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A unique core-collapse supernova in an elliptical galaxy

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We report on our discovery and observations of a very unique supernova, SN 2005cz, that exhibits previously unknown properties. The early-phase spectrum of this supernova (SN) is similar to those of helium-rich type Ib SNe that have been interpreted as Fe core-collapse-induced explosions of massive He stars. Its peculiarity is the appearance in the elliptical galaxy NGC 4589; this is puzzling because young, massive stars usually do not exist in elliptical galaxies that contain only old low-mass stars. The photometric and spectroscopic features of SN 2005cz are found to be quite unique: (1) It is very faint, producing a tiny amount of radioactive ^{56}Ni, (2) its light curve evolves very rapidly, suggesting a small ejecta mass, and, most surprisingly, (3) the oxygen emission line in late-phase spectra is much weaker than those of calcium, contrary to what is known from all other core-collapse SNe of envelope-

stripped progenitors. We suggest that these peculiarities indicate that SN 2005cz originated from a progenitor at the low-mass end of stars undergoing Fe-core collapse, i.e., a star of initially ~ 10 solar mass in a close binary system. The existence of this kind of peculiar core-collapse SNe might be related to some puzzling metal-poor stars that show extremely large Ca/Mg abundance ratios and small O/Fe ratios.

We discovered SN 2005cz on 2005 July 17.5 UT at $13''$ offset from the nucleus of the elliptical galaxy NGC 4589[1]. No object brighter than 18.5 mag was visible at the SN position on 2005 June 20[2]. The spectrum of SN 2005cz taken on July 28 UT (Fig. 1) shows strong He I 5876 Å and weak Hα lines, being well consistent with post-maximum spectra of type Ib supernovae (SNe Ib)[3]. The overall appearance of spectral features is quite similar to those of the SN Ib 2000H at $t = +29$ days, the SN IIb 1993J at $t = +24$ days (despite its stronger H lines), and also the typical SN Ic 1994I at $t = +26$ days (despite its lack of the strong He lines), where t is time after the maximum brightness (Fig. 1). The similarities between the spectra of SN 2005cz and SNe Ibc/IIb suggest that SN 2005cz originates from the core-collapse of an envelope-stripped massive star. We tentatively assume that the epoch of our first spectrum (Jul 28) is $t = +26$ days and the explosion date is Jun 17 (See Supplementary Table).

As time goes by, the ejecta become transparent to optical light, following the expansion and density decrease. Late-time spectra of SNe Ib/c are thus characterized by various emission lines, mostly of forbidden transitions. Fig. 2 shows the late-time spectrum of SN 2005cz at $t = +172$ days. It is very unique; unlike other SNe Ibc/IIb SN 2005cz shows only weak [O I] $\lambda\lambda$6300, 6364 and [Ca II] $\lambda\lambda$7291, 7323 (with a probably negligible contribution from [O II] $\lambda\lambda$7320, 7330) is much stronger than the [O I]. SNe Ibc/IIb that show such large ratio of [Ca II] to [O I] have never been reported in the literature. The ratio [Ca II]/[O I] can be used as a sensitive indicator of the progenitor's mass. Oxygen is ejected mostly from the oxygen layer formed during the hydrostatic burning phase; its mass depends sensitively on the progenitor mass and is smaller for lower-mass progenitors. On the other hand, Ca is explosively synthesized during the explosion. Theoretical models predict that the stars having main-sequence masses of $M_{\rm ms} = 13 M_{\odot}$ and $18 M_{\odot}$ produce 0.2 and $0.8 M_{\odot}$ of O, and 0.005 and $0.004 M_{\odot}$ of Ca, respectively (e.g., ref. 9). Therefore, the Ca/O ratio in the SN ejecta is sensitive to the progenitor mass[10,11]. To produce the extremely large Ca/O ratio, the mass of the progenitor star of SN 2005cz should be smaller than any other SNe Ib reported to date. For both SNe 1993J and 1994I that show weaker [Ca II] than [O I] (Fig. 2), the progenitors' masses are estimated to be $M_{\rm ms} \sim 12-15 M_{\odot}$ (ref. 12,13). Thus, the progenitor mass of SN 2005cz is $M_{\rm ms} \leq 12 - 15 M_{\odot}$.

Fig. 3 shows the absolute R-band light curve (LC) of SN 2005cz as compared with those of other SNe. The LC tail is similar to those of SN IIn 2008S and SN Ic 1994I (dimmed by 1.5 magnitudes in Fig. 3). ¿From this, we estimate the mass of ^{56}Ni as $M_{\rm 56Ni} = 10^{-1.5/2.5} \times 0.07 M_{\odot} \sim 0.018 M_{\odot}$ ($M_{\rm 56Ni} = 0.07 M_{\odot}$ for SN 1994I[18]).

Fig. 4 shows this quantitatively, with the "pseudo"-bolometric light curve of SN 2005cz. Except for the last point (upper-limit), we simply assume the bolometric correction $BC \equiv M_{\rm Bol} - M_R = 0.5$, derived from SNe 1998bw, 2002ap and 2008D at similar epochs [19,20,21]. As this is a very crude estimate, we adopt an error bar of ± 0.5 mag for the bolometric luminosity. Also, a simple γ-ray and positron deposition model is shown in Fig. 4, taking into account the decreasing opacity to Compton scattering ($\tau_{\gamma} \propto M_{\rm ej}^{2} {E_{\rm K}}^{-1} t^{-2}$) and assuming the full deposition of positrons. The decline rate from the intermediate to the late phase is consistent with $(M_{\rm ej,\odot}^{2}/E_{51}) \leq 1$, and the luminosity requires that $M_{\rm 56Ni} \leq 0.02 M_{\odot}$. Note that the upper limit to $M_{\rm 56Ni}$ decreases to $M_{\rm 56Ni} \leq 0.005 M_{\odot}$, if the explosion date is as late as 2005 Jul 15 (just a few days before the discovery). ¿From the ratio $M_{\rm ej}^{2}/E_{51}$, we see that $M_{\rm ej} \leq 1 M_{\odot}$ for $E_{51} \leq 1$, indicating a small progenitor mass ($M_{\rm ms} \leq 12 M_{\odot}$; ref. 22).

What is the origin of this peculiar SN 2005cz? The most unique features are (1) strong [Ca II] $\lambda\lambda$7291,7327 and weak [O I] $\lambda\lambda$6300,6363 in the late-phase, and (2) a low optical luminosity that indicates $M_{\rm 56Ni} \sim 0.005 - 0.02 M_{\odot}$.

The early-phase spectrum, which is very similar to those of SNe Ibc/IIb, strongly suggests a core-collapse origin. However, we encounter the serious questions (1) whether the above peculiarities can be explained by the core-collapse SN model, and (2) whether a core-collapse origin can be consistent with the fact that the host is an elliptical galaxy that usually contains only an old population of stars.

We suggest a star with $M_{\rm ms} \sim 10 M_{\odot}$ as a most likely origin of SN 2005cz. The evolutionary scenario is as follows[22,23]. If this star had been single, its mass (and thus its mass loss rate) would have been too small to lose most of its H-rich envelope. Thus this star was in a close binary system. Then it became a He star of $\sim 2.5 M_{\odot}$ after undergoing Roche lobe overflow. This He star formed a C+O core of $\sim 1.5 M_\odot$, which marginally exceeded the lower mass limit to form a Fe core[22,23]. The overlying He layer had $\sim 1 M_\odot$. Eventually, the He star underwent Fe core-collapse to explode as a SN Ib, leaving a $\sim 1.5 M_\odot$ neutron star behind. The ejecta had $\sim 1 M_\odot$, consistent with the observed constraint. The ejecta consists mostly of unburned material in the He layer and a small amount of explosively synthesized elements. The explosive burning products contain some Fe, Ca, and Si, but not much oxygen. Also the ejected part of the unburned oxygen-rich layer is extremely small. This scenario can explain the peculiar nebular spectrum with large [Ca II]/[O I] ratio, as well as the low luminosity and its relatively rapid decrease.

The pre-supernova evolution of $10 - 12 M_\odot$ stars have not been theoretically well studied. Our discovery of SN 2005cz and its analysis presented here emphasize the importance of an extensive study of this range. Our result of $M_{^{56}\mathrm{Ni}} \sim 0.005 - 0.02 M_\odot$ provides a good constraint on the unknown pre-supernova configuration and the mechanism of explosion (see Supplementary Fig. 3).

Stars with $M_{\mathrm{ms}} \sim 8 - 10 M_\odot$ form an electron-degenerate ONeMg core and undergo electron-capture-induced collapse[23]. In a close binary system, such a star forms an ONeMg white dwarf which can undergo accretion-induced collapse. Whether such a collapse produces a SN 2005cz-like explosion deserves further investigation. The most likely scenario to realize a SN Ib would be the merging of an ONeMg white dwarf and a He white dwarf, which needs detailed study.

The $\sim 10 M_\odot$ star model is consistent with the properties recently-inferred for the host galaxy of SN 2005cz. Hakobyan et al.[24] reexamined the morphology of the host galaxies of 22 core-collapse SNe (i.e., type II/Ibc) which had previously been classified as Elliptical or S0 galaxies before. They concluded that 19 cases were simply misclassifications of the host galaxy type. NGC 4589, the host of SN 2005cz, remains a genuine E2 galaxy. However, though the literature search related to NGC 4589, Hakobyan et al. pointed out that there is a Low Ionization Nuclear Emission-line Region (LINER) activity (Type "L2"[25]), and suggested the host to be a merger remnant. There is also evidence for dust lanes across the nucleus from an HST study[26]. Therefore, the appearance of an SN Ib in this particular early-type galaxy may not conflict with the general scenario of stellar evolution and explosion. According to a population synthesis model for the integrated light from the host galaxy[27], it has been suggested that about 90% of the host flux is contributed by an old population with life times longer than 10^{10} years (i.e., $M_{\rm ms} \leq 1 M_\odot$), whereas a relatively young population with life times $\sim 10^7 - 10^8$ years (i.e., $M_{\rm ms} \leq 10 M_\odot$) contributes to the remaining $\sim 10\%$. Thus, it is likely that SN Ib 2005cz is the end product of one of these young stars, which were produced by the galaxy merger about $\sim 10^8$ years ago.

The existence of 2005cz-like SNe, which have ejected material with little O and a relatively large amount of Ca, may have important implications to the chemical evolution of galaxies. In our Galaxy, a very Ca-rich, extremely metal-poor (EMP) halo star has recently been discovered[28]. Such an EMP star may have formed from the debris of 2005cz-like SNe. It would also be interesting to note that some dwarf galaxies contain EMP stars whose abundance ratios between the alpha-elements and Fe are much smaller than the halo stars[29,30]. The oxygen-poor 2005cz-like SNe might be related to the formation of such EMP stars.

We conclude that SN 2005cz is quite likely to be a core-collapse SN of a $\sim 10 M_\odot$ in a binary system. It should be kept in mind, however, that we cannot exclude an extreme case of other SN types (see Supplementary Fig. 2). Current theoretical models still have lots of freedom and further observational constraints are necessary to fully understand the final stage of the evolution of stripped stars of different masses. In particular, the mass range of 10-12 $M_\odot$ has not been investigated in much detail so far, although, as SN 2005cz suggests, envelope-stripped SNe resulting from these stars may have a very special abundance pattern in the ejecta and play an important role in the chemical evolution of galaxies.

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Competing Interests The authors declare that they have no competing financial interests.

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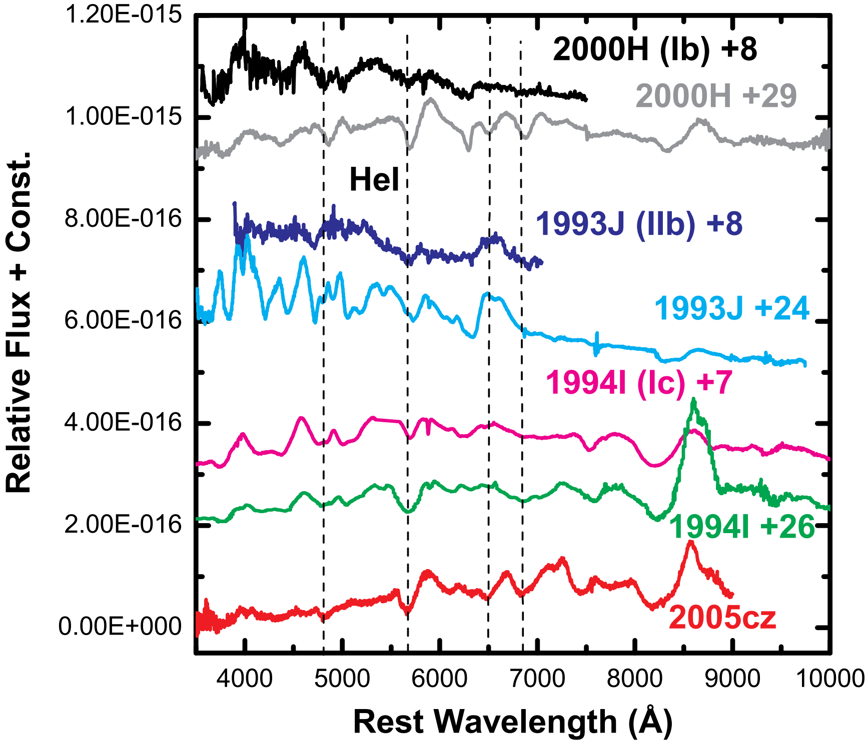
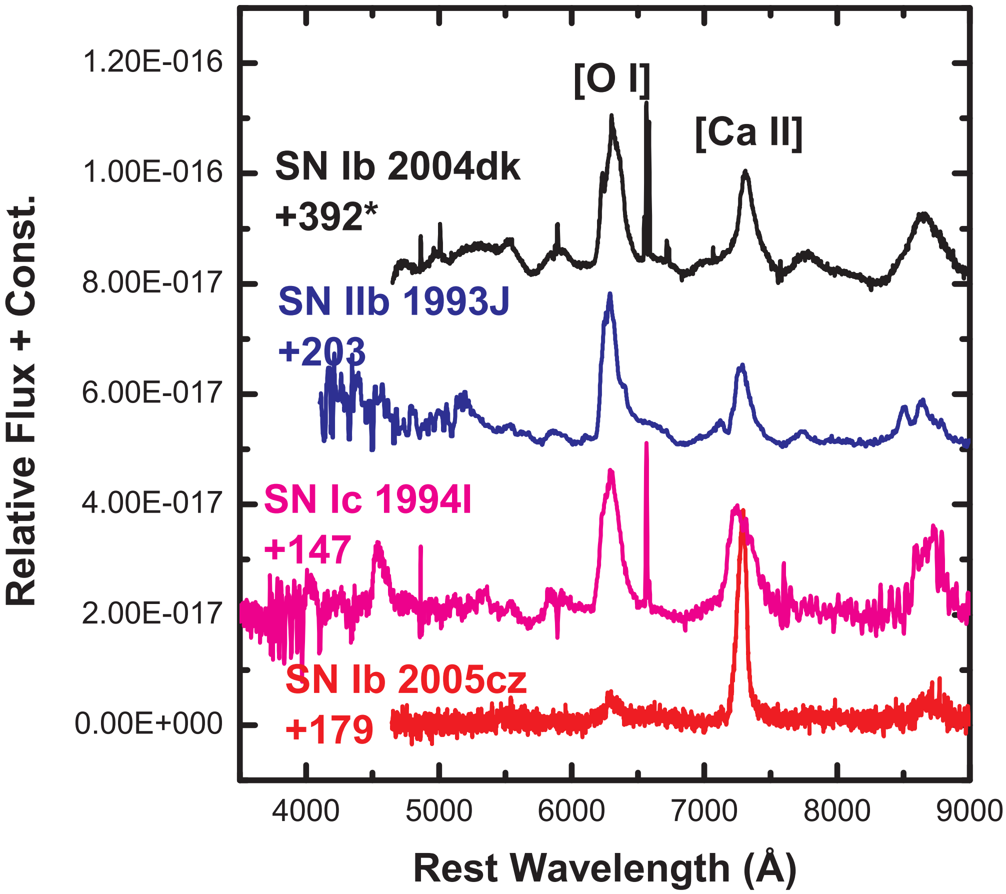
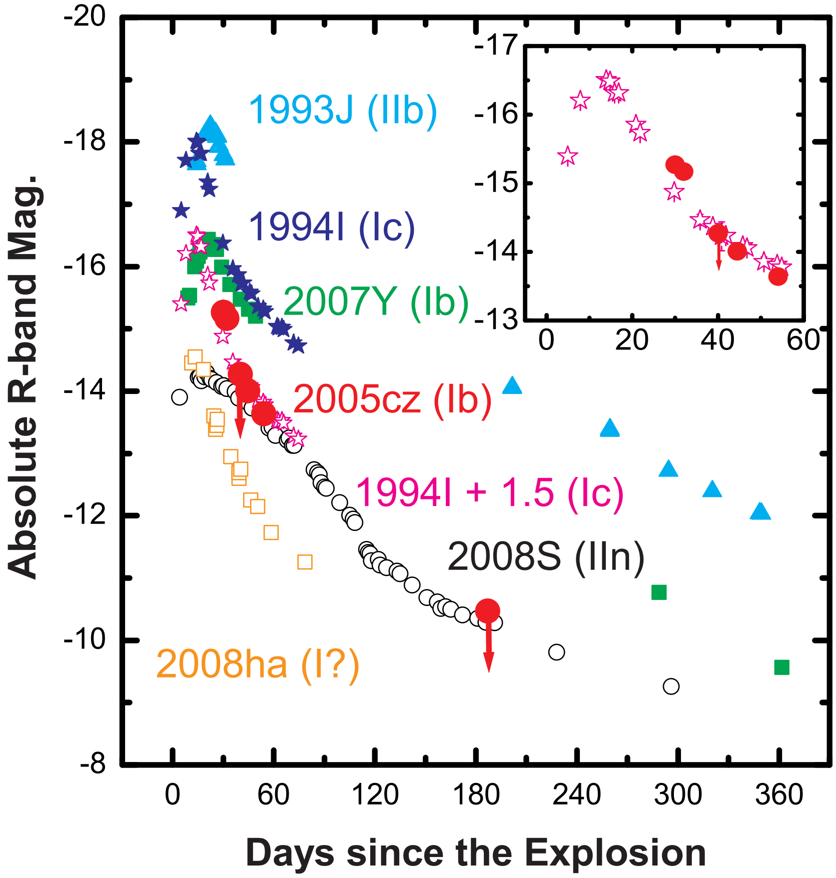
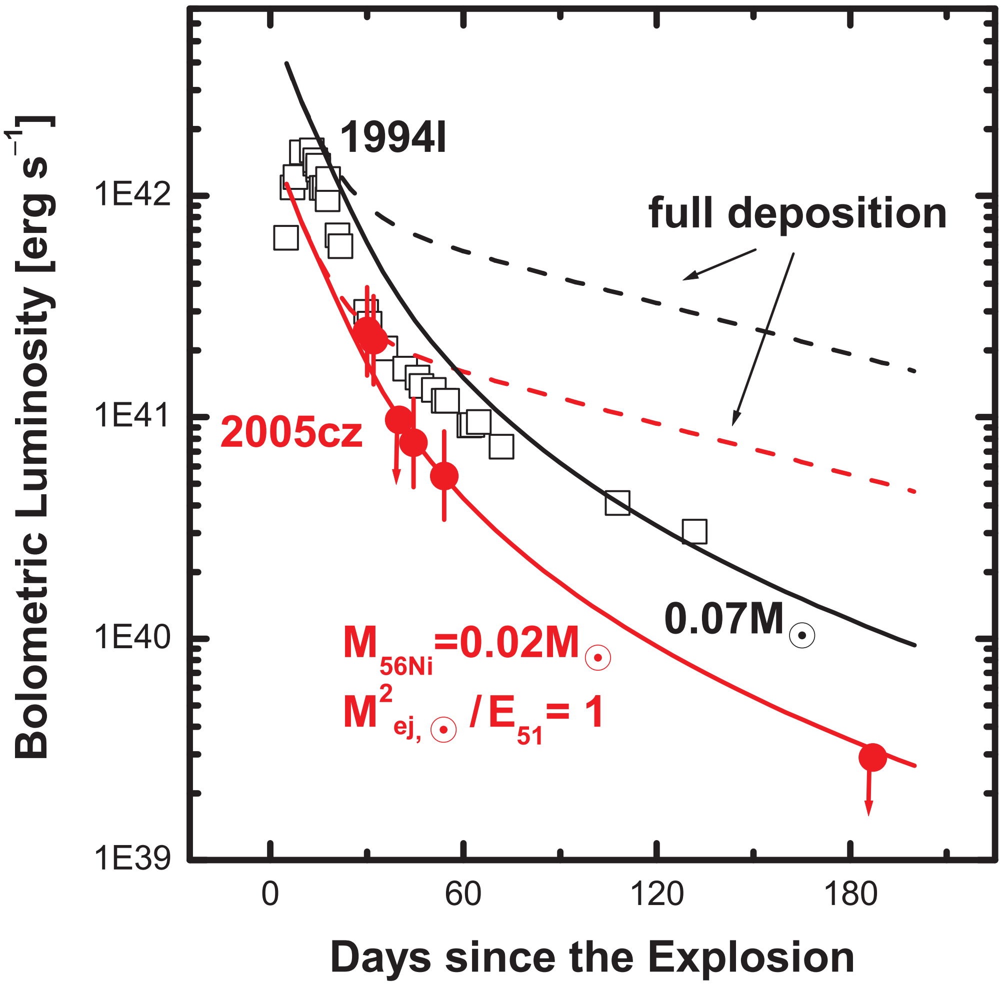

1.20E-015
1.00E-015
8.00E-016
6.00E-016
4.00E-016
2.00E-016
0.00E+000
Relative Flux + Const.
4000
5000
6000
7000
8000
9000
10000
Rest Wavelength (Å)
2000H (Ib) +8
2000H +29
HeI
1993J (IIb) +8
1993J +24
1994I (Ic) +7
1994I +26
2005cz


[O I]
[Ca II]
SN Ib 2004dk
+392*
SN IIb 1993J
+203
SN Ic 1994I
+147
SN Ib 2005cz
+179
Relative Flux + Const.
1.20E-016
1.00E-016
8.00E-017
6.00E-017
4.00E-017
2.00E-017
0.00E+000
4000
5000
6000
7000
8000
9000
Rest Wavelength (Å)


-20
-18
-16
-14
-12
-10
-8
Absolute R-band Mag.
0
60
120
180
240
300
360
Days since the Explosion
1993J (IIb)
1994I (Ic)
2007Y (Ib)
2005cz (Ib)
1994I + 1.5 (Ic)
2008S (IIn)
2008ha (I?)
-17
-16
-15
-14
-13
0
20
40
60


Bolometric Luminosity [erg s^{-1}]
1E42
1E41
1E40
1E39
0
60
120
180
Days since the Explosion
1994I
full deposition
2005cz
0.07M$_\odot$
M$_{56Ni}$=0.02M$_\odot$
M$^2_{ej,\odot}$ /E$_{51}$= 1

Supplementary Information

1 Supplementary Table

In this Table we present the log of the observations and part of the photometric results. The discovery and subsequent unfiltered images were taken with a 0.6-m reflector and a CCD (Kodak KAF-1001E) at Itagaki Astronomical Observatory (IAO) in Yamagata, Japan. The derived magnitudes are approximately consistent with R magnitudes. Other imaging observations were performed by the Calar Alto 2.2-m telescope (CA2.2) equipped with the Calar Alto Faint Object Spectrograph (CAFOS) in B, V, R and I bands, and by the 8.2-m Subaru Telescope equipped with the Faint Object Camera and Spectrograph (FOCAS[31]) in B and R bands. Imaging observations with Subaru were done in photometric conditions; standard stars around PG 1525-071 in August 2005 and around PG 0942-029 in December 2005 were observed for photometric calibration. The photometric reduction was performed using the IRAF package DAOPHOT. Since SN 2005cz was close to the bright core of the host galaxy, we subtracted the host galaxy component to perform more reliable photometry. For the unfiltered images at IAO, we used the pilot survey image taken with the same system on 2005 May 25 as the host template.[1] For the CA2.2 and Subaru images, we took data of the same field, as well as the standard stars around PG 0918+029, by CA2.2+CAFOS in a photometric night on 2009 Feb 19 and used them as host templates after point-spread-function-matching. The derived R (and unfiltered) magnitudes are shown in the Ta-

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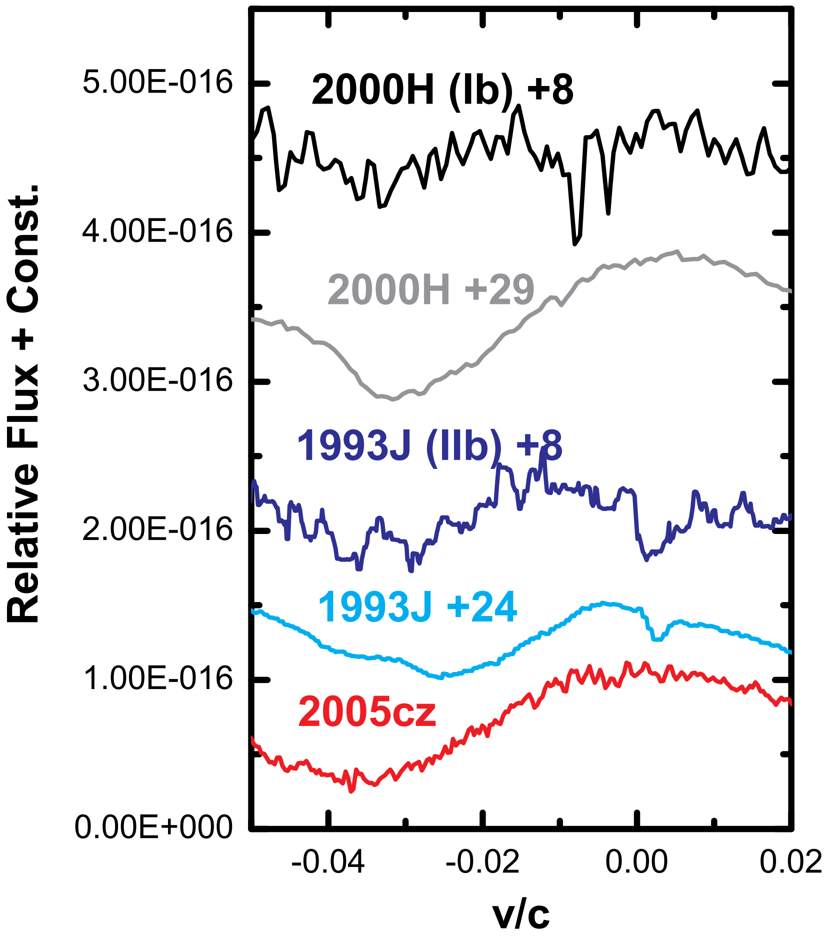
[1] The discovery magnitude of 16.0 reported in IAUC 8569[1] included a large bias caused by the steep brightness distribution of the host galaxy core.

ble. The other magnitudes are $B = 21.18 \pm 0.30$ mag, $V = 19.69 \pm 0.18$ mag, $I = 17.72 \pm 0.11$ mag on 2005 Aug 1, and $B = 21.0 \pm 0.2$ mag on 2005 Aug 10. On 2005 Jul 27 and Dec 27, the SN was not detected and we just derived 3σ upper-limit for the SN luminosity. For the Dec 27 data, we derived more reliable upper-limit of the bolometric luminosity (Fig. 4) as follows; first, we subtracted a continuum from the Subaru spectrum and then scaled it to the observed upper-limit ($R > 22.1$). We then integrated the flux at optical wavelengths. Finally, we assumed that the NIR contribution was 30% of the optical luminosity, a typical value seen in SNe Ib/c at late phases[32]. The early-time spectrum of SN 2005cz was obtained on 2005 Jul 28 UT with the 10-m Keck I Telescope equipped with the Low-Resolution Imaging Spectrometer (LRIS[33]). The total exposure time was 500 s. The seeing was $\sim 1''.2$ and the airmass was relatively large, ~ 2.3. The wavelength resolution measured from sky lines is 9 Å. The late-phase spectrum was obtained with Subaru+FOCAS on 2005 Dec 27 UT. The total exposure time was 1800 s. The seeing was $\sim 1''.0$ and the airmass was ~ 1.8. The wavelength resolution is 11 Å. The data were reduced with IRAF in a standard manner for long-slit spectroscopy. For the extinction within our Galaxy and the host galaxy, we adopted $E(B-V) = 0.03$ and 0.1 mag, respectively. The former was inferred from infrared dust maps[34] while the latter was estimated from the equivalent width of Na I D absorption feature in our early spectrum ($EW \leq 0.34$Å) and an empirical formula[35]. Although the formula allows for a range of $E(B-V) \leq 0.044 - 0.13$ mag, the extinction within the inner $3''$ of NGC 4589 has been estimated to be $E(B-V) \sim 0.1$ mag by the spectrum template fitting[36]. Since the SN position is reasonably separated from the dusty bar near the nucleus of the host galaxy, the extinction should not be large there. Therefore, we take $E(B-V) = 0.1$ mag as a reference value for the host extinction. We assumed that $t = +26$ days as the epoch of the first spectrum (Jul 28) because of the overall resemblance of the spectral features with SN Ic 1994I at $t = +26$ days and with SN Ib 2000H at $t = +29$ days. This estimate still includes a large uncertainty; e.g., the He I line velocities of $\sim 9,000 - 12,000$ km s^{-1} on Jul 28 (Supplementary Fig. 1) would be more typical for SNe Ib at $t = 0$ to $+10$ days. Since the mass estimate for ^{56}Ni is sensitively affected by the explosion date, we also consider an extreme case where the discovery was close to the explosion date, and give the possible range of $M_{^{56}\rm Ni}$ (see text). Anyway, the choice here does not affect our main conclusions.

Date (UT)	MJD	Epoch (days)	Telescope+ Instrument	Setup	R (mag)
2005 May 25.7	53516.7	—	IAO 0.6	Imaging(unfiltered)	—
2005 Jul 17.5	53568.5	$+15.5$	IAO 0.6	Imaging(unfiltered)	17.3 ± 0.1
2005 Jul 19.5	53570.5	$+17.5$	IAO 0.6	Imaging(unfiltered)	17.4 ± 0.1
2005 Jul 27.5	53578.5	$+25.5$	IAO 0.6	Imaging(unfiltered)	> 18.3
2005 Jul 28	53579	$+26$	KeckI+LRIS	Spectropolarimetry	—
2005 Aug 1.0	53583.0	$+30.0$	CA2.2+CAFOS	Imaging($BVRI$)	18.56 ± 0.12
2005 Aug 10.3	53592.3	$+39.3$	Subaru+FOCAS	Imaging(BR)	18.93 ± 0.05
2005 Dec 27.6	53731.6	$+178.6$	Subaru+FOCAS	Imaging(BR)/Spectroscopy	> 22.1
2009 Feb 19.0	54881.0	—	CA2.2+CAFOS	Imaging($BVRI$)	—

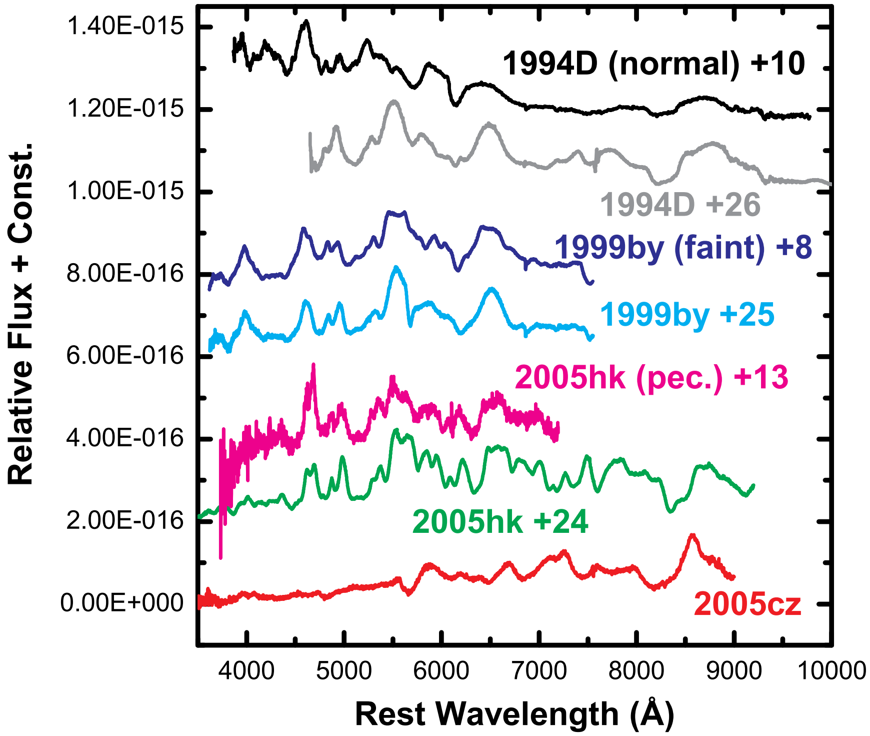
Table 1: Summary of observation of SN 2005cz

2 Supplementary Figure 1



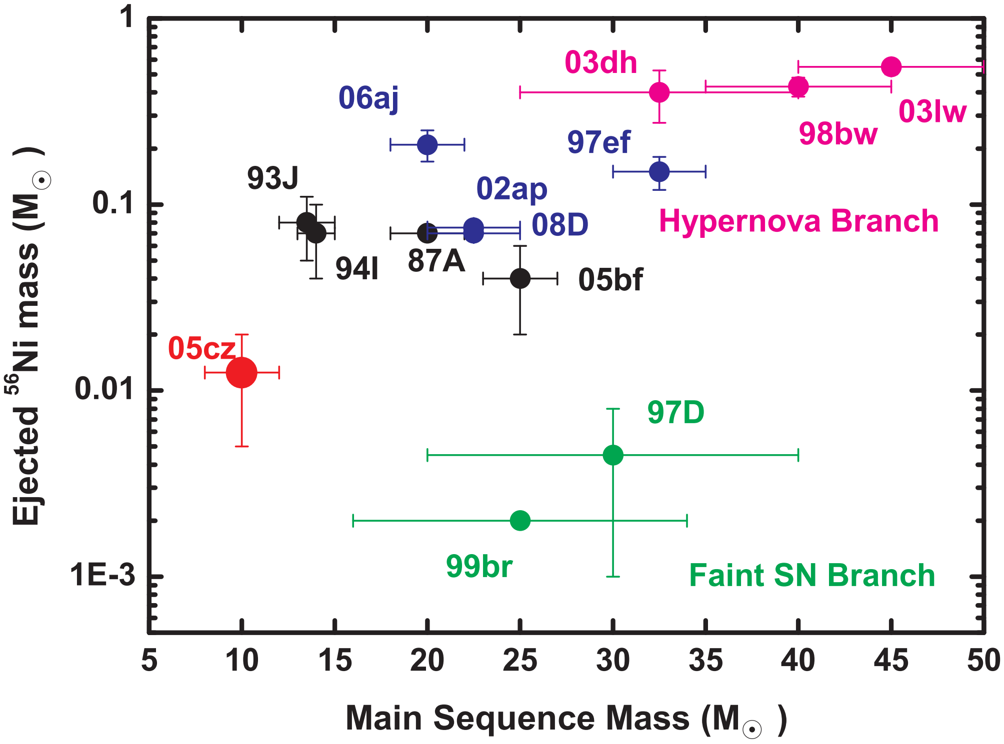
A close-up plot of the He I $\lambda5876$ line in the early-time spectrum of SN 2005cz and some SNe for comparison. The horizontal axis denotes the line velocity normalized by the speed of light.

3 Supplementary Figure 2



Early-time spectrum of SN 2005cz in comparison with SNe Ia. From top to bottom, we show the normal SN Ia 1994D at $t = +10$ days and $+26$ days[37], the faint SN Ia 1999by at $t = +8$ days and $t = +25$ days[38], and the peculiar SN Ia 2005hk at $t = +13$ days and $t = +24$ days[39]; none of them is similar to SN 2005cz on 2005 July 28.

4 Supplementary Figure 3



The relation between progenitor mass and synthesized ^{56}Ni mass. The three SNe shown by magenta symbols at the upper right of the panel are associated with γ-ray bursts. These SNe and SN 1997ef are called hypernovae, with the definition that the kinetic energy of the explosion exceeds 10^{52} erg. SN 2005cz locates roughly at the bottom of the sequence from hypernova to normal SNe.

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Figure 1 Early-time spectrum of SN Ib 2005cz taken on 2005 Jul 28 with the Keck Telescope (red). Also shown are spectra of SN Ib 2000H at $t = +8$ (black) and $t = +29$ days (gray)[4], SN IIb 1993J at $t = +8$ days (blue) and at $t = 24$ days (cyan)[5], and SN Ic 1994I at $t = +7$ days (magenta) and $t = +26$ days (green)[6,7]. A SN Ib is characterized by strong helium lines and weak silicon lines, while in a SN Ic both helium and silicon lines are weak. A SN IIb shows a SN II-like spectrum characterized by strong hydrogen features at early time, and becomes SN Ib/c-like at late time. All these SNe are thought to have partly or fully stripped off their outer layers of hydrogen and helium before the explosions. The epochs are also shown in the figure. The spectra are corrected for the host redshift and the reddening. We adopted a total (milky way + host) reddening of $E(B-V) = 0.13$ $(0.03 + 0.1)$ mag in SN 2005cz, $E(B-V) = 0.23$ $(0.23 + 0.0)$ mag in SN 2000H, $E(B-V) = 0.45$ mag in SN 1994I, and $E(B-V) = 0.3$ mag in SN 1993J. The flux is on an absolute scale for SN 2005cz, calibrated with the Calar Alto photometry obtained four nights later. For the comparison SNe, the flux is on an arbitrary scale and constants are added for presentation. The positions of prominent He I lines are shown by dotted lines.

Figure 2 A late-time spectrum of SN Ib 2005cz taken on 2006 Dec 27 ($t = +179$ days) with the Subaru Telescope. Also shown are SN Ib 2004dk at $t \sim 390$ days[8], SN IIb 1993J at $t = +203$ days[5], and SN Ic 1994I at $t = +147$ days[7]. The spectrum of SN 2004dk is typical for SNe Ib/c at late times (e.g., see fig.2 of ref. 8). The spectra are corrected for the host redshift, but not for reddening. The flux is on an approximate absolute scale for SN

2005cz, calibrated with the spectroscopic standard star (but not with photometry), while it is on an arbitrary scale for the comparison SNe. The asterisk of SN 2004dk denotes the days since its discovery (not maximum light).

Figure 3 Absolute R-band light curve of SN Ib 2005cz (red circles) as compared with those of SN IIb 1993J (cyan triangles), SN Ic 1994I (blue stars), SN Ib 2007Y (green squares), SN IIn 2008S (black open circles), and SN I? 2008ha (orange open squares). Also shown is the light curve of SN 1994I, but dimmed by 1.5 magnitudes (magenta open stars). For SN 2005cz, the first three points denote unfiltered magnitudes which are approximately R-band magnitudes. The two points with downward arrows are $3-\sigma$ upper-limits. The distance moduli and total reddening values are taken as follows: [μ, E(B-V)] = (32.23 mag, 0.13 mag) for 2005cz (see Supplementary Table), (27.8 mag, 0.3 mag) for 1993J, (29.6 mag, 0.45 mag) for 1994I, (31.43 mag, 0.112 mag) for 2007Y, (31.55 mag, 0.076 mag) for 2008ha, and (28.78 mag, 0.687 mag) for 2008S. We assumed $R_V = 3.1$ to convert the colour excess to the R-band extinction. The data points, as well as the distance and the reddening, are from the literature [5,14,15,16,17,]. The putative explosion date for SN 2005cz is assumed to be 2005 Jun 17, 30 days before the discovery and 15 days before the maximum (see Supplementary Table).

Figure 4 Pseudo bolometric light curve of SN Ib 2005cz (filled red circles), as compared with a simple γ-ray and positron deposition model with $M_{^{56}\mathrm{Ni}} = 0.02 M_\odot$ (red line). We also plot the bolometric light curve of SN Ic 1994I (open black squares; Richmond et al. 1996) and a simple deposition model with $M_{^{56}\mathrm{Ni}} = 0.07 M_{\odot}$ (black line) for comparison.