Red vs Blue: Early observations of thermonuclear supernovae reveal two distinct populations?

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ABSTRACT
We examine the early phase intrinsic \((B - V)_0\) color evolution of a dozen Type Ia supernovae discovered within three days of inferred time of first light \((t_{first})\) and have \((B - V)_0\) color information beginning within 5 days of \(t_{first}\). The sample indicates there are two distinct early populations. The first is a population exhibiting blue colors that slowly evolve, and the second population exhibits red colors and evolves more rapidly. Placing the first sample on the Branch diagram (i.e., ratio of Si II \(\lambda\lambda 5972, 6355\) pseudo-Equivalent widths) indicates all blue objects are of the Branch Shallow Silicon (SS) spectral type, while all early-red events – except for the peculiar SN 2012fr – are of the Branch Core-Normal (CN) or Cool (CL) type. Inspection of their light curves indicate early-blue events are typically more luminous with slower declining light curves than those exhibiting early-red colors. A number of potential processes contributing to the early emission are explored, and we caution that great care must be taken when interpreting early-phase light curves.

Keywords: supernovae: general

1. INTRODUCTION
Type Ia supernovae (SNe Ia) are well-studied astrophysical events generally thought to be the thermonuclear disruption of a carbon-oxygen (C/O) white-dwarf (WD) in a binary system. In order for future SN Ia experiments to expand upon our knowledge of dark energy, a substantial improvement upon their distance accuracy is required. This is likely only to be achieved by increasing our understanding of SNe Ia progenitors and their explosion physics. Early-phase observations of SNe Ia offer a unique window to better understand their origins. To date early observations have allowed for a direct constraint on the size of the WD progenitor of SN 2011fe (Nugent et al. 2011; Bloom et al. 2012) using the lack of a shock cooling signal (Piro et al. 2010), and in about a dozen cases, have provided robust constraints on the size of any potential companion (see Shappee et al. 2018, and references therein).

To date nearly 20 SNe Ia have been discovered within three days of their inferred time of first light \((t_{first})\), and this sample exhibits interesting diversity. The early light curves of one group rise exponentially and are well-fit by a single power law function (e.g., Nugent et al. 2011; Olling et al. 2015). In a second group, the early light curves exhibit a \(\approx 3\) day linear rise in flux followed by an exponential rise (e.g., Hosseinzadeh et al. 2017; Miller et al. 2018; Contreras et al. 2018). Such objects are better fit with a double (or broken) power law fit.
Figure 1. A mosaic of colored images of our early red vs. blue sample with the position of the SNe indicated with stars. Images were constructed using either SDSS gri-band, DSS IR-red-blue, or (in one case) Pan-STARRS gri-band archival images.

It is a matter of open debate on the physics driving single vs. double power-law fit SN Ia with possibilities ranging from companion interaction (Kasen 2010; Maeda et al. 2014) to enhanced mixing of radioactive elements (Piro & Nakar 2013; Piro & Morozova 2016; Magee et al. 2018). Furthermore, the full diversity of early phase properties is likely far from fully explored as highlighted by the early light curves of MUSSES1604, which showed unique evolution (Jiang et al. 2017).

In the following, we collect a sample of early phase SN Ia observations in order to examine their intrinsic $(B-V)_0$ color evolution. We then examine the location of the sample objects along the Phillips relation and the Branch et al. (2006) diagram. We find that SNe Ia exhibiting blue, slowly evolving $(B-V)_0$ colors are also of the Branch shallow silicon spectral type as compared to red, more rapidly evolving objects. This suggests at least two distinct populations of SNe Ia. The host properties of the sample are also examined and our findings are placed into context with leading models.

2. DATA SAMPLE

We have combed the literature to identify all objects useful to explore the diversity among the early color evolution of SNe Ia. Two selection criteria were imposed. First the discovery must have occurred within three days of $t_{first}$, and secondly, each object has early $B$- and $V$-band light curves. We found 13 objects fulfilling these criteria and present them in Table 1, along with a number of pertinent details including: host designation and redshift, Milky Way and host-galaxy reddening, inferred $t_{first}$, and $t_{rise}$. Additionally, estimates of the light curve decline-rate parameter $\Delta m_{15}(B)^2$; peak absolute $B$-band magnitude ($M_B$); Branch et al. (2006) and Wang et al. (2009) spectral types; our early-color sub-typing (i.e., red or blue; see § 3.1); and references to adopted host-reddening values, data and/or adopted values of $t_{first}$.

We note that two members of the early sample – SN 2009ig and SN 2012fr– are probable 2000cx-like su-

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2 This parameter is the difference in magnitude between $B$-band peak and 15 days later and is known to correlate with $M_B$ (Phillips 1993).
Red vs. Blue: Early SNe Ia color evolution

3. RESULTS

3.1. Early sample \((B - V)_0\) color evolution

Figure 2 contains the intrinsic \((B - V)_0\) color evolution for the early sample, color-coded in either red or blue. The color curves have been corrected for both Milky Way reddening, host-galaxy reddening and time dilation. Red objects exhibit \((B - V)_0 \gtrsim 0.2\) mag by +2 d, and as much as \(\approx 0.5\) mag at +0.5 d. The color of the blue objects ranges between \((B - V)_0 \sim -0.2\) to 0.05 mag within the first +2 d relative to \(t_{\text{first}}\) and evolve relatively slow compared to the red objects. By +4 d the color difference between the two groups is negligible.

Inspection of the color difference between the two populations reveal differences on the order of \(\sim 0.5\) mag, which corresponds to a difference in flux of \(\sim 50\%\). This is far too much of a flux difference to be attributed to spectral line features. Due to a scarcity of data, here we focus exclusively to the \((B - V)_0\), however, we do note that the blue vs red sub-types holds over different color combinations (see, e.g., Hosseinzadeh et al. 2017).

Figure 3. Luminosity decline-rate relation consisting of 1991T-like, normal and 1991bg-like SNe Ia observed by the Carnegie Supernova Project-I (Krisciunas et al. 2017). Color stars correspond to the comparison sample with blue stars corresponding to objects with blue colors at early phases and red stars are those exhibiting red colors. Excluding the peculiar 2000cx-like SNe 2009ig and 2012fr, objects with early, slowly evolving blue colors are generally brighter and exhibit slower declining light curves than objects with early, rapidly evolving red colors.

3.2. Early sample on the \(M_B\) vs. \(\Delta m_{15}(B)\) relation

Plotted in Figure 3 are the \(M_B\) and \(\Delta m_{15}(B)\) values listed in Table 1 of the early sample along with a sample of 1991T-like, normal, and 1991bg-like supernovae observed by the Carnegie Supernova Project I (Krisciunas et al. 2017). Objects exhibiting early blue colors tend to exhibit higher peak luminosities and slower decline rates. Interestingly, the two red objects that are as bright as the majority of the early blue objects are both peculiar, 2000cx-like objects (Contreras et al. 2018).

3.3. Early sample on the Branch diagram

We now examine the ratio of the pseudo-Equivalent Widths (pEWs) measured for the Si II \(\lambda 5972\) and Si II \(\lambda 6355\) spectral features in optical spectra obtained within three days of \(B\)-band maximum. This ratio is...
known to correlate with photospheric temperature (Nugent et al. 1995) and serves as basis for the Branch et al. (2006) spectral classifications consisting of: Core Normal (CN), Broad Lined (BL), Shallow Silicon (SS), and CooL (CL). CN are normal SN Ia. BL show higher than normal Si II λ6355 Doppler velocity. BL objects also correspond to high-velocity (HV) objects in the Wang et al. (2009) classification spectrum, as defined by exhibiting a Si II λ6355 Doppler velocity of ≥10,800 km s$^{-1}$. Finally, SS are typically bright 1991T/1999aa-like objects and the CL sub-type contains both transitional and 1991bg-like SN Ia.

The four Branch spectral types are indicated with different black symbols and the early sample is plotted as colored objects. All normal SNe Ia exhibiting blue colors are either of the shallow silicon (SS) sub-type or lie just along the interface between the SS and CN (core normal) types. Note the Branch SS type. However, such objects have yet to be discovered.

4. DISCUSSION

Using the early phase light curve colors, we have identified at least two distinct populations of SNe Ia, the properties of which are as follows:

- Events that are blue at early times, which are SS spectral types, require a double power law fit to the early light curve rise, and are more luminous at peak with a smaller $\Delta m_{15}(B)$.

- Events that are red at early times, which are mostly CN or CL spectral types (with the exception of two peculiar events), follow a single power law for the early light curve rise, and are less luminous at peak with a larger $\Delta m_{15}(B)$.

We now briefly discuss various processes that may be contributing to the early phase emission. These range from interaction with a non-degenerate companion, the presence of high-velocity $^{56}$Ni, interaction with circumstellar material (CSM), and opacity differences in the outer layers of the ejecta.

4.1. Interaction with a non-degenerate companion

Kasen (2010) presented simulations of an SN Ia interacting with a non-degenerate companion. This creates a shock cooling signature over the first few days, and has been a popular explanation for many of the early-blue events (e.g., Marion et al. 2016; Hosseinzadeh et al. 2017). Other similar simulations predict a lower luminosity and shorter duration (Marietta et al. 2000; Maeda et al. 2014; Kutsuna & Shigeyama 2015), but are still potentially consistent with the early-blue events depending on the size and distance of the companion.

If interaction with a non-degenerate companion produces early blue colors then a natural question arises: How does this explain the preference for these events to be of the Branch SS type? Moreover, the interaction model predicts the blue excess to be strongest when the companion sits between the explosion and the observers, so that less favorable viewing angles should still look red. Thus if this is the preferred explanation, then there should be early red events that are also bright and of the Branch SS type. However, such objects have yet to be discovered.

4.2. Presence of high-velocity $^{56}$Ni

Another way to produce additional heating at early times is if there is $^{56}$Ni located in the very outer layers. This could be due to significant mixing by instabilities or large scale flows during the explosive burning. Alternatively, $^{56}$Ni can be deposited in the outer layers from a helium-shell triggered double-detonation explosion (Woosley et al. 1980; Nomoto 1982), which can occur when there is a helium donor or even due to the helium-rich surface layers of a C/O WD during a double degenerate merger. Such scenarios have been explored by Piro & Morozova (2016) and Magee et al. (2018), which find similar timescales, luminosities, and colors to the early-blue events when there is $\sim 0.01 M_\odot$ of $^{56}$Ni in the surface layers.

The main criticism of the shallow $^{56}$Ni explanation is whether a large abundance of iron group elements (IGEs) in the surface layers negatively impacts the spectra of SNe Ia at peak (Hofflich & Khokhlov 1996; Nugent et al. 1995).
More detailed treatments of the helium detonation (Shen & Moore 2014) and the converging shock in the C/O core (Shen & Bildsten 2014) find that this scenario may still be viable with smaller helium masses and less IGEs, but additional work is needed to understand whether it can both explain the early blue phase and still be consistent with the full spectral evolution of the events. Furthermore, the current set of observations and models do not have the fidelity to distinguish between a smooth, shallow mixed distribution of $^{56}$Ni as discussed by Piro & Morozova (2016) and Magee et al. (2018) or a distinct blob of $^{56}$Ni located near the surface as might be expected for a double-detonation (see Maeda et al. 2018).

A related but slightly different way to produce additional early energy release is if there is nuclear burning in the outer layers (Hoeflich & Schaefer 2009). This differs from the double-detonation scenario in that a thin helium layer of $\sim 10^{-5} M_\odot$ mixed with some carbon (Wang et al. 2017) is triggered by the detonation front propagating out of the C/O core (rather than the helium layer igniting first). It has also been speculated that the helium layer could be triggered by $g$-modes driven by the convective simmering phase of carbon burning in single-degenerate scenarios (Piro 2011). In contrast, a hydrogen-rich layer would not burn due to the longer burning time scales which are well in excess of 1 s, compared to $10^{-2}$ s for a mixed helium-carbon layer.

4.3. Circumstellar interaction

Yet another method for producing additional heat at early times is through the interaction of the ejecta with CSM. This could occur in the collision of the ejecta with distinct shells of material that are from the companion or pulsational events during the explosion itself. Taking a typical expansion velocity in the corresponding outer layers ($\sim 40,000$ km s$^{-1}$) equates to a distance of $\sim 10^{15}$ cm (Hoeflich et al. 2002) within 1-5 days of $t_{\text{first}}$. With this scale in mind, early emission could be produced from the conversion of kinetic energy of the ejecta into heating through its interaction with CSM (Gerardy et al. 2007; Dragulín & Hoeflich 2016; Noebauer et al. 2016). However, due to the short time scales covered by our early sample this is likely not a viable process as the CSM would have to be bound to the system of size less than $\sim 10^{15}$ cm, or in the direct vicinity.

Alternatively, the CSM could be more confined to the WD such as in the tidally disrupted material that is present after a double-degenerate merger or the accretion flows in a single-degenerate scenario. In such cases, if the material is optically thick to the explosive shock wave, then the shock continues to propagate into the CSM and heat it (Piro & Morozova 2016). This produces a shock cooling signature at early times, with a luminosity that is proportional to the radius of the CSM. For the typical early luminosities of the early-blue events, this implies a radius of $\sim 10^{11} - 10^{12}$ cm for such material. Further work is needed to better understand if the CSM would impact the spectra and light curve evolution in other ways that can be tested with observations.

4.4. Composition/opacity differences

A final possibility we consider is whether the early blue excess could actually not be due to additional energy input but instead simply differences in opacity due to a different composition. If the outer layer of the ejecta is characterized by a lower opacity (e.g., due to a significantly amount of unburnt carbon), the photosphere would recede more rapidly and thus reach the $^{56}$Ni-rich region earlier. The overall affect of this is a faster release of energy, more heating, and thus bluer colors. This affect is demonstrated in Gall et al. (2018, see their Figure 11), where $10^{-2} M_\odot$ of unburnt carbon produces an earlier UV-blue phase lasting $\approx 4$ days.

4.5. Closing remarks

In conclusion, from the perspective of early phase colors, there appears to be at least two populations of SN Ia. Looking toward the future, the key question will be whether this represents a critical difference between the progenitors of these events, or if it is the result of smaller differences in composition, explosion energy, or some other detail of the explosions. Solving this mystery will require further theoretical modeling as well as gathering a larger sample of events to see how strongly this dichotomy persists and whether there are other properties that correlate with the early red and blue populations.

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### Table 1. Early Color Evolution Sample Parameters.

| SN     | Host    | Red-shift | $E(B-V)_{MW}$ | $E(B-V)_{host}$ | $t_{\text{first}}$ | $t_{\text{rise}}$ | $\Delta m_{15}(B)$ | $M_B$ | Spectral-type$^a$ | Color | References($^s$) |
|--------|---------|-----------|---------------|-----------------|--------------------|-------------------|-------------------|------|-----------------|-------|------------------|
| 2009ig | NGC 1015 | 0.00877   | 0.032         | -               | -                  | 55662.9           | 17.1              | 0.90 ± 0.07 | -19.46 ± 0.12 | CN, NV | red (1)          |
| 2011fu | M31     | 0.00806   | 0.058         | -               | -                  | 57569.7           | 17.6              | 1.07 ± 0.06 | -19.30 ± 0.19 | CN, normal | red (2)          |
| 2012g  | NGC 4424 | 0.00146   | 0.180         | 0.18 ± 0.05$^b$ | 56061.8           | 19.5              | 0.86 ± 0.02 | -19.62 ± 0.31 | SS, 91T/99aa-like | blue (3) |
| 2012br | NGC 1365 | 0.00546   | 0.018         | 0.03 ± 0.04$^c$ | 56225.8           | 16.9              | 0.82 ± 0.03 | -19.43 ± 0.14 | CN, SS, NV | red (4)          |
| 2012ht | NGC 3447 | 0.00356   | 0.025         | 0.05 ± 0.01$^c$ | 56278.0           | 17.6              | 1.27 ± 0.05 | -19.98 ± 0.07 | CN, normal | red (5)          |
| 2013dy | NGC 7250 | 0.00389   | 0.140         | 0.21 ± 0.01$^d$ | 56483.4           | 17.7              | 0.92 ± 0.03 | -19.65 ± 0.04 | SS, 91T/99aa-like | blue (6) |
| 2013gy | NGC 1418 | 0.01402   | 0.049         | 0.13 ± 0.06$^c$ | 56629.4           | 19.1              | 1.23 ± 0.06 | -19.32 ± 0.16 | CN, normal | red (7)          |
| iPTF 13eebh | NGC 890 | 0.01327   | 0.067         | 0.07 ± 0.02$^c$ | 56607.9           | 14.8              | 1.76 ± 0.02 | -18.95 ± 0.19 | CL, normal | red (8)          |
| ASASSN-14ip | NGC 4666 | 0.00510   | 0.021         | 0.35 ± 0.01$^c$ | 56998.5           | 16.7              | 0.80 ± 0.05 | -19.36 ± 0.06 | SS, 91T-like | blue (9)         |
| 2015F  | NGC 2442 | 0.00489   | 0.175         | 0.16 ± 0.03$^c$ | 57888.4           | 18.5              | 1.25 ± 0.05 | -19.47 ± 0.27 | CN, normal | red (10)         |
| iPTF16ahc | NGC 5221 | 0.02328   | 0.028         | 0.05 ± 0.03$^a$ | 57481.8           | 17.9              | 0.85 ± 0.05 | -19.20 ± 0.40 | SS, normal/91T-like | blue (11) |
| MUSSES1604D | - | - | - | - | - | - | - | - | - | - |
| 2017ehv | NGC 5643 | 0.00400   | 0.150         | -               | -                  | 57821.9           | 18.3              | 1.06 ± 0.05 | -20.04 ± 0.60 | SS, 91T-like | blue (13) |

$^a$Branch et al. (2006) and Wang et al. (2009) spectral classifications.

$^b$Silverman et al. (2012).

$^c$Based on SNooPy fits to photometry obtained by the Carnegie Supernova Project-II (Burns et al., in prep).

$^d$Pan et al. (2015).

$^e$Miller et al. (2018).

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Note—(1) Blondin et al. (2012), Foley et al. (2012), Marion et al. (2013); (2) Nugent et al. (2011), Vinkó et al. (2012), Pereira et al. (2013); (3) Silverman et al. (2012), Marion et al. (2014); (4) Contreras et al. (2018); (5) Yamazaki et al. (2014), This work; (6) Zheng et al. (2013), Pan et al. (2015), Zhai et al. (2016); (7) Holmbo et al. (2018); (8) Hsiao et al. (2018); (9) Hsiao et al. (2015); (10) Contreras et al. (2017), This work; (11) Pan et al. (2015), This work; (12) Miller et al. (2018), This work; (13) Miller et al. (2018), This work; (14) Miller et al. (2017), This work.

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