Abstract

This seminar reviews the different types of SN explosions, the physical mechanisms that trigger them and their various optical and spectral properties. Furthermore, the methods for systematic search of extragalactic SNe are presented, with their application in other branches of astronomy, in particular cosmology and the discovery of the accelerating universe through SN Ia surveys.
1 Introduction

Supernovae (SNe) are one of the most important objects known to astronomers today. Observations during and immediately after the explosion offer a large spectrum of different astrophysical and physical mechanisms that can be probed, such as neutrino and gravitational wave emissions, flame propagation and explosive nucleosynthesis, radioactive decays and shocks with circumstellar matter [1]. The nuclear reactions that occur during the supernova explosion are also crucial for the existence of heavier elements in galaxies. In addition, the SNe Type Ia provide the best way to measure distance to distant galaxies, due to their huge luminosity and the fact that they can be accurately calibrated.

For all these reasons, the search for SNe has been of great interest to astrophysicists in the last decades and the technology with which it is being carried out is rapidly developing, providing us with ever faster and more accurate methods for the detection of nearby as well as distant SNe.

As a result, the number of SNe discoveries per year is ever increasing, starting by 20/year in the early ’80s, and rapidly reaching a value of 200/year in the late ’90s.

2 Stellar evolution and supernovae

Stars of all masses spend the majority of their lifetime as main- sequence stars, burning hydrogen into helium in their cores via the two main nuclear reaction chains: p-p and CNO. During that period, the
hydrostatic equilibrium between the gravity and the inner pressure (thermal and radiation pressure) maintains the stability of the star:

$$\frac{dp}{dr} = -G \frac{M_{r} \rho}{r^{2}} = -\rho g$$  \hspace{1cm} (1)

When all of the hydrogen in the core is burned into helium, nuclear reactions stop and the core begins to collapse due to its gravity. The energy released from the gravitational collapse heats the outer shell of the core, creating conditions for fusion of the hydrogen into helium in the shell. The higher temperatures result in higher reaction rates, which in turn leads to higher energy production and an increase in the luminosity of the star by a factor of 1000-10000 \[2\]. This causes the outer layers to expand and the star begins its red giant phase. This phase typically lasts a few million years, until all of the hydrogen in the shell is used up. At that point, the parameter that determines the further evolution of the star is its mass. For red giants with mass less than 2.571M\(_{\odot}\) the density of the core becomes high enough, so that, due to the Pauli exclusion principle, the electron degeneracy pressure

$$p_{d} = \frac{(3\pi^{2})^{\frac{3}{6}}}{4} \hbar c \left( \frac{Z}{A} \right) \left( \frac{\rho}{m_{H}} \right)^{\frac{4}{3}}$$  \hspace{1cm} (2)

becomes the dominant contribution to the pressure of the core. The degenerate core continues to heat until it reaches a temperature of \(\approx 10^{8}\) and begins fusing helium into carbon via the triple-alpha process. Stars of lower masses end their red giant phase by ejecting their outer layers, forming a planetary nebula in the center of which is the hot inert carbon core of the star, which ultimately becomes a white dwarf star \[2\].

The maximum mass of a stable white dwarf was first derived by Indian astrophysicist Subrahmanyan Chandrasekhar, and is thus called the Chandrasekhar mass limit. A precise derivation using polytropic stellar models leads to a value of 1.44M\(_{\odot}\). Stars whose degenerate cores reach masses greater than 1.44M\(_{\odot}\) undergo ignition of new cycles of nuclear fusion into heavier elements in the core and the outer layers, which eventually leads to a supernova explosion.

3 Supernovae

The oldest confirmed record of a supernova dates back to 185 AD, when the explosion of SN 185\[1\] was recorded by Chinese astronomers and described as a new bright star in the sky, which took 8 months to fade. The gaseous shell RCW 86 is suspected as being the remnant of this event, as it matches the period of time that has passed since the explosion. Since then, various records about new bright stars have been made throughout the centuries, such as SN 393 (presence noted in China), SN 1006 (China, Egypt, Iraq, Italy, Japan and Switzerland), SN 1054 (China, Japan; remnant - Crab Nebula), SN 1181 (China, Japan), SN 1572 (Tycho Brahe), and the most recent SN explosion in our galaxy, SN 1604, which was systematically studied by Johannes Kepler, who published his observations in his work De Stella nova in pede Serpentarii \[4\].

3.1 Classification of SNe

The first extragalactic SN was observed on August 31, 1885, near the nucleus of NGC 224 (M 31). With the possibility to observe and analyze extragalactic SN the number of discoveries started increasing rapidly, providing astronomers with huge amounts of statistical data. The classification of the SNe began with Minkowski (1941), who came to the conclusion that there must be at least two

\[1\] Until 1885 SNe the names of SNe were simply given with the year of their discovery. From 1885 the name is formed by the year of discovery, immediately followed by a one- or two-letter designation. The first 26 supernovae of the year get an upper case letter from A to Z. Afterward, pairs of lower-case letters are used, starting with aa, ab, and so on \[3\]
different types of SNe: the first (Type I) that lack hydrogen lines in their spectra, which is the most abundant element in a typical star, alongside helium; and the second (Type II) that show hydrogen lines in their optical spectra. Other spectral properties have lead to additional subdivision of the two main types, resulting in several different types of SNe: SN Ia, SN Ib, SN Ic, SN IIL, SN IIP, SN I Ib and SN II In. [1] [5] The optical differences are later explained with the help of different models for the trigger mechanisms of the SN I and II, all of which mainly revolve around two key aspects: SN Type I are explosions of white dwarf stars accreting matter from a nearby companion, while SN Type II are explosions of evolved massive stars.

3.2 Observational and physical properties of the different types of SNe

3.2.1 Type Ia

The light curve and spectrum are one of the basic properties that determine the type of a SN. The light curve is a plot of the magnitude of the SN as a function of time, with t=0 corresponding to the time of maximum magnitude in the B-band of the spectrum.

![Figure 1: Composite blue (B) light curve of SNe Ia](image)

The B-band light curves of all SNe Ia look similar. They all begin with a very rapid increase in luminosity, where the brightness may change up to 3 magnitudes in 15 days. When it reaches the maximum magnitude it starts to decline at a rate of \( \sim 0.087 \text{ mag/day} \) for the next 3-4 weeks. The decline rate decreases after a month to \( \sim 0.015 \text{ mag/day} \) [7]. A typical SN Ia light curve is shown in Figure 1.

All observed differences between SN Ia were attributed to observational errors, until, with the improvement of the S/N ratio of the observations, it was definitely demonstrated that differences do exist, mainly in the absolute luminosities and the decline rates of the light curves. A relation between the two was established, with fast declining SNe being fainter. The relation between the maximum magnitude and decline rate is demonstrated in Figure 2, and more thoroughly explained in section 4.3.1.

The features that mark the spectrum of a SN are the absence of hydrogen lines and the presence of silicon lines. Intermediate mass elements such as O, Ca, Mg and S may be present, too. Two weeks after the SN reaches maximum luminosity, its spectrum shows lines of Fe and other heavy-mass elements, such as Co. The Doppler shifts of the spectral lines show that the debris emitting the light moves at a very high velocity (highest reaching 0.1c).
Figure 2: Brighter Type Ia supernovae decay more slowly than fainter ones. When time scales of individual light curves are stretched to fit the norm and brightness is scaled according to the stretch, most light curves match [8].

The differences in light curves and spectra are a direct consequence of the initial ratios of elements of the star that exploded. Theoretical models for the triggering mechanism of a Type Ia SN have all favoured the explosion of a white dwarf star as a most probable candidate. It occurs when a white dwarf star, made of C and O, accretes matter from a nearby companion. The mass accretion increases the temperature and density in the stellar core, making it possible for thermonuclear reactions to take place, burning C and O into heavier elements. At high densities, burning produces nuclear statistical equilibrium (NSE) isotopes, especially radioactive $^{56}$Ni which decays to $^{56}$Co and $^{56}$Fe. This decay is the major contribution to the brightness of SN, so the differences in maximum brightness and decline rate of the SN Ia are directly related to the fraction of the stellar mass that is $^{56}$Ni, ranging from 0.9$M_{\odot}$ for the slowest declining (most luminous) SNe to 0.1$M_{\odot}$ for the fastest declining (dimmer) ones. [9]. At lower densities, intermediate mass elements (IME), from Si to Ca, are synthesised. Both NSE and IME are observed in the optical spectra of the SNe Ia.

The outer layers, which are visible in the first few weeks after the explosion, are dominated by IME, with Si being the most abundant. The radial velocity of the ejecta is measured from the Doppler shift of the 6355 Å Si line, and the results show it decreases with time. The inner layers are dominated by NSE elements and are best observed after an year after the explosion, when dilution due to expansion causes the SN to behave like a nebula, thus exposing its deepest layers. Collisions with the fast particles produced by the $^{56}$Ni decay heat the gas, which cools down emitting radiation mostly in forbidden lines.

3.2.2 Type IIP/L

Unlike SN Ia, Type II SNe have very little in common. The only thing that puts them all in the same group is the presence of H lines in their spectra. Their light curves and spectra are notably different, but there are still parameters which enable subdivision. Based on the shape of the light curves they are divided in two main subtypes: Type IIP and Type IIL. Some SNe II light curves tend to remain on a plateau of almost constant luminosity for 2-3 months after the explosion, so they were labeled IIP (P-plateau), while other decline more or less linearly and were labeled IIL (L-linear). Many cases that are a combination of the two have been observed, so these two types are not absolutely separated. Typical light curves for SN IIP and IIL are shown in Figure 3 [1].

Although their observational properties may vary, a single case scenario can be used to explain the
physical mechanisms that triggered them: the core collapse of a massive evolved star. The electron
gas in such a star is nearly relativistic, so the electron degeneracy pressure is no longer a function of
$n^{5/3}$ and the star can not provide a stable degeneracy equilibrium with gravity. The gravity causes the
star to collapse, creating physical conditions that enable further nucleosynthesis into heavier elements
in the core, up to Ni and Fe. After Fe, it is energetically unfavorable to go to heavier- mass nucleons,
so the star ends up with an iron core and an unstable mechanical equilibrium, supported only by the
electron degeneracy pressure of the relativistic electron gas. With no more fusion processes to oppose
the gravity, a gravitational collapse takes place, heating the core to $T \sim 10^{10}$ K. This temperature is
high enough to trigger two processes:

- **Photo-disintegration of Fe and subsequent disintegration of the products**, resulting with $p$ and
  $n$ as final products of the chain reaction:

  \[
  \gamma + ^{56}\text{Fe} \leftrightarrow ... \leftrightarrow ^{13}\text{He} + 4n
  \]

  \[
  \gamma + ^{4}\text{He} \rightarrow 2p + 2n
  \]

- **Inverse beta decay for electrons with $W_k > 3.7$ MeV**:

  \[
  e^- + ^{56}\text{Fe} \rightarrow ^{56}\text{Mn} + \nu_e
  \]

  reaching to $e^- + p \rightarrow n + \nu_e$ by the time only nucleons are left in the core.

In both photodisintegration and inverse beta decay we have less stable nuclei being formed by
more stable ones, so the above reactions absorb energy, therefore decreasing the kinetic energy (thus,
the fluid pressure) of the core, so the unstable core quickly collapses. This collapse ends when the
core reaches nuclear density. For a brief moment of time during the gravitational free fall, the density
reaches density higher than nuclear and strongly bounces back to nuclear density. The bounce produces
a shock wave which moves outward at high velocities, blowing off the material in the surrounding layers
of the star. Once the shock reaches the outer atmosphere, the photons emitted by recombination,
powered by the shockwave and subsequent nuclear decays, become the visible SN explosion [11].

The heterogeneity of SN II is due to the different sizes and mass of the H envelope of the star
at the time of explosion. Different mechanisms, such as difference in metallicities or binary system
interaction, may lead to H envelopes of various masses, even for progenitors of the same initial
mass. The luminosity plateau in SN IIP can be explained with the recombination of H during the
expansion. The energy from the recombination maintains the photosphere at an almost constant radius and temperature. The mass of the envelope determines the length of the plateau and for very small envelope masses ($1 - 2M_\odot$) the decline is faster, resulting with a linear decay and SN IIL. The different lines profiles in the spectra of IIP and IIL are also related to the H envelope masses.

The emission lines in all SNe spectra are very broad due to the high expansion velocities of the ejecta, but a fraction of the SN II show narrow components on top of broad emission lines. These are labeled as SNe IIn (n-narrow). The light curves of SN IIn show much slower luminosity evolution than that of SN II and very high maximum luminosities. The theoretical models suggest an additional source of energy powering the light curve, like the conversion of the kinetic energy of the ejecta into radiation as the result of a shock collision with dense circumstellar medium (CSM). Differences in density and distribution of the CSM may explain the differences in luminosity evolution of SNe IIn [1].

3.2.4 Type Ib/c

Type Ib and Ic were introduced in order to classify the SNe which showed deviations from the typical light curves and spectra of both SN Ia and SN II. From a spectroscopic point of view, they are classified as Type I SNe due to the lack of H lines in their spectra, but additional anomalies have discarded the possibility to designate them as SNe Ia. The spectrum of SN Ib during maximum luminosity resembles the spectrum of SN Ia shows one or two months after maximum. The most prominent property that classifies these events as Type Ib is the absence of the deep SiII absorption line at 6150 Å. The theoretical models regarding this type of SNe assume core collapse of massive stars stripped from their H envelope. The SNe Ic show absence of an additional absorption lines, and are believed to be produced by core collapse massive stars which have lost their He envelope, too [1] [5].
3.2.5 Type IIb

The spectrum of a SN IIb evolves from that of a normal type II SN to that of a type Ib in a few weeks, therefore the label type IIb. The theoretical models for this type of SN explosion suggest explosion of a massive star with a very small H envelope (< 0.2M\(_\odot\)) [1].

4 Cosmology with SNe Type Ia

4.1 Basic cosmological concepts

Cosmology is the scientific study of the large scale structure of the Universe as a whole: its origin, evolution and ultimate fate. With the lack of sufficient scientific methods and technology, it long relied on philosophical concepts, but during the 20th century it rapidly advanced into both a theoretical and observational scientific branch.

4.1.1 Big Bang Theory

The Big Bang is a well-supported cosmological model of the evolution of our Universe. It assumes that the whole Universe was once in an extremely hot and dense state which expanded into space, time and everything we see today. The theoretical foundations of the Big Bang theory were first introduced with Einstein’s General Theory of Relativity (concept of relation between space-time and matter and its implications on a large scale) and the Cosmological Principle (the assumption of a large-scale isotropic distribution of matter in the Universe). The Big Bang model explains not only the origin of the Universe but also the synthesis and distribution of all matter in it. The theoretical concepts of the Big Bang theory have been strongly supported by three significant observations: Hubble’s law, the Cosmic Microwave Background Radiation (CMBR) and the abundances of the light elements H, He and Li [13].

4.1.2 Hubble’s law

Hubble’s law was the first observational confirmation that the Universe is not static, but has been, and still is, evolving. It was first announced in 1929 by American astronomer Edwin Hubble, who formulated it upon his spectral studies of galaxies at various distances from our own. The Doppler shifts of the spectral lines showed receding velocities of almost all of the galaxies, proportional to their distances from the Milky Way. The law is often expressed by the equation

\[ v = H_0d \] (3)

where \( v \) is the recession velocity of the galaxy, \( d \) its distance from us and \( H_0 \) the constant of proportionality (the Hubble constant), which is currently estimated to be 70.8 ± 1.6 (km/s)/Mpc.

Hubble’s law has two possible explanations. One, that we are at the center of an explosion of galaxies, which is inconsistent with the Cosmological Principle, and other, the broadly accepted assumption that the universe is uniformly expanding in all directions, which was established with the discovery of the CMBR and directly coincides with the concepts of General Relativity [13].

4.1.3 Friedmann equations

The Friedmann equations are the set of cosmological equations that govern the expansion of space, based on the concepts of General Relativity and the Cosmological Principle. They were first derived by Alexander Friedmann in 1922 and are to date one of the most important theoretical foundations of modern cosmology.

There are two independent Friedmann equations for modeling a homogenous Universe [14]:
• The Friedmann equation of energy

The Friedmann equation of energy is typically written in the form:

\[ H^2 = \frac{8\pi G}{3} \rho - \frac{kc^2}{R^2} \]  
(4)

where \( H \) is the Hubble constant, \( G \) is the gravitational constant, \( \rho c^2 \) is the energy density, \( R \) is the scale factor of the universe and \( k \) is the dimensionless constant related to the curvature of the universe.

The Hubble constant is related to the scale of the Universe by the equation:

\[ H = \frac{\dot{R}}{R} = \frac{\dot{a}}{a} \]  
(5)

where \( a \) is the dimensionless scale factor of the Universe: \( a = \frac{R}{R_0} \) with \( R_0 \) as the scale factor of the Universe at some canonical time \( t_0 \). The dimensionless scale factor \( a \) may also be expressed in terms of the observable redshift:

\[ \frac{1}{a} = \frac{1 + z}{1 + z_0} = 1 + z \]  
(6)

where \( z_0 = 0 \) is the redshift of the nearby object observed at the present epoch \( (a = 1) \).

The energy density of the Universe can be separated in hypothesized energy forms and expanded in inverse powers of \( a \):

\[ \rho = \sum_{-\infty}^{\infty} \rho_n a^{-n} \]  
(7)

where \( \rho_0, \rho_3 \) and \( \rho_4 \) represent the known energy forms: cosmological constant (\( \Lambda \)), matter and radiation energy density, respectively. The \( \rho_n \) values in the expansion are evaluated at the scale factor \( a = 1 \). We define a critical density: \( \rho_c = \frac{3H_0^2}{8\pi G} \) and introduce \( \Omega = \frac{\rho}{\rho_c} \). Eq. (7) can now be rewritten in terms of \( \Omega \):

\[ \Omega = \sum_{-\infty}^{\infty} \Omega_n a^{-n} \]  
(8)

where all \( \Omega_n \) have values given for \( a = 1 \). \( \Omega_m \) (mass density), which corresponds to \( n = 3 \), and \( \Omega_\Lambda \) (vacuum density), which corresponds to \( n = 0 \), play a major role in the further discussion.

• The Friedmann equation of acceleration

The second Friedmann equation is derived from the same set of assumptions as the first one, the only difference is that it’s a second-order differential equation, which indicates its accelerative nature. It is written in the form:

\[ \frac{\ddot{a}}{a} = -\frac{4\pi G}{3}(\rho + \frac{3p}{c^2}) \]  
(9)

where \( p \) is the isotropic pressure. Eq. (9) can be rewritten in dimensionless form using the perfect fluid state equation, given with the dimensionless parameter \( w = p/(\rho c^2) \):

\[ \frac{\ddot{a}}{a} = -\left(\frac{H_0^2}{2}\right)\left(\frac{8\pi G\rho}{3H_0^2}\right)(1 + 3w) = H_0^2 \sum_{n=-\infty}^{\infty} (1 - \frac{n}{2})\Omega_n a^{-n} \]  
(10)

where \( n = 3w + 3 \). The second Friedmann equation can also be rewritten in terms of energy labels in the same way as the first one.
The simplified versions of the two Friedmann equations can be obtained if we consider the domination of one form of energy $n (w = \frac{n}{3} - 1)$ for $\Omega_{\text{total}} = 1$. The Friedmann equation of energy combined with $H = \dot{a}/a$ yields:

$$\dot{a} = H_0 a^{1 - \frac{n}{2}} = H_0 a^{-\frac{3}{2}w - \frac{1}{2}}$$

(11)

and

$$\dot{a} = H_0^2 (1 - \frac{n}{2}) a^{1-n} = H_0^2 (-\frac{3}{2} w - \frac{1}{2}) a^{-3w-2}$$

(12)

The time-dependent solution of the simplified Friedmann equations is:

$$a = \left(\frac{n}{2}\right) \frac{1}{H_0^2} (H_0 t)^\frac{2}{n} = (\frac{3}{2} w + \frac{3}{2}) \frac{1}{H_0^2} (H_0 t)^\frac{2}{3w+3}$$

(13)

The solutions are so dependent on the type of model for the Universe we choose. Two notable solutions may be considered: a matter-dominated Universe with $w = 0$ which yields a time-dependence of $\propto t^{2/3}$ and radiation-dominated Universe with $w = 1/3$, which yields $a \propto t^{1/2}$.

### 4.2 SNe Ia as standard candles in cosmology surveys

The expansion history of the Universe, which has its theoretical foundations in the Friedmann equations, can be determined using "simple" observations of any type of astronomical objects with known intrinsic properties that may be deduced regardless of the distance of the object from us. Objects with such properties are called "standard candles" and have proven to be the best method of measuring extragalactic distances. In measurements concerning cosmology, the redshift of the light emitted from these distant objects plays a key role, too. As the light from an object travels to us through an expanding universe, the expansion stretches the wavelengths of the photons for the same scale factor $z$ by which the cosmos has expanded from the time the light was emitted. A collection of recorded redshifts and brightnesses of such objects over a sufficient range of distances would result in a historical record of the expansion of the universe. Certain types of stars have the highest priority in playing the role of standard candles, as their chemical properties are comparable on all time/distance scales, while objects such as galaxies can not be used for this purpose, due to the fact that their total flux ratios are individual and their chemical properties may vary with $z$.

When the uniformity of Type Ia SNe was first reported, and considering their high brightness, which makes them easily detectable even at large distances, they soon became a candidate for a standard candle for measurements of the expansion of the universe. The measurements would involve finding and measuring a few SNe Ia that occurred some 100 million years ago, and even some that are ten times away and thus obtain data for the expansion of the universe from several billions years ago to now. The acceleration or deceleration rate of the universe obtained with these measurements depends directly on the mass density of the universe, so we are practically measuring $\Omega_m$. If we assume the matter energy to dominate the universe, a value for the curvature of space may also be obtained by measuring $\Omega_m$ [8].

### 4.3 Observational strategy

The only problem with SNe at the time was the fact that they are rare, random and above all, unpredictable events. Given the fact that all of the worlds’ telescopes large and powerful enough to conduct such observations provide only limited and pre-determined time of observation, the possible occurrence of a supernova and its consequent week-to-week measurements was highly unlikely to get sufficient telescope time, if any at all. This and a series of other problems have resulted with very few distant SNe discoveries in years of observation. A new method had to be applied, and it was
first implemented by a group at the University of California, Berkley, conducted by 2011 Nobel prize
winner Saul Perlmutter and Cork Pennypacker. They introduced a systematic solution to the SN
search problem that guarantees batches of about a dozen freshly exploded SNe, all discovered on
a pre-specified observing date during the dark phase of the moon. Figure 5 shows their observing
strategy in detail. This method made it possible for proposals for time at major ground and space-
based telescopes (necessary for follow-up light curve and spectral observations) to be able to specify
discovery dates and the number of SNe to be found on a certain one-degree patch of the sky. As
a result, the Hubble Space Telescope (which has a field of view of only 10 sq. arc-minutes and
requires exact coordinates to be determined before the observation) could be used. The Berkley
team that initiated these observations soon grew to become an international collaboration group, called
Supernova Cosmology Project.

Due to the new systematic methods of SN search and the improved understanding in brightness
variations, another collaboration soon emerged, called High-Z Supernova Search, led by 2011 Nobel
prize winner Brian Schmidt of Australia’s Mount Stromlo Observatory.[8].

### 4.3.1 Measurements and calibration

The telescopes used for supernova surveys carry out photometric measurements of the flux coming
from the supernova in some wavelength band, which is directly related to the luminosity of the
supernova by:

\[ F = \frac{L}{4\pi d_L^2} \]  \hspace{1cm} (14)

where \( d_L \) is the luminosity distance of the supernova from the observer. Assuming that we know the
absolute luminosity \( L \) of the object, we may easily deduce \( d_L \), and plot it as a function of the redshift
\( z \) determined with spectral analysis. The plot \( d_L(z) \) is directly related to the expansion history of the
universe.

As we have seen, when using SNe Ia as standard candles in distance measurements, the absolute
luminosity differs for different SNe. Uncorrected observations of SNe have an RMS scatter of 40% [17],
so additional calibration is required to minimize it. The basic calibration mentioned in (3.2.1)
requires a timescale stretch parametrization of the B-band light curve. A method presented in [16] shows that a single parameter, called the stretch factor $s$, can effectively align almost all of the B-band light curves with a template light curve. The function:

$$\frac{I(t)}{I_{\text{max}}} = f_R \frac{t - t_{\text{max}}}{s(1 + z)} + b$$

is fitted to the data by adjusting the intensity $I_{\text{max}}$, the time of maximum $t_{\text{max}}$, the stretch factor $s$, so that the width factor $w = s(1 + z)$ scales the template axis, and a baseline level $b < 0.02$ that allows for small corrections in the background galaxy subtraction [17]. $f_R$ is generated from a B-band template, K-corrected\(^2\) to the R-band for the given redshift $z$.

Corrections for light curve shape and color decrease the RMS scatter of the data to 15-20%, while new techniques, such as spectral flux ratios [17] may further decrease this value to 12.5% or 11.9% for combination of both spectral flux ratios and color correction.

4.4 Results

![Figure 6: Plot of observed magnitudes versus redshift for distant and nearby Type Ia SNe, with combined measurements at the same redshift. The red curves represent models with zero vacuum energy and mass densities ranging from the critical density $\rho_c$ down to zero (empty cosmos). The blue line represents the best fit of the observed data, assuming a mass density of about $\rho_c/3$ plus a vacuum energy density twice as large, which implies an accelerated cosmic expansion.][15] [18]

The results of the surveys came as a surprise to cosmologists, especially the values for faintness of high-$z$ ($z > 1$) SNe. If we assume the expansion of the universe to be determined entirely by its mass density, there are two possible outcomes: a high mass density universe which would expand much

\(^2\)K-correction converts an observed magnitude to that which would be observed in the rest frame in another filter, allowing the comparison of the brightness of SNe Ia at various redshifts [?]
Figure 7: Plot of the history of cosmic expansion, assuming flat cosmic geometry. The black points represent the data obtained from high-redshift SNe. The curves in the blue region represent cosmological models in which the accelerating effect of the vacuum energy density (ranging from $0.95\rho_c$ (top curve) to $0.4\rho_c$) eventually overcomes the decelerating effect of the mass density. The curves in the orange region represent models in which the cosmic expansion is always decelerating due to high mass density (ranging from $0.8\rho_c$ up to $1.4\rho_c$). In the last two curves the expansion eventually stops and reverses into a cosmic collapse. [15] [18]

faster in the past than it does now, so faint (distant) SNe shouldn’t be found too far back in time; and low mass density universe where faint SNe are found further back in time. But if the initial mass density was too low, stars and galaxies wouldn’t have been able to form, so there is a limitation to how low the mass density can be. The observed high-z SNe were measured to be fainter than what would be expected even for an empty universe!

This implies that we can not assume a cosmological model with only mass density as the dominant parameter. The next simple model is the combination of mass density and the cosmological constant $\Lambda$ as opposing the gravitational collapse due to matter. The best fit to the sample of the discovered SNe implied that the vacuum energy density is larger than the mass density, thus yielding an accelerating universe. If we assume flat universe, the measurements indicate values for the density parameters to be:

$$ \Omega_\Lambda \equiv \frac{\rho_\Lambda}{\rho_c} \approx 0.7 $$  \hspace{1cm} (16)

and

$$ \Omega_m \equiv \frac{\rho_m}{\rho_c} \approx 0.3 $$  \hspace{1cm} (17)

The plot results are presented in Figure 6 and Figure 7.

The cosmological constant, as cosmologically appropriate as it may seem, is not the perfect candidate for the “accelerator” of the expansion of the universe. Numerous contradictions with particle physics have forced cosmologists to introduce a new form of energy, called “dark energy” that is not necessarily constant, unlike $\Lambda$. Considering the Friedmann equation of acceleration (10) we can deduce that the expansion accelerates for values of $w < -1/3$ after all matter, radiation and dark energy components are included, so extracting only the dark energy component we obtain a constraint of $w < -1/2$. Different dark energy models imply different expansion rates in different epochs, thus we
must make even more detailed observations of the history of the expansion of the universe in order to
determine the true value of \( w \) and its time dependence. For that purpose, SN Ia surveys are constantly
ongoing, steadily providing us with more and better data that gradually shapes the history of our
Universe and its biggest mysteries [8].

4.4.1 Alternative mechanisms that explain the dimming

Due to the fact that dark energy can not be thoroughly explained yet, many scientists have searched
for other possible explanations of the great amount of dimming of high-z SNe, which have proven to be inconsistent with the observed data:

- Extragalactic extinction - an existence of extragalactic dust which absorbs the light as it travels
  from the SN to the observer. A possible candidate for this type of dust is the metallic vapor
  thought to be expelled by SN explosion. Intergalactic dust generally reddens the light, so the
  color of light from the SN dimmed by this mechanisms would be expected to change as the
  extinction increases, which is inconsistent with the observations. [19]

- Gravitational lensing - assumes dimming due to lensing by mass located between the origin
  supernova and the observer. If the clumping of matter in the line of sight is under-dense, the
  supernova will appear dimmer. On the other hand, the regions of over-dense matter in the line
  of sight would cause the supernova to appear brighter, so in a sufficient amount of data, these
  effects would average out. If we assume that the over-dense regions are rare, we may explain
  the observed dimming of SNe, although N-body simulations suggest that gravitational lensing,
  as such, can not explain the amount of observed dimming. [19]

- Supernova progenitor evolution - assumes that the progenitor stars of SNe or their local envi-
  ronment is not constant, but evolves with time. Different metallicities at different \( z \) will affect
  the light curves and spectra of observed SNe, although these types of changes have not been
  observed yet. [19]

5 Conclusion

Supernovae of all types play a major role in the understanding of many important astrophysical
processes regarding stellar interaction and evolution, while their observational properties have also
categorised them as powerful standard candles in extragalactic distance measurements, enabling many
large distance observations that were impossible to conduct with the previous standard candles. As
a result, systematic methods of SN detection at high redshifts developed rapidly during the last
decade of the 20th century, resulting in one of the most fundamental discoveries in cosmology: the
accelerating expansion of the Universe.

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