Optical Light Curves of Supernovae

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Summary. Light curves are the most readily available and most frequently used astrophysical tools for variable phenomena. Supernovae are no exception to this. The information that can be extracted from detailed light and colors curves, together with the detailed study of the spectral evolution, tells us about the progenitor star, the various energy input sources, the explosion environment, material in the line of sight and cosmological effects. Over the past decade we have come to understand the power of detailed light curve studies and how they tie into the exploration of other astrophysical topics.

1 Introduction

This short review presents a general description of recent developments. More details can be found in the recent books edited by Weiler [58] and Hillebrandt and Leibundgut [29] and the reviews therein.

The importance of supernovae for cosmology has been stressed many times. After a long history of plans and predictions (e.g. [1, 9, 56]), the last decade has finally come through with large data sets confirming some of the foresights and added new surprises. Among the most interesting ones are the diversity of thermonuclear explosions (Type Ia Supernovae) and the richness in appearance of core-collapse supernovae. In addition, the emergence of GRBs as special core-collapse objects is enlarging the studies of supernovae.

Since light curves trace the temporal evolution of the supernova emission, they are most sensitive to the energy sources provided in the explosion, the radiation escape and modulations by external processes. The most important energy inputs are the supernova shock and the radioactivity from nucleosynthesis. These inputs are modulated by cooling due to the expansion and recombination, where shock energy is 'stored' for some time. The following sections will describe the energy source shaping the light curves and point towards important parameters which can be deduced from the light curves.

The importance of light curves also stems from the relative ease with which they can be acquired. With modern detectors and telescope technology it has become possible to obtain the essential photometry with robotic or semi-automatic telescopes. Hence, we are now faced with a wealth of light curves, many of them still unpublished, from several institutes (see [38] for a list of references). The wavelength coverage has been extended into the near-infrared with new insights into the explosion physics, the homogeneity of the supernova subclasses and the emission mechanism. In each section will we point out the distinguishing features for the two main supernova mechanisms.

2 Energy Input

As mentioned above a supernova can draw from two major energy sources. While in core-collapse supernovae the energy comes from the gravitational energy freed in the collapse, the energy source of thermonuclear supernovae is the binding energy from fusion of intermediate-mass elements to the iron group. The collapse is converted to an explosion through mechanisms that are not fully understood (e.g. the role of the neutrino emission). However, once the shock is started, it propagates through the stellar envelope and ionizes the ejecta. The first electro-magnetic sign of the supernova explosion is when the shock breaks out of the stellar surface [17, 31]. This short phase (depending on the size of the progenitor star this is around a few hours) has never been observed. However, the rapid cooling due to the adiabatic expansion has been traced for SN 1987A [2], SN 1993J [42] and SN 1999ex [53]. The cooling and the expansion of the ejecta are balanced after a couple of days and the drop in the light curve is reversed into a brightening phase, during which the photosphere expands at roughly constant temperature. Depending on the size, mass and structure of the progenitor star and the explosion energy, the light curve peaks within a few days. When the temperature drops to about 5500K the hydrogen starts to recombine and the additional photons are added to the light curve [8, 50]. Again, depending on the mass and the explosion energy, the energy output is balanced into an extended plateau phase. This phase can reach up to 100 days in some cases. For explosions in stars that lack the hydrogen envelope this plateau phase is absent. This explains why Type Ib/c and some Type II supernovae have a rapid decline onto the radioactive tails.

During the implosion and the subsequent infall the material reaches densities and temperatures where explosive nucleosynthesis takes place. Some of the newly created elements are in radioactive isotopes and release nuclear energy on many different time scales. Since ^{56}Ni is close to the nuclear statistical equilibrium for these conditions, it becomes the major energy storage right after the explosion. Its radioactive decay produces $\gamma-$rays, which are converted in the debris to optical and infrared photons through down scattering. The half-life of ^{56}Ni of 6.1 days is swamped in the shock signatures, but the decay of the daughter nucleus ^{56}Co to stable ^{56}Fe has a half-life of 77.1 days and is the main power source after the recombination phase. The decline of the light curve after the plateau phase is tracing the ^{56}Co decay time extremely well. This has been observed for the classical SN 1999em [15, 26] and SN 1987A [5] for several hundred days. For explosions with massive envelopes all energy produced in the radioactive decays is converted into optical and infrared radiation. In cases, where there are no massive envelopes, e.g. SNe Ib/c and SNe Ia, some of the $\gamma-$rays escape without leaving the energy behind. The decline rates then reflect the changes in the column densities and the $\gamma-$ray escape fraction. Eventually, even the massive envelopes thin out sufficiently so that some of the radioactive energy can escape.

One other energy source for supernovae is to tap into the kinetic energy available in the explosion. By converting kinetic energy of material into light (mostly through shocks and ionization) the supernovae can become significantly more luminous and also sustain the luminosity for a lot longer. Considering that for a typical core-collapse supernova about 100 times more kinetic energy is available than is emitted in light, this contribution can easily outshine the regular display.

For the thermonuclear supernovae the stars are incinerated from the inside out and no powerful shock is formed. In addition, the progenitor stars are very small, indeed tiny, if they really are white dwarfs, that a shock break out would last only for minutes and is unobservable. In this case, there is no preceding neutrino signal either. All energy is coming from the binding energy freed by burning material to the most densely bound nuclei in the iron group. The energy release is through the radioactive channel of ^{56}Ni through ^{56}Co to ^{56}Fe. The light curves show signatures of the Ni decay as well as the Co decay. No other energy input is expected in this case (for the only exception known so far see below).

3 Shaping Light Curves

The basic energy input for the supernova explosions are modified by the way the radiation escapes the ejecta and how the radiation interacts with material around the supernova. Through various different physical effects the light curves can take many different shapes. The two main types of supernovae can be treated separately, mostly because the thermonuclear supernovae display a much simpler behavior than the core-collapse variety.

3.1 Thermonuclear Supernovae

Type Ia Supernovae show less individuality among their light curve (and spectroscopic) behavior than the core-collapse explosions. This is a signature that they are coming from a more homogeneous parent population and also that their environment is less varied. The underlying physics of SN Ia explosions is probably also simpler than for core-collapse supernovae, although the calculations are extremely difficult involving physics at largely different scales [30]. The observational light curve can be summarized rather simply. Fig. 1 shows the main input sources, the radioactive decay chain of ^{56}Ni to

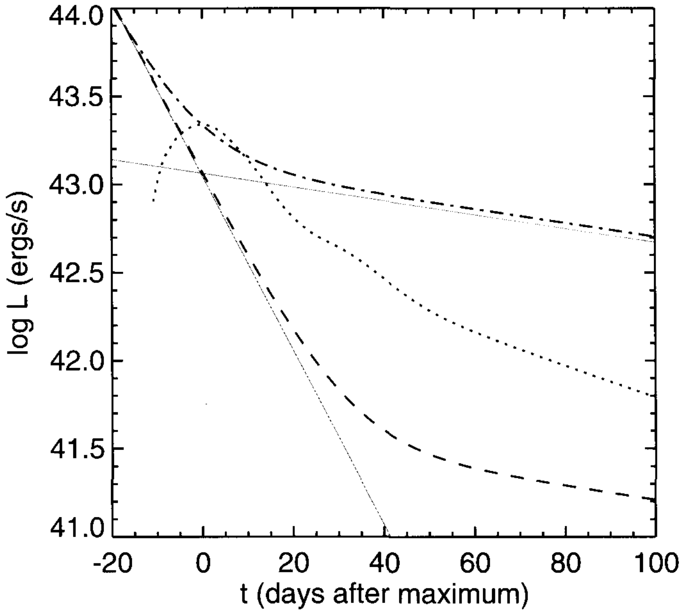

Fig. 1. Schematic of the energy input from radioactive ^{56}Ni and ^{56}Co to a thermonuclear supernova. The thin lines are for the pure ^{56}Ni (dashed) and ^{56}Co (dotted) decays. The dash-dotted line shows the total energy input from the decay chain, while the dashed line indicated the case when only the 5% of the ^{56}Co decay coming from electron capture is retained in the ejecta. The thick dotted line shows the observed bolometric light curve of SN 1992bc. Figure taken from [11].

^{56}Co and ^{56}Fe. The emission is modified by the fact that not all decay energy is released immediately at the surface. Right after explosion the surface expands at a nearly constant temperature of around 10000K and the brightness increase is mostly due to the increase in surface [51]. Before maximum most of the energy in fact is trapped within the dense ejecta and is released only slowly (e.g. [37]).

After about three weeks the emission reaches a maximum as the debris thins out and the mean free path of the photons increases to the size of the ejecta. Interestingly, this happens first in the near infrared [28, 32, 44, 48], where the light curves peak first. The optical light curves reach maximum about one week later. The color evolution around maximum is very fast with the supernova rapidly becoming redder within a couple of weeks. At this time the ejecta become progressively transparent to infrared and optical photons. Right after maximum the light curve slightly "overshoots" the energy input from the radioactive decays (as clearly seen in Fig. 1). These are photons that are produced from the previous radioactive decays and are escaping only now [49]. After the maximum phase the light curves are dominated by the continuous increase of the $\gamma-$ray escape and the reduction of the deposited energy in the ejecta. There are quite some differences in the decline rates of the light curves in the various filters. Typically, the UV and blue light dims faster than the near-infrared. At wavelengths redder than R (about 650nm) the light curves display a re-brightening of the supernovae around two to three weeks after maximum [32, 44, 48]. The reason for this re-brightening is not completely clear. The main arguments are that the wavelength-dependent opacities allow redder photons to escape more easily and hence a re-distribution of the energy takes place.

Five weeks after explosion the thermonuclear supernovae decline towards oblivion. The ^{56}Co decay has a positron channel, where 19% of the energy is released. The positrons were assumed to deposit their energy within the ejecta and would not escape. In this case the light curves should follow the half-life of the cobalt decay. However, this is not observed and although the light curves do turn over [12, 36, 45], it appears that much of the energy from the positron channel still escapes [46]. This indicates that the magnetic fields in the explosion most likely have a radial form to allow the positrons to escape before annihilating.

The only real exception to the above picture is coming from the recent discovery of SN 2002ic. This object appears to have exploded within a very dense circumstellar environment and is displaying a very slow light curve [27]. The suspicion is that this explosion is interacting with this material and hence a lot of the kinetic energy of the explosion is converted to photons (cf. section 3.2).

3.2 Core-collapse Supernovae

The display of core-collapse supernovae is much more complex. This comes from the fact that many different physical processes play important roles here. The shock created in the explosion accelerates the material to velocities of about 10% of the speed of light. The progenitor stars are at different stages of their evolution, often influenced by companion stars, and depending on the amount of hydrogen still left in the envelope the appearances can be dramatically altered. As described above the early phases are dominated by emission coming from the shock and recombination. Type II supernovae can have quite a varied appearance at these phases, which indicates large differences in synthesized nickel mass, explosion energy and total mass [24]. The drop from the plateau onto the radioactive tail is a sensitive measure of the nickel mass as well [16]. Afterwards the energy from the radioactive decays powers the light curves for several hundred days. The decline rate at this stage gives a good indication of how massive the progenitor star was. If it tracks the half-life of ^{56}Co, then all energy is thermalized, while for faster declines less massive progenitors are indicated. SNe Ib/c typically have faster declines [13, 35]. The light curve of SN 1987A is a good example of a massive supernova [5] (see also Fig. 2).

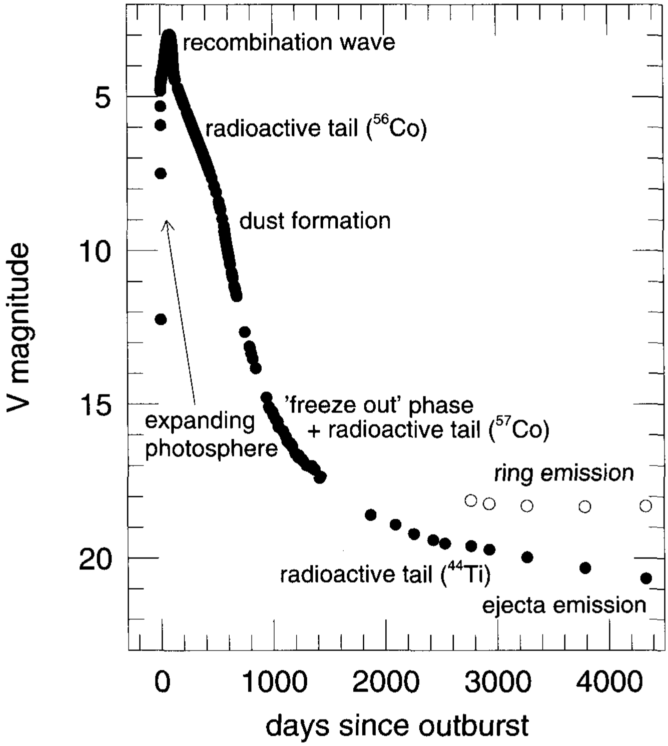

Fig. 2. The V light curve of SN 1987A as an example of the various phases core-collapse supernovae exhibit. Figure taken from [38].

For massive supernovae the absolute luminosity after about 120 days, together with the age of the supernova, gives a relatively accurate measure of the amount of ^{56}Co synthesized in the explosion [16, 24]. This measurement is now available for many core-collapse supernovae and is typically a factor 10 less than assumed in thermonuclear supernovae but spans almost a factor of 100 [47].

Only SN 1987A has been observed to late enough phases so that further changes in the light curves could be observed. Dust formation within the supernova lead to a dimming due to obscuration from the dust grains. Although precursor molecules for dust formation, mostly carbon monoxide, have been observed in many core-collapse supernovae [21, 22, 52], dust itself was only inferred from the observations of SN 1987A and recently possibly in SN 1999em [15, 41]. The SN 1987A light curve started to drop around 500 days when the dust formed.

Later SN 1987A started to show a flattening of the light curve. While the first explanations were pointing toward increased abundances of ^{44}Ti, which would have been very difficult to explain within the nucleosynthesis picture, it turned out that the emission is coming from material that was ionized by the soft X-ray emission from the shock breakout and was recombining very slowly. This "freeze-out" was explained by Fransson and Kozma [19].

The light curve of SN 1987A has now declined further, although the decline in the near-infrared has slowed down to only a few tenths of magnitudes per year. The ejecta are now much fainter than the surrounding ring of dense pre-supernova material. The supernova shock has reached this ring after 15 years. The X-ray emission has already started to increase from this shock over the last few years [43] and also several dense intrusions have started to brighten [54].

Distances from Core-collapse Supernovae

The brilliance of core-collapse supernovae has enticed people to investigate their capabilities as distance indicators. Following early work by Baade [3], originally done for Cepheid stars, the expanding photosphere method (EPM, [14]) has been applied to several supernovae. The most comprehensive data sample has been assembled by Hamuy [23]. A critical test has become the distance to SN 1999em, which was determined through EPM [15, 26, 40] and which also has a Cepheid distance available [41]. The discrepancy is most likely attributable to the fact that the correction factor for the dilution of the black body flux in EPM are strongly model dependent and need to be calculated for each supernova individually.

Recently, Mario Hamuy has realized that the expansion velocity and the luminosity during the plateau phase correlate and that Type II SNe may be quite good distance indicators (see his article in these proceedings and [25]). The distance accuracy achieved this way can be better than 20%.

Supernovae with Circumstellar Interaction

Some supernovae explode in a dense environment. In this case, the shock breakout ionizes the material around the explosion. The ring around SN 1987A is only on example. In essence the supernova can create its own temporary HII region around itself. Within days, however, the material shock will start to interact with the dense circumstellar material [7]. The light curve in these cases are drowned in the photons from this interaction. The best studied cases so far are SN 1986J [39], SN 1988Z [57], SN 1995N [20] and SN 1998S [18]. The light curves of these objects evolve very slowly and they stay bright for a long time (typically over several years). Quite often these objects are also very luminous. Their spectral appearance is also markedly different from other supernovae. These objects are also detected as radio sources (see, e.g., [58]).

4 Conclusions

Light curve data of supernovae have reached a new quality in the past few years with increased temporal and wavelength coverage (e.g. [4, 6, 15, 25, 32, 33, 34, 53]). This will likely continue with more robotic telescopes and increased searches. Very importantly the amount of well-sampled infrared light curves is increasing rapidly. Although only little energy is radiated at these wavelengths during the first year or so of a supernova, it provides important information on the explosion physics. At late stages the supernovae have cooled down so much that most of the energy is actually emerging in the infrared and the predictions are that the light curves decay only very slowly as observed in SN 1987A, but also in SNe Ia.

The physics of supernovae can only be understood by combining as many observables as possible. The light curves, as the tracer of the temporal evolution of the luminosity, are essential and fundamental ingredients. The emission is shaped through various physical processes that can be identified and hence used for the interpretation of what is observed. One important tool, not discussed in this review, for such investigations are bolometric light curves, which combine all emerging flux. Such bolometric light curves are being assembled for some objects [10, 16]. They provide a convenient tool to investigate the physics behind the SNe Ia (e.g. [55]).

Supernovae are central to many astrophysical topics and the enhanced interest in them is creating a flood of data. The coming years will see the systematic exploration of these data for the physical interpretation of these brilliant events.

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