Two classes of fast-declining type Ia supernovae

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Received; accepted

Abstract

Fast-declining Type Ia supernovae (SN Ia) separate into two categories based on their bolometric and near-infrared (NIR) properties. The peak bolometric luminosity (Lmax), the phase of the first maximum relative to the optical, the NIR peak luminosity and the occurrence of a second maximum in the NIR distinguish a group of very faint SN Ia. Fast-declining supernovae show a large range of peak bolometric luminosities (Lmax differing by up to a factor of ~8). All fast-declining SN Ia with Lmax < 0.3 × 1043 erg s−1 are spectroscopically classified as 91bg-like and show only a single NIR peak. SNe with Lmax > 0.5 × 1043 erg s−1 appear to smoothly connect to normal SN Ia. The total ejecta mass (Mej) values for SNe with enough late time data are ≲1 M⊙, indicating a sub-Chandrasekhar mass progenitor for these SNe.

Key words. supernovae:general

1. Introduction

Type Ia supernovae have long been linked with the explosion of a C/O white dwarf (Hoyle & Fowler 1960). Ignition of the white dwarf can lead to fusion of (the) C/O to 56Ni releasing enough energy to unbind the progenitor and through the deposition of the energy released in the radioactive decay of 56Ni to 56Co, and on to 56Fe, power the electromagnetic display of the supernova. This scenario is extremely robust and is supported both by theoretical studies (Hillebrandt & Niemeyer 2000) and observations over many decades, although the exact white dwarf mass and ignition scenario remain the subject of extensive debate.

In the past two decades the study of supernovae has been blessed with an great increase in high quality data through a series of systematic surveys for transients and extended temporal and wavelength coverage. Dedicated supernova searches have discovered several SN Ia with unusual photometric and spectroscopic properties. Some peculiar SN Ia exhibit fast optical post-peak declines and a deep trough-like feature at ~4200 Å in their maximum light spectra, attributed to Ti II. The prototypical example of this class is SN 1991bg (Filippenko et al. 1992; Leibundgut et al. 1993; Mazzali et al. 1997; Li et al. 2011) showed that SN 1991bg-like events comprise a large fraction (15–20%) of the SN Ia population in a volume-limited sample and appear distinct from normal SN Ia in their width-luminosity relationship. SN 1991bg-like events have been shown to prefer elliptical and lenticular galaxies (Howell 2001).

Based on multi-epoch spectra and multi-band optical light curves of a sample of fast-declining, SN 1991bg-like SN Ia, Taubenberger et al. (2008) suggested that this class may have a different physical origin to normal SN Ia, although the possibility that they are a low-luminosity, fast-declining extension of normal SN Ia cannot be excluded. These SNe show markedly different optical colour evolution and low 56Ni mass values as calculated from UBVRI pseudo-bolometric light curves. Supernovae with intermediate properties between normal and sub-luminous SN Ia would lend support to the latter hypothesis (Garnavich et al. 2004).

The optical width-luminosity relation for SN Ia (Phillips et al. 1999, Burns et al. 2011) shows a notable break for fast-declining objects (∆m15(B) > 1.6). Fast-declining SN Ia are fainter given their ∆m15(B) assuming a linear relation, possibly due to the inability of ∆m15(B) to properly characterise fast-declining SNe since their light curves settle onto a linear magnitude decline at approximately 15 days past B maximum. Burns et al. (2014) proposed a different ordering parameter, s_BV, to improve the treatment of fast-declining objects. s_BV is defined as the epoch at which the (B − V) colour curve is at its maximum value, divided by 30d. Using this metric the fast-declining SNe appear less distinct and more as a continuous tail of the distribution of normal SN Ia.

In the near infrared SN Ia are remarkably uniform around maximum (Elias et al. 1981; Meikle 2000; Krisciunas et al. 2004; Folatelli et al. 2010; Dhawan et al. 2015). While a majority of SN Ia show a homogeneous behaviour around the maximum, there are some clear out-
liers. Garnavich et al. (2004) reported that the 91bg-like SN 1999by was fainter in the NIR (JHK filters) than the average derived for normal SN Ia in Krisciunas et al. (2004). Subsequent studies found a bi-modality in the NIR light curve properties of fast-declining SN Ia (e.g. Krisciunas et al. 2009; Folatelli et al. 2010; Kattner et al. 2012; Phillips 2012). Events whose NIR primary maxima occur after B-band maximum ($t_B(max)$) are sub-luminous in all bands compared to normal SN Ia. These sub-luminous SN Ia also tend to lack or have very weak second maxima in their NIR light curves. However, objects that peak in the NIR before $t_B(max)$ have NIR absolute magnitudes comparable to normal SN Ia and show prominent (albeit, early) second maxima. Following these results, Hsiao et al. (2015) proposed the definition of “transitional” SNe as fast-declining SN Ia with an NIR maximum before $t_B(max)$.

In this paper we analyse the NIR and bolometric properties of fast-declining SN Ia to determine whether they are an extension of normal SN Ia or a distinct subclass. In section 2, we describe our sample and in section 3 we show that fast-declining SN Ia are found in two distinct groups. In sections 4.2 and 4.3 we examine other distinguishing characteristics of the groups. The discussion and conclusions are presented in sections 4.

2. Data

We compiled a sample of fast-declining SN Ia with $\Delta m_{15} > 1.6$ from the literature. We do not include objects similar to 2002cx (dubbed ‘Type Iax’) supernovae Foley et al. (2013). Some of Iax SNe are fast decliners (e.g. SN 2002cx, Li et al. 2003; SN 2005hk, Jha et al. 2006; Phillips et al. 2007). SN 2008ha, Foley et al. (2009) and could have been included in our sample, but the evidence for them being different kinds of explosions is mounting (e.g. Li et al. 2003; Jha et al. 2006). We discuss some of the SN Iax features in the conclusions.

Most of our data is compiled from the Carnegie Supernova Project (CSP; Contreras et al. 2010; Stritzinger et al. 2011) augmented by the CfA supernova survey on PAIRITEL (Wood-Vasey et al. 2008; Friedman et al. 2015). To these objects we add SN 1999by (Garnavich et al. 2004) and iPTF13efh (Hsiao et al. 2015). The objects in our sample along with the sources of the data are presented in Table 1.

Our sample has 15 SNe. Ten of these SNe are spectroscopically classified as 91bg-like (Garnavich et al. 2004; Folatelli et al. 2013). Seven SNe in our sample show a pronounced NIR second maximum, three of which are spectroscopically 91bg-like (2008gt, 2007ba and 2008R).

For SNe with $z > 0.01$, we use luminosity distances with $H_0 = 70 \text{ km s}^{-1} \text{Mpc}^{-1}$, $\Omega_m = 0.27$ and $\Omega_{\Lambda} = 0.73$. For nearby SNe with $z < 0.01$ we use independent distances to the host galaxy from the literature. A summary of the methods used for the distances and the references is provided in Table 1.

For SNe observed by the CSP, we have published values of $s_{BV}$. For other SNe we calculated the $s_{BV}$ from SNooPY (Burns et al. 2011) fits to the data.

3. Luminosity vs colour-stretch: Evidence for two classes of fast-declining SNe

As has been discussed in Dhawan et al. (2015) the infrared spectral region (JHK) is a significant contributor to the bolometric luminosity of SN Ia. We calculate the pseudo-bolometric light curve by integrating over a $u \rightarrow H$ (UVOIR) SED based on monochromatic fluxes derived using the transmission curves for each survey (see Contardo, Leibundgut & Vacca 2006 for a detailed explanation of the method). The light curves are corrected for host galaxy and Milky Way extinction. We determine the absolute UVOIR peak luminosity ($L_{\text{max}}$) by fitting a cubic spline to the constructed pseudo-bolometric light curve.

The $s_{BV}$ versus $L_{\text{max}}$ relationship (Figure 1) exhibits two distinct groups among the fast declining SN Ia. One group extends the trend of normal Ia supernovae with lower luminosity having an earlier $s_{BV}$ while a second group is detached and appears to follow a different relation. The relation for the faint subgroup has a significantly different slope ($\sim 2\sigma$ level; Table 2). We note that the error in the slope for fitting all SNe as single group is lower than the two separate subgroups. However, this is because the total sample size is greater than the comparatively smaller subsamples of the two separate groups.

A simple $\chi^2$/DoF analysis shows that a fit to two sub-classes (fitting two slopes simultaneously) is favoured (reduced $\chi^2 = 1.03$) compared to a single line fit (reduced $\chi^2 = 1.90$). We also apply the hypothesis testing technique of comparing the logarithm of the Bayesian Evidence ($lnZ$; see Skilling 2004 for details about $Z$). $Z$ is the integral of the likelihood over the prior region

$$Z = \int L\pi d\theta$$

where $L$ is the likelihood, $\pi$ is the prior and $\theta$ is the set of the parameters. We calculate $lnZ$ using a multi-modal nested sampling algorithm, MultiNest (Feroz et al. 2013).

The $\Delta lnZ$ for the single population relative to the two sub-classes is $~ -6.97$ suggesting a strong preference for the two subclasses over the single population (Trotta 2008, suggest that $\Delta lnZ < -5$ is strong evidence for the alternate model over null hypothesis).

This is an intriguing result suggesting that there are two separate populations of fast-declining SN Ia which we refer to as SN Ia-faint here, as opposed the group that appears to join the normal SN Ia. The fainter group consists of SNe 1999by, 2005ke, 2006mr, 2007N, 2007ax and 2009F.

We note that Burns et al. (2014) their Fig. 10) find a relation between the pseudo equivalent width of the Si II 5972 Å line and $s_{BV}$, which has a more complicated form than a simple linear relation for SNe with $s_{BV} < 0.5$. This would be further evidence that the SN Ia-faint group of fast-declining SN Ia are a separate population.

4. Characterising fast-declining, low-luminosity SN Ia

There appear to be at least three distinguishing characteristics of the SN Ia-faint subgroup. In addition to their extreme low luminosity, they appear to reach the NIR peak at a later stage compared to optical wavelengths and do not show a second maximum in their near-infrared light curves.
Table 1. SN sample used in this analysis.

| SN       | $t_d$(max) | $\Delta t_d$(B) | $s_{BV}$ | $s_{SBF}$ | Reference | $t_d$(Y) | $t_d$(J) | $\mu$ | Distance Method | Distance Reference | Data Reference |
|----------|------------|-----------------|---------|---------|-----------|----------|----------|------|----------------|-------------------|---------------|
| SN 1996bg | 54088.8 | 1.93 | 0.46 | This paper | N/A        | N/A      | 30.82 ($\pm$ 0.15) | TF | T15   | H02,L04                     |               |
| SN 2006ge | 52484.3 | 1.83 | 0.49 | This paper | N/A        | N/A      | 31.65 ($\pm$ 0.28) | SBF | T01   | K09                       |               |
| SN 2006kl* | 53481.6 | 1.80 | 0.39 | B14 | N/A        | N/A      | 35.14 ($\pm$ 0.09) | LD | WVS C10 F15 |               |               |
| SN 2006kl* | 53096.6 | 1.78 | 0.41 | B14 | N/A        | N/A      | 31.84 ($\pm$ 0.08) | SBF | T01   | K09                       |               |
| SN 2006ge | 54093.1 | 1.66 | 0.56 | B14 | N/A        | N/A      | 31.15 ($\pm$ 0.23) | SBF | A01   | C10                       |               |
| SN 2006kl* | 54124.3 | 1.79 | 0.29 | B14 | N/A        | N/A      | 33.91 ($\pm$ 0.16) | LD | S11   |               |               |
| SN 2006kl* | 54187.5 | 1.85 | 0.36 | B14 | N/A        | N/A      | 32.20 ($\pm$ 0.14) | TF | T09   | S11                       |               |
| SN 2006lu  | 54196.2 | 1.88 | 0.54 | B14 | N/A        | 20.0 ($\pm$ 0.4) | 36.18 ($\pm$ 0.05) | LD | T09   | S11                       |               |
| SN 2007on  | 54321.1 | 1.90 | 0.57 | B14 | 18.7 ($\pm$ 0.4) | 18.2 ($\pm$ 0.1) | 31.45 ($\pm$ 0.08) | SBF | J03   | S11                       |               |
| SN 2008hwC | 54384.3 | 1.85 | 0.50 | B14 | 15.5 ($\pm$ 0.7) | 14.1 ($\pm$ 0.7) | 33.73 ($\pm$ 0.16) | LD | S11   |               |               |
| SN 2008fha | 54812.1 | 1.83 | 0.60 | This paper | ... | 14.0 ($\pm$ 1.0) | 34.28 ($\pm$ 0.13) | LD | F15   |               |               |
| SN 2009fdi | 54841.8 | 1.97 | 0.33 | B14 | N/A        | N/A      | 33.73 ($\pm$ 0.16) | LD | S11   |               |               |
| SN 2010iy  | 55247.5 | 1.73 | 0.61 | This paper | ... | ... | ... | ... | ... | ... |               |               |
| iPTF13ebh | 56622.9 | 1.79 | 0.63 | H15 | 19.4 ($\pm$ 0.2) | 17.2 ($\pm$ 1.5) | 33.63 ($\pm$ 0.16) | LD | H15   |               |               |

Notes. (1) SN Ia with only one maximum are marked as ‘N/A’. Ellipses indicate insufficient data to determine a second maximum. (2) SN Ia In the SN Ia-faint group are shown in italics (see text)

* Spectroscopically classified as SN 1991bg-like

** Methods for distances to the SN hosts are as follows: LD: luminosity distance (using parameters detailed in the text), TF: Tully-Fisher relation, SBF: surface brightness fluctuation. Note that 0.16 mag (Jensen et al. 2003) is subtracted from SBF distances from Tonry et al. (2001) to put them on the same scale as Friedman et al. (2001). Note that objects that do not have a luminosity distance presented here are not in the Hubble flow i.e. have z < 0.01.

References. A01: Ajhar et al. (2001), T01: Tonry et al. (2001), H02: Höflich et al. (2002), J03: Jensen et al. (2003), G04: Garnavich et al. (2004), K09: Kriacunas et al. (2009), WV08: Wood-Vasey et al. (2008), C10: Contreras et al. (2010), S11: Stritzinger et al. (2011), T09: Tully et al. (2009), T13: Tully et al. (2013), F15: Friedman et al. (2015), H15: Hassel et al. (2015)

Table 2. Slope and intercept for the $L_{max}$ - $s_{SBF}$ relation

| Sample | Slope | Intercept |
|--------|-------|-----------|
| SN Ia-faint | 0.76 ($\pm$ 0.17) | -0.08 ($\pm$ 0.06) |
| Normal SN Ia | 1.24 ($\pm$ 0.14) | -0.05 ($\pm$ 0.11) |
| Complete | 1.40 ($\pm$ 0.08) | -0.27 ($\pm$ 0.04) |

4.2. Lack of NIR second maximum

A further characteristic property of SN Ia-faint is a lack of a second infrared maximum. Table 1 indicates the phase of the second maximum when it could be measured. Objects without a second maximum are labelled ‘N/A’ and correspond to the low-luminosity objects. There is a clear separation of the class of SN Ia-faint in this respect. We cannot confirm UV to NIR (UVOIR) luminosity of SN 2005bl independently, but the lack of a second maximum, the late phase of the first maximum and low $s_{SBF}$, indicate that this object also belongs to the SN Ia-faint subgroup.

4.3. Low $^{56}$Ni and ejecta mass

We can further investigate the properties of fast-declining SN Ia by calculating the ejecta masses and production of $^{56}$Ni.

From our calculated $L_{max}$, we estimate the $^{56}$Ni mass using:

$$L_{max} = 2.0(0.03) \times 10^{44} \frac{M_{56Ni}}{M_{\odot}} \text{ergs}^{-1}.$$  

This is a simple implementation of Arnett’s rule (Arnett 1982, Arnett et al. 1985) for a rise time of 19 days. Variations in Arnett’s rule have been encapsulated in a parameter $\alpha$ (see Branch 1992). We use $\alpha = 1$. Taubenberger et al. (2008) find that fast-declining SN Ia have shorter rise times (typically 13 - 16 d) which would imply lower $^{56}$Ni masses by 40-15% for the same $L_{max}$. The resulting $^{56}$Ni masses for 13 and 19 days rise times are reported in Table 4.

Unsurprisingly, the values of $^{56}$Ni mass in Table 4 are significantly lower than the averages derived for normal

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1 Moreover, a low $^{56}$Ni mass (~ 0.1 M$_{\odot}$) from UVBRi light curve calculations by Taubenberger et al. (2008) lends further evidence to its classification as SN Ia-faint.
Figure 1. $L_{\text{max}}$ versus $s_{\text{BV}}$ for normal SN Ia (red) and fast-declining SN Ia (black). The best fit linear relations for the faint sub-group of the fast-declining SN Ia, the normal SNe, as well as the best fit assuming that all SNe belong to the same group are plotted as solid lines. The $L_{\text{max}}$ values for the normal SN Ia were calculated in Dhawan et al. (2016) and the $s_{\text{BV}}$ values are from Burns et al. (2014). **Inset:** The $u \rightarrow H$ pseudo-bolometric light curve for SN 2006mr (green), the faintest SN in the sample is plotted in comparison with the normal SN 2002bo (red; Benetti et al. 2004). From the bolometric light curves it is clear that SN 2006mr has a faster post-maximum evolution and settles earlier onto the exponential tail than SN 2002bo which was well described by a $M_{\text{Ch}}$ delayed detonation model (Benetti et al. 2004; Blondin, Dessart, & Hillier 2015). The reduced $\chi^2$ for the single population is 1.90 whereas for the two subclasses is 1.03.

The SN Ia (0.5 - 0.6 $M_{\odot}$; e.g. Stritzinger et al. 2006; Scalzo et al. 2014; Dhawan et al. 2016). The $^{56}$Ni mass values we derive range from 0.05 - 0.38 $M_{\odot}$ indicating a significant diversity in the sample. A basic assumption in equation 2 is that the ejecta mass is the same for all SN Ia when determining a nickel mass. If the SN Ia-faint have a lower ejecta mass then the derived nickel masses estimates presented here are too large (Pinto & Eastman 2000). Of course equation 2 does not apply if other processes than photon diffusion or a different energy source are at work in low-luminosity SNIa. We allow the rise to vary between 13 and 19 days in our derivation of the $^{56}$Ni mass. The results are presented in Tab. 4.

To calculate the ejecta mass we use (see Jeffery 1999 for a detailed derivation):

$$M_{\text{ej}} = 1.38 \cdot \left( \frac{1}{3} \right) \cdot \left( \frac{v_e}{5000 \text{ kms}^{-1}} \right)^2 \cdot \left( \frac{t_0}{36.80 \text{ d}} \right)^2 M_{\odot} \quad (3)$$
of the bolometric light curve is governed by a combination of Arnett's rule implicitly assumes an ejecta mass for the fast-declining SN Ia and we explored two different scenarios. The least luminous and the fiducial decay time scale, and hence, can determine both the maximum bolometric luminosity and the fiducial time scale, and hence, can derive both M_{ej} and M_{Ni} masses for fast-declining SN Ia with sufficient early time coverage to determine a peak luminosity

\[ E_{dep} = E_{Ni} + E_{Co,e+} + [1 - exp(-\tau)] \cdot E_{Co,\gamma} \]  

Among the fast-declining SN Ia we have 5 objects for which we can determine both the maximum bolometric luminosity and the fiducial decay time scale, and hence, can derive both M_{ej} and M_{Ni}. As described above, the application of Arnett's rule implicitly assumes an ejecta mass through its impact on the diffusion timescale. The rise time of the bolometric light curve is governed by a combination of M_{Ni}, and M_{ej} and as noted earlier attempted to capture any uncertainties in this combination by adopting two rise times for the calculation (13 and 19 days). These rise times have been consistently applied also to the determination of M_{ej}. In addition, the fiducial time scale depends on the density structure of the ejecta, which may differ for the fast-declining SN Ia and we explored two different e-folding velocities (2700 km s^{-1} and 3000 km s^{-1}) to represent the range of possible ejecta structures. The least luminous delayed detonation models of Blondin et al. (2013) had a density profile well characterised by an e-folding velocity of 2500 km s^{-1} while the typical value for more luminous models was close to 3000 km s^{-1} (which is similar to the typical e-folding velocity for the sub-M_{Ch} models of Sim et al. (2010)). The results are presented in Table 5. We take the range of results to define the uncertainty in our determination of the ejecta mass. The observational error contribution is negligible by comparison. For our analysis, we use q_{1}=1. Recent theoretical studies (e.g. Blondin et al. 2013, 2016) find α to be within 20% of unity. Even for α = 1.2, we would obtain a longer transparency timescale, t_{0} by ~15%. However, the high values of α imply a more centrally concentrated 56Ni distribution and hence, a higher value for q. Moreover, the high α values correspond to the least luminous models (e.g. Blondin et al. 2013). For SNe corresponding to these luminosities, there is independent evidence for a central concentration of 56Ni (for e.g. from low iron line widths in nebular spectra; for e.g., see Blondin et al. 2012) which would imply a significantly higher q value than assumed here (q=1 compared to q=1/3 used here), hence, counterbalancing the effect of a higher α (see Equation 3). The derived M_{ej} of the SN Ia-faint are a clear indication that these are sub-Chandrasekhar explosions. The highest M_{ej} are found for the shortest rise times and the highest e-folding velocity, i.e. the shallowest density structure.

Combining Tables 4 and 5 (for a rise time of 13 days), we calculate the ratio of the M_{ej} to M_{SNi} (hereafter, R_{M}) for fast-declining SN Ia. Fast-declining SN Ia in the SN Ia-faint sub-group have significantly larger R_{M} values compared to normal SN Ia (Figure 3). An interesting object is

| SN Ia | t_{Y} (d) | t_{J} (d) | t_{H} (d) | M_{Y} (mag) | M_{J} (mag) | M_{H} (mag) |
|-------|----------|----------|----------|-------------|-------------|-------------|
| 1999bg | ... | 2.98 (±0.63) | ... | ... | -18.33 (±0.19) |... |
| 2005bl | ... | 1.12 (±0.09) | ... | ... | -17.96 (±0.13) |... |
| 2005ke | 1.88 (±0.52) | 1.33 (±0.23) | 2.05 (±0.28) | -17.42 (±0.08) | -17.45 (±0.08) | -17.50 (±0.08) |
| 2006mr | 5.46 (±0.41) | 3.26 (±0.12) | 5.11 (±0.47) | -17.17 (±0.23) | -17.27 (±0.23) | -17.50 (±0.08) |
| 2007N | 6.62 (±1.03) | 4.92 (±2.00) | 5.96 (±1.30) | -17.48 (±0.18) | -17.65 (±0.21) |... |
| 2007ax | 5.56 (±0.24) | 4.41 (±1.63) | -17.01 (±0.14) | -17.00 (±0.15) |... |
| 2007ba | 1.12 (±0.63) | -1.05 (±1.9) | -0.42 (±1.40) | -18.65 (±0.06) | -18.64 (±0.11) |... |
| 2007on | -2.88 (±0.10) | -2.67 (±0.10) | -3.49 (±0.10) | -18.28 (±0.19) | -18.37 (±0.19) | -18.18 (±0.19) |
| 2008hs | -2.77 (±0.63) | -3.21 (±1.69) |... | -17.96 (±0.15) | -17.82 (±0.15) |... |
| 2009F | 5.14 (±0.90) | 1.80 (±1.00) |... | -17.64 (±0.19) | -17.57 (±0.17) |... |
| 2010Y | -1.88 (±1.70) |... | -18.21 (±0.26) |... |
| iPTF13ebh | -2.02 (±0.10) | -0.48 (±0.09) | -2.62 (±0.91) | -18.57 (±0.16) | -18.58 (±0.16) | -18.46 (±0.16) |

Notes. (1) SN Ia in the SN Ia-faint group are shown in italics.
Table 5. Fiducial time scales ($t_0$), ejecta masses ($M_{ej}$) and bolometric decline rate for the low-luminosity SN Ia with sufficient early and late time coverage to determine a peak luminosity and a late time slope (see text for assumptions about $v_e$, $\kappa$, and $q$).

| SN     | $t_0$ ($t_0 = 14$ d) | $t_0$ ($t_0 = 19$ d) | $M_{ej}$ ($t_0 = 14$ d) | $M_{ej}$ ($t_0 = 19$ d) | $M_{ej}$ ($t_0 = 14$ d) | $M_{ej}$ ($t_0 = 19$ d) | $M_{ej}$ ($t_0 = 14$ d) | $M_{ej}$ ($t_0 = 19$ d) | $M_{ej}$ ($t_0 = 14$ d) | $M_{ej}$ ($t_0 = 19$ d) | Decline rate |
|--------|----------------------|----------------------|--------------------------|--------------------------|--------------------------|--------------------------|--------------------------|--------------------------|--------------------------|--------------------------|-------------|
| 2005ke | 31.69 (±0.85)         | 26.49 (±0.60)         | 0.04 (±0.24)              | 0.04 (±0.20)              | 0.04 (±0.20)              | 0.04 (±0.20)              | 0.04 (±0.20)              | 0.04 (±0.20)              | 0.04 (±0.20)              | 0.04 (±0.20)              | 0.0009 (±0.0004) |
| 2006en  | 26.72 (±0.47)         | 24.67 (±0.40)         | 0.73 (±0.19)              | 0.61 (±0.17)              | 0.62 (±0.17)              | 0.51 (±0.16)              | 0.51 (±0.16)              | 0.50 (±0.16)              | 0.50 (±0.16)              | 0.50 (±0.16)              | 0.0009 (±0.0003) |
| 2007en  | 28.27 (±0.60)         | 26.07 (±0.50)         | 0.91 (±0.21)              | 0.70 (±0.18)              | 0.70 (±0.18)              | 0.56 (±0.16)              | 0.56 (±0.16)              | 0.56 (±0.16)              | 0.56 (±0.16)              | 0.56 (±0.16)              | 0.0004 (±0.0003) |
| 2007en  | 29.70 (±0.77)         | 26.89 (±0.16)         | 0.00 (±0.21)              | 0.72 (±0.19)              | 0.74 (±0.19)              | 0.60 (±0.16)              | 0.60 (±0.16)              | 0.60 (±0.16)              | 0.60 (±0.16)              | 0.60 (±0.16)              | 0.0003 (±0.0001) |
| 2007en  | 36.49 (±0.60)         | 24.69 (±0.40)         | 0.72 (±0.19)              | 0.60 (±0.16)              | 0.62 (±0.16)              | 0.51 (±0.14)              | 0.51 (±0.14)              | 0.51 (±0.14)              | 0.51 (±0.14)              | 0.51 (±0.14)              | 0.0003 (±0.0001) |

Notes. (1) Only using UBVRI data.

Figure 2. The pseudo-bolometric peak luminosity versus the timing of the NIR (Y’J’H’ filters) maximum for SNe in our sample. SNe that peak earlier in the NIR (squares) than the optical also appear to be an extension to the normal SN Ia whereas all SNe with an NIR peak after the optical (diamonds) appear to be a distinct population in Figure 1. We note that in the Y-band there is one exception, SN 2007ba which has a high bolometric peak luminosity but a Y-band first maximum shortly after $t_B$(max).

SN 2007on, which is the only fast-declining SN Ia connected to the normal SN Ia, and displays a $R_M = 4.5$ and is much closer to the value of normal SN Ia with $R_M < 4$. We also show in Figure 3 the values from different explosion models. The observed ratios of the SN Ia-faint agree better with sub-MCh model values than with the MCh values, although the errors are large due to large uncertainties in the individual $M_{ej}$ and $M_{SNI}$ values.

For longer rise times the derived $M_{ej}$ decrease and the $M_{SNI}$ estimates increase, which leads to small $R_M$. In this case, the points tend to drop further below the line of MCh explosions.

5. Discussion and Conclusion

The ejecta-mass estimates for our SN sample (Table 5) suggest that fast-declining SN Ia are associated with sub-MCh progenitors. Pure detonations of sub-MCh WDs have also been shown to compare favourably with the narrow light curves of low-luminosity SN Ia and hence reproduce the faint end of the width-luminosity relation (Sim et al. 2010; Blondin 2015; Blondin et al. 2016). One possible mechanism to trigger a sub-MCh WD explosion is the detonation of a surface layer of He, accreted from a companion (e.g. Bildsten et al. 2007), which in turn triggers a secondary carbon detonation in the WD core (known as the double detonation scenario Woesley & Weaver 1994; Livne & Arnett 1995; Fink et al. 2010; Shen & Moore 2014).

Two SNe in the SN Ia-faint subgroup (SN 1999by and SN 2005ke) show significantly larger continuum polarisation...
however, this explosion mechanism would not be a viable candidate for fast-decliners with two NIR maxima (e.g. SN 2007on) since the $^{56}$Ni is highly mixed in the ejecta, producing theoretical light curves with only a single maximum in the NIR.

We have shown that SN Ia that exhibit $s_{BY}$ below 0.5 deviate from the $L_{max}$–$s_{BY}$ relation for normal SN Ia, show a low NIR peak luminosity, late NIR maxima and also lack a prominent second maximum in the NIR filters. This behaviour distinguishes them from fast-declining SN Ia with $s_{BY}$ above 0.5 which seem to extend the normal SN Ia sequence to fainter magnitudes. From this work it is evident that the $s_{BY}$ metric of (Burns et al. 2014) is a powerful diagnostic of the nature of the explosion. From the low bolometric luminosity we infer small $^{56}$Ni mass and from fitting an energy deposition function to the tail of the bolometric light curve, we infer a sub-$M_{\text{Ch}}$ ejecta mass. The low values for these global parameters, combined with the differences in the NIR and bolometric properties of the two subgroups of fast-declining SN Ia could point to two different explosion scenarios leading to fast-declining SN Ia.

References

Ajhar E. A., Tonry J. L., Blakeslee J. P., Riess A. G., Schmidt B. P., 2001, ApJ, 559, 584
Arnett W. D., 1982, ApJ, 253, 785
Arnett W. D., Branch, D., Wheeler, J. C., 1985, Nature, 314, 337
Benetti S., et al., 2004, MNRAS, 348, 261
Bildsten, L., Shen, K. J., Weinberg, N. N., & Nelemans, G. 2007, ApJ, 662, L95
Blondin S., et al., 2012, AJ, 143, 126
Blondin S., Dessart L., Hillier D. J., Khokhlov A. M., 2013, MNRAS, 429, 2127
Blondin S., Dessart L., Hillier D. J., 2015, MNRAS, 448, 2766
Blondin S., et al., 2016, MNRAS, submitted
Blondin S., 2015, s2a.conf, 319
Branch D., 1992, ApJ, 392, 35
Burns C. R., et al., 2011, AJ, 141, 19
Burns C. R., et al., 2014, ApJ, 789, 32
Contrado G., Leibundgut B., Vacca W. D., 2000, A&A, 359, 876
Courtes C., et al., 2010, AJ, 139, 519
Dhawan S., Leibundgut B., Spypromilo J., Maguire K., 2015, MNRAS, 448, 1345
Dhawan S., Leibundgut B., Spyromillo, J., & Blondin, S. 2016, A&A, 588, A84
Elias, J. H., Froglow, J. A., Hackwell, J. A., Persson, E. E., 1981, ApJ, 251, L13
Feroz F., Hobson M. P., Cameron E., Pettitt A. N., 2013, arXiv, arXiv:1306.2144
Filippenko A. V., et al., 1992, AJ, 104, 1543
Filippenko A. V., et al., 1992, ApJ, 384, L15
Fink M., Roepke F. K., Hillebrandt W., Seitenzahl I. R., Sim S. A., Kromer M., 2010, A&A, 514, A53
Fink M., et al., 2014, MNRAS, 438, 1762
Folatelli G., et al., 2010, AJ, 139, 120
Folatelli G., et al., 2013, ApJ, 773, 53
Foley R. J., et al., 2013, AJ, 138, 376
Framsson, C., Jerkstrand, A., 2015, ApJ, 814, L2
Freedman W. L., et al., 2001, ApJ, 553, 47
Friedman A. S., et al., 2015, ApJS, 220, 9
Foley R. J., et al., 2013, ApJ, 767, 57
Foley R. J., Jha S. W., Pan Y.-C., Zheng W. K., Bildsten L., Filippenko A. V., Kasen D., 2016, MNRAS, 461, 433
Garnavich P. M., et al., 2004, ApJ, 613, 1120
Hillebrandt W., Niemeyer J. C., 2000, ARA&A, 38, 191
Höflich P., Gerardy C. L., Fesen R. A., Sakai S., 2002, ApJ, 568, 791
Howell D. A., 2001, ApJ, 554, L193
Howell D. A., Höflich, P., Wang, L., & Wheeler, J. C. 2001, ApJ, 556, 302
Hoyle F., Fowler W. A., 1960, ApJ, 132, 565
Hsiao E. Y., et al., 2015, A&A, 578, A9
Jeffery D. J., 1999, astro, arXiv:astro-ph/9907015

The SN Ia faint subgroup are spectroscopically 91bg-like (see Table 1), however three SNe not in this subgroup are also classified as 91bg-like since they show strong Ti II in their maximum light spectra (Folatelli et al. 2013). Therefore, the presence of spectroscopic 91bg-like features is not an exclusive hallmark of the SN Ia faint subgroup, although the Ti II feature in the SN Ia-faint subgroup SNe is stronger than the feature in the three SNe not in this subgroup.

The SN Ia faint subgroup are characterised by single-peaked NIR light curves. Kasen (2006) find in their lowest $^{56}$Ni mass models that the NIR light curves are single peaked since the shift from doubly to singly ionized iron group elements (IGEs) that creates the second maximum occurs only ~20 days after explosion hence, coinciding with the primary maximum. Objects in our SN Ia-faint subgroup have inferred $^{56}$Ni masses $\lesssim 0.1 M_{\odot}$ indicating that their different NIR light curve morphology is a direct result of the low $^{56}$Ni yield. We note that other fast-declining SNe, e.g. 1991bg, 1998de, show no i-band second maximum (Filippenko et al. 1992; Turatto et al. 1996; Modjaz et al. 2001) and a late i-band peak (similar to the NIR properties of the SN Ia-faint subgroup) which would also make them members of this subclass.

Type Iax supernovae (Foley et al. 2013) also show a single NIR maximum despite displaying a large range of decline rates (1.2 < $\Delta m_{15}(B)$ < 2.4) and inferred $^{56}$Ni masses ($\sim 0.001$ - 0.18 $M_{\odot}$). This is understood as a result of a high degree of mixing of $^{56}$Ni (seen in 3-D deflagration models; e.g. Kromer et al. 2013; Fink et al. 2014) in the ejected material and is observationally supported by the rapid rise of the light curve to maximum (see for e.g. Yamanka et al. 2015) and the presence of iron in early time spectra (for e.g. Li et al. 2003). The nebular phase spectra of SN Ia, which, in some cases show P-Cygni line profiles, unlike the forbidden iron lines in nebular spectra of SN Ia (e.g. Jha et al. 2006; Foley et al. 2016), along with the peculiar maximum light spectroscopic and photometric properties would point towards them being distinct explosions from the fast-declining SNe analysed here.

Pure deflagrations which only partially unbind the progenitor, leaving a bound remnant (e.g. Kromer et al. 2013; Fink et al. 2014) can explain the low $M_{eJ}$ of the SN Ia-faint subgroup, though the corresponding $^{56}$Ni masses are higher than the values inferred from observations (Table 1). The presence of iron in the B-band and bolometric light curves of SN Ia-faint subgroup member SN 2005bl (Taubenberger et al. 2008; Fink et al. 2014), but cannot explain the extremely red colours for these SNe. We note, however, this explosion mechanism would not be a viable
Acknowledgements. This research was supported by the DFG Cluster of Excellence Origin and Structure of the Universe’. B.L. acknowledges support for this work by the Deutsche Forschungsgemeinschaft through TRR33, The Dark Universe. We all are grateful to the ESO Visitor Programme to support the visit of S. B. to Garching when this work was started. We thank Andrew Friedman for providing CfAIR2 light curves in machine-readable form and Stefan Taubenberger for discussions on rise times of fast declining SNe Ia.