Abstract. In general, Light Echoes (LE) are beautiful, rather academical and therefore unavoidably useless phenomena. In some cases, however, they can give interesting information about the environment surrounding the exploding star. After giving a brief introduction to the subject, I describe its application to the case of Type Ia Supernovae and discuss the implications for progenitors and their location within the host galaxies.

1. Introduction

The idea about a possible connection between the characteristics shown by Type Ia Supernovae (hereafter SNe Ia) and the properties of their host galaxies has been around for quite a while. Several authors have pointed out that the observed features of Ia’s, such as intrinsic luminosity, colour, decline rate, expansion velocity and so on, appear to be related to the morphological type of the host galaxy (Filippenko 1989, Branch & van den Bergh 1993, van den Bergh & Pazder 1992, Hamuy et al. 1996, Hamuy et al. 2000, Howell 2001; see also the contributions by Mannucci, Della Valle, Petrosian and Garnavich in these proceedings). Since these objects represent a fundamental tool in Cosmology, it is clear that a full understanding of the underlying physics is mandatory in order to exclude possible biases when one is to disentangle between different cosmological scenarios.

In this framework, recognizing the existence of Ia sub-classes is a fundamental step. In this respect, a milestone in the SN history is year 1991, when two extreme objects were discovered, i.e. SN1991T (Filippenko et al. 1992a) and SN1991bg (Filippenko et al. 1992b). The former was an intrinsically blue, slow declining and spectroscopically peculiar event, while the latter was intrinsically red, fast declining and also showing some spectral peculiarities. From that time on, several other objects sharing the characteristics of one or the other event were discovered, indicating that these deviations from the standard Ia were, after all, not so rare. Of course, one of the most important issues which were generated by the discovery of such theme variations concerned the explosion mechanism and, in turn, the progenitor’s nature.

The growing evidences produced by the observations in the last ten years have clearly demonstrated that the sub-luminous events (1991bg-like) are preferentially found in early type galaxies (E/S0), while the super-luminous ones (1991T-like) tend to occur in spirals (Sbc or later). This has an immediate consequence on the progenitors, in the sense that sub-luminous events appear to arise from an old population while super-luminous ones would rather occur
in star-forming environments and therefore would be associated with a younger population. This important topic has been discussed by [Howell 2001], to which I refer the reader for a more detailed review. What is important to emphasize here is that 1991T-like events tend to be associated with young environments and are, therefore, the most promising candidates for the study of Light Echoes (LEs). Or, in turn, if LEs are detected around such kind of SNe, this would strengthen their association with sites of relatively recent star formation.

2. Known Light Echoes in SNe Ia

Due to the typical number density of dust particles which are responsible for the light scattering, LEs are expected to have an integrated brightness about ten magnitudes fainter than the SN at maximum (see for example [Sparks 1994]). For this reason, a SN Ia in the Virgo cluster is supposed to produce, if any, an echo at a magnitude $V \sim 21.0$. This has the simple consequence that it is much easier to observe such a phenomenon in a Ia than in any other SN type, due to its high intrinsic luminosity. As a matter of fact, only four cases of scattered LEs are known: the SNe Ia 1991T [Schmidt et al. 1994, Sparks et al. 1999] and 1998bu [Cappellaro et al. 2001], and the type II SN1987A [Xu, Crotts & Kunkel 1995 and references therein] and 1993J [Sugerman & Crotts 2002]. As expected, the LE detections for the two core-collapse events occurred in nearby galaxies: LMC $(d=50$ kpc) and M81 $(d=3.6$ Mpc) respectively.

The first case of a LE in a Ia (1991T) seems to confirm the scenario outlined in the Introduction, in the sense that the SN was over-luminous and the host galaxy (NGC4527) is an Sbc and also a liner. Slightly less convincing is the other known case (1998bu), since the galaxy (NGC3368) is both an Sbc and a liner, but the SN is not spectroscopically peculiar. The only characteristic in common with SN1991T is its decline rate $\Delta m_{15}$, which is lower than average, even though not so extreme as in the case of 1991T. Nevertheless, the HST observations by [Garnavich et al. 2001] show that a significant amount of dust must be present within 10 pc from the SN. Of course no statistically significant conclusion can be drawn from such a small sample, which definitely needs to be enlarged. For this reason, during the past years, I have been looking for new cases, the most promising of which was represented by SN1998es in NGC 632. This SN, in fact, was classified as a 1991T-like by [Jha et al. 1998], who also noticed that the parent galaxy was an S0, hosting a nuclear starburst [Pogge & Eskridge 1993]. Moreover, the SN was found to be projected very close to a star forming region and to be affected by a strong reddening, which all together made SN 1998es a very good candidate for a LE study.

The host galaxy was imaged with the ESO-VLT at almost three years from the explosion. While I will give the details in a forthcoming paper, here I can anticipate that no LE was detected, down to a limiting magnitude of $V \sim 25$. This allows one to definitely exclude the presence of a 1991T-like LE, which would have been clearly detectable by the VLT observations. Since the two objects suffered a similar extinction, the only plausible explanation is that in 1998es the dust was confined at a larger distance from the SN, at least a factor 10 farther than in 1991T. Therefore, at least for this object, the conjecture discussed in Sec. is not confirmed. As a matter of fact, as a result of a
systematic LE search including 64 historical SNe, Boffi, Sparks & Macchetto (1999) have reported 16 possible candidates, only one of which is a genuine Ia, i.e. SN 1989B (but see also Milne & Wells 2002). Therefore, one may first inquire why only two events have been detected and immediately conclude that this is simply because in the vast majority of the cases there is not enough, and/or not close enough dust around Ia’s. Not an unexpected conclusion for supposedly long-lived and small mass progenitors.

Nevertheless, a consideration needs to be done. In the case of ground based observations, I must notice that there are only a few Ia’s observed at more than one year past maximum. In fact, this has always been a problem, both due to their faintness and to the presence of the host galaxy background. Therefore, it is difficult to give a final answer on the basis of the exceedingly small list of LE detections and we will probably have to wait a bit more in order to have a statistically significant sample. This is even more true if only over-luminous SNe are associated with dusty regions.

3. The Light Echo Phenomenon

Starting with the pioneering work by Couderc (1939), the problem has been addressed by several authors (see for example Dwek 1983, Chevalier 1986, Schaefer 1987, Emmering & Chevalier 1989, Sparks 1994, Xu, Crotts & Kunkel 1994 and Sugerman 2003). The interested reader can refer to these publications for a detailed description of the phenomenon, while here I will give only a brief introduction.

The definition of LE is borrowed from the equivalent effect one can easily experience with acoustic waves. A sound emitted by a source can be reflected by the environment and reach the listener at different times. If the time delay is larger than the input sound duration one has an echo, while in the other cases one should rather talk about a reverb. If the environment is complex, the resulting signal will be the superposition of the input transient (which in the astronomical context corresponds to the source burst) and a large number of delayed and filtered signals. In mathematical terms this is described by the convolution of the signal with the impulse response function (IRF), which contains the geometrical and physical properties of the environment (see for example Spjuti 2001 for a good introduction to this subject). In the parallel astrophysical case, the ingredients of the IRF are the density distribution of dust particles, the scattering efficiency as a function of wavelength (i.e. the extinction law), the dust albedo and the scattering efficiency as a function of scattering angle (i.e. the scattering phase function).

In the simplest case, the problem is solved in the so-called single scattering approximation, which assumes that once a photon is scattered by the dust, it escapes the system with no further interaction. As already shown by Chevalier (1986), this assumption holds when the dust optical depth is low. When the optical depth grows, multiple scattering becomes relevant and it produces quite interesting effects. For a detailed description the reader is referred to Patat (2004), where the Monte Carlo treatment, the ingredients and the results are thoroughly discussed.
Due to the short duration of a Type Ia burst, the apparent LE is approximately confined within a thin paraboloidal shell, with the SN in its focus. As a consequence, at any given time, the observed properties of the convolved signal reflect the geometrical structure and the physical properties of a well defined portion of the dusty environment. Therefore, the hope behind this kind of analysis is that a LE can be used as a tomographic probe. And this is indeed the case when the echo is resolved, as it has been shown for SN 1987A by Crotts, Xu and collaborators (see Xu, Crotts & Kunkel 1995 and references therein). The problem becomes ill posed when the LE is unresolved, since the simulations show that one can produce pretty similar light curves and spectra with different dust distributions. This is because there is a partial degeneracy in the dust-density/dust-distance plane, which leaves one with the question whether there are lots of dust far from the SN or a small amount of dust close to the SN.

4. Applications to SNe Ia

As an example application to the study of SNe Ia environments, I will discuss here the simple case of an event occurring in a face-on dusty disk. The density profile of such a system can be modeled using the typical double exponential formulation, which is parameterized through $R_d$ and $Z_d$, the characteristic radial and vertical scales for the dust distribution. In the case of a spiral galaxy, typical values are $R_d=4.0$ kpc and $Z_d=0.14$ kpc. The central density, $n_0$, is constrained by $\tau(0)$, i.e. the central optical depth of the disk seen face-on. Imposing a typical value $\tau_V(0)=1$ and for a $R_V=3.1$ Milky Way dust mixture, $n_0$ turns out to be $2.3 \text{ cm}^{-3}$. Now, if we place the SN at 6 kpc from the center and at 0.1 kpc above the galactic plane (which implies an optical depth $\tau_V=0.06$ for the SN), the resulting LE is about 10 mag fainter than the SN at maximum, and shows a very low luminosity decline rate.

In conclusion, under rather normal conditions, a Type Ia SN exploding in the disk of a spiral should always produce an observable LE, without the SN being heavily reddened. Of course, placing the SN in the inner parts of the disk would increase the echo luminosity and the extinction suffered by the SN itself. For example, leaving all the other parameters unchanged and placing the SN on the galactic plane would enhance the LE by 0.7 mag, while the optical depth would grow to $\tau_V \sim 0.1$, which is anyway still a rather low value. Since there are good reasons to believe that $1 \leq \tau_V(0) \leq 5$, a Type Ia within 1-2 dust scale heights should always produce an observable LE, unless it is located very far from the galactic center. As a conclusion, it seems that SNe Ia tend to explode far from the host galaxy disk, at vertical distances from the galactic plane that are significantly larger than the dust height scale $Z_d$, otherwise they would always produce detectable LEs.

As I have mentioned before, remarkable exceptions are SNe 1991T and 1998bu, whose LEs have been resolved by HST (see Sparks et al. 1999 and Garnavich et al. 2001). Due to the smaller distance of its host galaxy, the case of 1998bu is particularly interesting. The most recent HST-ACS images available show a very clear ring-like structure, as originally noticed by Garnavich and collaborators from the WFPC2 images taken about two years after the SN had exploded. This is clearly visible in Fig. 1 where I have also plotted the projected...
distance scale from the resolved central knot, whose centroid practically coincides with the SN position. Overimposed are also a number of circles, which define the loci of constant distance \( r \) from the SN, derived using the LE paraboloid equation (see for example [Patat 2004]). Since background dust would appear at projected distances smaller than \( ct \) (which here corresponds to about 1.5 pc), all the resolved structures visible in Fig. 1 are generated by foreground material, which extends to at least 300 pc from the SN. In general, the LE can be roughly subdivided into 3 regions: a) an external ring, b) a central resolved disk and c) a filamentary structure extending from the center to the strong density enhancement visible at about \( r=180 \) pc. Region a) is most likely produced by dust confined within a non-planar and sheet-like cloud, strongly inclined with respect to the line of sight and highly inhomogeneous. The dust illuminated at this epoch and belonging to this structure is placed at distances which range between 120 and 300 pc from the SN. Even taking into account the artificial broadening effect produced by the finite duration of the input SN flash and the instrumental spatial resolution, the maximum sheet thickness must be larger than 100 pc. But the most interesting aspect of this LE, in connection to our original problem, is the detection of dust relatively close to the SN. The original finding by Garnavich et al. (2001) is confirmed by the latest HST observations presented here, which reveal details on even closer regions: dust is certainly present at \( r < 10 \) pc. A sufficiently small distance to claim that the SN progenitor was associated to the dust cloud. A thorough and more quantitative analysis of these and other HST archival data, including polarimetry, is in progress. This will provide a detailed study of the LE evolution with time, a probe for the SN environment at different locations and a tool to get dust density estimates.

Notwithstanding the difficulties which are intrinsic to the method, I still think LEs can give us some insights on the SNe Ia explosion environment.

Observers, watch out the late phases of your Ia’s!

Benché l’astronomia nel corso di molti secoli abbia fatto gran progressi nell’investigare la composizione e i movimenti dei corpi celesti non è ella sin qui arrivata a segno tale che moltissime cose non restino indecise, e forse ancora mol’altre occulte.\(^1\)

Galilei (1632)

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\(^1\)Even though astronomy during many a century has made great progresses in investigating the constitution and motion of celestial bodies, it has not yet reached such a level that many things do not remain undecided, and perhaps many others still unknown.
Figure 1. Image of SN 1998bu obtained on 2003-04-23 (∼4.9 yrs after the explosion) with the High Resolution Camera of ACS (F435W), mounted on board of the HST. The projected scale (∼ 1.3 pc pixel$^{-1}$) corresponds to a host galaxy distance of 10.5 Mpc. The circles trace the loci at constant radial distance from the SN and were placed at 10, 50, 150 and 350 pc respectively.