supernovae of the last century, SN 1937C (supernovae are named by the year of their discovery followed by a letter matching the order of discovery within that year), which reached an apparent magnitude of 8. By the start of the Second World War they had found fifty supernovae and made critical spectroscopic observations that led to the standard classification scheme for supernovae that is still used today. If a supernova has no hydrogen in its spectrum, it is called a “Type I,” while if hydrogen is present it is a “Type II.” Future supernova discoveries would lead to division of these broad classes into sub-types and the physics of the explosions are not well described by this binary scheme, but taxonomy comes before understanding.

Some form of supernova search using photographic plates continued at Palomar for the next forty years. Other observatories began to contribute as well, leading to an average of about fifteen supernova discoveries per year by the start of the 1980s. It is also possible (but difficult) to discover supernovae visually. Robert O. Evans has discovered over forty supernovae mostly through directly visual observation with a small telescope. But a transformation in the way supernovae are discovered and studied arrived with the availability of Charged-Coupled Device (CCD) detectors in the late 1980s. CCDs are nearly ten times more sensitive than photographic plates or the eye, meaning that a 12-inch telescope plus a CCD goes as deep as a 1-meter scope using photography.

CCDs opened up a much larger volume of space for the amateur astronomer to search for supernovae. Arbour, Aoki, Armstrong, Boles, Puckett, Schwartz, and others made important contributions to supernova studies by discovering hundreds of events over the past twenty years.

Professional astronomers also put the new technology to use. Electronic detectors plus computer image manipulation led to automated searches that minimize human interaction (Li *et al.* 2000). The increasing size of CCD chips and the ability to mosaic detectors in a single instrument revolutionized supernova searching. Instead of shooting an image of a single galaxy with the hope that a supernova will appear, hundreds or even thousands of galaxies could be imaged simultaneously with a single exposure. This led to mass production of supernova discoveries at intermediate and high redshift (Frieman *et al.* 2008; Schmidt *et al.* 1998).

3. The core-collapse supernovae

Zwicky's speculation that supernovae result from the formation of a neutron star was right on, at least for a significant fraction of supernovae. Stars that begin their lives with masses more than about eight times the mass of the Sun eventually run out of energy production in their cores. Once this happens they are unable to resist gravity and the core collapses into a neutron star or black hole. The gravitational energy is turned into kinetic as the outer envelope is ejected at high velocity. In fact, the process we call a core-collapse supernova is more complicated. It probably requires neutrino deposition, asymmetric shocks, and additional exotic physics to launch the envelope into space.

The model of supernova production, gravitational energy released in core collapse, did not fully explain the variety of spectra seen in the 1930s through the 1960s. The broad features in the spectra caused by the high velocity of the ejected gas made it difficult to identify the lines. The presence of hydrogen was clear in Type II events but the identification of other elements in Type II and those found in Type I supernovae remained controversial (Branch 1990).

In fact, nature was playing a trick on astronomers. Type I supernovae actually came from two completely different progenitors and energy sources. It was not until the early 1980s that the peculiar spectra seen in a number of Type I supernovae led to the division of that class into subtypes Ia and Ib. Wheeler and Levreault (1985) asserted that the origin of the Type Ib supernovae was similar to Type II despite significant differences in their spectra. Soon, another subclass, Type Ic, was added that, like Type II and Type Ib, was from massive star core-collapse. We now know that Type Ia supernovae are not generated by the collapse of the center of a massive star, but are caused by the nuclear fusion of a compact, low mass star.

The spectral classification scheme was well established by the early 1990s. Hydrogen-rich spectra are from Type II events just as Zwicky had set out. Type Ib supernovae are core-collapse events rich in helium and Type Ic explosions are core-collapse supernovae with little hydrogen or helium. Type Ib and

Ic progenitors have lost their hydrogen and/or helium through a wind or by transferring it to a companion star.

The success of the scheme was short-lived, as a supernova was discovered in the nearby galaxy M81 at the end of March 1993 that did not stick to a single category. SN 1993J showed hydrogen in its early spectrum (Garnavich and Ann 1994) but later displayed strong lines of helium. Apparently SN 1993J had only a thin layer of hydrogen atop a helium atmosphere so that as the supernova aged and we viewed deeper layers, the classification shifted from II to Ib. Other, less bright supernovae have since shown this transformation and this intermediate class has been called "Type-IIb."

4. The supernova of the century: SN 1987A

There has not been a supernova discovered in our Galaxy for over 300 years, but in 1987 we got the next best thing. The first supernova of 1987 was found in the nearest galaxy to the Milky Way, the Large Magellanic Cloud (LMC) at a distance of only 150,000 light-years. This sounds like a huge distance, but SN 1987A became the first naked-eye supernova since Kepler's in 1604 and reached 2nd magnitude (see Figure 1). It explosion was so bright major observatories with their large telescopes had difficulty observing it near maximum light. Its proximity and location in a well-studied galaxy meant that the progenitor of a supernova could finally be identified from archival studies.

SN 1987A was a Type II event and was clearly caused by the core collapse of a massive star. The prevailing theory for core-collapse supernovae was that they happened during the red supergiant phase of stellar evolution when the outer layers are puffed out and reach cool temperatures at the surface. But careful astrometry of archival plates showed that the star at the position of the explosion was a blue, more compact star (Lasker 1987). Confusion dominated the early days of this historic event, but eventually it was confirmed that the first supernova progenitor identified was not what had been expected. Further stellar modeling showed that the low heavy element content in the LMC means that evolving massive stars spend some of their time as blue compact supergiants and can explode during that phase.

SN 1987A had more surprises in store. Several months after discovery the ultraviolet spectrum of the supernova began to change. Emission lines from highly ionized atoms grew in strength over a year and then began to fade. When the Hubble Space Telescope finally reached orbit and its bad optics were fixed, images of SN 1987A revealed one of the most spectacular sights in the sky: a triple ring system tilted to our line-of-sight and centered on the supernova debris. The gas in the rings had been released during the red supergiant phase of the star and left drifting slowly away from the star as it shrank to a blue supergiant. This circumstellar gas was then ionized and set glowing by the X-rays and ultraviolet light from the explosion (Figure 2).

SN 1987A has been intensively studied by HST for nearly a decade. From the observations it is clear that SN 1987A is beginning to make a comeback. The fast-moving supernova ejecta is beginning to sweep up the inner circumstellar ring and the collision is creating hard radiation as well as heating the gas. The entire remnant is getting brighter (Larsson *et al.* 2011). How bright the rejuvenated supernova will become is hard to predict, but it is possible that SN 1987A will again be visible in small telescopes in the southern hemisphere.

5. The GRB/supernova connection

Gamma-ray bursts (GRB) are short bursts of high energy photons that appear to come from all directions on the sky. They were first detected by Defense Department satellites in the 1960s, but were a national security secret so they were known to very few people. Throughout the 1990s, NASA's Compton Gamma-ray Observatory discovered thousands of GRB, but with little improvement in understanding their origin. From this study it became clear that there were two classes of GRB, short bursts that last less than 2 seconds and long bursts than can last a couple of minutes. The range of models published to explain the GRB phenomenon was vast. Some theorists speculated that GRB came from within our Solar System, others from the halo of the Milky Way, and still others that believed GRB were at cosmological distances.

But there was no way to estimate the distance and, therefore the energetics, of GRB from gamma-rays alone. Gamma-rays are difficult to focus, so the positional errors on any burst covered large tracts of sky. In 1997 the small Italian satellite BeppoSAX began detecting GRB. It was designed to also look for X-rays from the bursts which could be localized to a small patch of sky. This led to the discovery of optical afterglows from GRB and a revolution in GRB science (Groot *et al.* 1997). Optical afterglows were clearly connected with very distant galaxies, meaning the bursts were at cosmological distances and extremely energetic events.

The optical afterglows from GRB fade very quickly, on timescales of hours to days. The light curves of long GRB often show breaks in the rate of fading and these are signs of beaming of the energy output (Stanek *et al.* 1999). That the burst comes out as a narrow beam greatly reduces the energy budget of GRB and places them near the total energy derived from core-collapse supernovae.

Late-time bumps in the optical light curves of GRB afterglows and the association between GRB and young stars produced speculation that the long GRB phenomenon has its origin in supernova explosions. This was finally proven by the nearby GRB 030329, which reached 13th magnitude and was widely studied. Days after the burst spectroscopy revealed a Type Ic supernova getting brighter while the GRB afterglow light faded (Stanek *et al.* 2003). Since then several more Type Ic supernovae have been directly associated with long GRB. The prevailing model is that very massive star cores collapse directly to black holes and that accretion into the black hole can power an “engine” for seconds or minutes. Narrow jets shoot out from the star, producing gamma-rays and later X-rays, optical, and radio emission. If the jets are pointed in our direction we get to see a GRB.

Short GRB are even more difficult to study than long bursts and less is known about their origin.

6. Thermonuclear supernovae

Type Ia supernovae (SNIa) derive their energy from thermonuclear fusion. A low mass star like the Sun will eventually evolve into a white dwarf star. This is a remnant core after the outer layers of hydrogen and helium have been ejected. The white dwarf is rich in the elements synthesized in the late stages of its stellar life: carbon and oxygen. It is also very small and extremely dense. A white dwarf has the mass of the Sun but the diameter is close to that of the Earth. These white dwarf stars sound exotic, but they are the most common way stars end their lives.

Normal stars resist collapse by fusing elements in their cores and the resulting energy creates a pressure that pushes against gravity. Failure to generate energy is what makes massive star cores collapse. What prevents white dwarf stars from losing to gravity? Quantum mechanics. The density of white dwarfs is so high that electrons nearly occupy the same position, so in the quantum world they must have different momentum. In fact, electrons must have very high momenta to avoid occupying the same quantum states and the pressure created by these “degenerate” electrons supports the white dwarf from collapse. A young Chandrasekhar (1931) predicted that electrons could only support stars with masses less than about 1.4 $M_\odot$, so we expect no white dwarfs more massive than this.

An isolated white dwarf will stay unchanged for as long as atoms last. But a white dwarf in a binary star system has a chance of becoming an energy producer once again. That is, if some of the matter of the companion can be transferred to the white dwarf, then the mass of a white dwarf could be pushed toward Chandrasekhar’s limit. Exactly how mass is transferred remains uncertain. A normal star may leak mass on to the white dwarf through the gravitationally neutral point between the two. Or, the white dwarf can capture mass from the wind of a stellar giant. It may even be that a companion white dwarf merges with the heavier white dwarf and that sets the fusion reaction starting. Whichever way mass is transferred, as the white dwarf approaches 140% of the mass of the Sun, carbon is predicted to begin to fuse near its center. Once fusion begins the energy generated is enough to continue the burning and a runaway fusion explosion occurs.

Despite the small mass of a white dwarf, SNIa tend to generally be more energetic than core-collapse events. Some of the brightest supernovae of the past century, such as SN 1937C, SN 1972E, and SN 2011fe, have been Type Ia thermonuclear supernovae. The reason SNIa are bright is that they synthesize a sizable amount of radioactive nickel during the carbon fusion. The mass of nickel produced ranges from 0.1 to 0.9 $M_{\odot}$ and this is the main source of luminosity and light curve shape diversity in SNIa.

The radioactive nickel decays to radioactive cobalt (week time scale) that then decays to stable iron (three month time scale), emitting energetic gamma-rays and positrons that are thermalized in the thick ejecta and drive the optical light curve. Arnett (1982) showed that maximum light occurs when the radioactive energy deposition equals energy loss through light emission. This "Arnett rule" allows us to directly estimate the nickel yield in supernovae just by measuring the peak luminosity.

The light curves and spectra of SNIa tend to be very uniform. Theory says they explode near the Chandrasekhar limit, so they come from a fairly narrow range of mass and conditions. This is not to say that all SNIa are identical. Some of the most interesting supernova research in the past 20 years has been attempts to understand the extreme SNIa events. Still, the majority of SNIa are very predictable, almost boring in their consistency.

7. The distance scale and the accelerating universe

Progress in astrophysics over the last century has only been possible by the ever-improving methods of distance estimation. Accurate distances are critical for the physical modeling of new phenomena and the development of cosmological models. Variable stars such as Cepheid and RR Lyrae pulsators have played critical roles in mapping the size of the Milky Way and the distances to nearby galaxies. The current expansion rate of the universe, the Hubble parameter, has been tightly constrained by the distance indicators pioneered over many decades. But supernovae, in particular Type Ia supernovae, appear to be the best distance indictors of the century.

While SNIa are very uniform, their peak luminosities vary by more than a factor of two, making them poor "standard candles." But Phillips (1993) calibrated a relation between the peak luminosity and the decline rate of the SNIa light curve. The absolute magnitude of a SNIa could be determined by observing the optical light curve near maximum light. The technique was expanded by Riess *et al.* (1996) to use the color of the supernovae as an estimate of the amount of dust scattering light coming from the explosion. Using the color and light curve information, SNIa distances were accurate to 7%, an unheard-of precision for astronomical distances.

With this new and powerful tool, cosmologists set off to sharpen estimates of the local expansion rate of the universe. This still required using Cepheid variables to calibrate the zeropoint of the SNIa distance scale using the handful of galaxies where both stars could be studied (Jha *et al.* 1999). Hubble (1929) estimated the Hubble parameter was 500 km/s/Mpc early in the century, but with the help of SNIa, we now know $H_o = 72$ km/s/Mpc with an precision of 5%.

SNIa are bright at maximum light and can be seen to very large distances. Their refinement as standardizable candles in the 1990s set two groups off on a quest for the next big cosmological parameter: the matter density of the universe. The "Supernova Cosmology Project" and the "High-Z Supernova Search" began discovering SNIa five to seven billion light-years away with the goal of measuring the expansion rate in the past (see Figure 3). The idea was that matter in the universe slows the universal expansion over time due to gravity, so by measuring the change in the expansion rate one can infer the mass density (Garnavich *et al.* 1998).

To their surprise, both research groups discovered that the expansion rate of the universe has not been slowing down, but has been speeding up. That is, the universal expansion is accelerating (Reiss *et al.* 1998; Perlmutter *et al.* 1999)! This was shocking news since it requires something other than matter to be a major player in the mass/energy budget of the universe. The unknown energy that drives the accelerating universe has been dubbed "dark energy" and remains one of the biggest mysteries to be solved in the next century of the AAVSO.

References

Arnett, W. 1982, *Astrophys. J.*, **253**, 785.

Baade, W., and Zwicky, F. 1934, *Proc. Natl. Acad. Sci.*, **20**, 254.

Baade, W., and Zwicky, F. 1938, *Astrophys. J.*, **88**, 411.

Branch, D. 1990, in *Supernovae*, Astron. Rechen-Institut (ARI), Heidelberg, 30.

Chandrasekhar, S. 1931, *Astrophys. J.*, **74**, 81.

Frieman, J. A., *et al.* 2008, *Astron. J.*, **135**, 338.

Garnavich, P. M., and Ann, H. B. 1994, *Astron. J.*, **108**, 1002.

Garnavich, P. M., *et al.* 1998, *Astrophys. J.*, **493**, 53.

Garnavich, P. M., *et al.* 2010, *Bull. Amer. Astron. Soc.*, **42**, 358.

Groot, P. J., *et al.* 1997, *IAU Circ.*, No. 6584, 1.

Hubble, E. 1929, *Proc. Natl. Acad. Sci.*, **15**, 168.

Iwamoto, K., *et al.* 2000, *Astrophys. J.*, **534**, 660.

Jha, S., *et al.* 1999, *Astrophys. J., Suppl. Ser.*, **125**, 73.

Kasliwal, M. M. 2011, Ph.D. thesis, California Inst. Technol.

Koenig, T. 2005, in *1604–2004: Supernovae As Cosmological Lighthouses*, eds. M. Turatto, S. Benetti, L. Zampieri, W. Shea, ASP Conf. Ser. 342, Astron. Soc. Pacific, San Francisco, 53.

Larsson, J., *et al.* 2011, *Nature*, **474**, 484.

Lasker, B. 1987, *IAU Circ.*, No. 4318, 1.

Li, W. D., *et al.* 2000, in *Cosmic Explosions*, AIP Conf. Ser, 522, Amer. Inst. Physics, Melville, NY, 103.

Perlmutter, S., *et al.* 1999, *Astrophys. J.*, **517**, 565.

Phillips, M. M. 1993, *Astrophys. J., Lett. Ed.*, **413**, L105.
Riess, A. G., Press, W. H., and Kirshner, R. P. 1996, *Astrophys. J.*, **473**, 88.
Riess, A. G., *et al.* 1998, *Astron. J.*, **116**, 1009.
Schmidt, B. P., *et al.* 1998, *Astrophys. J.*, **507**, 46.
Stanek, K. Z., Garnavich, P. M., Kaluzny, J., Pych, W., and Thompson, I. 1999, *Astrophys. J., Lett. Ed.*, **522**, L39.
Stanek, K. Z., *et al.* 2003, *Astrophys. J., Lett. Ed.*, **591**, L17.
Wheeler, J. C., and Levreault, R. 1985, *Astrophys. J., Lett. Ed.*, **294**, L17.

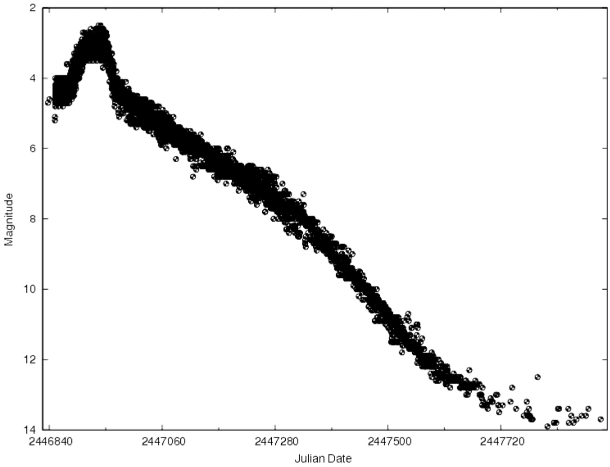

Figure 1. The AAVSO light curve of SN 1987A. The light curve begins a faster decline 400 days after peak brightness because dust begins to form in the inner ejecta.

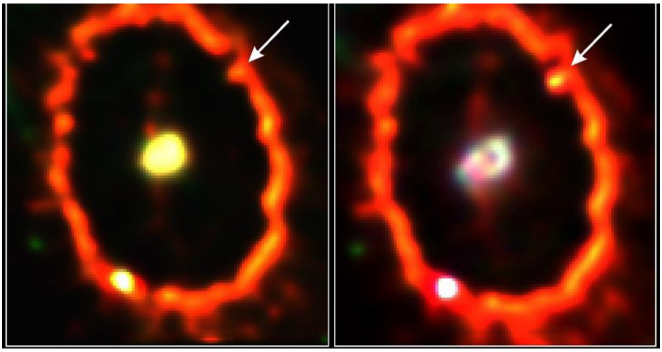

Figure 2. HST images of SN 1987A and the inner ring in 1994 (left) and 1997 (right). The arrow points to the first "hotspot" on the ring where the fast-moving supernova ejecta is running into the slower circumstellar gas. The ring is now filled with these hotspots as the ejecta begins to sweep up the circumstellar gas.

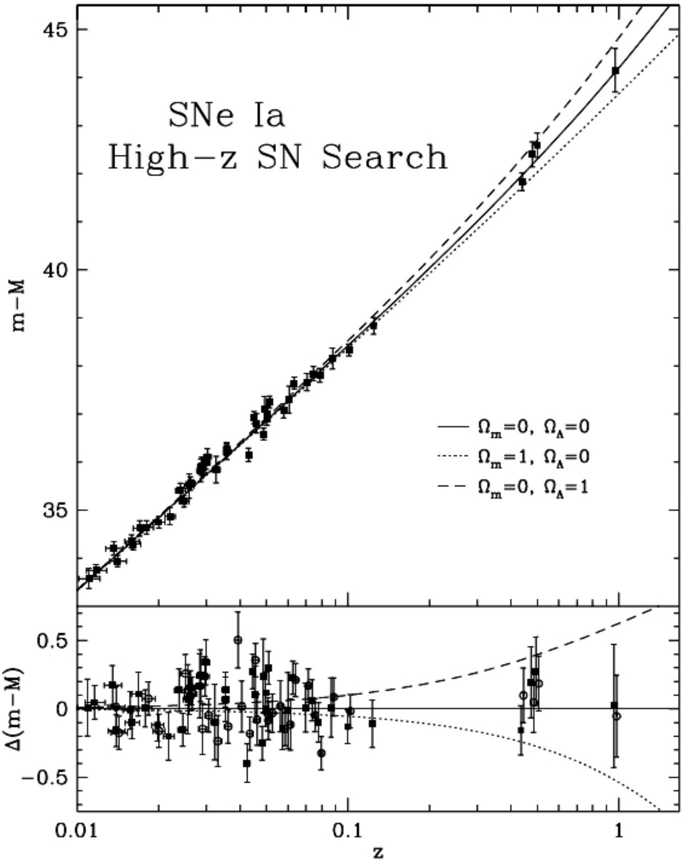

Figure 3. The Hubble diagram (distance versus velocity) for nearby supernovae and four high-redshift supernovae discovered by the High-Z Supernova Search Team (Garnavich *et al.* 1998). The lower panel displays the distance residuals about a universe with no matter (Ω_m) and no dark energy (represented by a vacuum energy Ω_Λ). The squares and circles indicate the supernova distances calculated by two different techniques. The high-redshift supernovae in the diagram tend to fall on the empty universe model meaning that the matter density in the universe is low. A few months after publication of these results more supernovae were added to the analysis that demonstrated the expansion is accelerating and a dark energy is required.