Evidence for Two Distinct Populations of Type Ia Supernovae

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Type Ia supernovae (SNe Ia) have been used as excellent standardizable candles for measuring cosmic expansion, but their progenitors are still elusive. Here, we report that the spectral diversity of SNe Ia is tied to their birthplace environments. We found that those with high-velocity ejecta are substantially more concentrated in the inner and brighter regions of their host galaxies than are normal-velocity SNe Ia. Furthermore, the former tend to inhabit larger and more luminous hosts. These results suggest that high-velocity SNe Ia likely originate from relatively younger and more metal-rich progenitors than do normal-velocity SNe Ia and are restricted to galaxies with substantial chemical evolution.

Type Ia supernovae (SNe Ia) are among the most energetic and relatively uniform stellar explosions in the universe and were used to discover its accelerating expansion (1, 2). They are thought to originate from a thermonuclear explosion of an accreting carbon-oxygen (C-O) white dwarf (WD) near the Chandrasekhar mass limit [M_C ≈ 1.4 solar mass (M☉)] in a close binary system (3, 4). Two competing scenarios have been proposed for the progenitor systems: single-degenerate (SD) (3, 5) and double-degenerate (DD) models (4, 7). In the former, the mass-donating star can be a main-sequence (MS)/subgiant star (8), a red-giant star (RG) (9), or even a helium star (10, 11), whereas it is another WD in the latter scenario (4, 7). Recent results suggest that both scenarios are possible (12–18).

There is increasing evidence for spectral diversity among SNe Ia. Of particular interest are those showing higher expansion velocities as inferred from the blueshifted Si II 615-nm feature in optical spectra (19). Those fast-expanding SNe Ia also generally exhibit a steep Si II temporal velocity gradient (20). This spectral difference in velocity or velocity evolution of the ejecta has been proposed to be a geometric effect of an asymmetric explosion (21, 22). Given a common origin for SNe Ia having different ejecta velocities, they should be found in similar stellar environments. This can be tested by examining SN positions in their hosts, the surface brightness at these locations, and the properties of their hosts.

We conducted such an analysis with a well-defined SN sample having 188 SNe Ia (supplementary text S1) from the Lick Observatory Supernova Search (LOSS) (23). The SN Ia sample consists of 123 “Branch-normal” (spectroscopically normal) objects (24), 30 peculiar ones of the SN 1991bg variety (25), 13 peculiar ones such as SN 1991T (26, 27), and 7 peculiar ones such as SN 2002cx (28), with respective fractions of 65.4, 16.0, 6.9, and 3.7% (table S1). There are 15 SNe Ia (8.0% of all) that cannot be subclassified because of an absence of early-time spectra. We concentrated on the Branch-normal SNe Ia, which are thought to be relatively uniform. We obtained the main parameters of the host galaxies from two large online astronomical databases: the NASA/Infrared Processing and Analysis Center (IPAC) Extragalactic Database (NED) (29) and HyperLeda (30).

The location of a SN in its host galaxy can be estimated by the radial distance of the SN from the nucleus (R_SN). Assuming that the galaxies are circular disks and only appear to have different major and minor axes because of their inclination, R_SN can be calculated if we know the position angle and the axial ratio of each galaxy. The radius of the galaxy (R_gal) is simply the semi-major axis at the 25.0 B-mag arc sec−2 isophote. The ratio R_SN/R_gal is then the fractional radial distance of the SN. For SNe Ia in elliptical galaxies, no tilt correction is applied because these galaxies can be regarded as spheroids. The typical host galaxy of our sample (fig. S1) has a major axis of about 1.3 to 1.4′ and can be measured with a precision of ~0.1′. This results in a typical uncertainty of ~0.05 in the determination of R_SN/R_gal.

We measured the velocity of the Si II 615-nm line for 165 SNe Ia (out of 188) by using the published spectral data sets (31–33). We normalized this velocity to the maximum-light value with a series of templates of Si II velocity evolution established from well-observed SNe Ia, with a typical uncertainty of 300 to 400 km s−1 (supplementary text S1 and fig. S2).

It is clear that Branch-normal SNe Ia with v_Si II < 12,000 km s−1 (the normal-velocity group (NV)) span a wide radial distribution, occurring at places from the innermost region to about two to three times the optical radius of the entire galaxy. In contrast, those with v_Si II ≥ 12,000 km s−1 (the high-velocity group (HV)) are rarely found at large galactic radii (fig. 1B). For example, only 3 out of the 40 HV SNe Ia are detected in regions with R_SN/R_gal > 0.7 (two of which are in elliptical galaxies), whereas 14 ± 2 would have been expected at the detection rates of the NV SNe Ia (which are about 34 ± 5% at R_SN/R_gal > 0.7). Such a difference has a statistical significance of about 5σ, highlighting the paucity of HV SNe Ia in outskirts of galaxies. Binning the data in velocity space with an interval of about 2000 km s−1 further shows a correlation between the ejecta velocity of SNe Ia and the locations in their host galaxies (Fig. 1A, gray quadrangles). To better understand such a relationship between the velocity and the host galaxy, we note that the velocity distribution can be fit by a double-Gaussian model. One com-

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component, with a stronger and narrower peak at 10,800 km s\(^{-1}\), is responsible for the NV group, whereas the other component, with a weaker and broader peak at 13,000 km s\(^{-1}\), accounts for the HV group. Adopting a velocity cut of \(v_{\text{Si II}} = 12,000\) km s\(^{-1}\) to divide these two groups puts 40 SNe Ia in the HV group and 83 in the NV group. Accordingly, we estimate the fraction of the HV population to be 1/3 of the Branch-normal sample and 1/5 to 1/4 of the entire SN Ia sample. The Si II velocity distinction is not sharp between these two groups, so blending could occur to some extent. Nevertheless, this blending is small at larger velocities and will not affect the result that the SNe Ia with higher velocities tend to occur nearer the galaxy centers.

HV SNe Ia show the highest central concentration among the samples, with 90% occurring in regions within \(R_{\text{SN}}/R_{\text{gal}} \leq 0.7\); this fraction is 66, 77, and 89% for NV SNe Ia, SNe II, and SNe Ibc, respectively (Fig. 2). The contrast is even more apparent when examining the distribution toward the galaxy center. We caution, however, that a higher fraction of CC SNe may be missing in the central regions of galaxies during LOSS because of their lower luminosity relative to SNe Ia.

A Kolmogorov-Smirnoff (K-S) test finds a probability of 0.5% that HV and NV SN Ia groups have a similar radial distribution in galaxies. This probability further decreases to 0.1% if one increases the velocity cut dividing these two groups from 12,000 to 13,000 km s\(^{-1}\). Possible selection effects in the radial distribution have been explored, and none can account for such a significant discrepancy between HV and NV SN Ia groups (supplementary text S2 and fig. S3). Thus, HV SNe Ia have higher metallicities, and their progenitors are therefore less likely to be from the halo population that consists of old, metal-poor stars located far away from the galactic center (34).

Because the radial distances give only a rough estimate of the properties of SN progenitors, more sophisticated methods are necessary to provide additional constraints. A simple statistic of the “fractional flux” allows a measurement of how SNe are distributed within their hosts (35). This can be achieved by measuring in the host-galaxy images the fraction of total galaxy light contained in pixels fainter than or equal to the light in the pixel at the location of the SN. The “fractional flux” was obtained with the Sloan Digital Sky Survey (SDSS) u'g'r'i'-band images (36) for 64 “Branch-normal” SNe Ia (39 NV + 25 HV), 102 SNe II, and 39 SNe Ibc of the entire SN sample (supplementary text S3).

The surface brightness of SN II locations has an approximately linear distribution, roughly tracing the distribution of the light in their hosts (Fig. 3). SNe Ibc seem to be more concentrated in brighter regions of the host galaxies, which is consistent with the knowledge that they arise in larger star-forming regions that produce more-massive stars. Of the SN Ia sample, the locations of the HV group and the NV group track their hosts’ light differently, with a very low

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**Fig. 1. Relations between the Si II velocity of SNe Ia and the birth location in their host galaxies.** (A) The Si II velocity obtained around \(B\)-band maximum light (\(v_{\text{Si II}}\) ordinate) as compared with the fractional radial distance in the host galaxy (\(R_{\text{SN}}/R_{\text{gal}}\) abscissa) for 165 SNe Ia. The Branch-normal SNe Ia with \(v_{\text{Si II}} \geq 12,000\) km s\(^{-1}\) (HV group), those with \(v_{\text{Si II}} < 12,000\) km s\(^{-1}\) (NV group), SN 1991T-like SNe, and SN 1991bg-like SNe are shown by red triangles, blue circles, purple stars, and dark yellow squares, respectively. The SNe Ia in spiral and elliptical/lenticular galaxies are represented with solid and open symbols, respectively. The gray diamonds show the radial distances averaged in binned velocity space, which are 0.63 ± 0.08 in 9000 to 12,000 km s\(^{-1}\), 0.42 ± 0.06 in 12,000 to 14,000 km s\(^{-1}\), and 0.34 ±0.06 in ~ 14,000 to 16,000 km s\(^{-1}\), respectively. The horizontal and vertical dashed lines mark the place with \(v_{\text{Si II}} = 12,000\) km s\(^{-1}\) and with \(R_{\text{SN}}/R_{\text{gal}} = 0.7\). (B) The number distribution of the fractional radial distance. The red and blue areas are for the HV and NV groups of SNe Ia. The purple and dark yellow areas are for the SN 1991T-like and SN 1991bg-like SNe Ia. The red and blue curves are for the high-velocity and normal-velocity components, with respective peaks centered at 13,000 and 10,800 km s\(^{-1}\). The black curve represents the combined result of these two components.
probability ($P = 0.04$ in $u'$, 0.07 in $g'$, and 0.08 in $r'$) that they come from the same stellar populations. The NV SN Ia locations are apparently fainter than those of CC SNe (Fig. 3); the HV SN Ia distribution, on the other hand, is similar to the CC SN distribution.

The light radii and luminosities of galaxies in the HV sample and the NV sample also differ significantly (Fig. 4). A two-dimensional K-S test gives a probability of 0.5% that they come from the same population. The mean-light radius of the hosts estimated for these two groups is $20.67 \pm 0.83$ kpc for HV and $16.61 \pm 0.67$ kpc for NV. The mean absolute $K$-band magnitudes are $-24.53 \pm 0.13$ mag (HV) and $-24.17 \pm 0.10$ mag (NV), with the HV hosts being, on average, brighter by about 40%. In general, the HV SNe Ia tend to occur in larger and more luminous hosts, and the fraction found in galaxies with $R_{\text{gal}} < 15$ kpc is very low, 15% (versus 46% for the NV counterparts). This difference is not due to an observational bias because the host galaxies of these two groups do not show significantly different distributions in either morphologies or redshifts (supplementary text S4 and figs. S4 and S5).

Our analysis thus reveals substantial differences in the progenitor environments of SNe Ia having different Si II velocities. The HV SNe Ia are much more concentrated in regions close to the galaxy center and in bright regions of their host galaxies and also tend to reside in larger and more luminous hosts relative to the NV group. It is generally accepted that all galaxies (on average) have metallicities that systematically decrease outward from their galactic centers and that their global metallicities increase with galaxy size (39). Higher metallicity is therefore expected for the HV SN Ia progenitor population. Meanwhile, the fact that the surface brightness at HV SN Ia locations roughly traces the light of their host galaxies, as with CC SNe, suggests that the progenitor populations are relatively young. Thus, the HV SN Ia population may have a younger and more metal-rich progenitor system than that of the NV SN Ia population, and a larger initial MS mass of the exploding WD may be expected for the former because of the shorter evolutionary time needed before explosion.

Calculations of stellar evolution show that both stellar mass and metallicity have substantial effects on the nature of C-O WDs that may become progenitors of SNe Ia. The maximum MS mass to form C-O WDs is found to increase dramatically toward higher metallicity (40); stars with MS masses up to 8 to 9 $M_{\odot}$ produce massive WDs ($\sim 1.1 M_{\odot}$) that can reach $1.4 M_{\odot}$ in a shorter time via mass transfer from a companion star. Thus, the HV SN Ia group might represent the young-population SNe Ia, corresponding to the “prompt” component with short delay times (41, 42), whereas the NV group may belong to the “older” component with long delay times. Five out of the 40 (12.5%) SNe Ia in the HV sample are in elliptical galaxies that are luminous (table S1 and fig. S4) and massive. However, among these, some (such as SN 2002dj and SN 2000B) show dust structure and molecular gas (43, 44), which is suggestive of recent or ongoing star formation in them; they do not contradict the conclusion that HV SNe Ia likely arise from young stellar populations.

Having young and metal-rich progenitors may explain the numerous recent detections of circumstellar medium (CSM) signatures among HV SNe Ia. Time-variable absorption features of the Na I doublet (D1 589.6 nm and D2 589.0 nm), which is likely suggestive of changes in CSM ionization due to a variable SN radiation field, have been reported for a few SNe Ia such as SNe 2006X, 2007e, and 1999cl (12, 45, 46). A common feature of these SNe Ia is that they belong to the HV subclass (table S1). Additionally, the velocity structure of the line-of-sight Na I lines provides another possible diagnostic of CSM around SNe. A trend of blueshifts was found among SNe Ia according to a study of Na I absorption lines of a larger SN sample (13). It was noticed, however, that the SNe Ia with a blueshifted absorption feature generally have higher Si II velocities (47). This evidence is consistent with their systematically redder color around maximum light (perhaps because of additional CSM absorption) relative to the NV population (19) and can be understood in terms of an empirical metallicity dependence of mass outflow (48). At higher metallicity, stars lose more mass and produce stronger outflows than those of their lower-metallicity counterparts. Thus, detection of abundant outflows in the vicinity of the HV SNe Ia is not unexpected.

The higher Si II velocity seen in HV SNe Ia may be related in part to an increase in stellar metallicity. As the metallicity increases in the C+O layer of the exploding WDs, the line-forming
The Hubble constant ($H_0$) has been derived by adopting the mass density ($\Omega_0$) = 0.27, the cosmological constant ($\Omega_{\Lambda}$) = 0.73, and the Hubble constant ($H_0$) = 73 km s$^{-1}$ Mpc$^{-1}$ (37). Foreground galactic absorption corrections (38) have been applied to the absolute magnitudes. In the center, the high-velocity SN Ia hosts are represented as red triangles, and the normal-velocity SN Ia hosts are represented as blue dots. The absolute magnitudes of the hosts are shown on the abscissa, and the lengths of the semimajor axes of the hosts are shown on the ordinate. The plot is then projected to the top and the right, where a histogram is displayed for each host population in each of the dimensions, absolute magnitude, and semimajor axis.

region moves toward shallower parts of the atmosphere because of an increased line opacity, leading to larger line velocities (49). In addition, the high-velocity Si II layers are perhaps formed because of the density increase caused by interaction between the SN ejecta and the material around the exploding WD, which could be an accretion disk or a filled Roche lobe (50). The angular variations in observing such an interacting system may explain the variation of the polarization across the Si II line (51) and its correlation with the ejecta velocity for HV SNe Ia (22). This is consistent with the result that the observed differences in some SNe Ia might be due to a projection effect (21). However, these data and analyses are insensitive to a separate population of NV SNe Ia that is intrinsically different from HV SNe Ia.

The dependence of SN Ia ejecta velocity on progenitor environment could be relevant when using SNe Ia as cosmological yardsticks because the HV and NV populations have different colors around maximum light (49), and their ratio may change with redshift. The observed relative fraction of the HV and NV population might become smaller at great distances because of a decrease in the HV SN Ia rate in low-metallicity environments and the increased difficulty of spectroscopically classifying SNe in the central regions of distant galaxies.

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Supplementary Materials

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Supplementary Text
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References (52–58)
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