Seeking for the Progenitors of Type Ia Supernovae

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Type Ia supernovae are thought to be thermonuclear explosions of accreting white dwarfs that reach a critical mass limit. Despite their importance as cosmological distance indicators, the nature of their progenitors has remained controversial. Observations carried out by our team with VLT-UVES led us to the detection of circumstellar material in a normal Type Ia supernova. The expansion velocities, densities and dimensions of the circumstellar envelope indicate that this material was ejected from the system prior to the explosion. The relatively low expansion velocities appear to favour a progenitor system where a white dwarf accretes material from a companion star which is in the red-giant phase at the time of the explosion.

The quest

Due to their enormous luminosities and their homogeneity, Type Ia Supernovae (hereafter SN Ia) have been used in cosmology as reference beacons, with the ambitious aim of tracing the evolution of the Universe (Riess et al. 1998; Perlmutter et al. 1999). Despite the progress made in this field, the nature of the progenitor stars and the physics which governs these powerful explosions are still uncertain. In general, they are thought to originate from a close binary system (Whelan and Iben 1973), where a white dwarf accretes material from a companion until it approaches the Chandrasekhar limit and finally undergoes a thermonuclear explosion. This scenario is widely accepted, but the nature of both the accreting and the donor star is not yet known, even though favourite configurations do exist (see Parthasarathy et al. 2007 for a recent review). But why is it so important to investigate the nature of the progenitor system? Besides the fundamental implications on the cosmological usage of SNe Ia, there are actually several other reasons to bother (Livio 2000). First of all, galaxy evolution depends on the radiation, kinetic energy and nucleosynthesis yields of these powerful events. Secondly, the knowledge of the initial conditions of the exploding system is crucial for understanding the physics of the explosion itself. Finally, identifying the progenitors and determining the SN rates will allow us to put constraints on the theory of binary-star evolution.

Having in mind *why* we want to do this, the next question is, as usual, *how*. A discriminant between some of the proposed scenarios would be the detection of circumstellar material (CSM). However, notwithstanding the importance of the quest, all attempts at detecting direct signatures of the material being transferred to the accreting white dwarf in normal SNe Ia were so far frustrated, and only upper limits to the mass-loss rate could be placed from optical, radio and UV/X-ray emission. Claims of possible ejecta-CSM interaction have been made for a few normal objects, in which the presence of CSM is inferred by the detection of high-velocity components in the SN spectra. However, it must be noted that these features can be explained by a 3D structure of the explosion and, therefore, circumstellar interaction is not necessarily a unique interpretation. Furthermore, no velocity or density estimate is possible for the CSM material, even in the case that the high-velocity components in the SN spectra are indeed the effects of ejecta-CSM interaction.

Two remarkable exceptions are represented by the peculiar SNe 2002ic and SN 2005gj, which have shown extremely pronounced hydrogen emission lines, that have been interpreted as a sign of strong ejecta-CSM interaction. However, the classification of these supernovae as SNe Ia has been questioned, and even if they were SN Ia, they must be rare and hence unlikely to account for normal Type Ia explosions. As a matter of fact, the only genuine detection may be represented by the underluminous SN 2005ke, which has shown an unprecedented X-ray emission, at a 3.6 σ-level, accompanied by a large UV excess (Immler et al. 2006). These facts have been interpreted as the signature of a possible weak interaction between the SN ejecta and material lost by a companion star.

All the channels explored so far to detect CSM around Type Ia SN progenitors are based on the fact that sooner or later the fast SN ejecta will crash into the slow-moving material lost by the system in the pre-explosion phases in the form of stellar wind. This implicitly requires two conditions to be fulfilled: a) there has to be interaction; and b) the amount of CSM and its density must reach some threshold values in order to produce a detectable interaction. Therefore, methods based on ejecta-CSM interaction will not be able to reveal this material if its amount is small and/or if it is placed rather far from the explosion site. But there is another possibility of revealing CSM, basically because of the transient nature of the SN event and its high luminosity.

In fact, if the SN is surrounded by a dusty environment, the scattered light will add with some delay to the SN signal (this is why this phenomenon is also known as a *light echo*), leaving certain signatures in the observed light curves and spectra (see Patat 2005 for a review on this subject). These effects are expected to be dependent on the distance of the scattering material from the SN itself. More precisely, if the dust is contained in a distant cloud (like for example in an intervening spiral arm of the host galaxy), the late time epochs of the observed SN evolution will be completely dominated by the light echo, as in the well-known cases of SNe 1991T and 1998bu. On the contrary, if the scattering material is confined within a small region surrounding the SN, the effects although present at all epochs, are subtle and can be confused with intrinsic SN properties (Patat et al. 2006).

Of course, if the dust is close enough to the SN, this is expected to feel the strong radiation field produced during the explosion. Therefore, is is reasonable to expect variations in the physical conditions of the CSM, like dust evaporation and/or gas photoionisation.

It was while investigating these effects that we saw a possible way of revealing low amounts of CSM material without the need of having matter interaction. In fact, since in SNe Ia the UV flux bluewards of 350 nm undergoes severe line blocking by heavy elements like Fe, Co, Ti and Cr, they are capable of ionising possible CSM only within a rather small radius. Once the UV flux has significantly decreased past the post-maximum phase, then, if the material has a sufficiently high density, it can recombine, producing time-variable absorption features. Of course, if the material where these features arise is reached by the fast-moving ejecta, it will be shocked and ionised, causing the disappearance of such absorptions.

Among all possible inter/circumstellar absorption lines, the ubiquitous sodium D lines (589.0 and 589.6 nm) are the best candidates for this kind of study. In fact, besides falling in an almost telluric absorption-free spectral region, they are produced by a very strong transition, and hence detectable for rather small gas column densities. In addition, the ionisation potential of Na I is low (5.1 eV), and this ensures that even a weak UV field is able to have a measurable effect on its ionisation, without the need for direct interaction.

With this idea in mind, the experimental path was rather clearly traced: obtain multi-epoch, high-resolution spectroscopy of the next bright SN Ia and look for absorption-line variability.

SN 2006X in M100

The first chance to test our idea came when SN 2006X was discovered in the Virgo Cluster spiral galaxy M100 on 4 February 2006 (Figure 1). A few days later, the object was classified as a normal Type Ia event occurring 1–2 weeks before maximum light and suffering substantial extinction. Prompt Very Large Array (VLA) observations have shown no radio source at the SN position, establishing one of the deepest and earliest limits for radio emission from a Type Ia, and implying a mass-loss rate of less than a few 10^{-8} solar masses per year (for a low wind velocity of 10 km s^{-1}). The SN was not visible in the 0.2–10 keV X-rays band down to the SWIFT satellite detection limit. All of this made of SN 2006X a perfect candidate to verify our idea.

An ESO Director General Discretionary Time proposal was submitted on 15 February and approved immediately afterwards. The observations started on 18 February and were carried out with the Ultraviolet and Visual Echelle Spec-

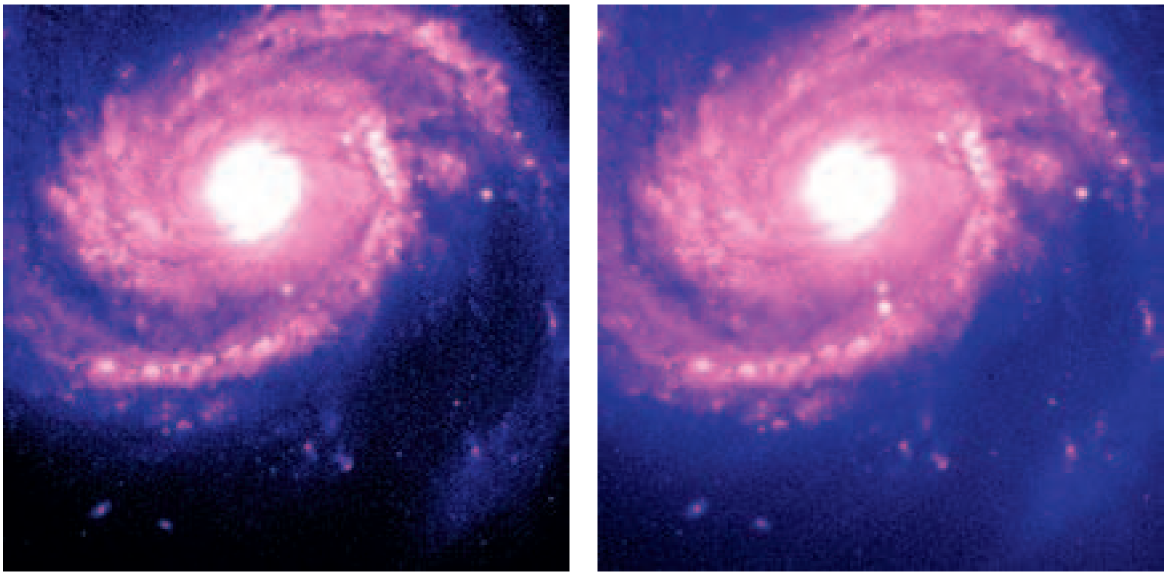

Figure 1: The host galaxy M100 before (left) and after (right) the explosion of SN 2006X. The images were taken with VLT-FORS1 in the *R* passband.

trograph (UVES) mounted at the Very Large Telescope on four different epochs, which correspond to days −2, +14, +61 and +121 with respect to the *B*-band maximum light. Additionally, a fifth epoch (day +105) was covered with the High Resolution Echelle Spectrometer mounted at the 10-m Keck telescope. The data show a wealth of interstellar features, but the most remarkable finding is the clear evolution seen in the profile of the Na I D lines (Patat et al. 2007a). In fact, besides a strongly saturated and constant component, arising in the host galaxy disc, a number of features spanning a velocity range of about 100 km s^{-1} appear to vary significantly with time (Figures 2 and 3). SN 2006X is situated on the receding side of the galaxy, and the component of the rotation velocity along the line of sight at the apparent SN location is about +75 km s^{-1}, which coincides with the strongly saturated Na I D component, the saturated Ca II H and K lines, and a weakly saturated CN vibrational band (see Figure 2). This feature, and its lack of time evolution, proves that the deep absorption arises within the disc of M100 in an interstellar molecular cloud (or system of clouds) that is responsible for the bulk of the reddening suffered by SN 2006X.

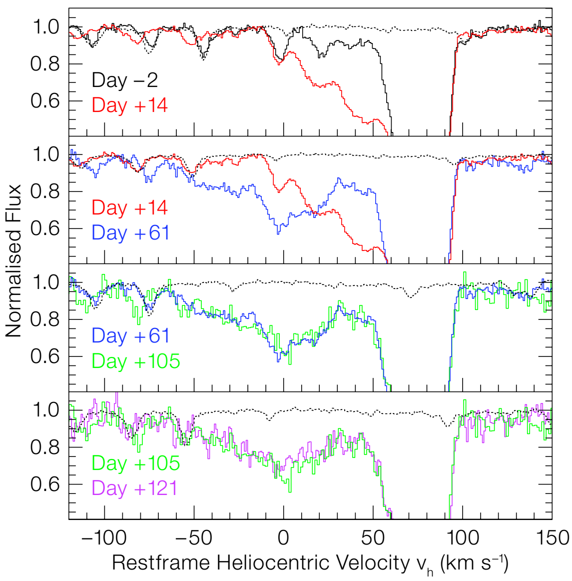

Figure 2: Time evolution of the sodium D_2 component region as a function of elapsed time since *B*-band maximum light. The heliocentric velocities have been corrected to the rest-frame using the host galaxy recession velocity. All spectra have been normalised to their continuum. In each panel, the dotted curve traces the atmospheric absorption spectrum.

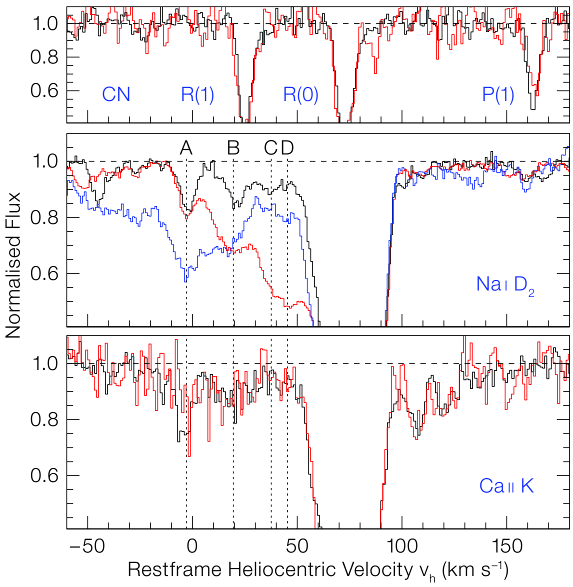

Figure 3: Evolution of the Na I D_2 and Ca II K line profiles between day −2 (black), day +14 (red) and day +61 (blue, Na I D_2 only). The vertical dotted lines mark the four main variable components at −3 (A), +20 (B), +38 (C) and +45 (D) km s^{-1}. For comparison, the upper panel shows R(0), R(1) and P(1) line profiles of the CN (0–0) vibrational band. Colour coding is as for the other two panels.

In contrast, the relatively blue-shifted structures of the Na I D lines show a rather complex evolution. For the sake of discussion, four main components, which we will indicate as A, B, C and D, can be tentatively identified in the first two epochs (Figure 3). Components B, C and D strengthen between day −2 and day +14 while component A remains constant during this time interval. The situation becomes more complicated on day +61: components C and D clearly start to decrease in strength; component B remains almost constant; component A becomes definitely deeper and is accompanied by a wide absorption that extends down to a rest-frame heliocentric velocity of about −50 km s^{-1} (Figure 3). After this epoch there is no evidence of evolution, and component A remains the most intense feature up to the last phase covered by our observations, more than four months after the explosion.

Variable interstellar absorption on comparably short timescales has been claimed for some Gamma Ray Bursts (GRB), and it has been attributed by some authors to line-of-sight geometrical effects, due to the fast GRB expansion coupled to the patchy nature of the intervening absorbing clouds. Our data clearly show that despite the marked evolution in the Na I D lines, Ca II H and K components do not change with time (see Figure 2). Therefore, in the case of SN 2006X, transverse motions in the absorbing material and line-of-sight effects due to the fast SN photosphere expansion (typically 10^4 km s^{-1}) can be definitely excluded, since they would cause variations in all absorption features.

For this reason we conclude that the Na I features seen in SN 2006X, arising in a number of expanding shells (or clumps), evolve because of changes in the CSM ionisation conditions induced by the variable SN radiation field. In this context, the different behaviour seen in the Na I and Ca II lines is explained in terms of the lower ionisation potential of Na I (5.1 eV) with respect to Ca II (11.9 eV), their different recombination coefficients and photoionisation cross sections, coupled to a UV-deficient radiation field. Regrettably, not much is known about the UV emission of SNe Ia shortwards of 110 nm. As we have already anticipated, from a theoretical point of view, one expects a severe UV line blocking, which reduces dramatically the flux of ionising radiation. Nevertheless, in the case of a SN Ia, the models show that this flux is sufficient to fully ionise Na I up to a distance of one light year (~ 10^{18} cm). However, since the recombination timescale must be of the order of 10 days to account for the observed variations, this requires a large electron density (10^5 cm^{-3}). Given the low abundance of any other element, such a high electron density can be produced only by partial hydrogen ionisation. On account of the severe line blocking, the flux of photons capable of ionising H is expected to be very small and this implies that the gas where the Na I time-dependent absorptions arise must be confined within a few 10^{16} cm from the SN.

In a SN Ia, the UV flux decreases by a factor of ten in the first two weeks after maximum light. Since at a distance of 10^{16} cm from the SN, the ionisation timescale for Na I is much shorter than the recombination timescale, the ionisation fraction grows with time following the increase of the UV flux during the pre-maximum phase, while after maximum it decreases following the recombination timescale. This would explain the overall growth of the blue component's depth, as shown by our data, in terms of an increasing fraction of neutral Na, while the different evolution of individual components would be dictated by differences in the densities and distances from the SN. Moreover, once all the sodium has recombined (which should happen within a month), there should be no further evolution, in qualitative agreement with the observations. Additionally, since the flux of photons that can ionise Ca II is more than four orders of magnitude less than in the case of Na I, the corresponding ionisation fraction is expected to be of a few per cent only. Therefore, the recombination does not produce measurable effects on the depth of Ca II H and K lines, as is indeed observed.

An upper limit to the H mass contained in the clumps generating the observed absorptions can be estimated from our observations, after making some conservative assumptions and using the Na I column densities deduced from the data. The H mass turns out to be a few 10^{-4} solar masses (this value is reduced by a factor 100 for material at about 10^{16} cm, the most likely distance for components C and D; see below). Even in the case of complete ionisation, such an H mass would produce an Hα luminosity which is two orders of magnitude below the upper limits set by our observations at all epochs and by any other SN Ia observed so far. Therefore, the absence of narrow emission lines above the detection limit is not in contradiction with the presence of partially ionised H up to masses of the order of 0.01 solar masses.

However, photo-ionisation alone cannot account for the fact that not all features increase in depth with time (Figure 2). In fact, on day +61, components C and D turn back to the same low intensity they had on day −2. One possible explanation is that the gas is re-ionised by some other mechanism, like the ejecta-CSM interaction. In this case, the absorbing material generating components C and D must be close enough to the SN so that the ejecta can reach it in about one month after the explosion (10^{16} cm for maximum ejecta velocities of 4×10^4 km s^{-1}). Similarly, in order not to be reached by the ejecta more than four months after, components A, B and the broad high-velocity components must arise at larger distances (> 5×10^{16} cm). This scenario is not ruled out by the lack of radio emission from SN 2006X. In fact, in the light of our current understanding of the ejecta-CSM interaction mechanism, the presence of similar shells with masses smaller than a few 10^{-4} solar masses, cannot be excluded by radio non-detections of SNe Ia in general. Our findings are also consistent with upper limits on the radio flux set by our VLA observations, obtained about ten months after the explosion, which also confirm that SN 2006X is not more radio luminous than any other normal SNe Ia.

A new beginning?

If we adopt the velocity of the CN lines as indicative of the host galaxy rotation component along the line of sight at the SN location, then our observations provide solid evidence of CSM expanding at velocities that span a range of about 100 km s^{-1} (Figure 2).

The most important implication of these observations is that they show that this circumstellar material was ejected from the progenitor system in the recent past. This almost certainly rules out a double-degenerate scenario for SN 2006X, where the supernova would have been triggered by the merger of two CO white dwarfs. In this case, no significant mass loss would

Figure 4: Artist's impression of the favoured configuration for the progenitor system of SN 2006X before the explosion. The White Dwarf (on the right) accretes material from the Red Giant star, which is losing gas in the form of stellar wind (the diffuse material surrounding the giant). Only part of the gas is accreted by the White Dwarf, through an accretion disc which surrounds the compact star. The remaining gas escapes the system and eventually dissipates into the interstellar medium (see ESO Press Release 31/07).

be expected in the phase immediately preceding the supernova. Thus, a single-degenerate model is the favoured model for SN 2006X, where the progenitor accreted from a non-degenerate companion star.

Mean velocities for the circumstellar material of 50 km s^{-1} are comparable to those reported for the winds of early red giant (RG) stars; velocities matching our observations are also expected for late subgiants. The observed material is moving more slowly than would be expected for winds from main-sequence donor stars or from compact helium stars. Of the two major formation channels proposed for SN Ia with a non-degenerate donor star, these wind velocities seem more consistent with the shorter-period end of the 'symbiotic' formation channel. Symbiotic systems are interacting binaries consisting of a late-type mass-losing giant in orbit with a hot companion, which accretes material from wind or Roche lobe overflow; they have been proposed as a viable channel for Type Ia SN explosions (Munari and Renzini 1992). The observed structure of the circumstellar material could be due to variability in the wind from the companion RG; considerable variability of RG mass loss is generally expected.

A potentially more interesting interpretation of these distinct features is that they arise in the remnant shells (or shell fragments) of successive nova outbursts, which can create dense shells in the slow-moving material released by the companion, also evacuating significant volumes around the progenitor star. Our calculations have difficulty in matching the velocities in our observations if the nova shells are decelerated in a spherically symmetric wind. However, if the wind is concentrated towards the orbital plane this discrepancy could be removed, since the nova shell would be more strongly decelerated in the equatorial plane; in that case we would be observing the supernova close to the orbital plane. Not only might this be expected a priori, but observations of the 2006 outburst of RS Ophiuchi show that the nova ejecta are bipolar and that there is an equatorial density enhancement which strongly restrains the expansion of the nova shell, thus providing some support for such a scenario.

One crucial issue is whether what we have seen in SN 2006X represents the rule or is rather an exceptional case. Other cases of SNe Ia showing negative velocity components are known, like SNe 1991T and 1998es. Unfortunately, multi-epoch high-resolution spectroscopy is not available for these objects (to our knowledge, the SN 2006X data set is unique in this respect), and therefore time variability cannot be demonstrated. Nevertheless, the data clearly show components approaching the observer at velocities which reach at least 50 km s^{-1} with respect to the deep absorption that we infer to be produced within the discs of the respective host galaxies. This, and the fact that SN 2006X has shown no optical, UV and radio peculiarity, supports the conclusion that what we have witnessed for this object might be common at least for some normal SN Ia, even though variations due to different inclinations of the line of sight with respect to the orbital plane may exist.

What we have seen in 2006X is far from being completely understood and we are certainly left with more questions than answers. Even though the results obtained with multi-epoch, high-resolution observations of this event have already triggered a couple of similar studies (Patat et al. 2007b, Simon et al. 2007), the sample is simply too small to allow for any conclusion. Most likely, there is more than one channel leading to the same explosive theme, on top of which nature adds some variations, as the non perfect homogeneity of SNe Ia seems to tell us.

Rather than the end of an old story, we consider these findings as the beginning of a new one. We hope that the telescope time that has been allocated to our project will bring more insights into this field, answering at least a few of the questions that SN 2006X has posed us.

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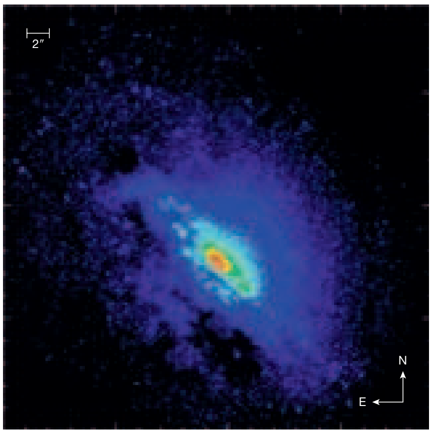

Colour coded *K*-band adaptive optics image obtained with VLT NACO and the Laser Guide Star Facility of the galaxy NGC 4945 which contains an obscured active nucleus. Close to the nucleus several luminous star clusters can be resolved. See ESO Press Photo 27e/07 for more details.