# Detection of Circumstellar Material in a Normal Type Ia Supernova

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# Detection of Circumstellar Material in a Normal Type Ia Supernova

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Type Ia supernovae are important cosmological distance indicators. Each of these bright supernovae supposedly results from the thermonuclear explosion of a white dwarf star that, after accreting material from a companion star, exceeds some mass limit, but the true nature of the progenitor star system remains controversial. Here we report the spectroscopic detection of circumstellar material in a normal type Ia supernova explosion. The expansion velocities, densities, and dimensions of the circumstellar envelope indicate that this material was ejected from the progenitor system. In particular, the relatively low expansion velocities suggest that the white dwarf was accreting material from a companion star that was in the red-giant phase at the time of the explosion.

As a result of their extreme luminosities and high homogeneity, type Ia supernovae (SNe Ia) have been used extensively as cosmological reference beacons to trace the evolution of the universe (*1*, *2*). However, despite recent progress, the nature of the progenitor stars and the physics that govern these powerful explosions remain poorly understood (*3*, *4*). In the presently favored single-degenerate model, the supernova (SN) progenitor is a white dwarf that accretes material from a nondegenerate companion star in a close binary system (*5*); when it approaches the Chandrasekhar limit, the white dwarf explodes in a thermonuclear blast. A direct method for investigating the nature of the progenitor systems of SNe Ia is to search for signatures of the material transferred to the accreting white dwarf in the circumstellar material (CSM). Previous attempts have aimed at detecting the radiation that would arise from the interaction between the fast-moving SN ejecta and the slow-moving CSM in the form of narrow emission lines (*6*), radio emission (*7*), and x-ray emission (*8*). The most stringent upper limit to the mass-loss rate set by radio observations is as low as $3 \times 10^{-8}$ solar masses per year ($M_\odot$ year$^{-1}$) for an assumed wind velocity of 10 km s$^{-1}$ (*7*). Two notable exceptions are represented by two peculiar SNe Ia, SN 2002ic and SN 2005gj, which have shown extremely pronounced hydrogen emission lines (*9*, *10*) that have been interpreted as a sign of strong ejecta-CSM interaction (*11*). However, the classification of these supernovae as SNe Ia has recently been questioned (*12*), and even if they were SNe Ia, these supernovae are unlikely to account for normal SNe Ia explosions (*7*) that, of those observed so far, lack any signature of mass transfer from a hypothetical donor. Here we report direct evidence of CSM in a SN Ia that has shown normal behavior at x-ray, optical, and radio wavelengths.

SN 2006X was discovered in the Virgo cluster spiral galaxy NGC 4321 (*13*). A few days

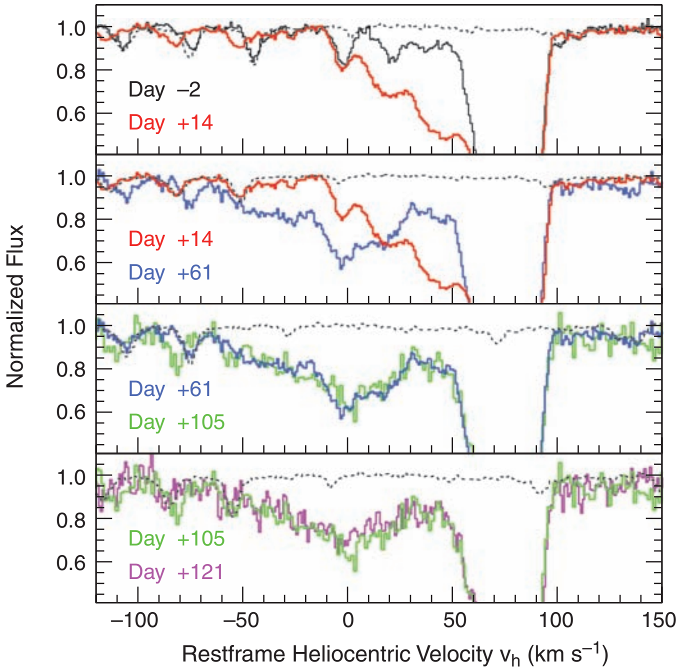

**Fig. 1.** Time evolution of the Na $D_2$ component region as a function of elapsed time since *B*-band maximum light. We corrected the heliocentric velocities to the rest-frame using the host galaxy recession velocity. All spectra have been normalized to their continuum. In each panel, the dotted curve traces the atmospheric absorption spectrum.

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after its detection, the object was classified as a normal SN Ia event occurring 1 to 2 weeks before maximum light, which was affected by substantial extinction (*14*). Prompt observations with the Very Large Array (VLA) telescope have shown no radio source at the SN position (*15*), establishing one of the deepest and earliest limits for radio emission from a SN Ia and implying a mass-loss rate of less than a few $10^{-8}$ $M_\odot$ year$^{-1}$ (for a low wind velocity of 10 km s$^{-1}$). The SN was not visible in the 0.2-to-10 keV x-ray band down to the detection limit of the Swift satellite (*8*).

We have observed SN 2006X with the Ultraviolet (UV) and Visual Echelle Spectrograph mounted at the ESO 8.2-m Very Large Telescope. Observations were carried out on four different epochs, which correspond to days −2, +14, +61, and +121 with respect to *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 (*16*). The most notable finding from our data is the clear evolution seen in the profile of the Na I D doublet lines (5889.95, 5895.92 Å). Indeed, besides a strongly saturated and constant component arising in the host galaxy disk [supporting online material (SOM) text S2 and fig. S1], a number of features spanning a velocity range of about 100 km s$^{-1}$ appear to vary substantially with time (Fig. 1 and fig. S2). SN 2006X is projected onto 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$^{-1}$ (*17*), which coincides with the strongly saturated Na I D component, the saturated Ca II H&K lines, and a weakly saturated CN molecular vibrational band (0-0) (Fig. 2 and fig. S1). This and the lack of time evolution prove that the deep absorption arises within the disk of NGC 4321 in an interstellar molecular cloud (or system of clouds) that is responsible for the bulk of the reddening suffered by SN 2006X (SOM text S2).

In contrast, the relatively blue-shifted structures of the Na I D lines show a rather complex evolution. The number of features, their intensity, and their width are difficult to establish. Nevertheless, 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 (Fig. 2). 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, but component B remains almost constant, and component A becomes deeper and is accompanied by a wide absorption that extends down to a rest-frame heliocentric velocity $v_h \cong -50$ km s$^{-1}$ (Fig. 1 and fig. S2). 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 4 months after the explosion.

Variable interstellar absorption on comparably short time scales has been claimed for some gamma-ray bursts (GRBs), and it has been attributed by some authors to line-of-sight geometrical effects, resulting from the fast GRB expansion coupled to the patchy nature of the intervening absorbing clouds (*18*). Our data clearly show that despite the marked evolution in the Na I D lines, Ca II H&K components do not change with time (Fig. 2, fig. S3, and SOM text S3 and S4). 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, because 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 ionization conditions induced by the variable SN radiation field. In this context, the different behavior that is seen in the Na I and Ca II lines is explained in terms of (i) the lower ionization potential of Na I (5.1 eV, corresponding to 2417 Å) with respect to Ca II (11.9 eV, corresponding to 1045 Å), (ii) their different recombination coefficients, and (iii) their photoionization cross sections coupled to a UV-deficient radiation field (SOM text S4). Regrettably, not much is known about the UV emission of SNe Ia shortward of 1100 Å (*8*, *19*). Theoretically, a severe UV line blocking, by heavy elements such as Fe, Co, and Mg, is expected (*20*). An estimate of the Na I ionizing flux, $S_{UV}$, can be derived from a synthetic spectrum of a SN Ia at maximum light (*21*), which turns out to be $S_{UV} \sim 5 \times 10^{50}$ photons s$^{-1}$. One can verify that this flux is largely sufficient to fully ionize Na I up to rather large distances (~$5 \times 10^{18}$ cm).

Nevertheless, because the recombination time scale $\tau_r$ must be of the order of 10 days, this requires an electron density $n_e$ as large as $10^5$ cm$^{-3}$ (SOM text S4). Given the low abundance of any other element besides hydrogen, such a high electron density can be produced only by partial hydrogen ionization. As a result of the severe line blocking suffered by SNe Ia (*20*), the flux of photons capable of ionizing H is very small (~$4 \times 10^{44}$ photons s$^{-1}$), and this requires that the gas where the Na I time-dependent absorptions arise must be confined within a few $10^{16}$ cm from the SN (SOM text S4). In a SN of this type, the flux in the 1120-to-2640 Å band decreases by a factor of 10 in the first 2 weeks after maximum light (*8*, *19*). Because, at a distance of ~$10^{16}$ cm from the SN, the ionization time scale $\tau_i$ for Na I is much shorter than $\tau_r$, the ionization fraction grows with time following the increase of the UV flux during the pre-maximum phase, whereas, after the maximum phase, the ionization fraction decreases following $\tau_r$. This result would explain the overall growth of the blue components' depth, as shown by our data, in terms of an increasing fraction of neutral Na, whereas the different evolution of individual components would be dictated by differences in the densities and distances from the SN. Moreover, once all the Na II has recombined [which should happen within a few $\tau_r$ (i.e., ~1 month)], there should be no further evolution, which is in qualitative agreement with the observations. Additionally, because the flux of photons that can ionize Ca II is more than four orders of magnitude less than that of Na I (SOM text S4), the corresponding ionization fraction is expected to be only a few percent. Therefore, the recombination of Ca III to Ca II does not produce measurable effects on the depth of the Ca II H&K lines, as is indeed observed (SOM text S3).

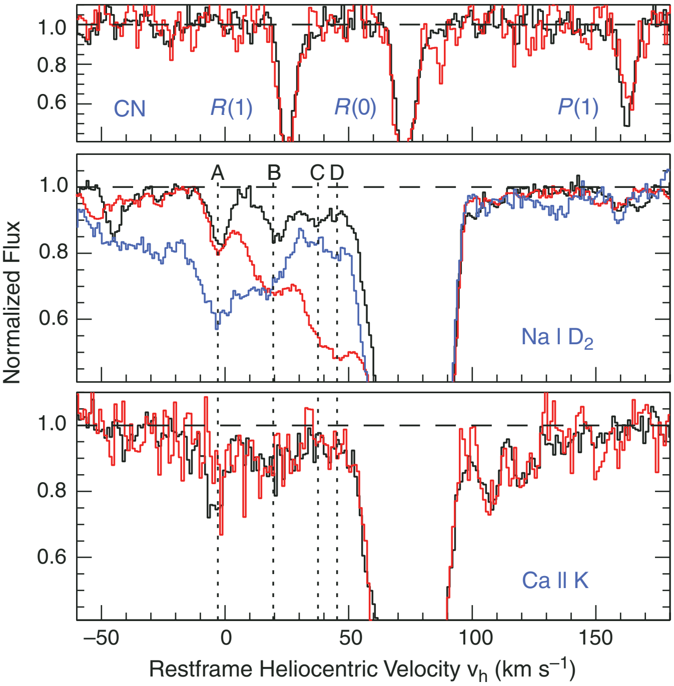

**Fig. 2.** Evolution of the Na I $D_2$ and Ca II K line profiles between day −2 (black), day +14 (red), and day +61 (blue, Na I $D_2$ only). The vertical dashed lines mark the four main variable components at −3 ("A"), +20 ("B"), +38 ("C"), and +45 ("D") km s$^{-1}$. For comparison, the upper panel shows the *R*(0), *R*(1), and *P*(1) line profiles of the (0-0) vibrational band of the CN $B^2\Sigma - X^2\Sigma$. The velocity scale refers to the *R*(0) transition (3874.608 Å).

The H mass [$M$(H)] contained in the shells generating the observed absorptions can be estimated from our observations after some conservative assumptions are made. The Na I column density $N$(Na I) deduced from the most intense feature (component D, day +14) is $N(\text{Na I}) \cong 10^{12}$ cm$^{-2}$. Assuming that the material generating this component is homogeneously distributed in a thin spherical shell with radius $10^{17}$ cm, a solar Na/H ratio (log Na/H = −6.3), and complete Na recombination, an upper limit to the shell mass can be estimated as $M(\text{H}) \leq 3 \times 10^{-4} M_\odot$ (this value is reduced by a factor of 100 for material at about $10^{16}$ cm, the most likely distance for components C and D). Even in the case of complete ionization, such a H mass would produce an Hα luminosity of ~$4 \times 10^{34}$ erg s$^{-1}$, which is two orders of magnitude below the 3-σ upper limits set by our observations at all epochs (table S2) and by any other SN Ia observed so far (*6*). Therefore, the absence of narrow emission lines above the detection limit does not contradict the presence of partially ionized H up to masses of the order of 0.01 $M_\odot$.

However, photoionization alone cannot account for the fact that not all features increase in depth with time (Fig. 2). Indeed, on day +61, components C and D return to the same low intensity values that they had on day −2. One possible explanation is that the gas is re-ionized 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 1 month after the explosion (~$10^{16}$ cm for maximum ejecta velocities of $4 \times 10^4$ km s$^{-1}$). Similarly, in order not to be reached by the ejecta more than 4 months after the explosion, component A, component B, and the broad high-velocity components must arise at larger distances (>$5 \times 10^{16}$ cm). This scenario is not ruled out by the lack of radio emission from SN 2006X (*15*). Indeed, in light of our current understanding of the ejecta-CSM interaction mechanism (*22*), the presence of similar shells with masses smaller than a few $10^{-4} M_\odot$ cannot be excluded by radio nondetections of SNe Ia in general (*7*). Our findings are consistent with upper limits on the radio flux set by our VLA observations, obtained about 10 months after the explosion (SOM text S1), which are comparable to the best upper limits set on the radio luminosity of other normal SNe Ia (*7*).

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$^{-1}$ (Fig. 2).

The most important implication of these observations is that this CSM was ejected from the progenitor system in the recent past. For instance, with a shell radius of $10^{16}$ cm and a wind velocity of ~50 km s$^{-1}$, the material would have been ejected some 50 years before the explosion. This almost certainly rules out a double-degenerate scenario for SN 2006X, where the supernova would have been triggered by the merger of two carbon-oxygen white dwarfs. In this case, no substantial mass loss would be expected in the phase immediately preceding the supernova. Thus, a single-degenerate model is the favored model for SN 2006X, where the progenitor accreted from a nondegenerate companion star.

Mean velocities for the CSM of ~50 km s$^{-1}$ are comparable to those reported for the winds of early red giant (RG) stars (*22*); 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. These wind velocities seem more consistent with the shorter-period end of the symbiotic formation channel than with the other major formation channel proposed for a SN Ia with a nondegenerate donor star (*23*). The observed structure of the CSM could be due to variability in the wind from the companion RG; considerable variability of RG mass loss is generally expected (*24*).

An alternative interpretation of these distinct features is that they arise in the remnant shells of successive novae, which can create dense shells in the slow-moving material released by the companion star (*25*, *26*). This scenario seems to require an aspherical shell geometry in order to match the observed low velocities (SOM text S6). Not only might this be expected a priori (*27*), but observations of the 2006 outburst of RS Ophiuchi also show that there is an equatorial density enhancement that strongly restrains the expansion of the nova shell (*28*–*30*).

One crucial issue to resolve regarding what we have seen in SN 2006X is whether it represents the rule or whether it is an exceptional case. Other cases of SNe Ia showing negative velocity components are known, such as SN 1991T and SN 1998es (fig. S5 and SOM text S5). Unfortunately, multi-epoch high-resolution spectroscopy is not available for these objects (to our knowledge, the SN 2006X data set is distinctive in this respect), and therefore time variability cannot be demonstrated. Nevertheless, the data clearly show components approaching the observer at velocities that reach at least 50 km s$^{-1}$ with respect to the deep absorption that we infer to be produced within the disks of the respective host galaxies. This, and the fact that SN 2006X has shown no optical, UV, and radio peculiarities whatsoever, supports the conclusion that what we have witnessed for this object is common to normal SNe Ia, and possibly to all SNe Ia, even though variations resulting from different inclinations of the line of sight with respect to the orbital plane may exist.

### References and Notes

1. A. G. Riess *et al.*, *Astron. J.* **116**, 1009 (1998).
2. S. Perlmutter *et al.*, *Astrophys. J.* **517**, 565 (1999).
3. D. Branch, M. Livio, L. R. Yungelson, F. Boffi, E. Baron, *Publ. Astron. Soc. Pac.* **107**, 1019 (1995).
4. W. Hillebrandt, J. C. Niemeyer, *Annu. Rev. Astron. Astrophys.* **38**, 191 (2000).
5. J. Whelan, I. Iben, *Astrophys. J.* **186**, 1007 (1973).
6. S. Mattila *et al.*, *Astron. Astrophys.* **443**, 649 (2005).
7. N. Panagia *et al.*, *Astrophys. J.* **646**, 396 (2006).
8. S. Immler *et al.*, *Astrophys. J.* **648**, L119 (2006).
9. M. Hamuy *et al.*, *Nature* **424**, 651 (2003).
10. G. Aldering *et al.*, *Astrophys. J.* **650**, 510 (2006).
11. The subluminous SN Ia 2005ke has shown an unprecedented x-ray emission, which has been interpreted as the signature of a possible weak interaction between the SN ejecta and material lost by a companion star (*8*). Nevertheless, this finding and the strong UV excess might be related to the nature of this SN.
12. S. Benetti *et al.*, *Astrophys. J.* **653**, L129 (2006).
13. S. Suzuki, M. Migliardi, *IAU Circ. 8667* (2006).
14. R. Quimby, P. Brown, C. Gerardy, *Cent. Bur. Electron. Telegrams* **421** (2006).
15. C. J. Stockdale *et al.*, *Cent. Bur. Electron. Telegrams* **396** (2006).
16. See supporting material on *Science* Online.
17. R. J. Rand, *Astron. J.* **109**, 2444 (1995).
18. H. Hao *et al.*, *Astrophys. J.* **659**, L99 (2007).
19. N. Panagia, paper presented at the *Supernova* 1987A*: 20 Years after: Supernovae and Gamma-Ray Bursters Conference*, Aspen, CO, 19 to 23 February 2007 (American Institute of Physics), in press; preprint available at http://arxiv.org/abs/0704.1666.
20. W. A. Pauldrach *et al.*, *Astron. Astrophys.* **312**, 525 (1996).
21. R. A. Chevalier, C. Fransson, in *Supernovae and Gamma-Ray Bursters*, K. W. Weiler, Ed. (Lecture Notes in Physics 598, Springer, New York, 2003), pp. 171–194.
22. P. G. Judge, R. E. Stencel, *Astrophys. J.* **371**, 357 (1991).
23. I. Hachisu, M. Kato, *Astrophys. J.* **558**, 323 (2001).
24. L. A. Willson, *Annu. Rev. Astron. Astrophys.* **38**, 573 (2000).
25. I. Hachisu, M. Kato, *Astrophys. J.* **558**, 323 (2001).
26. W. M. Wood-Vasey, J. L. Sokoloski, *Astrophys. J.* **645**, L53 (2006).
27. I. Hachisu, M. Kato, K. Nomoto, *Astrophys. J.* **522**, 487 (1999).
28. T. J. O'Brien *et al.*, *Nature* **442**, 279 (2006).
29. M. F. Bode *et al.*, *Astrophys. J.* **652**, 629 (2006).
30. M. F. Bode *et al.*, *Astrophys. J.*, in press; preprint available at http://arxiv.org/abs/0706.2745.

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