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REPORTS

An Unusually Fast-Evolving Supernova

Dovi Poznanski,[1,2]* Ryan Chornock,[1] Peter E. Nugent,[2] Joshua S. Bloom,[1] Alexei V. Filippenko,[1] Mohan Ganeshalingam,[1] Douglas C. Leonard,[3] Weidong Li,[1] Rollin C. Thomas[2]

Analyses of supernovae (SNe) have revealed two main types of progenitors: exploding white dwarfs and collapsing massive stars. Here we describe SN 2002bj, which stands out as different from any SN reported to date. Its light curve rose and declined very rapidly, yet reached a peak intrinsic brightness greater than −18 magnitude. A spectrum obtained 7 days after discovery shows the presence of helium and intermediate-mass elements, yet no clear hydrogen or iron-peak elements. The spectrum only barely resembles that of a type Ia SN, with added carbon and helium. Its properties suggest that SN 2002bj may be representative of a class of progenitors that previously has been only hypothesized: a helium detonation on a white dwarf, ejecting a small envelope of material. New surveys should find many such objects, despite their scarcity.

Supernovae (SNe) are usually classified on the basis of telltale lines in their spectra (*1*). Those empirical types are routinely associated with progenitor systems according to the current understanding of their explosion mechanisms. Type Ia SNe are interpreted as the thermonuclear disruption of a white dwarf, and the other types are interpreted as the core collapse of a massive star. SN 2002bj, which we describe here, would formally belong, according to that classification, to the type Ib class because of the lack of H and the presence of He in the optical spectra we have obtained. However, the overall observed properties of this SN are unprecedented, and the taxonomic classification is misleading.

[1]Department of Astronomy, University of California, Berkeley, CA 94720–3411, USA. [2]Computational Cosmology Center, Lawrence Berkeley National Laboratory, 1 Cyclotron Road, Berkeley, CA 94720, USA. [3]Department of Astronomy, San Diego State University, Mail Code 1221, San Diego, CA 92182–1221, USA.

*To whom correspondence should be addressed. E-mail: dovi@berkeley.edu

SN 2002bj was discovered independently at magnitude (mag) 14.7 by the Lick Observatory SN Search (LOSS) and by amateur astronomers (*2*) on 28.2 February 2002 (universal time dates are used throughout this paper) in the galaxy NGC 1821. The distance, corrected for local bulk flows (assuming a Hubble constant of 73 km s^{-1} Mpc^{-1}), is 50 ± 5 Mpc [see supporting online material (SOM) for a discussion of the host galaxy properties and distance]. A prediscovery LOSS image with limiting magnitude 18.4 (Galactic extinction corrected) on 21.2 February 2002 (a week before discovery) shows nothing at that position.

As part of our SN followup program, we obtained optical broadband photometry of SN 2002bj in the B, V, R, and I bands for nine epochs over 20 days until it faded below the detection threshold (SOM). Our photometry does not show a rising phase, but the nondetection constrains the rise to be less than 7 days long. The decline was almost as fast, dropping by 4.5 mag (in the *B* band) in 18 days. SN 2002bj evolves on unprecedented time scales (Fig. 1).

The spectrum we obtained a week after detection is extremely blue, with weak yet remarkable features (*3*). Using a χ^2 fit, we have digitally compared our (continuum-removed) spectrum with about 4000 spectra of nearly 1400 SNe, allowing for velocity offsets. Not a single spectrum fits well. The closest matches were SNe Ia, mostly due to the absorption feature near 6150 Å (rest frame), usually attributed to Si II (Fig. 2). The best of those (SN 2009dc) is a superluminous, slowly declining, C-rich, possibly super–Chandrasekhar-mass SN Ia (*4*–*6*). These few very luminous SNe reported so far evolve slowly and eject substantial amounts of unburned material, suggesting massive white dwarf progenitors. That is, the closest spectroscopic match has one of the most substantially different light curves. Although the spectra are broadly similar, SN 2002bj has prominent He I lines, which are not expected in a SN Ia. In addition, the spectrum of SN 2009dc had to be artificially redshifted by 3000 km s^{-1} in order to match that of SN 2002bj, implying that SN 2002bj had slower ejecta at the time when the spectrum was taken.

Using the code SYNOW (*7*), we produced synthetic spectra and identified most of the features as coming from helium and intermediate-mass elements such as C, Si, and S, but no H (SOM). Although this empirical fit does not produce meaningful abundances, the lack of Fe or other Fe-peak elements in the fit is peculiar. As exceptional is the considerable S II contribution, when compared to Ca II (a ratio never seen before in other SNe). We also report a tentative identification of V II. Although based on only a single line, the relevant spectral region (~3950 Å) would have emission from Ca II without it. The spectrum was taken in spectropolarimetry mode, yet there are no polarization line features down to 0.1 to 0.2%. The continuum is consistent with polarization by dust in the Milky Way (see SOM for details).

Using our photometry, we determined the bolometric evolution of SN 2002bj (SOM). The total radiated energy in optical bandpasses was on the order of 10^{49} erg, starting at a peak of 10^{43} erg s^{-1}. Assuming blackbody emission, we derived the temporal evolution of the effective temperature, radius, and photospheric velocity. The temperature and velocity declined very rapidly, indicating rapid recession of the photosphere in a low-mass envelope. We estimated the mass of the ejecta using the scaling relation that ties it to the photospheric velocity and rise time $M_{\mathrm{ej},1} = (\frac{t_1}{t_2})^2 \frac{v_1}{v_2} M_{\mathrm{ej},2}$ (*8*). This scaling assumes that the opacity is similar to that of a SN Ia. SN 2002bj rose at least three times faster than a normal SN Ia (depending on the assumed explosion date); thus, although its velocity at peak is uncertain (see discussion in SOM), the ejected mass has to be smaller than ~0.15 solar mass ($M_\odot$), about 10% that of a SN Ia.

The luminosity and short rise time of SN 2002bj translate to 0.15 to 0.25 $M_\odot$ of ^{56}Ni when using Arnett's law (*8*, *9*), if the light curve is solely powered by radioactive ^{56}Ni and its decay product ^{56}Co. Under this same assumption, the rapid decline we measured requires a sharp drop of the gamma-ray deposition efficiency of an order of magnitude in less than 3 weeks.

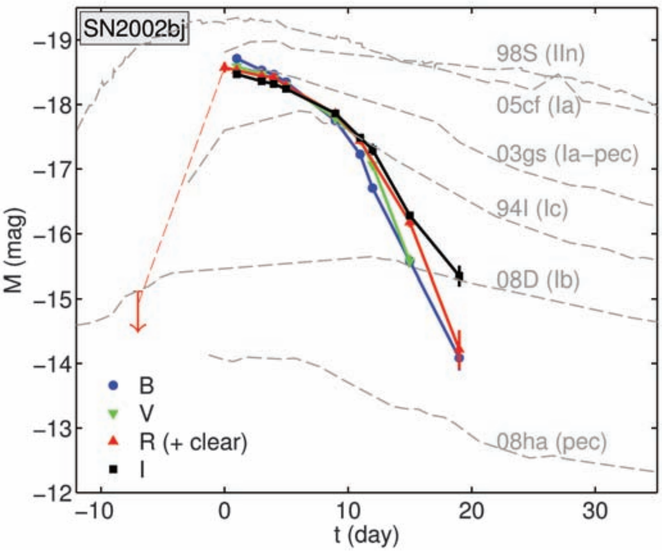

Fig. 1. Comparison of the light curve of SN 2002bj to those of SNe of various types (gray dashed lines; R-band magnitudes offset to the same *B*-band maximum date). SN 2002bj is quite luminous at peak for a core-collapse event, yet faint compared with typical SNe Ia. SN 1994I (*21*) is often cited as a "fast" SN Ic; SN 2003gs (*22*) was recently presented as one of the fastest SNe Ia; and SN 2008ha (*14*) is a faint, peculiar, and fast SN of debated breed. SN 2002bj is significantly faster than any of these. SN 1998S (*23*), SN 2005cf (*24*), and SN 2008D (*25*) are standard representatives of type IIn, Ia, and Ib SNe, respectfully; they are shown for reference. The dashed red line shows the slowest rise slope of SN 2002bj allowed by the data.

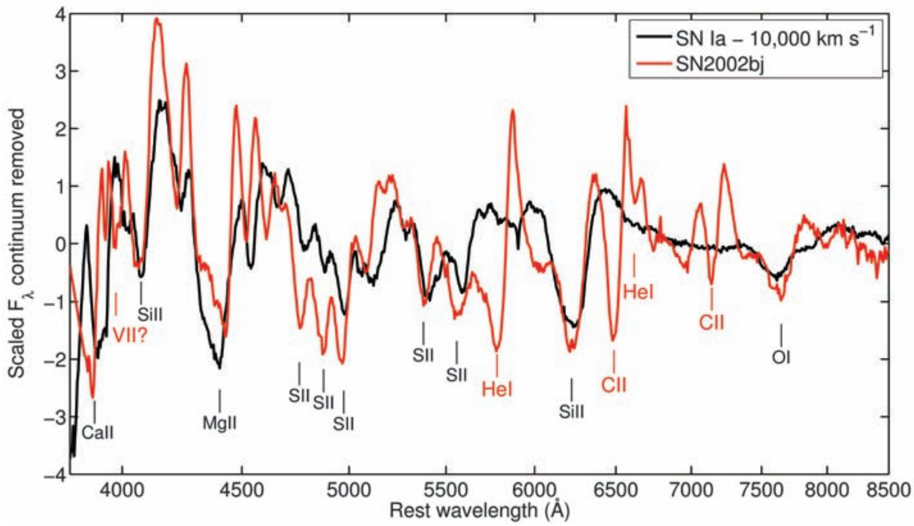

Fig. 2. The unique spectral features of SN 2002bj (shown in red; continuum removed) are difficult to identify a priori. F_λ, flux per unit of wavelength. This spectrum, taken 7 March 2002 (7 days after discovery), is reminiscent of SNe Ia, with the notable exception of the prominent He and C lines, never seen before in such SNe. We show (in black) a typical SN Ia spectrum near maximum light (SN 2001bf), redshifted by 10,000 km s^{-1} in order to match ejecta velocities. The spectral features identified in black are present in both objects, and the ones in red are seen only in SN 2002bj.

The small ejected mass we derived, the lack of Fe-peak elements in the spectrum, and the relatively large amount of ^{56}Ni required to explain the high luminosity are difficult to reconcile without assuming an additional energy source.

SN 2002bj looks spectroscopically somewhat like a SN Ia but with He, C, and an exceptionally fast light curve. Recently, a mechanism has been proposed (*10*) by which binary white dwarfs of the AM CVn class may undergo a thermonuclear explosion of the He accreted on the primary star. Such a scenario will produce roughly 10% of the luminosity of a SN Ia, for about 10% of the typical time; hence, these objects were dubbed ".Ia" SNe.

These SNe are expected to be faint (between −15 and −18 mag at peak in the *V* band) and rapidly evolving (1 to 6 days of rise time, with the brighter objects usually rising more slowly). The decline was not explicitly discussed by Bildsten *et al.* (*10*), but the low ejected mass implies a rapid decline. The short time scales of these events may allow the detection of the short-lived radioactive nuclei ^{52}Fe or ^{48}Cr, in addition to the standard ^{56}Ni that drives SN Ia light curves. ^{48}Cr decays to ^{48}V within a day and then to ^{48}Ti in a week. The decay of these nuclei may (partially) power the optical light curve. The rate of .Ia events is predicted to be roughly a few percent of the SN Ia rate per unit of local volume.

The spectral signature was not predicted, but some properties seem to result naturally in that scenario. Because this is a thermonuclear He detonation on a white dwarf, we do not expect any H, but He does seem reasonable, as well as intermediate-mass elements that either survive the convective burning phase and detonation (*11*) or are produced in the explosion.

Although other recent SNe have been proposed to be related to He detonations on a white dwarf [SN 2005E (*12*) and perhaps also SN 2008ha (*12*–*14*)], these events have more massive ejecta (0.2 to 0.3 $M_\odot$) and much slower light curves, and thus do not fit the current predictions of .Ia models, though they may be explained with related phenomena involving much more massive He shells.

The light curve of SN 2002bj is as fast as predicted in this model but slightly more luminous than expected (*15*). The high luminosity yet small ejecta mass may be reconciled if some short-lived ^{48}Cr or ^{52}Fe are synthesized, as their yield per unit of mass is higher than that of ^{56}Ni on short time scales. Our tentative identification of V II in the spectrum supports this hypothesis (^{48}V is the daughter of ^{48}Cr), and the peculiar composition of the spectrum may support it, as well. SNe Ia usually display a prominent secondary peak in their infrared light curve, attributed to line-blanketing by singly ionized Fe-peak elements (*16*). The lack of a secondary peak in the light curve of SN 2002bj is consistent, within that picture, with our non-detection of Fe-peak elements in the spectrum.

Bildsten *et al.* (*10*) assumed that the ejecta will have velocities of ~15,000 km s^{-1}, which is equivalent to all of the binding energy released from fusing He converted into kinetic energy (because the star is assumed to be left bound). We infer for SN 2002bj photospheric velocities that drop rapidly from about 8400 km s^{-1} at detection to 2000 km s^{-1} 3 weeks later. Extrapolating to an explosion date 7 days before detection, the initial velocity could have been between 14,000 km s^{-1} (linear extrapolation) and ~25,000 km s^{-1} [exponential extrapolation as often seen in SNe (*17*, *18*)]. A rise time that is faster by a factor of 2 would imply velocities twice as high. The only direct measurement we have is from the spectrum 7 days after detection: about 4000 km s^{-1}. This is consistent with the derived photospheric velocity at that time if the rise time was about 7 days.

Out to a distance of 60 Mpc, the LOSS survey is complete (99%) for SNe Ia, and 31 have been found. Because SN 2002bj is quite luminous, the incompleteness correction for it is almost as small (94%), resulting in a relative rate of 3.4% of the SN Ia rate for SN 2002bj–like SNe (*19*). This is in good agreement with the predictions for SNe .Ia.

The SN .Ia model, still in its infancy, lacks more stringent predictions such as detailed light curves and spectral composition and evolution. Nevertheless, all the diagnostics we could apply seem consistent with this interpretation. The evidence here is tentative, but the existence of V, if seen in future discoveries of objects of this class, points to a different nucleosynthetic chain and therefore may serve as a smoking gun for a truly different SN explosion channel. Regardless of the interpretation, current and future surveys should focus on short cadences—repeat visits on daily rather than weekly time scales—in order to find many more SNe resembling SN 2002bj.

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Supporting Online Material

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Figs. S1 to S4
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Polarization-Induced Hole Doping in Wide–Band-Gap Uniaxial Semiconductor Heterostructures

John Simon, Vladimir Protasenko, Chuanxin Lian, Huili Xing, Debdeep Jena*

Impurity-based p-type doping in wide–band-gap semiconductors is inefficient at room temperature for applications such as lasers because the positive-charge carriers (holes) have a large thermal activation energy. We demonstrate high-efficiency p-type doping by ionizing acceptor dopants using the built-in electronic polarization in bulk uniaxial semiconductor crystals. Because the mobile hole gases are field-ionized, they are robust to thermal freezeout effects and lead to major improvements in p-type electrical conductivity. The new doping technique results in improved optical emission efficiency in prototype ultraviolet light-emitting–diode structures. Polarization-induced doping provides an attractive solution to both p- and n-type doping problems in wide–band-gap semiconductors and offers an unconventional path for the development of solid-state deep-ultraviolet optoelectronic devices and wide–band-gap bipolar electronic devices of the future.

The direct-gap III-V nitride semiconductor family and its alloys span the widest spectral range of band gaps (E_g) among all semiconductors, ranging from the infrared (InN, E_g = 0.7 eV) through the visible and the ultraviolet (UV) (GaN, E_g = 3.4 eV) to the deep UV range (AlN, E_g = 6.2 eV). This property is the basis for its applications in short-wavelength lasers (*1*, *2*) and in light-emitting diodes (LEDs) for solid-state lighting applications (*3*, *4*). In addition, the wide band gaps, availability of heterojunctions, high electron-saturation velocities, and high breakdown fields enable high-speed and high-power electronic devices. Compact short-wavelength, solid-state light sources will enable a wide range of applications such as high-density optical data storage, water treatment, sterilization of medical equipment, UV-enabled security marks on credit cards and currency bills, and biological and cellular imaging.

Currently, the III-V nitride semiconductors offer the most viable approach toward the realization of high-efficiency, deep-UV optical emitters based on semiconductors (*2*). A problem that has persisted since the early 1990s and is becoming increasingly troublesome is the high resistivity of p-type GaN and AlGaN layers. The activation energy E_A of the most commonly used acceptor dopant (Mg) in GaN is ~200 meV (*5*–*7*), several times the thermal energy k_BT at room temperature (where k_B is the Boltzmann constant, and T is temperature). The activation energy of acceptors increases with the band gap, reaching E_A ~ 630 meV in AlN (*1*). For comparison, the donor (Si) activation energies are E_D ~ 15 meV for GaN and E_D ~ 282 meV for AlN (*1*). Thus, the thermal activation of holes is highly inefficient at room temperature for GaN and becomes increasingly problematic for higher–band-gap AlGaN and AlN layers. As a result, injection of holes is a severe impediment for light-emitting devices in

Department of Electrical Engineering, University of Notre Dame, 275 Fitzpatrick Hall, Notre Dame, IN 46556, USA.

*To whom correspondence should be addressed. E-mail: djena@nd.edu

Science

An Unusually Fast-Evolving Supernova

Dovi Poznanski, Ryan Chornock, Peter E. Nugent, Joshua S. Bloom, Alexei V. Filippenko, Mohan Ganeshalingam, Douglas C. Leonard, Weidong Li and Rollin C. Thomas

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We Are Stardust

Supernovae form as the result of stellar explosions and are classified according to the properties of their spectra. **Poznanski *et al.*** (p. 58, published online 5 November) present a peculiar supernova that is characterized by extremely fast temporal evolution and unusual spectroscopic features, such that it defies classification. SN2002bj appears to be a member of a new class of supernovae, possibly formed by a helium detonation on a white dwarf ejecting a small envelope of material.