A significantly off-centre ^{56}Ni distribution for the low-luminosity type Ia supernova SN 2016brx from the 100IAS survey*

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ABSTRACT

We present nebular-phase spectra of the Type Ia supernova (SN Ia) 2016brx, a member of the 1991bg-like subclass that lies at the faint end of the SN Ia luminosity function. Nebular spectra are available for only three other 1991bg-like SNe, and their Co line centres are all within $\lesssim 500\,\mathrm{km\,s^{-1}}$ of each other. In contrast, the nebular Co line centre of SN 2016brx is blue-shifted by $>1500\,\mathrm{km\,s^{-1}}$ compared to them and by $\approx 1200\,\mathrm{km\,s^{-1}}$ compared to the rest frame. This is a significant shift relative to the narrow nebular line velocity dispersion of $\lesssim 2000\,\mathrm{km\,s^{-1}}$ of these SNe. The large range of nebular line shifts implies that the ^{56}Ni in the ejecta of SN 1991bg-like events is off-centre by $\sim 1000\,\mathrm{km\,s^{-1}}$ rather than universally centrally confined as previously suggested. With the addition of SN 2016brx, the Co nebular line shapes of 1991bg-like objects appear to connect with the brighter SNe Ia that show double-peaked profiles, hinting at a continuous distribution of line profiles among SNe Ia. One class of models to produce both off-centre and bimodal ^{56}Ni distributions is collisions of white dwarfs with unequal and equal masses.

Key words: supernovae: general – (stars:) supernovae: individual: SN 2016brx.

1 INTRODUCTION

SNe Ia are believed to be the result of thermonuclear explosions of white dwarfs (WDs), but the triggering mechanism of the explosion and progenitor systems are unknown (e.g. see the reviews by Maoz,

Mannucci & Nelemans 2014; Wang 2018). Nebular-phase spectra can probe the inner region of the SN ejecta because the material is optically thin. Nebular spectra of SNe Ia are dominated by Co and Fe emission lines, both of which are decay products of the ^{56}Ni synthesized in the explosion. In particular, the identification of Co and its decay through the [Co III] nebular emission lines near 5900 Å provide important evidence that SNe Ia are powered by the decay chain ^{56}Ni → ^{56}Co → ^{56}Fe (Axelrod 1980; Kuchner et al. 1994; Childress et al. 2015). Since they can only be obtained

several months to years after the explosion, nebular spectra are also challenging to obtain because the supernovae are optically faint at these late phases. Owing to this, there are few published nebular spectra (see e.g. Maeda et al. 2010; Dong et al. 2015; Graham et al. 2017; Maguire et al. 2018).

The least luminous SNe Ia on the width-luminosity relation (Phillips 1993), the so-called 1991bg-like events named after the prototype SN 1991bg (Filippenko et al. 1992; Leibundgut et al. 1993; Turatto et al. 1996), are also the most challenging objects for obtaining nebular spectra. The nebular spectra of SN 1991bg have narrow line widths (velocity dispersion $\sigma_v \approx 1000\,\mathrm{km\,s^{-1}}$), allowing for precise line identification (Turatto et al. 1996).

The [Co III] nebular emission feature near 5900 Å consists of two lines at 5888 and 5906 Å (wavelength in air, NIST ASD 2018; Smillie et al. 2016). The 5888 Å line is expected to be about 3–4 times stronger than the 5906 Å line and the expected (weighted) mean line position is at (5888 × 3.5 + 5906)/4.5 = 5892 Å[1]. Any deviation from the theoretically expected position could either imply a misunderstanding of the atomic physics or a Doppler shift due to an off-centre distribution of ^{56}Ni in the ejecta. It came as a surprise that in the nebular spectrum of SN 1991bg the feature peaked at 5906 Å, coinciding with the theoretically expected weaker line of the two. This led Mazzali et al. (1997) to suggest that the 5906 Å line may instead be dominant and thus ^{56}Ni is centrally concentrated in the ejecta of SN 1991bg. There are two other 1991bg-like events with nebular spectra, namely SN 1999by (Garnavich et al. 2004; Silverman et al. 2012) and SN 2005ke (Folatelli et al. 2013), and like 1991bg, they have both narrow line widths ($\sigma_V \lesssim 2000\,\mathrm{km\,s^{-1}}$) and line centres within $\sim$350 km s^{-1} of 5906 Å.

Here we examine two nebular spectra of the 1991bg-like event SN 2016brx. For this fourth 1991bg-like SN with nebular spectra, the $\sim$5900 Å [Co III] nebular feature peaks at 5870 Å, which is blue-shifted by nearly 2000 km s^{-1} compared to 5906 Å. Taken together with the other three SNe in this class, it supports the theoretically expected central wavelength of 5892 Å for the $\sim$5900 Å [Co III] feature, and suggests that 1991bg-like SN Ia have asymmetric ^{56}Ni ejecta with typical centroid velocities (blue- or red-shifted) of $\sim$1000 km s^{-1}.

2 OBSERVATION

SN 2016brx was discovered by Stuart Parker in the elliptical galaxy NGC 7391 ($z = 0.010167$; Jones et al. 2009) at UT 2016 April 19 17:18:51 (Parker 2016). It was classified as an SN Ia based on a du Pont/WFCCD (Wide-Field CCD) spectrum taken on UT 2016 June 17 (Morrell & Shappee 2016). The supernova was also detected by the All-Sky Automated Survey for Supernovae (ASAS-SN, Shappee et al. 2014) in V band (Holoien et al. 2017). In Appendix A, we show that the du Pont spectrum and light curve are consistent with an SN 1991bg-like event.

Late-time spectra of 2016brx were obtained at the 10.4m Gran Telescopio Canarias (GTC) and the 6.5m Magellan Clay telescope as part of the nebular spectra for 100 type IA Supernovae (100IAS)

survey. The goal of 100IAS is to systematically obtain nebular spectra from a volume-limited sample of low-z SNe Ia primarily based on ASAS-SN SN discoveries and/or recoveries, where the survey completeness can be quantified based on ASAS-SN detections.

The late-time spectra of SN 2016brx were obtained using the GTC OSIRIS (Optical System for Imaging and low-Intermediate-Resolution Integrated Spectroscopy) spectrograph on UT 2016 August 13 and the Magellan Clay LDSS3 (Low Dispersion Survey Spectrograph 3) on UT 2016 October 20. According to the peak time derived in Appendix A, their post-maximum phases are approximately at $\approx$+ 120 d and $\approx$+ 190 d, respectively. The integration times for the GTC (OSIRIS) and Magellan (LDSS3) spectra were 3600 and 12600 s, obtained in 1800 s exposures, and the spectral resolutions were $R \approx 540$ and $R \approx 650$. We follow standard calibration and reduction procedures using IRAF tasks. The spectra are available on WiseREP (Yaron & Gal-Yam 2012).

3 RESULTS

In Fig. 1, we show the rest-frame Magellan spectrum of SN 2016brx (phase $\approx$190 d, red solid line) along with the nebular spectrum of the 1991bg-like event SN 1999by (phase =184 d, blue solid line; Silverman et al. 2012). The emission lines in the two spectra have similar line profiles and ratios, confirming the 1991bg-like nature of SN 2016brx. Remarkably, however, the spectral features of SN 2016brx are blue-shifted relative to those of SN 1999by. In particular, the Fe and Co spectral features in the range 4500–7000 Å are systematically shifted in velocity between the two supernovae.

The [Co III] feature near 5900 Å is particularly useful for studying the underlying ^{56}Ni velocity distribution (e.g. Mazzali et al. 1997; Dong et al. 2015) since it has little contamination from other lines[2] (e.g. Axelrod 1980; Maguire et al. 2018; Brandt & Katz, in preparation). As discussed in §1, the centroid position of this feature in previous 1991bg-like SNe were puzzlingly close to the (theoretically expected) weaker 5906 Å line rather than the stronger line at 5888 Å, and it was suggested that the 5906 Å line might actually be the stronger one (Mazzali et al. 1997).

The inset of Fig. 1 shows the region around 5900 Å, showing that the [Co III] feature in 2016brx at $\approx$190 d (red solid lines) is centred at $\approx$5870 Å. The GTC spectrum of 2016brx taken at $\approx$120 d is shown as a black solid line. We model the spectra in the range of 5700–6000 Å with Gaussian profiles, and the best-fitting line centres are at 5868 and 5871 Å for the Magellan and GTC spectra, respectively. The line widths of the two spectra are also similar with $\sigma_{v,190\,\mathrm{d}} = 2100\,\mathrm{km\,s^{-1}}$ and $\sigma_{v,120\,\mathrm{d}} = 2350\,\mathrm{km\,s^{-1}}$. The consistency in line centres and shapes of the $\sim$5900 Å features over the two epochs demonstrates that the stability of the [Co III] feature. Taking the theoretically expected value of 5892 Å as the reference wavelength (see Section 1), the feature in SN 2016brx is blue-shifted by about 1200 km s^{-1}, while in SN 1999by it is red-shifted by about 1100 km s^{-1} based on Gaussian line-profile fitting. The Gaussian line-profile fitting results for all four SN 1991bg-like SNe with nebular spectra are listed in Table 1. The fact that the velocity blue-shift of SN 2016brx is comparable in amplitude with the velocity redshifts of earlier events points to a consistent picture in which the atomic physics is correct (the 5888 Å line is stronger) and

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[1]The radiative rate (Einstein A coefficient) of the 5888 Å line is about 2.6 times larger than that of the 5906 Å line (e.g. Axelrod 1980; Storey & Sochi 2016) and the non-LTE occupation of the upper level of the transition for the 5888 Å line is higher than that of the 5906 Å line by a factor of [1.15–1.5] across a broad range of electron densities ($10^{5.5}\mathrm{cm^{-3}}$–$10^{7.5}\mathrm{cm^{-3}}$) and temperatures (5000–10 000 K; Brandt & Katz, in preparation). This results in an expected ratio of $2.6 \times [1.15$–$1.5] = [3$–$4]$ between the lines.

[2]There are claims in the literature for a significant contribution of Na I D (e.g. Mazzali & Hachinger 2012), but this interpretation is not supported by the studies of Dessart et al. (2014); Childress et al. (2015); Maguire et al. (2018), and Brandt & Katz (in preparation)
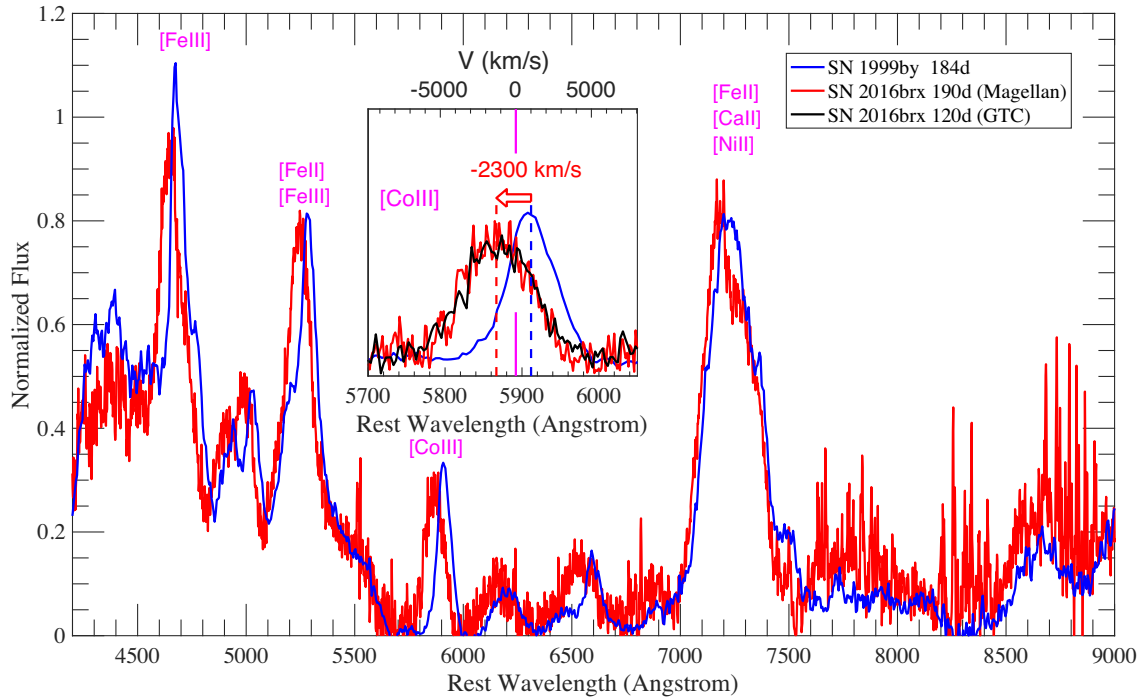
Figure 1. The rest-frame nebular-phase spectra of SN 2016brx. The ≈190 d Magellan nebular spectrum of SN 2016brx is shown in red solid lines. It has similar line profiles and ratios to the spectrum of the 1991bg-like event SN 1999by at a similar phase of 184 d (Silverman et al. 2012) shown in blue solid lines. However, the Fe and Co nebular features (essentially all prominent lines between ~4500 and 7000 Å) of SN 2016brx are systematically blue-shifted compared to SN 1999by. The ~5900 Å [Co III] feature is shown in the inset, and the line centre for 2016brx (marked with red dashed line) is blue-shifted by ≈2300 km s^{-1} relative to 1999by (marked with blue dashed line). The inset also includes the ≈120 d GTC spectrum of SN 2016brx (black solid line). The line centres of both the Magellan and GTC spectra are consistently blue-shifted by ~1200 km s^{-1} with respect to the rest frame, while that of the SN 1999by is red-shifted by ~1100 km s^{-1}. The rest-frame line centre of [Co III] at 5892 Å is marked by a magenta solid line.

Table 1. [Co III] nebular velocity shifts and widths for four 1991bg-like SNe Ia. Best-fitting Gaussian profiles using a line ratio of 3.5 between 5888 and 5906 Å lines are reported.

SN	Phase (d)	v_{shift} (km s^{-1})	σ_v (km s^{-1})
2016brx	120	−1070	2350
2016brx	190	−1220	2100
2005ke	120	540	2150
1999by	183	1050	1550
1991bg	143	770	1200
1991bg	203	640	1000

the 1991bg-like events have asymmetric ^{56}Ni ejecta with centroid velocities of ~1000 km s^{-1}.

The [Co III] features at ~5900 Å for both Magellan and GTC spectrum of 2016brx have velocity dispersions of $\sigma_v \approx 2200$ km s^{-1}, consistent with the low values measured for the other 1991bg-like events ($\sigma_v \approx 1100$ km s^{-1} for 1991bg, $\sigma_v \approx 1600$ km s^{-1} for 1999by and $\sigma_v \approx 2200$ km s^{-1} for 2005ke). In comparison, we measure the σ_v of 2011fe, a 'normal' SN Ia, and it is ≈4000 km s^{-1}.

4 A CONTINUOUS DISTRIBUTION OF NEBULAR LINE MORPHOLOGIES?

There is evidence that type Ia supernovae have a continuous distribution of observational properties, including their light curves (e.g. Phillips 2012; Burns et al. 2014), early spectra (e.g. Nugent et al. 1995; Branch, Chau Dang & Baron 2009), and nebular line widths (e.g Mazzali et al. 1998; Kushnir et al. 2013). An intriguing yet un-

resolved question is whether the least luminous subclass of SNe Ia – the 1991bg-like events – are isolated or connected with the brighter SNe Ia. Key clues may lie in objects whose luminosities are between 1991bg-like events ($M_B \gtrsim -18$) and 'normal' SNe Ia ($-19.7 \lesssim M_B \lesssim -19$). Many of the objects in this intermediate luminosity range of $-19 \lesssim M_B \lesssim -18$ are called 'transitional' objects in the literature (e.g. Branch et al. 2006; Pastorello et al. 2007; Gall et al. 2018). Their photometric properties appear to connect 1991bg-like events with the rest of SNe Ia population on a continuum (e.g. Burns et al. 2014).

In Fig. 2, we show the ~5900 Å [Co III] nebular features of the fainter half ($M_B \gtrsim -19$) of the SNe Ia sample[3] from Dong et al. (2015) along with 2016brx (red solid line). The 1991bg-like events (the bottom 4 in Fig. 2) are all single peaks with narrow widths (σ_V ranging from ~1000–2000 km s^{-1}), while the rest in the sample are wider (by a factor of >2) and have heterogeneous morphologies including double-peaked profiles with both blue- and red-shifted components (Dong et al. 2015; Mazzali et al. 2018). Are 1991bg-like events distinct?

The 1991bg-like events 1991bg and 1999by have [Co III] line width and shape that are starkly different from the brighter 2007on and 2005am with their double-peaked profiles. In particular, the lines of the brighter objects are wider than those of the former by a factor of several. However, the 1991bg-like events 2005ke

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[3]We have added the early nebular spectrum of 2005ke at 120 d, which was not included in Dong et al. (2015) because it did not satisfy the criterion of phase >170 d.
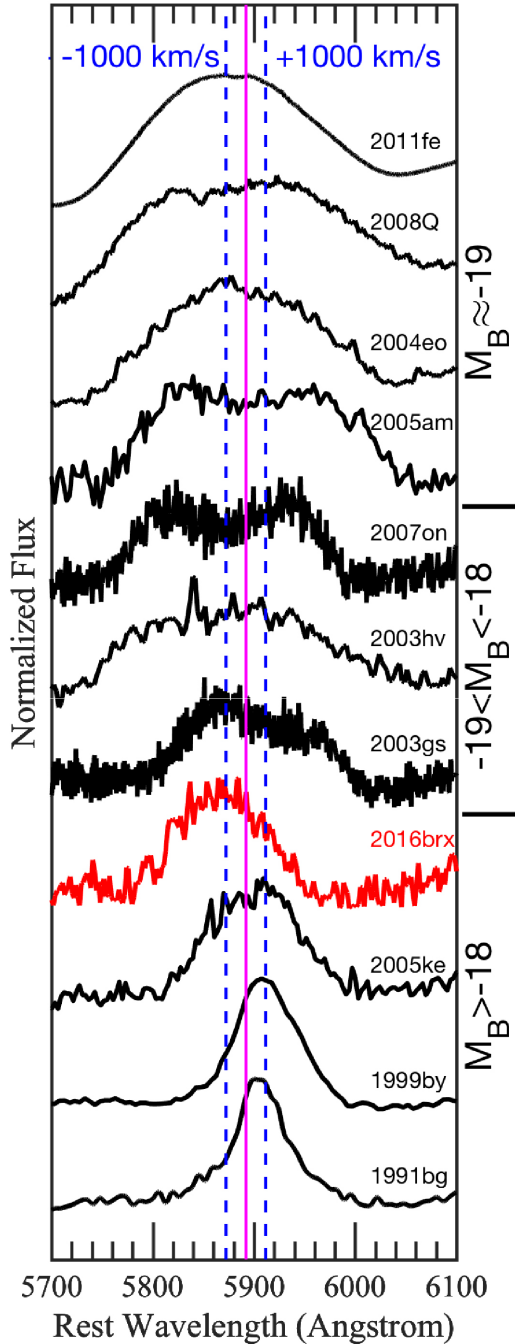
Figure 2. A possibly continuous distribution of nebular [Co III] line profiles for SNe Ia. The [Co III] nebular features at 5900 Å are shown for 2016brx and all the nebular spectra of the faint half of the sample from Dong et al. (2015). The bottom four SN 1991bg (Turatto et al. 1996), SN 1999by (Silverman et al. 2012), SN 2005ke (Silverman et al. 2012), and SN 2016brx (this work, shown in red) are 1991bg-like events at the low end of SNe Ia luminosity function ($M_B > -18$). The three supernovae in the middle, SN 2003gs (Silverman et al. 2012), SN 2003hv (Leloudas et al. 2009), and SN 2007on (Folatelli et al. 2013; Gall et al. 2018) have peak luminosities of $-19 < M_B < -18$. The four supernovae at the top, 2005am (Leonard 2007), 2004eo (Pastorello et al. 2007), 2008Q (Silverman et al. 2012), and 2011fe (Shappee et al. 2013) have $M_B \approx -19$.
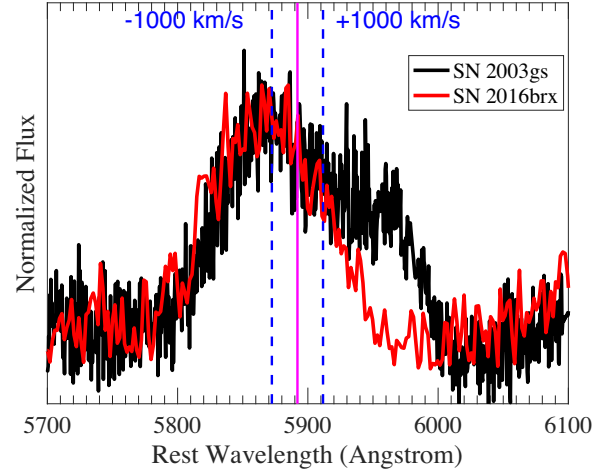

Figure 3. A comparison of the [Co III] nebular features at ∼5900 Å of 2016brx and 2003gs. The flux is normalized to the line maximum.

and 2016brx have wider profiles, and along with the brighter event 2003gs with its non-equal double peaks, bridge much of the gap. In Fig. 3, the spectrum of 2016brx is compared to 2003gs. While 2003gs shows two peaks, the flux is dominated by the blue-shifted component, which happens to have a nearly identical shape (including width and blue shift) to the profile of 2016brx. The difference between the two appears to be the presence of a weaker red-shifted component in 2003gs. Furthermore, the photometric properties of 2005ke bridge the gap between 1991bg and the transitional events (Phillips 2012).

It is thus possible that the nebular profiles of 1991bg-like and the brighter objects do not form distinct groups but rather form a continuum roughly along a sequence ordered by [Co III] line width (which is correlated with luminosity, Kushnir et al. 2013). 1991bg represents the faintest event with the narrowest width. 1999by and 2005ke/2016brx are progressively wider. 2003gs is brighter, and its dominant component of the nebular profile is similar to the profile of 2016brx (both in width and shift) but has a small extra red-shifted component. Then objects like 2007on have different combinations of blue-shifted and red-shifted components. Even brighter objects such as 2008Q and 2005am are wider and possibly transition to 'normal' SNe Ia. More observations are needed to probe the nebular spectra landscape of subluminous objects to verify the continuity.

5 DISCUSSION

The shifted [Co III] lines in the 1991bg-like events provide direct evidence for significant deviation of ∼1000 km s^{-1} from spherical symmetry in the distribution of the ^{56}Ni produced in these explosions. Maeda et al. (2010) claimed to find asymmetry in stable iron-group elements (e.g. ^{58}Ni and ^{54}Fe) of SNe Ia by deriving velocities from [Fe II] and [Ni II] nebular lines, especially the spectral feature at ∼7200 Å that they attribute to [Fe II]λ7155 and [Ni II]λ7383. However, possibly significant contamination from [Ca II] lines can introduce model-dependent uncertainties (e.g. Botyánszki & Kasen 2017). The large width of the ∼7200 Å feature in 2016brx likely indicates a blend of [Fe II], [Ni II], and [Ca II], and thus detailed models are needed to derive reliable centroid velocities from this feature.

A simple possibility to account for the ^{56}Ni centroid shift is the velocity of the exploding WD. Motion within the galaxy is

typically much slower than $1000\,\mathrm{km\,s^{-1}}$ and thus unlikely to explain the observed shifts. In particular, the central velocity dispersion of NGC 7391, which hosts 2016brx, is $250\,\mathrm{km\,s^{-1}}$ (Simien & Prugniel 1998), which is much smaller than the observed shift of $\approx 1200\,\mathrm{km\,s^{-1}}$. If the WD explodes during a merger with another less massive WD in a tight orbit shrinking due to gravitational-wave radiation (e.g. Iben & Tutukov 1984; Guillochon et al. 2010; Pakmor et al. 2013; Shen et al. 2018; note that an ignition has not been demonstrated to occur), it may reach the observed shift velocity of $1000\,\mathrm{km\,s^{-1}}$ if its lighter WD companion is heavier than $\approx 0.5 M_{\odot}$ (see Fig. B1 in Appendix B).

An orbital-velocity origin for the shift cannot account for the double-peaked profiles seen in supernovae brighter than 1991bg-like events, implying that a different explanation for these deviations from spherical symmetry is required. Deviations from spherical symmetry may arise due to asymmetries in the explosion itself (e.g. Maeda et al. 2010; Raskin et al. 2010; Kushnir et al. 2013; Dong et al. 2015; Bulla et al. 2016). In particular, bimodal ^{56}Ni distributions were shown to occur naturally in 3D simulations of collisions of equal-mass WDs (Dong et al. 2015). We are not aware of any other model that has so far been demonstrated to produce such a feature (see, e.g. van Rossum et al. 2016). Given that a shifted single peak does not have the mirror-symmetry expected in an equal mass collision, a collision interpretation for the shifted lines of 1991bg-like events would require an unequal mass collision. Future 3D calculations of the collisions will allow this question to be addressed in more detail.

Both velocity shifts and double-peaked profiles are indicative of asphericity, which provide important clues for the explosion mechanism of SNe Ia. Whether or not they are related is a key issue for identifying their physical origin. More nebular spectra of SNe Ia fainter than -19 are required to map the diverse landscape of ^{56}Ni morphologies and address this issue observationally. In particular, a large and complete sample of these spectra are required to understand their distribution and whether they form a continuous distribution. This is a primary goal of the 100IAS survey.

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SUPPORTING INFORMATION

Supplementary data are available at *MNRASL* online.

APPENDIX A: CLASSIFICATION AND PHASE ESTIMATES OF SN 2016BRX
APPENDIX B : ORBITAL VELOCITY SHIFT DUE TO A SIMPLE BINARY WD MERGER MODEL

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