We discover clear doubly-peaked line profiles in 3 out of ~ 20 type Ia supernovae (SNe Ia) with high-quality nebular-phase spectra. The profiles are consistently present in three well-separated Co/Fe emission features. The two peaks are respectively blue-shifted and red-shifted relative to the host galaxies and are separated by ~ 5000 km/s. The doubly-peaked profiles directly reflect a bi-modal velocity distribution of the radioactive $^{56}\text{Ni}$ in the ejecta that powers the emission of these SNe. Due to their random orientations, only a fraction of SNe with intrinsically bi-modal velocity distributions will appear as doubly-peaked spectra. Therefore SNe with intrinsic bi-modality are likely common, especially among the SNe in the low-luminosity (~ 40% of all SNe Ia) part on
the Philips relation ($\Delta m_{15}(B) \gtrsim 1.3$). Bi-modality is naturally expected from direct collisions of white dwarfs (WDs) due to the detonation of both WDs and is demonstrated in a 3D $0.64 M_\odot$-$0.64 M_\odot$ WD collision simulation.

Type Ia supernovae (SNe Ia) are well known as the cosmological “standard candles” that enabled the discovery of the accelerating expansion of the universe (1, 2). The absolute luminosities of these events are calibrated thanks to a tight empirical correlation (the Phillips relation (3)) between their peak luminosities and the rates at which their brightnesses decline after the peak ($\Delta m_{15}(B)$). It is widely accepted that SNe Ia are powered by the decay of $^{56}$Ni produced from the explosion of Carbon-Oxygen White Dwarfs (WDs), but the explosion mechanisms and progenitor systems remain unknown. The two most discussed scenarios, single-degenerate (accretion of a WD exceeding the Chandrasekhar limit) and double-degenerate mergers (merger of two close WDs that spiral in due to gravitational radiation), have a number of theoretical and observational challenges (4, 5). For both scenarios, a serious challenge is that a successful ignition of an explosive detonation has never been convincingly demonstrated.

Direct, head-on collisions of WDs would undoubtedly lead to successful explosions due to the strong shocks formed during the high-velocity impacts (6–11), but they had long been thought to be extremely rare – only occurring in dense stellar environments such as globular clusters – and responsible for only a negligible fraction of SNe Ia. It was recently shown by Katz & Dong (13) that the rate of direct collisions in common field triple systems may be as high as that of SNe Ia due to non-secular corrections to the Lidov-Kozai mechanism (14–16), raising the possibility that the majority of SNe Ia result from collisions. Evidence supporting this scenario was provided in Kushnir et. al. (6) in which high resolution numerical simulations of WD collisions reproduced several robust observational features of SNe Ia. In particular it

\footnote{It was also suggested that “in some cases something akin to a ‘collision’ or at least a very strong tidal interaction occurs.” in triple systems (12).}
was established that the full range of $^{56}\text{Ni}$ necessary for all SNe Ia across the Phillips relation, from the faint-end of SN 1991bg-like events to luminous 1991T-like events, can be produced by direct collisions of typical WDs.

Here we present new direct evidence for collisions as a significant channel of type Ia SNe. Motivated by the expectation of significantly non-spherical $^{56}\text{Ni}$ in WD collisions, we search for unusual nebular emission features in archival type Ia observations. We analyze 155 nebular-phase (> 170 days after the maximum light) spectra of 55 SNe Ia from the literature (17–21). We focus on 20 SNe with nebular spectra having the highest Signal-to-Noise-Ratio (SNR) in the wavelength range $\sim 5000 \AA - 7000 \AA$, among which we identify three SNe with clear evidence of doubly-peaked velocity profiles. Figure 1 shows one example, SN 2007on, which exhibits clear doubly-peaked profiles for three well-spaced Fe and Co emission-line features. In the nebular phase, the SN spectrum is dominated by emission lines, and the line profiles directly probe the underlying velocity distribution of the emitting materials along the line of sight (LOS) due to the Doppler effect. At such a late phase, $^{56}\text{Ni}$ has completely decayed into $^{56}\text{Co}$ and $^{56}\text{Fe}$, and the Co/Fe lines retain the velocity distribution of the $^{56}\text{Ni}$.

A general challenge in interpreting the SNe line profiles is that many spectral features are the results of “blends” from more than one line at similar wavelengths. A reasonable concern is that an observed doubly-peaked line profile could be due to two (or more) adjacent lines within an underlying single-peak velocity distribution. Several lines of evidence show that this is not the case for SN 2007on, so that the profile requires a bi-modal velocity distribution:

1. The doubly-peaked line profiles occur for three widely-separated spectral features emitted by two elements (Co and Fe), and they have the same peak-to-peak spacing $\Delta \lambda / \lambda \approx 0.02$. Furthermore, the shapes of the three observed profiles are consistent with the same underlying velocity distribution. This is demonstrated in the bottom panel of Figure 1, where the spectra in three regions are shown to be well fitted by the convolution of a
template spectrum with the same double-component velocity kernel (red line in the sub-panel of the middle panel). The template (black line in the middle panel) is chosen to be the nebular-phase spectrum of SN 1999by due to its exceptionally narrow line width (similar to the famous SN 1991bg with SN 1999by having a higher SNR). A remarkable coincidence would be required in order that three additional lines conspire to produce such consistent profiles.

2. Other supernovae at a similar phase (and thus a similar ratio of decaying Co and stable Fe) have similar line ratios among the three features but do not show the doubly-peaked profile. This is illustrated in the top panel of Figure 1 from comparison with the well-observed, “normal” supernova, SN 2011fe – the closest type Ia SNe seen in decades. While the line ratios of the two SNe are practically identical, the profiles of SN 2011fe show a clearly single-peaked profile. The features also show stable shapes in the nebular phase when multiple spectra have been taken for the same supernova.

3. The profile in the spectral range $\sim 5800 - 6000$ Å is overwhelmingly dominated by one [CoIII] feature. Hence the line profile is “clean” and reliably reflects the underlying velocity distribution without the need of modeling. This is supported by nebular spectrum modeling (22,23) and re-affirmed by examining the spectra of SN 1991bg and SN 1999by where the line widths are sufficiently narrow to allow for clear line identifications (24). The Co origin of the line has been firmly established by examining the multiple-epoch spectra for the same SNe taken in the intervals 170-400 days, during which the Co decays significantly. During the intervals, the lines maintain the same shape while the relative strengths with respect to Fe lines weaken according to the nuclear decay rate of Co (25).

\[2\text{The [CoIII] feature at 5900 Å is composed of two narrowly separated components at 5890 Å and 5909 Å, but their velocity separation (\sim 1000 km/s) is much smaller than the peak-to-peak separation of the double-line profile (\sim 5000 km/s)}\]
For SN 2007on, another nebular spectrum was taken at $\sim 356$ days after the peak (26), and the doubly-peak profile is clearly present in the Co feature at 5900 Å, albeit with lower SNR than the one taken at $\sim 286$ days. The other two features at $\sim 5300$ Å and $\sim 6600$ Å are not as reliable as the 5900 Å due to the possible contributions from nearby lines.

SNe with high-SNR nebular spectra spanning the full range of $\Delta m_{15}(B)$ are shown in Figure 2 (in ascending order of their $\Delta m_{15}(B)$ if available) in order to identify doubly-peaked lines, we attempt to fit each of them using a simple, single-peak velocity convolution kernel with $dM/dv_{\text{los}} \propto 1 - (v_{\text{los}}/v_{\text{mod}})^2$. The spectra and best fits are shown in Fig. 2. The Fe and Co features of most SNe can be well described by a single-peak velocity distribution. We identify 3 supernovae, SN 2007on, SN 2005am and SN 2003gs with clearly doubly-peaked spectra that consistently appear in the three features (marked in red). An additional SN, SN 2008Q, shows a (sloped) “flat-top” profile, which significantly deviates from a single peak. In Figure 3, we show that each of these four spectra can be well fitted by convolving a two-component velocity profile with the template of SN 1999by. We identify an additional SN, SN 2003hv with $\Delta m_{15}(B) = 1.6$ with hints of doubly-peak line profiles with unequal peaks, but the data do not allow unambiguous identification. Note that SN 2003hv was reported to have nebular line blue-shifted by $\sim 3000$ km/s (26), and this could be the result of an underlying bi-model velocity distribution with two unequal components. There are unquantified selection effects in this sample, so the numbers above are not suitable for statistical studies. Nevertheless, the SNe Ia with underlying doubly-peaked components are certainly not rare. Moreover, as suggested by the $\Delta m_{15}(B)$ values of these SNe, the bi-modal velocity distribution must be quite common.

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3We exclude from the sample two SNe (SN 1986G and SN 2004bv) with a strong Na I D absorption feature at $\lambda\lambda 5890, 5896$ Å identified at earlier epochs since such a feature hinders clear identification of doubly-peak profile at $\sim 5900$ Å. It is also important to be cautious about spectra with over-subtraction H-α emission line at 6563 Å from the host-galaxy, which may confuse the analysis of the feature at $\sim 6600$ Å.
among fast declining ($\Delta m_{15}(B) > 1.3$), low-luminosity SNe, which comprise 40% of all SNe Ia in a volume-limited sample (27).

A bi-modal velocity distribution is naturally expected from direct WD-WD collisions due to the detonations of both WDs. In the high-resolution 2D simulations performed by Kushnir et al. (6) for zero impact-parameter WD-WD collisions, detonation of both WDs occurs in all cases, leading to two centers of explosion. However, while there are some cases with bi-modal $^{56}$Ni velocity distributions resulting from these 2D simulations, their occurrence turned out to be rare and restricted to highly-tuned viewing angles. In Figure 4 we present the results of a 3D simulation of the collision of two 0.64$M_\odot$ white dwarfs with a non-zero impact parameter of 0.2. The simulation is performed using FLASH 4.0 (29) (an adaptive mesh refinement Eulerian code with thermonuclear burning using a 13 isotope alpha-chain reaction network (28)) with a resolution of 8km (see Kushnir et. al. 2014 in prep for further details), comparable to the converged resolutions used in the 2D simulations by Kushnir et. al (2013) (6). The upper panel shows the projected velocity distribution of the total ejecta mass and that of the $^{56}$Ni mass in the orbital plane of the colliding WDs. The $^{56}$Ni mass consists of two components with centers that are separated by several thousand km/s. The distributions of $^{56}$Ni along the line of sight are shown in the bottom panel for numerous viewing angles. The chance of seeing doubly-peaked line profiles that are similar in velocity separations to the observed ones is significant. It is also interesting to note that a narrow velocity distribution similar to that seen in SN 1999by or SN 1991bg is observed from directions perpendicular to the line connecting the centers of the two $^{56}$Ni components. A comprehensive study with the full range of impact parameters is required to derive useful statistics of the expected velocity distributions and will be presented in Kushnir et. al (2014).

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The impact parameter is defined as the ratio between $r_p$, which is the minimal separation between the WDs along their trajectory that would have been obtained if they were point masses, and the sum of the two WD radii. In the 3D simulation presented here, $r_p = 3300$ km.
Our results imply that any proposed scenario to explain the majority of SNe Ia must have a considerable fraction of the explosions producing bi-modal velocity distributions of $^{56}$Ni. Direct collisions of WDs is a promising channel for which the $^{56}$Ni distribution can be definitively calculated with no free parameters from the models. High-quality nebular-phase spectra, with an emphasis on SNe with fast post-peak decline $\Delta m_{15}(B) > 1.3$, are needed to quantify the occurrence rate of the doubly-peaked profiles. Bi-model velocity distributions can sometimes masquerade as single-peak line profiles, and for some of them, their bi-modal nature may be revealed by detecting the shifts of line peaks with respect to the rest frame. By comparison of accurate computations and comprehensive observations in the near future, the collision models can be unambiguously tested as the primary channel for type Ia SNe. The rich and detailed structure of the nebular line profiles will either be a smoking gun of the collision model or rule it out.

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Supplementary material

Two-component velocity convolution kernel for fitting of the doubly-peaked line profiles

Each of the 4 SNe with a doubly-peaked or flat-top line profile was fitted in Figure 3 by convolving a velocity kernel of two components with a template spectrum (SN 1999by). The kernel is given by

\[
\frac{dM}{dv_{\text{LOS}}} \propto \left( 1 - \frac{(v_{\text{LOS}} - v_{\text{shift,1}})^2}{v_{\text{mod,1}}^2} \right) + r \left( 1 - \frac{(v_{\text{LOS}} - (v_{\text{shift,2}})^2}{v_{\text{mod,2}}^2} \right) \tag{1}
\]

and it has 5 free parameters, including the two shifts \(v_{\text{shift,1,2}}\), the two widths \(v_{\text{mod,1,2}}\) and the peak ratio of the components, \(r\). The shifts can be alternatively described as a velocity shift \(v_{\text{shift}} = 0.5(v_{\text{shift,1}} + v_{\text{shift,2}})\) and velocity separation \(v_{\text{sep}} = v_{\text{shift,2}} - v_{\text{shift,1}}\).

The fit parameters for models presented in Figure 3 are given in the table below.

| SN     | \(v_{\text{shift}}\) | \(v_{\text{mod,1}}\) | \(v_{\text{mod,2}}\) | \(v_{\text{sep}}\) | \(r\) |
|--------|----------------|----------------|----------------|----------------|-----|
| SN 2007on | -209 | 1338 | 2000 | 5330 | 0.89 |
| SN 2003gs | 1330 | 1300 | 1270 | 4300 | 0.6  |
| SN 2005am | 1111 | 3347 | 4195 | 6500 | 0.91 |
| SN 2008Q  | -422 | 2927 | 7105 | 6745 | 1.24 |
Figure 1: The nebular spectrum of SN 2007on (top panel, black) has a clear doubly-peaked line profile appearing in three different Co/Fe emission features. The single-peak nebular spectrum of the “normal” SN 2011fe at a similar epoch is shown for comparison (green). The three double-peak profiles reflect the same bi-modal line-of-sight velocity distribution of the emitting Co/Fe materials. This is shown by fitting the spectrum with the convolution of a template spectrum using the same double-component velocity kernel (inset of middle panel, red). The template is chosen to be the narrow-width spectrum of SN 1999by (middle panel, black). The convolved spectrum (bottom panels, red) is compared with each of the three features of SN 2007on (bottom panels, black) by linear fitting that allows free normalizations and baseline shifts for each feature. The three features are due to blends of [FeIII] and [FeII] (∼5300Å), [CoIII] (∼5900Å), and blends of [CoIII] and [FeII] (∼6600Å), respectively (22–24)
Figure 2: High-quality nebular spectra of SNe spanning the full range of $\Delta m_{15}(B)$ on the Phillips relation ($0.8 < \Delta m_{15}(B) < 2$) are presented (middle panel, black). The spectra are sorted by the $\Delta m_{15}(B)$ values (shown on the right). Most of the spectra are single-peaked and are well fitted by a simple quadratic velocity distribution convolving with the template spectrum of SN 1999by. The best fits are shown in the sub-panels (green) where they are scaled to allow comparison with the corresponding spectral features (black) due to Fe and Co emissions, respectively. SN 2005am is identified with either doubly-peaked (SN 2007on, SN 2005am and SN 2003gs) or flat-top (SN 2008Q) line profiles, and the profiles are consistent between at least two features. SN 2003hv shows hints of double-peak profiles at $\sim 5300\text{Å}$ and $\sim 6600\text{Å}$, but it is ambiguous at $\sim 5900\text{Å}$. Note that the spectrum of SN 2005am is taken from two epochs (298d and 381d) since the high SNR spectrum at 298d did not cover the $\sim 5300\text{Å}$ feature.
Figure 3: The four SNe spectra that cannot be well described by single-peaked components are shown here. For each SN, a simple common velocity kernel with two quadratic components is used to fit all three features by convolution with the template spectrum of SN1999by (see Fig. 1). The convolved spectra are in excellent agreement with all the features of SN 2007on, SN 2003gs and SN 2005am. The agreement is reasonable for the features of SN 2008Q. The agreement suggests that the underlying velocity distribution are bimodal for these SNe. The spectrum shown in the upper sub-panels for SN 2003gs is binned to enhance clarity.
Figure 4: Results of a 3D simulation of a 0.64$M_\odot$-0.64$M_\odot$ WD collision with an impact parameter of 0.2. The results shown are at a late phase when the ejecta are expanding homologously. The projected velocity distribution of the $^{56}$Ni mass in the orbital plane is shown in the top right panel, and that for the total mass shown in the top left panel. $^{56}$Ni mass is concentrated in two well separated components, which are related to the two ignition spots in the two WDs. The resulting line of sight velocity distributions that are observed at numerous viewing angles are shown in the bottom left panels (blue). The viewing direction is described by spherical coordinates with $\theta$ the polar angle measured with respect to the $z$ axis (direction of the angular momentum) and $\phi$ is the azimuthal angle in the $x-y$ plane, measured with respect to the $x$ axis. The resulting velocity distribution can be directly compared to the line profiles near 5900Å, which is a “clean” [CoIII] line with minor blend at the red side. The observations are shown in velocity space, $v = c(\lambda - 5900\text{Å})/5900\text{Å}$ for several SNe shown in Fig. 2.