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Type Ia supernova explosion mechanism and implications for cosmology

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Abstract. Type Ia Supernovae (SNe Ia) are believed to be thermonuclear explosions of a white dwarf, and are one of the most mature cosmological standardized candles. However, the explosion mechanism has not yet been fully clarified. Furthermore, they show observational diversities which may be a consequence of either the diversity in the explosion physics and/or surrounding environments, an issue yet to be clarified. In this paper, it is argued that an asymmetry in the explosion is likely a generic feature, and that the diversity arising from various viewing angles can be an origin of observational diversities of SNe Ia seen in their spectral features (suspected possible biases in cosmology) and colors (related to the extinction estimate in cosmology). These findings indicate that at least a part of observational diversities are intrinsic, rather than caused by environment effects, and open up a possibility of using SNe Ia as more precise distance indicators than currently employed.

Key words. Supernovae – general: Nuclear reactions, Nucleosynthesis, Abundances: Cosmology – distance scale –

1. Introduction

It is widely accepted that a majority, if not all, of Type Ia Supernovae (SNe Ia) are thermonuclear explosions of a carbon-oxygen white dwarf (WD) reaching to the Chandrasekhar limiting mass (Nomoto et al. 1994; Branch 1998; Hillebrandt & Niemeyer 2000). Thermonuclear runaway may well start with the ignition of subsonic deflagration bubbles (Nomoto et al. 1984). The deflagration flame may turn into a supersonic detonation wave (Khokhlov 1991). However, details of the explosion mechanism are still actively debated.

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SNe Ia are one of the most mature standardized candles (Riess et al. 1998; Perlmutter et al. 1999). Their optical luminosities are different for different SNe Ia, but the peak luminosity is correlated to the luminosity decline rate so that brighter SNe Ia evolve slower (Phillips et al. 1999). Thus the decline rate can be used as a luminosity indicator.

However, SNe Ia do show a diversity in their spectral evolution (Branch et al. 1988; Benetti et al. 2004, 2005). In the early, photospheric phase, spectra of SNe Ia are characterized by blueshifted absorption features, as a result of the absorption by the material moving toward the observer. The absorption velocity decreases as a function of time. The velocity gradient ($\dot{v}_{\rm Si}$) is defined as a rate of the decrease

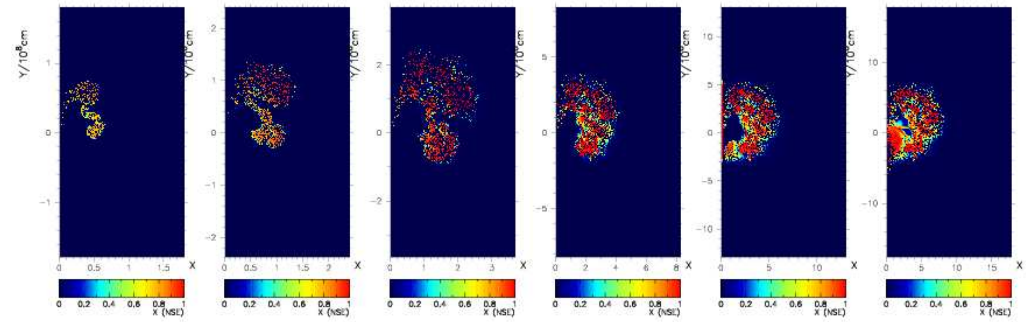

Fig. 1. Temporal evolution of distribution of Fe-peak elements (at 0.7, 0.9, 1.1, 1.3, 1.5, 1.7 seconds after the ignition of the deflagration flame, from left to right), in an offset ignition model of Maeda et al. (2010b) (see also Kasen et al. 2009). Shown here is the mass fraction of iron-peak elements, from 0 (blue/dark) to 1 (red/bright), as indicated by color bars below each panel.

in the Si II $\lambda6355$ absorption velocity. SNe that show $\dot{v}_{\rm Si} > 70$ km s^{-1} day^{-1} are classified as the high velocity gradient (HVG) group, while those showing smaller $\dot{v}_{\rm Si}$ are called the low velocity gradient (LVG) SNe Ia. It has been shown that $\dot{v}_{\rm Si}$ is *not* correlated with the decline rate (Benetti et al. 2005). The origin of such a diversity beyond the 'one-parameter' description (by the decline rate) has not yet been clarified, raising some concern about using SNe Ia as cosmological standard candles.

In addition, SNe Ia show a variation in their peak colors beyond the decline rate. Without knowing a source of the variation and thus their intrinsic colors, it is difficult to estimate the extinction within the host galaxy – an important source of the uncertainty in the SN cosmology.

2. Asymmetric explosions

The thermonuclear sparks are possibly ignited in off-center regions, not exactly at the center; a perturbation within the progenitor, e.g., caused by convection before the explosion, could result in the asymmetric, offset ignition (Kuhlen et al. 2006). Figure 1 shows an example of the thermonuclear flame propagation in a model where the thermonuclear sparks are ignited at an offset (Kasen et al. 2009; Maeda et al. 2010b). The deflagration flame first propagates outward as well as laterally (Röpke et al. 2007), producing mainly stable Fe-peaks like ^{58}Ni. The central region of the progenitor WD is not burned by the deflagration, and thus does not experience strong expansion at this stage. Later on, the detonation is initiated on the deflagration front. The detonation wave does not directly penetrate into the central region, since this direction is blocked by the deflagration ashes. The detonation thus propagates outward (as in classical 'spherical' models) but it also propagates laterally to the direction opposite to the initial deflagration ignition. Finally, the detonation flame reaches to the other hemisphere and the central region, where a large amount of unburned materials can fuel the detonation. During the detonation, a large amount of ^{56}Ni (which decays into ^{56}Co then into ^{56}Fe, powering the observed SN Ia luminosity) is produced. The resulting configuration is thus (1) highly asymmetric distribution of the deflagration products (e.g., stable Fe-peaks), and (2) more or less spherically symmetric distribution of the detonation products (e.g., ^{56}Ni).

3. Signatures of asymmetry

Despite the theoretical expectation, no observational signatures of the explosion asymmetry have been identified previously. Late-time spectroscopy is a strong probe to the geometry of SN ejecta. The homologously expanding SN ejecta become progressively transparent because of the expansion and density decrease. At $\gtrsim 150$ days after the explosion, the whole SN ejecta become transparent. At this 'late-

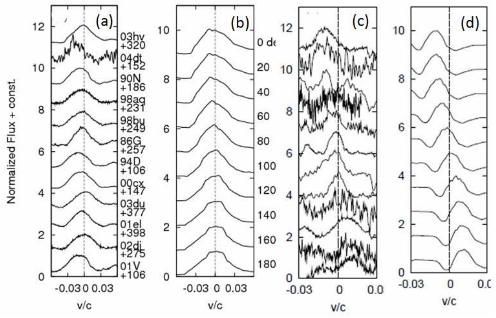

Fig. 2. Late-time spectra of various SNe Ia (Maeda et al. 2010a). (a) Observed and (b) model line profiles of [Fe III] blend at 4700Å, and (c) observed and (d) model line profiles of [Ni II] λ7378. The model profiles are shown for various viewing angles (see Maeda et al. 2010a, for details). The wavelength is corrected for the host galaxy recession velocities.

phase', photons from different positions show different Doppler shifts, and thus emission-line profiles can be used to trace the distribution of materials: For example, if a blob is ejected toward a specific direction, an emission line from such a blob should show blueshift if viewed from the direction of the ejection, but redshift from the opposite direction.

The offset ignition model predicts that emission from the deflagration ash (showing an offset) should show a variation in the wavelength for different viewing directions, while that from the detonation ash (spherically distributed) should show little variation. Based on this idea, we have investigated physical conditions and emission processes within the SN Ia ejecta in late-phases. The results are summarized as follows (Maeda et al. 2010a).

- **Lines which show variations:** Lines from a low ionization stage (singly-ionized) and/or with low excitation temperature, and those from (stable) Ni, are in this group. This line group includes [Fe II] λ7155, [Ni II] λ7378, [Fe II] λ8621, [Fe II] 1.257μm, [Fe II] 1.644μm, [Co III] 11.88μm. These lines are mostly from the deflagration ash.
- **Lines which show little variations:** Lines from a high ionization stage (doubly-ionized) and/or with high excitation temperature are in this group. This line group includes [Fe III] blend at 4,700Å and [Fe III]/[Fe II] blend at 5,250Å. These lines are mostly from the detonation ash.

We compiled the existing late-time spectra of SNe Ia. Figure 2 shows the [Fe III] blend at 4,700Å and [Ni II] λ7378 for 12 SNe Ia. The [Fe III] blend does not show significant shift for all SNe Ia. On the other hand, we discovered that [Ni II] λ7378 does show variations in its central wavelength for different SNe Ia; some SNe show redshift and others blueshift. Also, we confirmed that the wavelength of [Ni II] λ7378 does not show any significant temporal evolution when late-time spectra at multiple epochs are available. These observed behaviors reject a possibility that the shift is produced by non-complete transparency or by contaminations from other lines. We emphasize that no wavelength shift of the [Fe III] blend at 4,700Å does not reject the asymmetry in the explosion. As explored above, an offset ignition also naturally explains this behavior.

Although the above observations indicate that an asymmetric, offset ignition is a generic feature of SNe Ia, the argument is based on only a few lines. This can be further tested for individual SNe for which late-time spectra are obtained with wide wavelength coverage, using various lines. This test has been performed for SN 2003hv. We have found that the lines in its late-time spectrum from an optical through mid-IR can indeed be divided into two groups, one showing the blueshift (with similar degree) and the other showing virtually no shift, and that grouping into these two is fully consistent with the above expectation. A model introducing the offset velocity of $\sim 3,500$ km s^{-1} reproduces all the emission lines, without other parameters invoked to explain these different behaviors for different lines.

4. Spectral evolution diversity

The spectral evolution diversity is one of the biggest issues in SN cosmology (§1), since it would introduce a systematic error in using them as cosmological standard candles if the diversity reflects multiple populations. In

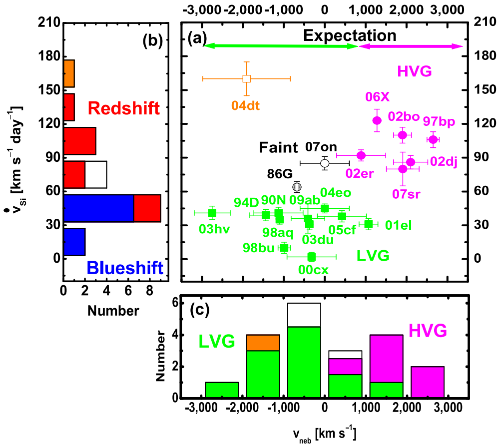

Fig. 3. A comparison between the velocity gradient ($\dot{v}_{\rm Si}$) and the late-time emission-line velocity shift ($v_{\rm neb}$) (Maeda et al. 2010c). The arrows on top indicate the expected ranges of HVG and LVG SNe Ia based on the relative observed frequencies.

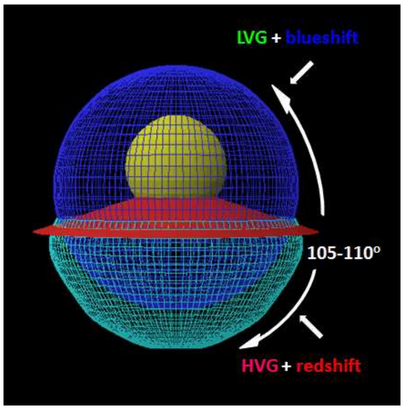

Fig. 4. A schematic picture of SN Ia ejecta (Maeda et al. 2010c). If viewed in the direction $0-110°$, an SN appears as an LVG SN in the early phase and shows blueshift in the late phase. It appears as an HVG SN and shows redshift if viewed from the other directions ($110-180°$).

Maeda et al. (2010c), we investigated the origin of this diversity. Figure 3 provides a comparison between the velocity gradient ($\dot{v}_{\rm Si}$; see §1) and the late-time emission-line velocity shift ($v_{\rm neb}$; measured by the Doppler shift of [Fe II]λ7155 and [Ni II]λ7378). We have found that these two are correlated, with HVG SNe showing redshift in late-time spectra, This indicates that these two observables must have the *same* physical origin. The correlation therefore strongly indicates that HVG and LVG SNe do not have intrinsic differences, but this diversity is merely a consequence of different viewing directions. As illustrated in Figure 4, if viewed from the direction of the offset ignition, the SN appears as an LVG SN at early phases and shows blueshifts in the late-time emission-lines. From the opposite direction, it appears as an HVG SN, and shows redshifts at late-phases.

5. Peak color

The peak color diversity is another major issue in SN cosmology. It has been shown that SNe show a variation in their $B-V$ color at peak, even after the color is standardized using the correlation between the color and the decline rate. The cause of this variation has not been specified, and thus it has not been clarified how much intrinsic variation SNe have. This can introduce an uncertainty in the extinction estimate, thus in the distance estimate.

Figure 5 shows a relation between the late-time emission-line velocity shift (thus the 'viewing direction') and the $B-V$ color of SNe (after correcting for the dependence on the decline rate). If we focus on a sub-sample of SNe which likely suffer from insignificant host extinction (selected based on the host type and SN location within the host), we see a clear correlation between the two. This indicates that a large part of this intrinsic variation is caused by the different viewing directions.

Furthermore, comparing these two observed quantities for all 20 SNe for which late-time spectra are available, we have found that the relation derived for the 'low-extinction' sample applies to the whole sample as well, except for highly red SNe which clearly suffer from significant host extinction. This suggests that the intrinsic color variation is at the level of $B-V\sim0.2$ mag, and the variation within this level is not caused by the host extinction but rather the intrinsic color of SNe.

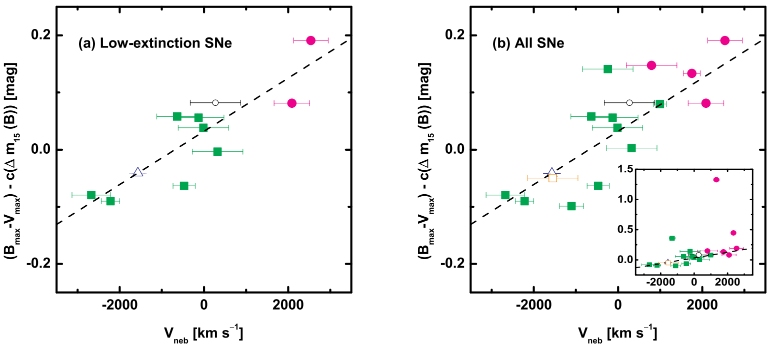

Fig. 5. The observed peak $B - V$ color (after correcting for the dependence on the decline rate) versus the nebular velocity shift, for (a) low-extinction SNe and (b) entire sample(Maeda et al. 2011). The dotted line is the best fit liner relation (3.3σ significance) for the low-extinction sample, which also seems to apply to the entire sample except for the highly red SNe with $B - V \gtrsim 0.2$ mag.

6. Concluding remarks

An asymmetric explosion scenario provides a unified solution for several major unresolved issues in SNe Ia. We have found observational evidences (1) that SNe Ia explosions are generally asymmetric driven by an offset ignition, and (2) that the spectral evolution diversity of SNe Ia is accounted for by the random viewing directions, and (3) that the color variation is explained in the same way.

These findings have many implications for cosmology using SNe as standardized candles. (1) Even if the spectral diversity would be accompanied by a bias in the distance calibration, using a large number of SNe will result in a cancellation of this effect as the viewing direction is a random effect. (2) Knowing the origin of the diversity of the color, it provides various possible options so that the intrinsic color can be derived for individual SNe.

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