A study of Si II and S II features in spectra of Type Ia supernova

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ABSTRACT
We studied the spectral features of Si II λ5972, 6355 and S II W-trough for a large sample of Type Ia supernovae (SNe Ia). We find that in NV (Normal-Velocity) subclass of SNe Ia, these features tend to reach a maximum line strength near maximum light, except for Si II λ5972. Spectral features with higher excitation energy, such as S II W-trough, are relatively weak and have relatively low velocity. SNe Ia with larger Δm15(B) tend to have lower velocities especially at phases after maximum light. NV SNe show a trend of increasing line strength with increasing Δm15(B), while 91T/99aa-like SNe show an opposite trend. Near maximum light, the absorption depth of Si II λ5972 shows the strongest correlation with Δm15(B), while at early times the sum of the depths of Si II λ54130 and 5972 shows the strongest correlation with Δm15(B). The overall correlation between velocity and line strength is positive, but within NV SNe the correlation is negative or unrelated. In normal SNe Ia, the velocity-difference and depth-ratio of a longer-wavelength feature to a shorter-wavelength feature tend to increase with increasing Δm15(B). These results are mostly well explained with atomic physics, but some puzzles remain, possibly related to the effects of the saturation, line competition or other factors.

Key words: (stars:) supernova: general - methods: data analysis - techniques: spectroscopic

1 INTRODUCTION
Type Ia supernovae (SNe Ia) remain the best distance indicators on cosmological scales (Phillips 1993; Phillips et al. 1999; Riess et al. 1998, 2016, 2019; Perlmutter et al. 1999; Betoule et al. 2014; Dhawan et al. 2018; Jones et al. 2018; Scolnic et al. 2018; Freedman et al. 2019). However, their progenitor systems (e.g., Whelan & Iben 1973; Nomoto 1982; Nomoto et al. 1997; Iben & Tutukov 1984; Webbink 1984; Maoz et al. 2014; Cao et al. 2015; Olling et al. 2015; Maeda & Terada 2016; Blondin et al. 2017; Liu et al. 2018; Livio et al. 2018; Jha et al. 2019; Flörs et al. 2020) and the explosion mechanisms (Nomoto et al. 1984; Nomoto & Leung 2018; Khokhlov 1991; Hillebrandt & Niemeyer 2000; Maeda et al. 2010, 2018; Sim et al. 2012, 2013; Ruiter et al. 2013; Shen et al. 2014; Jha et al. 2019; Wu et al. 2020) remain unclear. Spectroscopic information is a key to unraveling the persistent mysteries. Many physical properties, such as the element distributions, the kinematics of the ejecta, the photospheric temperature, and the optical depth can only be determined by spectroscopic methods (e.g., Sternberg et al. 2011; Dilday et al. 2012; Parrent et al. 2014; Maguire et al. 2018; Wilk et al. 2018; Jacobson-Galán et al., 2019).

SN Ia spectra are characterized by strong absorption features of intermediate mass elements (IME) ions, such as Si II, S II and Ca II (see Filippenko et al. 1997, for a comprehensive review). Of particular interest is the prominent feature Si II λ6355. The blueshifted velocity of the photospheric-velocity feature (PVF) of Si II λ6355 is representative of the ejecta velocity at the photosphere, typically about 11,000 km s$^{-1}$ at B-band maximum (Benetti et al. 2005; Maeda et al. 2010; Wang et al. 2009, 2013). In some early spectra, there is a high velocity feature (HVF) of Si II λ6355, detached from the PVF, which can be attributed to Si II absorptions formed in regions above the photosphere. Typical velocity of the HVF of Si II λ6355 is about 18,000 km s$^{-1}$, while this HVF can reach above 30,000 km s$^{-1}$ for Ca II (Mazzali et al. 2005a,b; Tanaka et al. 2008; Silverman et al. 2015; Zhao et al. 2015, 2016; Li et al. 2020). The HVF of Si II λ6355 usually only appears in early spectra, while the HVF of Ca II HK or Ca II NIR may also appear in some post-maximum spectra (Hatano et al. 1999;
Mazzali et al. 2005b; Childress et al. 2014; Maguire et al. 2014; Silverman et al. 2015). Our recent study revealed an anti-correlation between the properties of Si II λ6355 HVF and those of the O I λ7773 HVF (Zhao et al. 2016), which suggests that the HVFs may be associated with IME burnings in the outermost layers (see also, Kato et al. 2018; Mulligan & Wheeler 2017; Mulligan et al. 2019).

The strength of absorption features can be quantified with the pseudo-equivalent width (pEW; see, for example, Hachinger et al. 2006; Blondin et al. 2011) or the absorption depth normalized to the pseudo-continuum (see, for example, Nugent et al. 1995; Blondin et al. 2011). The excitation energy of the absorption feature is calculated by \( E_{\text{exc}} = E_{\text{upper}} - E_{\text{lower}} = \frac{hc}{\lambda} \), where \( E_{\text{lower}} \) is the lower energy level, and \( E_{\text{upper}} \) is the upper energy level, \( \lambda \) is the rest-wavelength. The effect of \( E_{\text{exc}} \) can be seen from the strong absorptions of PVFs (photospheric-velocity feature) and HVFs of Si II λ6355 and Ca II NIR (Zhao et al. 2015), while the effect of \( E_{\text{exc}} \) can be seen from comparison between lines Ca II HK and Ca II NIR, or between Si II λ4130 and Si II λ5972. The ionization degree also significantly affects the strength of absorption features, especially in 91T/99aa-like SNe (Mazzali et al. 1995; Fisher et al. 1999; Hachinger et al. 2008; Sasdelli et al. 2014; Taubenberger 2017).

While SNe Ia are known as standardizable candles, they actually have very diverse spectroscopic properties, including different velocity and strength of the observational features (including the HVFs), and presence/absence of some rare absorption features, such as variable sodium lines, H or He lines (e.g., Patat et al. 2007; Dilday et al. 2012; Jacobson-Galán et al., 2019). The photospheric temperature, which is associated with the amount of 56Ni produced in the explosion (Nugent et al. 1995; Hoeflich et al. 1996; Mazzali et al. 2001; Kasen & Woosley 2007; Churazov et al. 2014), is considered to be the main cause for the spectroscopic diversity, but even two SNe Ia with similar brightnesses could exhibit very different spectral features (The opposite could also be the case; some SNe Ia with similar spectral features actually have significantly different peak luminosities; see, for example, Foley et al. 2020). Physically, the spectroscopic property of SNe Ia is determined by the initial chemical compositions of the WD progenitors (e.g., Hachinger et al. 2006; Nomoto et al. 2013), the explosion and burning modes (e.g., Whelan & Iben 1973; Nomoto 1982; Fink et al. 2010; Maeda et al. 2010; Bulla et al. 2016; Maguire et al. 2018), the birthplace environments (e.g., Wang et al. 2013; Mandel et al. 2017; Hill et al. 2018; Meng et al. 2019) and other factors. For example, the appearance of unburnt carbon feature C II λ6580 may indicate a large amount of carbon in the WD progenitor (Parrent et al. 2011; Thomas et al. 2011; Folatelli et al. 2012; Silverman et al. 2012d; Hsiao et al. 2015), and tend to be related with the explosion mechanism/progenitor property (Li et al. 2020).

The near-ultraviolet (NUV) features of SNe Ia were found to be strongly correlated with the progenitor metallicity (Ellis et al. 2008; Mazzali et al. 2014; Brown & Crumpler 2020). The variable sodium or calcium feature reveals dense CSM around some SNe Ia (Hanuy et al. 2003; Patat et al. 2007; Sternberg et al. 2011; Maguire et al. 2013; Wang et al. 2019), which is in favor of the single-degenerate scenario (Whelan & Iben 1973; Nomoto 1982; Dilday et al. 2012). At the same time, there are also observational indications suggesting that the double-degenerate scenario may be responsible for some SNe Ia (e.g., Li et al. 2011; Schaefer & Pagnotta 2012; Kerzendorf et al. 2014); clearly more study is necessary in this respect.

Spectroscopic information could be used to improve the accuracy of distance determinations of SNe Ia, either through spectroscopic parameters that indicate the intrinsic diversities (Bailey et al. 2009; Wang et al. 2009; Foley & Kasen 2011; Maeda et al. 2011; Blondin et al. 2011; Silverman et al. 2012c; Burns et al. 2014; Mandel et al. 2014; Brown et al. 2018) or through others that reflect the explosion environments (Wang et al. 2013; Anderson et al. 2015; Hill et al. 2018). For example, Wang et al. (2009) found that the SN Ia subclass with high Si II λ6355 velocities (\( v \geq 11,800 \text{ km s}^{-1} \)) is the upper band maximum \(^{2}\) and the subclass with normal Si II λ6355 velocities (8,000 < \( v < 11,800\text{ km s}^{-1} \)) is the lower band maximum and different observed colors. Using different extinction ratios for the two subclasses reduced the luminosity dispersion from 0.178 mag to 0.125 mag. Also, there are some studies showing intrinsic correlation between the velocity and the light curve time scale (Zhang et al. 2010; Ganeshalingam et al. 2011; Kawabata et al. 2020). Some characteristic features, i.e., C II λ6580 absorption, may help select a subsample of “well-behaved” SNe Ia for more precise distance measurements (Parrent et al. 2011; Thomas et al. 2011; Folatelli et al. 2012; Silverman et al. 2012d).

Previous studies of the spectral features mostly focus on near-maximum light epochs (e.g., Branch et al. 2006; Hachinger et al. 2006; Wang et al. 2009; Blondin et al. 2011; Silverman et al. 2012b,c). Due to the lack of early-time spectra (\( t \lesssim -7\text{ d} \)), study on early-time spectral behaviors of SN Ia is still limited. Some information, such as features from unburnt materials, are often seen in the early phase. Different models usually predict similar maximum spectral features; the early spectral information can be a key to further constrain explosion models (e.g., Maeda et al. 2018). A comparison between features of early time and near-maximum light tells much about the influences of temperature, luminosity, and change in element abundances, which forms a fundamental problem for interpreting the spectral diversity of SN Ia (e.g., Blondin et al. 2012; Folatelli et al. 2013; Maguire et al. 2014; Stahl et al. 2020). A comparison between different features also provides important clues about the physics behind the spectral diversity of SN Ia. In this work, we collect a large sample of early spectra of SNe Ia as well as spectra near maximum light, and carefully examine the evolutions of four important spectral features Si II λ4430, 5972, 6355 and S II W-trough. We also examine the differences and correlations between these features, and their

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1 A table of the energy levels of important lines in spectra of SNe Ia near maximum light can be found on website: http://supernova.lbl.gov/~dnkasen/tutorial/

2 Throughout this paper the maximum is referred to the \( B \)-band maximum.
dependencies on the SN brightness. We address many details of the evolutions of these spectral features, and the results may be useful for future studies of SN Ia spectroscopy and SN Ia cosmology.

This paper is organized as follows. In Section 2 we present the spectroscopic sample used in this study, and describe our measurement procedure. Section 3 presents the temporal evolutions of the velocities and pEWs for different subclasses, and explore the correlation between velocity and pEW. In Section 4 we focus on the link between spectral properties and the luminosity decline rate $\Delta m_{15}(B)$\(^3\). In Section 4 we also examine the temporal evolutions of the velocity-differences and depth-ratios between different features, and present the evolutions of correlations of several possible spectral luminosity indicators with $\Delta m_{15}(B)$. In Section 3 and 4, the physical implications of our observational results are also discussed. We close the paper in Section 5 with our concluding remarks.

2 DATA AND MEASUREMENTS

Data source: Most spectra used in this work were compiled from the CfA supernova program (Matheson et al. 2008; Blondin et al. 2012), the Berkeley supernova program (Silverman et al. 2012a,b; Stahl et al. 2020) and the Carnegie Supernova Project (CSP, Folatelli et al. 2013). These SNe Ia are mostly included in our previous study (Zhao et al. 2015), where more information can be found. Photometric parameters are taken from the literature. After $t \approx +6$ d\(^4\), serious blends and spectral distortions make it difficult to perform an accurate measurement for most features of Si II and S II. Therefore our sample includes only spectra taken before $+6$ d. All spectra cover the wavelengths of the absorption features Si II $\lambda\lambda$5972, 6355 and S II W-trough (5,300 - 6,000 Å).

Sample selection: The original database contains more than 5,000 spectra of SNe Ia, but only about 2,000 spectra (from about 400 SNe Ia) were obtained before $+6$ d. We further selected about 120 SNe Ia which have at least 5 spectra at different phases between $-15$ and $+5$ d. The purpose of selecting relatively extensively observed SNe is to reduce the influence of the SN diversity on the mean evolutions. If using different objects at different phases, the evolutionary trends could be covered by the SN diversity, especially for those with slow evolutions. To take an extreme example, suppose we would use a sample including only two spectra from SN 1998aq at $-9.2$ d ($V_{5635} = 10,944$ km s\(^{-1}\)) and SN 2003kg at $-6.2$ d ($V_{5635} = 11,530$ km s\(^{-1}\)), a false-der component, however, has been disputed, and most people use $5640$ Å (e.g., Hachinger et al. 2006; Blondin et al. 2011). In this work, we also use $5454$ Å as the rest-wavelength of the bluer component, but $5620$ Å for the redder component. The adoption of $5620$ Å rest-wavelength was calculated by $(1.43219 \times 5606.15 \, Å +1.40281 \times 5640.35 \, Å)/(1.43219 +1.40281) \approx 5620$ Å, where $5606.15$ and $5640.35$ Å are the wavelengths of the two lines that blend into the redder component of S II W-trough, and $1.43219$ and $1.40281$ are the corresponding oscillator strengths, respectively. Using $5620$ Å rest wavelength for the redder component leads to a mean velocity difference of about 400 km s\(^{-1}\) between these two components, while using $5640$ Å rest wavelength leads to a mean velocity difference of about 1,400 km s\(^{-1}\).

Since two lines with very similar energy levels are expected to have very similar velocities, it is more physically plausible to use $5620$ Å as the rest wavelength of the redder component of S II W-trough ($E_{\text{lower}}$: 13.73 eV vs. 13.70 eV, $E_{\text{osc}}$: 2.21 eV vs. 2.27 eV).

Smoothing: Before fitting, we smoothed each observed spectrum with a locally weighted linear regression (nearby neighbors were more heavily weighted; see, for example, Cleveland 1979). For fittings of S II W-trough and Si II $\lambda\lambda$5972, 6355, the smoothing window was 125 – 150 Å. This span effectively reduces the influence of noise, and also well preserves the profiles of the features. For Si II $\lambda\lambda$4130, the span is much smaller ($\approx 35$ Å). This well preserves the details of Si II $\lambda\lambda$4130 which could be very weak at early times.

Pseudo-continuum: As demonstrated in Figure 1, the pseudo-continua are defined by connecting the featureless points in the spectrum. Note that the two ends of a feature are not necessarily featureless, because there could be serious blending between two neighboring features. For example, the red end of Si II $\lambda\lambda$5972 of SN 2004as in Figure 1 is much lower than the straight line that well fit the featureless points near 5400, 5850 and 6600 Å. The red end of S II $\lambda\lambda$6520 of SN 2004ef shows a similar behavior, as shown in Figure 1. For some spectra at early times, more sophisticated method for determining the pseudo-continuum is required if a “perfect” fitting is desired. This is however beyond the scope of this paper, and this does not affect the conclusions of this work. For most spectra, the pseudo-continuum is well-fitted by the classical method, i.e., connecting featureless points. In Figure 1, typical examples of the pseudo-continuum are shown. In some cases the pseudo-continuum (between 5,400 and 6,500 Å) appears to be linear, while in other cases the pseudo-continuum appears to be “Λ”-shape (e.g., 2004eo at $-10.4$ d) or “V”-shape (e.g., 2004ef at $-6.7$ d).

Spectral fitting: The measurement procedure is overall similar to that applied in our previous works (Zhao et al. 2015, 2016). The Si II $\lambda\lambda$4130 feature was fitted with a single-gaussian model. S II W-trough, Si II $\lambda\lambda$5072 and 6355, HVF of Si II $\lambda\lambda$6355, C II $\lambda\lambda$6580 and an unknown feature near (for example, for SN 2000fa we have 5 spectra at $-11$, $-9$, $+1$, $+2$ and $+4$ days, but these data hardly reveal details of the evolutionary trend). By considering the above factors, we obtained our final sample with 79 SNe Ia.

The rest-wavelengths of the two components of S II W-trough: Multiple lines contribute to the absorption feature of S II W-trough, merging together as a doublet absorption. The rest-wavelength of the bluer component is usually taken to be $5454$ Å. The rest-wavelength of the redder component, however, has been disputed, and most people use $5640$ Å (e.g., Hachinger et al. 2006; Blondin et al. 2011). In this work, we also use $5454$ Å as the rest-wavelength of the bluer component, but $5620$ Å for the redder component. The adoption of $5620$ Å rest-wavelength was calculated by $(1.43219 \times 5606.15 \, Å +1.40281 \times 5640.35 \, Å)/(1.43219 +1.40281) \approx 5620$ Å, where $5606.15$ and $5640.35$ Å are the wavelengths of the two lines that blend into the redder component of S II W-trough, and $1.43219$ and $1.40281$ are the corresponding oscillator strengths, respectively. Using $5620$ Å rest wavelength for the redder component leads to a mean velocity difference of about 400 km s\(^{-1}\) between these two components, while using $5640$ Å rest wavelength leads to a mean velocity difference of about 1,400 km s\(^{-1}\).
5600 Å were fitted consistently and simultaneously with a 7-component gaussian function. In most cases, these features were well-separated by applying velocity constraints. For example, S II λ5454 with velocity 7,000 ≤ V_{5454} ≤ 12,000 km s\(^{-1}\) is located at λ5240 ≤ λ_{5240} ≤ 5328 Å, while its neighboring feature S II λ5620 with similar velocity is located at 5400 ≤ λ_{5620} ≤ 5490 Å. This means the two components of the S II W-trouch will never be mistaken. All fittings were visually inspected to ensure that a good fit was obtained. The velocity and line strength measurements are listed in Table 1.

**Measurement uncertainties:** The smoothed-and-interpolated spectra (using “linear-interpolation” method in MATLAB, with 0.5 Å interval) are generally well fitted by the multiple-gaussian function, with the coefficient of determination (R-squared) ranging from 0.925 to 0.999. However, for each component the uncertainty could be much higher due to the blendings. The uncertainties (for each component) are given in Table 1. They are the total uncertainties with contributions from the gaussian fitting, the flux error, and the wavelength uncertainty (depending on the wavelength interval).

### 3 TIME EVOLUTION OF THE SI II AND S II FEATURES

#### 3.1 Temporal evolution of line velocity

The velocity of a given feature is derived from the blueshift of its deepest absorption (i.e., the minimum of the feature after the pseudo-continuum is removed) relative to the rest-wavelength. Each feature in the spectrum has its own velocity, depending on where the absorption is located in the ejecta (e.g., Patat et al. 1996). The velocity evolution of S II λ6355 has been studied intensively (e.g., Benetti et al. 2005; Wang et al. 2009; Foley et al. 2011; Blondin et al. 2012), while the velocity evolution for other lines may need further investigation. Velocity evolutions of lines S II λ4130, 5972 and S II W-trouch have been studied by, e.g., Silverman et al. (2012b), Folatelli et al. (2013), and Stahl et al. (2020). Our sample is most similar to that of Blondin et al. (2012), who did not give these velocity evolution measurements. Below we present the velocity evolutions for these lines as well as S II λ6355.

Figure 2 shows the velocity evolutions for different subclasses in the Wang et al. (2009) classification scheme. For each point, we took the mean of the measurements within ±0.5 d, i.e., t ± 0.5 d. In general, the velocities decrease with time as expected (due to the recession of the photosphere following the expansion and the decrease in density). The only exception is the velocity of S II λ5072 (V_{5072}), which somehow surprisingly increases with time after t ≈ −2 d, and even surpasses the velocity of S II λ6355 (V_{6355}) after t ≈ +2 d (see discussion in §4.6). No systematic bias was found in the analysis method that could cause the abnormal behavior of V_{5072}.

During the phase from t ≈ −14 to +5 d, the NV objects have an average velocity gradient of about 200 km s\(^{-1}\)d\(^{-1}\), while the HV objects have corresponding value of about 300 km s\(^{-1}\)d\(^{-1}\), and the 91T/99aa-like objects (Filippenko et al. 1992b; Phillips et al. 1992; Li et al. 2001; Garnavich et al. 2004; Sasdelli et al. 2014; Taubenberger 2017) have an average velocity gradient of about 100 km s\(^{-1}\)d\(^{-1}\). During the phase from t ≈ −7 to +3 d, the representative 91bg-like (Filippenko et al. 1992a; Mazzali et al. 1997; Howell et al. 2001; Hachinger et al. 2009; Taubenberger 2017) object, SN 1998de is found to have a velocity gradient of about 400 km s\(^{-1}\)d\(^{-1}\). It is clear that faster decliners tend to have more rapidly declining velocities, possibly due to their faster decreases in temperature.

Velocities obtained here are generally consistent with previous studies, including the rising trend of V_{5072} after B-band maximum (e.g., Silverman et al. 2012b). We use a sample that is most similar to Blondin et al. (2012). The V_{6355} measured around the B-band maximum is about 11,000 km s\(^{-1}\) for normal SNe Ia in Blondin et al. (2012), compared to about 10,600 km s\(^{-1}\) obtained in our work. Minor difference could be due to two reasons: Firstly, the determination of the position of the absorption minima. Whether it is directly determined from the smoothed flux or determined by a gaussian fitting can lead to different results in the velocity measurement. Secondly, the blending of some features (e.g., SII λ6355 at early times) with other lines or the HVF may also seriously affect the velocity measurement (e.g., Zhao et al. 2015).

#### 3.2 Temporal evolution of line strength

The absorption strength can be quantified by the pseudo-equivalent width (pEW, see, e.g., Blondin et al. 2011; Zhao et al. 2015, for details), or the absorption depth (H)
A study of Si II and S II features in spectra of Type Ia supernova

Table 1. Measured velocities and line strengths. This is a sample of the full table, which is available online (see “Supporting Information”).

| SN    | Phase | Subtype | \(\Delta m_{15}(B)\) | \(V_{4130}\) | \(W_{4130}\) | \(W_{5972}\) | \(W_{6355}\) | \(W_{5454}\) | \(W_{6355}\) | \(W_{5454}\) | \(W_{5620}\) | \(W_{3929}\) | \(W_{4545}\) | \(W_{5455}\) | \(W_{5620}\) | Source | Ref. |
|-------|-------|---------|------------------------|------------|-----------|-------------|-------------|-------------|-------------|-------------|-------------|-------------|-------------|-------------|-------------|-----------|-------|
| 1994D | -11.5 | NV      | 1.37                   | 11447(573) | 16(1)     | 12177(609) | 27(1)       | 21303(620)  | 10(1)       | 20306(513)  | 10(1)       | 10044(547)  | 28(2)       | 11022(552) | 44(2)      | CII 1  |
| 1994D | -9.5  | NV      | 1.37                   | 10597(530) | 19(2)     | 11370(569) | 23(2)       | 21609(609)  | 10(5)       | 10398(520)  | 27(2)       | 11083(555) | 37(2)       | CII 1       |
| 1994D | -5.5  | NV      | 1.37                   | 10331(510) | 18(2)     | 11584(556) | 18(2)       | 5620(543)   | 10(5)       | 9618(481)   | 31(5)       | 10153(508) | 35(5)       | CII 1       |
| 1994D | -2.5  | NV      | 1.37                   | 10607(504) | 23(1)     | 10608(533) | 19(2)       | 11054(553)  | 97(7)       | 9362(469)   | 39(3)       | CII 1       |
| 1994D | 0.5   | NV      | 1.37                   | 9962(499)  | 23(1)     | 10782(460) | 24(2)       | 10886(542)  | 104(8)      | 8770(439)   | 40(3)       | 9522(487)  | 45(2)       | CII 1       |
| 1994D | 2.5   | NV      | 1.37                   | 11197(560) | 31(3)     | 10913(541) | 106(8)      | 5454(428)   | 42(4)       | 9252(463)   | 54(2)       | CII 1       |
| 1994D | 3.5   | NV      | 1.37                   | 9146(458)  | 20(1)     | 11249(563) | 34(3)       | 10740(538)  | 10(9)       | 8535(418)   | 42(4)       | 8624(442)  | 56(2)       | CII 1       |
| 1994D | 4.5   | NV      | 1.37                   | 12349(550) | 32(2)     | 10793(460) | 10(8)       | 8361(419)   | 36(3)       | 8786(440)   | 51(2)       | CII 1       |

Notes: Uncertainties are listed in parentheses.

\(^{a}\) Phase of spectra are in rest-frame days relative to the time of \(B\)-band maximum light.

\(^{b}\) Wang-scheme classification (Wang et al. 2009). The velocity boundary between HV-SNe and NV-SNe is around 11,800 km s\(^{-1}\).

\(^{c}\) \(B\)-band light-curve decline rate \(\Delta m_{15}(B)\).

\(^{d}\) Velocity of Si II \(A4130\), for the photospheric (PHO) component.

\(^{e}\) Pseudo-equivalent width of Si II \(A4130\), for the PHO component.

\(^{f}\) Velocity of Si II \(A3972\), for the PHO component.

\(^{g}\) Pseudo-equivalent width of Si II \(A3972\), for the PHO component.

\(^{h}\) Velocity of Si II \(A6355\), for the PHO component.

\(^{i}\) Pseudo-equivalent width of Si II \(A6355\), for the PHO component.

\(^{j}\) Velocity of S II \(A5454\), for the PHO component.

\(^{k}\) Pseudo-equivalent width of S II \(A5454\), for the PHO component.

\(^{l}\) Velocity of S II \(A5620\), for the PHO component.

\(^{m}\) Pseudo-equivalent width of S II \(A5620\), for the PHO component.

\(^{n}\) Data source references: CSN- CIGN supernova program (Matheson et al. 2008; Blondin et al. 2012); Lick-Berkeley Supernova Program (Silverman et al. 2012a,b; Stahl et al. 2020); CSP- Carnegie Supernova Project (Folatelli et al. 2013); THU- Tsinghua Supernova Program (Zhang et al. 2015a); ALe07 = (Altavilla et al. 2007); CH13 = (Childress et al. 2013); PV13 = (Pereira et al. 2013); ZH15 = (Zhang et al. 2015b); ZH13 = (Zhang et al. 2013). Most of the spectra are available on the online “open supernova catalog” (Guillochon et al. 2017).

\(^{o}\) Photometric references: 1 = (Blondin et al. 2012); 2 = (Brown et al. 2019); 3 = (Childress et al. 2013); 4 = (Childress et al. 2014); 5 = (Folatelli et al. 2012); 6 = (Folatelli et al. 2013); 7 = (Eannelli et al. 2013); 8 = (Jha et al. 2008); 9 = (Pignata et al. 2004); 10 = (Silverman et al. 2015); 11 = (Stritzinger et al. 2011); 12 = (Wang et al. 2009); 13 = (Zhang et al. 2015); 14 = (Zhang et al. 2017).

Figure 2. Evolutions of the velocities (V) with time for the four subclasses defined by Wang et al. (2009). The velocities are averaged over 1 d intervals. Color coded are the four lines we study: Si II \(A4130\) (blue diamond); Si II \(A5972\) (red circle); Si II \(A6355\) (black square); the two components of S II W-trough (green/brown). Due to lack of extensively observed 91bg-like objects, we can only use SN 1998de as a representative. Note that the y-axis ranges have been increased in the bottom panels to encompass the larger variations in the velocities of HV and 91bg-like SNe.

Figure 3 shows the pEW evolutions for different subclasses in the classification scheme proposed by Wang et al. (2009). Each point was averaged over 1 d intervals, i.e., \(t \pm 0.5\) d. NV objects: In general, the pEWs of NV objects increase with time before the \(B\)-band maximum. An exception for this tendency is pEW of Si II \(A5972\), which decreases until \(t \approx -1\) d. The other longer-wavelength feature, Si II \(A6355\), also weakens with time before \(t \approx 7\) d, after which it remains vir-

which is defined as the deepest absorption of the feature normalized to the pseudo-continuum. The temporal evolutions of the pEWs of Si II \(\lambda\lambda4130, 5972, 6355\) and S II W-trough have been studied by, e.g., Silverman et al. (2012b), Folatelli et al. (2013), and Stahl et al. (2020), but not given by Blondin et al. (2012). As mentioned previously, our sample is very similar to that of Blondin et al. (2012), and below we present the pEW evolutions for our sample.
ntually unchanged. It appears from Figure 3 that the pEW of S II W-trough of NV objects reaches a maximum value near $t \approx +2$ d, though the trend is less noticeable than in 1991T/99aa-like SNe Ia. For Si II $\lambda4130$, though the average pEW shows a slight trend of increasing after $+2$ d, there are actually more than half of NV objects exhibiting a decrease or plateau of pEW after $t \approx +2$ d. Specifically, after $+2$ d, SNe 1994D, 2002er, 2003g and 2005cf show a decreasing pEW, SNe 1998aq, 2004at, 2005ef and 2011fe show constant pEW, while SNe 2002de, 2003du, 2006S, 2007af, 2008ar, 2008bf and 2009ab show a slowly increasing pEW (see Table 1). The delay in reaching the maximum line-strength relative to the maximum light could be due to our using $B$-band maximum light as the 0 d, as $V$-band maximum is usually 1 - 2 d later than the $B$-band maximum. We notice that Si II $\lambda5972$ behaves differently than other features, with a minimal pEW near $t \approx -1$ d (see discussion in §4.6). The fact that the features generally reach an extremum (i.e., maximum or minimum) pEW near maximum light suggests that the line strengths are significantly influenced by the luminosity. However some features (i.e., Si II $\lambda6355$) seem not to follow the trend. This can be explained as other factors such as saturation, temperature, element abundance, which can also affect the absorption strengths.

**Other subtypes:** HV objects are characterized by large and nearly constant line strengths of Si II $\lambda6355$ and S II W-trough, which may imply a high degree of saturation. The evolutionary trends of the velocities and the pEWS of HV SNe are overall similar to those of NV SNe, supporting the classification of both “HV-Ia” and “NV-Ia” objects as “normal” SNe Ia. The 91T/99aa-like objects are characterized by weak Si II $\lambda6355$ and nearly constant strength of Si II $\lambda4130$.

The evolutionary trends we showed above are generally consistent with the results given by some recent studies (Silverman et al. 2012b; Folatelli et al. 2013; Stahl et al. 2020), except for pEW$S_{\lambda6355}$. Our results are similar to that of Folatelli et al. (2013), with a decreasing trend of pEW$S_{\lambda6355}$ before $B$-band maximum. In Stahl et al. (2020), four-day mean value of pEW$S_{\lambda6355}$ slightly decreases from 20 $\AA$ to 17 $\AA$ at $-17 < t < -9$ d, but it then increases progressively from 17 to 25 $\AA$ at $-9 < t < +5$ d. Stahl et al. (2020) also gives the four-day mean value of pEW$S_{\lambda5072}$ using the data from Silverman et al. (2012b), which increases from 18 to 26 $\AA$ at $-12 < t < -5$ d, it then remains nearly unchanged between $-5$ and $+5$ d ($\approx 26$ $\AA$). The discrepancy may be due to the different sample or different measurement method (see discussion in §2). Nevertheless, our measurement of pEW$S_{\lambda5072}$ is still roughly consistent with the previous studies. For example, at $B$-band maximum, Silverman et al. (2012b) give a mean value of pEW$S_{\lambda5072}$ $\approx 25$ $\AA$ for normal SNe, while we give a corresponding value of $\approx 23$ $\AA$. At $-5$ d, Silverman et al. (2012b) give a mean value of $\approx 26$ $\AA$ for normal SNe, while we give pEW$S_{\lambda5072} \approx 25$ $\AA$.

### 3.3 Correlation between velocity and line strength

The correlation between $V_{\lambda6355}$ and pEW$S_{\lambda6355}$ has been previously studied by, e.g., Wang et al. (2009), Blondin et al. (2012) and Maguire et al. (2014). In Wang et al. (2009), a clear trend of larger pEW corresponding to higher velocity at maximum light was observed in both NV and HV subclasses. In Blondin et al. (2012), HV SNe show positive velocity-pEW correlation, while NV SNe show no clear velocity-pEW correlation. In Maguire et al. (2014), HV SNe show no clear velocity-pEW correlation, while NV SNe show a slight trend with larger pEW corresponding to larger velocity. The discrepancy between these results may be due to sample selection. Also note that the correlation could be seriously affected by the evolutionary effect, depending on how velocity and pEW evolve in the phase range. In this section, we do not reinvestigate the velocity-pEW correlation at maximum light, but instead focus our analysis on the evolution of this correlation.

Figure 4 shows the correlation between velocity and pEW for Si II $\lambda6355$ and S II W-trough. The data are restricted to be within $\pm 2$ d from the selected epochs to reduce the evolutionary effect: left panels are for the sample at $-6 \pm 2$ d, right panels of the same figure are for the sample at $3 \pm 2$ d. The overall trend is positive, but mainly due to the fact that HV SNe generally have both higher velocities and pEWS than the NV counterparts. Within each subclass, the exact correlation seems to depend on the phase.

For Si II $\lambda6355$ in the spectra of HV or 91T/99aa-like SNe, the velocity and pEW appear to be positively correlated near $t \approx -6$ d, but this correlation becomes weak near $+3$ d. The reason of the positive velocity-pEW correlation near $t \approx -6$ d is unclear. Physically, the velocity and pEW may not affect each other directly, but they might be indirectly connected through temperature, luminosity or element abundance. For the NV SNe, the velocity-pEW correlation of Si II $\lambda6355$ is weak if there is any near $-6$ d, and seems to show a negative correlation near $t \approx +3$ d. A negative correlation can be explained as a result of lower optical depth in outer layers, in addition to the relatively high degree of homogeneity within NV-Ia subclass, which reduces the effect of element abundance and luminosity. Negative velocity-pEW correlation is also seen in both photospheric and HVF components of O I $\lambda7773$ (Zhao et al. 2016). The change in $V_{\lambda6355} - pEW_{\lambda6355}$ may be related to the changes in $\Delta m_{15}(B)$ (dependence of $V_{\lambda6355}$ and pEW$S_{\lambda6355}$, $t \approx +3$ d, possibly due to decrease in temperature, $V_{\lambda6355}$ becomes anti-correlated with $\Delta m_{15}(B)$, while pEW$S_{\lambda6355}$ is positively correlated with $\Delta m_{15}(B)$ (see §4.1 and 4.2 for more details).

For S II W-trough near $t \approx -6$ d, the velocity-pEW correlation appears to be insignificant within the HV or 91T/99aa-like objects, and it may be negative for the NV objects. This negative correlation for NV objects somehow disappears near $t \approx +3$ d, as shown in the bottom-right panel of Figure 4. This may be due to a negative correlation between $V_{\lambda52}$ and $\Delta m_{15}(B)$, which is weak at $t \approx -6$ d, but strong at $t \approx +3$ d (discussed later in §4.1 and 4.2).

### 3.4 Comparison between 91T/99aa-like and 91bg-like SNe

The effects of the temperature on the absorption features have been introduced in §1. Here, we make comparison between the “hot” 91T/99aa-like objects and the “cool” 91bg-like objects to see the details. (a) As shown in Figure 2, the velocities of 91T/99aa-like objects stay almost unchanged after $t \approx -8$ d relative to $B$-band maximum. In contrast,
Figure 3. Evolutions of the pseudo-equivalent widths (pEWs) with time for the four spectroscopic subclasses defined by Wang et al. (2009). The pEWs are averaged over 1 d intervals. Due to lack of extensively observed 91bg-like object, we can only use SN 1998de as a representative. Colors and shapes of data points are the same as in Figure 2.

Figure 4. Top-left panel: pEW of the Si II λ6355 feature as a function of the velocity of Si II λ6355 feature for SN Ia spectra within 2 d of −6 d since maximum light. If more than one measurement was available, the one closest to the central phases was used. Bottom-left panel: Similar to the top-left panel, but for the S II W-trough feature. Right panels: Similar to the left panels, but for spectra near +3 d. The sample has been split into subclasses as defined by Wang et al. (2009). Blue asterisks are normal-velocity (NV) objects, red circles are high-velocity (HV) objects, black squares are 91T/99aa-like objects, green pentagrams are 91bg-like objects. Other objects, including peculiar or uncertain subtype objects are marked with brown diamond.
the velocities of 91bg-like objects decrease rapidly with time; (b) As shown in Figure 3, the pEWs of 91T/99aa-like objects keep increasing with time. On the other hand, the pEWs of 91bg-like objects keep decreasing with time, except for the lowly excited feature Si II λ6355. (c) As shown in Figure 4 (which shows relations between the velocities and pEW or Si II λ6355 and S II W-trough at different epochs), 91T/99aa-like objects have much weaker Si II λ6355 but much stronger S II W-trough than 91bg-like objects. These may serve as an example of temperature effect, which is important for understanding the spectral diversity, as will be further discussed in the next section.

4 THE DECLINE-RATE DEPENDENCES OF THE SI II AND S II FEATURES

4.1 The decline-rate dependence of the velocity

While some studies (Hatano et al. 2000; Benetti et al. 2005; Foley et al. 2011) suggested no clear correlation between the velocity of Si II λ6355 at B-band maximum and ∆m15(B), others suggest that the velocity at B-band maximum is anti-correlated with ∆m15(B) (Hachinger et al. 2006). In this section, we show how the velocity-∆m15(B) correlation evolves with time.

Figure 5 shows the Pearson correlation coefficients (ρ, as defined in Eq. 1) between the velocities and the ∆m15(B). The negative Pearson coefficients suggest that the velocities are generally anti-correlated with the ∆m15(B). The Pearson coefficients are mostly very small, suggesting that the correlations are modest, insignificant or even nonexistent at most phases. The Pearson correlation coefficient is defined as follows:

\[
\rho_{x,y} = \frac{\text{cov}(x, y)}{\sigma_x \sigma_y} = \frac{\sum_{i=1}^{n} (x_i - \bar{x})(y_i - \bar{y})}{\sqrt{\sum_{i=1}^{n} (x_i - \bar{x})^2 \sum_{i=1}^{n} (y_i - \bar{y})^2}}
\]

where \(x\), \(y\) are the standard deviations of \(x\) and \(y\), respectively, and \(\text{cov}(x, y)\) is the covariance between \(x\) and \(y\).

Figure 5 also shows how the correlations evolve with time. The correlations are very weak at early times, then grow stronger with time until +4 d, implying a stronger dependence of the velocity on ∆m15(B) at cooler temperature. For some reason the correlations between the velocities and ∆m15(B) weaken with time after +4 d. The correlation is strongest for S II W-trough, and weakest for Si II λ6355, implying a stronger dependence on the SN brightness for lines from highly-excited levels. A relatively strong correlation seems to exist between \(V_{SW}\) at \(t \approx +3\) d and ∆m15(B), as shown in the bottom-right panel of Figure 6.

When the sample is restricted to only a subclass, the correlation of the velocity with ∆m15(B) appears somewhat weaker. In fact, as shown in Figure 6, the correlation is largely driven by 91bg-like objects which have both lower velocities and luminosities than other subtypes. This may explain the relatively strong velocity-∆m15(B) correlation in Hachinger et al. (2006), as their sample contains a higher fraction of SN 91bg-like events.

At \(-6\) d, line velocities of 91T/99aa-like SNe seem to have stronger correlations with ∆m15(B) than that of other subclasses, as shown in Figure 6. This may be due to a more significant ionization effect in 91T/99aa-like object, as their photospheric temperatures are relatively high (Benetti et al. 2005). A higher degree of ionization can cause the singly ionized absorptions to move outward to the cooler, faster-moving layers, and thereby an anti-correlation between the velocity and ∆m15(B). It is also noted that \(V_{SW}\) appears to have a stronger correlation with ∆m15(B) than \(V_{6355}\). For example, at \(-6\) d, when ∆m15(B) increases from 0.8 to 1.0 mag, \(V_{SW}\) (of 91T/99aa-like SNe) decreases from 12,000 to 6,000 km s\(^{-1}\), while \(V_{6355}\) (of 91T/99aa-like SNe) only decreases from 13,000 to 10,000 km s\(^{-1}\), as shown in the left panels of Figure 6 (see also the discussion in §4.3). A possible reason is the relatively high energy levels of S II W-trough, which makes the line more sensitive to the photospheric temperature.

4.2 The decline-rate dependence of the line strength

Hachinger et al. (2006) and Blundin et al. (2012) have studied the correlation between pEW and ∆m15(B) for various lines at maximum light, with the aim to find better spectroscopic luminosity indicator. In this section, we further explore the temporal evolutions of the correlations between the line strengths and the ∆m15(B), and compare them among different subclasses of SNe Ia. Unlike most studies, here we use the absorption depth (\(H\)) to represent the line strength, as it shows a slightly stronger correlation with ∆m15(B) (see §4.5 for more details).

Figure 7 shows positive correlations between the depths of Si II and S II absorption features and ∆m15(B). The sample is restricted to NV-SNe Ia whose high degree of homogeneity (meaning relatively similar velocities and line strengths of IME features, as well as relatively similar luminosities) leads to a tighter relation with ∆m15(B). One possible explanation for the positive correlations is that the dimmer objects tend to suffer less burning and have hence more IME left in the ejecta. Another possible reason is that...
in dimmer objects the photospheric temperature is relatively low, in favor of low-ionization lines such as Si II λ6355.

It is somewhat surprising that dimmer objects display stronger absorptions in Si II λλ4130, 5972 and S II W-trough than brighter objects, since these lines originate from rather highly excited levels. These positive correlations between the line strengths and Δm_{15}(B), together with the pEW-evolutions (see §3.2), seem to suggest a less importance of temperature effect on those prominent features than the luminosity. Nonetheless, the correlation is weak for Si II λ6355 which has the lowest excitation energy, and also weak for S II W-trough which has the highest excitation energy, suggesting that only the lines with proper (excitation & ionization) energies may have a strong correlation with the peak brightness.

In the left panels of Figure 8, we compare the decline-rate dependence of pEW_{Si6355} at t ≈ −6 d to that of pEW_{SW}. Although these two lines are produced with very different excitation and ionization energies, it appears that their pEWS have similar correlations with Δm_{15}(B). For NV SN, the pEWS appear to be positively correlated with Δm_{15}(B), which has been discussed in the previous paragraph. For HV SNe which have relatively large pEWS, the pEW-Δm_{15}(B) correlation is insignificant.

In 9IT/99aa-like SNe, as shown in Figure 8, the pEWS of both Si II and S II lines appear anti-correlated with the decline rate, i.e., brighter 9IT/99aa-like objects tend to have stronger absorptions of Si II λ6355 and S II W-trough. This is rather puzzling because brighter 9IT/99aa-like objects are expected to have more complete burning of IME to 56Ni. It may not be a result of either temperature effect or luminosity effect, because a dimmer/colder condition prefers the formation of Si II λ6355. A possible explanation is that oxygen burning in 9IT/99aa-like object may contribute substantially to the formation of IME. Brighter 9IT/99aa-like SNe may then have more IME than the dimmer ones. Moreover, for 9IT/99aa-like objects, pEW_{Si6355} appears to have a stronger correlation with Δm_{15}(B) than pEW_{SW}. For example, at −6 d, when Δm_{15}(B) increases from 0.8 to 1.0 mag, pEW_{Si6355} decreases from 70 to 10 Å, while pEW_{SW} only decreases from 60 to 30 Å, as shown in the left panels of Figure 8. This may be due to the relatively low abundance of Si II in 9IT/99aa-like objects.

**Figure 6.** Velocities of Si II λ6355 and S II W-trough at −6 and +3 d as a function of Δm_{15}(B). Measurements within 2 d were used, and if more than one measurement was available, the one closest to the central phase was used. Colors and shapes of data points are the same as in Figure 4.

**Figure 7.** Time-evolutions of the correlations between several indicators and the Δm_{15}(B). Superscript “NV” denotes the NV subclass which has a stronger correlation with Δm_{15}(B) than other subclasses. Measurements within 2 d were used, and if more than one measurement was available, the one closest to the central phases was used. The sample size is marked on the right for each point.

### 4.3 Velocity differences

The ejecta velocity of SNe Ia varies from object to object, partially due to the asymmetric explosion and line-of-sight effect (Maeda et al. 2010, 2011), and partially due to SN Ia diversity that arises from different progenitor systems and/or explosion mechanisms (see the references given in §1). Even in the same spectrum, different lines still show different velocities, suggesting a layered structure of the SN Ia ejecta (with velocity increasing outward). In this section, we explore the temporal evolution of the velocity differ-
ences shown between the four spectral features that we study here, and their correlations with $\Delta m_{15}(B)$. Unless otherwise stated, throughout this work a velocity-difference between two features of the same species is defined as the velocity of the longer-wavelength feature minus the velocity of the shorter-wavelength feature.

Deeper layers (corresponding to slower layers) of the ejecta tend to have higher temperatures favoring the occupations of highly-excited states. Therefore, lines from highly-excited states are expected to have lower velocities than lines from lowly-excited states. This is confirmed in Figure 9 which shows rapid increases of the velocity-differences after maximum light, and it could be a sign of accelerating separation between ejecta layers with different thermal condition. The only exception is $V_{5454} - V_{5502}$, which remains very small, likely due to that these two lines have very close energy levels (see discussion in §2).

Scatter plots in the upper panels of Figure 10 show details about how $V_{5972} - V_{4130}$ and $V_{5972} - V_{5620}$ are related to $\Delta m_{15}(B)$. The sample is restricted to spectra obtained about 6 d prior to maximum brightness, when the velocities decline linearly with time (see Figure 2). The correlations are overall positive, i.e. fast-decliners tend to have greater $V_{5972} - V_{5620}$ and $V_{5454} - V_{5620}$ than slow-decliners (SN 1991T and SN 1997br appear to be two outliers. In fact, they are also considered as peculiar objects in Hachinger et al. 2006). The direct reason is that $V_{5620}$ and $V_{5454}$ decrease more rapidly with increasing $\Delta m_{15}(B)$ than $V_{5972}$ and $V_{5620}$ (see Figure 5). Physically, this could be explained as that lines with higher excitation and ionization energies are more strongly influenced by the decrease of temperature and luminosity. However, in 91T/99aa-like subclass, $V_{5454} - V_{5620}$ appears independent of $\Delta m_{15}(B)$. This is likely due to that these two lines have similar energy levels, and 91T/99aa-like objects have relatively high temperature and luminosity.

4.4 Depth ratios

The correlation between the line-strength ratio and $\Delta m_{15}(B)$ has been studied before (e.g., Benetti et al. 2005; Hachinger et al. 2006; Blondin et al. 2012), with the aim to better calibrate SNe Ia as standard candles, or to trace the element abundances in SN Ia ejecta. Most studies focus on correlations at maximum light, and use pEW-ratios to quantify the strength-ratios. However, as mentioned before, the pEW measurement is easily affected by line-blending, and we therefore use the depth-ratio instead. The other reason we use the depth-ratio is that few of this ratio have been identified so far. A depth-ratio would be more robust against line-blending. As an example, we show in Figure 8 the depth-ratio $S_{5620}/S_{5972}$ as a function of $\Delta m_{15}(B)$ and $\Delta m_{12}(B)$. This ratio measures the strength-ratio between the $S_{5620}$ and $S_{5972}$ lines. The two lines are most likely blended in most SNe Ia, but $S_{5620}/S_{5972}$ is less so. As for the $\Delta m_{15}(B)$-dependence, we see that $S_{5620}/S_{5972}$ increases with $\Delta m_{15}(B)$, however this correlation is not as strong as that of the strength-ratio $S_{5620}/S_{5972}$.
defined as the ratio of the depth of the longer-wavelength feature to the depth of the shorter-wavelength feature.

In Figure 9 we show the time evolution of the depth-ratios. Since some 91T/99aa-like or 91bg-like objects have extreme values of the depth ratios that are not suitable for averaging, this figure includes only normal SNe Ia, i.e. NV or HV groups. It appears that the time evolutions of the depth-ratios share some similarities with the evolutions of the velocity-differences. $H_{5635}/H_{5972}$ stays almost unchanged before maximum light ($\approx 0.88$), suggesting a stable relative-abundance of Si II to H (see also, Zhao et al. 2015, for a comparison between Si II and Ca II). $H_{5635}/H_{4130}$ shows the most significant variation with time, possibly due to a competition between these two lines (see discussion in §4.6).

Fast decliners tend to have lower temperatures (except for some peculiar objects, for example, Iax SNe; see, e.g., Foley et al. 2013; Jha 2017), favoring the occupation of lowly-excited states. Therefore, a depth ratio of a longer-wavelength feature to a shorter-wavelength feature (e.g., $H_{5635}/H_{4130}$) is expected to increase with increasing $\Delta m_{15}(B)$. This is confirmed in Figure 11, with $H_{5635}/H_{4130}$, $H_{5635}/H_{5972}$ and $H_{5635}/H_{5454}$ showing positive correlations with $\Delta m_{15}(B)$ (as indicated by the positive Pearson coefficients). The only exception is $H_{5635}/H_{5972}$, which is anti-correlated with $\Delta m_{15}(B)$, possibly due to high degree of saturation of Si II $\lambda$ 6355. Line saturation is quite serious for Si II $\lambda$ 6355 which has rather low energy level. At near- or post-maximum epochs, higher saturation is quite serious for Si II $\lambda$ 6355 which has rather low energy level. At near- or post-maximum epochs, higher luminosity and lower temperature favor for the formation of absorption lines from lowly excited levels. For example, as shown in Figure 12, $H_{5635}$ at $B$-band maximum light ceases to grow after reaching an upper limit of about 0.7 at $\Delta m_{15}(B) \approx 1.4$ mag. While at $t \approx -6$ d, pEW$_{6355}$ still persistently grows with $\Delta m_{15}(B)$, as shown in Figure 8.

After maximum light, the correlations between the depth-ratios and $\Delta m_{15}(B)$ decrease quickly with time, as shown in Figure 11. This may be caused by the decreases of temperature and luminosity, and the layers’ separations (see discussion in §4.3). $H_{5635}/H_{5454}$ also shows a positive correlation with $\Delta m_{15}(B)$, which may be partially due to the fact that dimmer SNe Ia tend to have larger abundance of Si relative to S.

The bottom-left panel of Figure 10 shows details about how the depth ratio $H_{5635}/H_{5454}$ (at $t \approx -6$ d) is related to $\Delta m_{15}(B)$. The correlation is overall positive as mentioned above. However, within the 91T/99aa-like subclass, the correlation is reversed, i.e., dimmer objects tend to have smaller $H_{5635}/H_{5454}$. This negative correlation results from $H_{5635}$’s decreasing more rapidly with $\Delta m_{15}(B)$ than $H_{5454}$ in 91T/99aa-like objects, as mentioned in §4.2. The physical reason is unclear. But since temperature and luminosity effects are unlikely the reason, we speculate that brighter 91T/99aa-like objects might have more Si-rich materials than dimmer 91T/99aa-like objects (see discussion in §4.2).

The bottom-right panel of Figure 10 shows a complicated correlation between $H_{5635}/H_{5454}$ at $t \approx -6$ d and $\Delta m_{15}(B)$. It appears that there is a positive correlation (i.e., dimmer objects have larger $H_{5635}/H_{5454}$) for SNe Ia with $\Delta m_{15}(B) > 1.3$ mag, but a negative correlation at $\Delta m_{15}(B) < 1.3$ mag. The positive correlation at $\Delta m_{15}(B) > 1.3$ mag can be explained as that dimmer objects have lower temperatures that would affect Si II $\lambda$ 1340 more seriously. It is unclear why the correlation is reversed at $\Delta m_{15}(B) < 1.3$ mag. A possible reason is that brighter objects might have less Si II in the ejecta (as a result of more complete IME burning; see, for example, Benetti et al. 2005), and thus an even smaller chance for the absorption of Si II $\lambda$ 1340 (i.e., a more intense competition between Si II features, see the discussion in §4.6).

4.5 Spectroscopic luminosity indicators

Correlations between spectroscopic indicators (velocities, pEWS, pEW-ratios etc.) and photometric parameters ($\Delta m_{15}(B)$, $B - V$ color etc.) have been extensively studied in attempts to improve the accuracy of SN Ia distance
measurements (see references given in §3). Using a new sample, we reinvestigate the \( \Delta m_{15}(B) \)-dependencies of the line strengths of the four lines studied here. Unlike most previous studies, we use the depth to quantify the line strength, instead of the pEW. This is because, as previously mentioned, the depths generally have stronger correlation with \( \Delta m_{15}(B) \) than the corresponding pEWs. For example, at \( t = -6, -3, 0, \) and +3 d, the Pearson correlation coefficient \( \rho \) (pEW\text{Si5972}, \( \Delta m_{15}(B) \)) = 0.55, 0.71, 0.84, and 0.88, respectively, while \( \rho \) (H\text{Si5972}, \( \Delta m_{15}(B) \)) = 0.79, 0.85, 0.90, and 0.91, respectively. Also, note that measurement of the depth usually has lower uncertainty than that of the pEW. A pEW-measurement usually involves the whole line profile, and consequently it is more subject to line blending and contamination than the depth.

Figure 7 shows several spectroscopic indicators as a function of the \( \Delta m_{15}(B) \). The sample is restricted to NV-SNe whose homogeneous spectroscopic properties can help improve the cosmological distance measurements. At early times, H\text{Si5972} + H\text{Si4130} shows an even stronger correlation with \( \Delta m_{15}(B) \) than H\text{Si5972} alone, possibly due to an effect of limited element abundance (see §4.6). At maximum light, pEW\text{Si5972} shows the strongest correlation with \( \Delta m_{15}(B) \), in line with the results of Hachinger et al. (2006) and Blondin et al. (2012). In practice, since it is much easier to obtain a near-maximum spectrum than an early-time spectrum, H\text{Si5972} should be more useful than H\text{Si5972} + H\text{Si4130}. H\text{Si4130} also has a strong correlation with \( \Delta m_{15}(B) \), making it another good indicator of the peak luminosity. And, it is particularly useful for high-z SNe Ia (Nordin et al. 2011), as line Si II \( \lambda 4130 \) still remains visible in their spectra.

Scatter plots in Figure 13 show more clearly how well H\text{Si4130}, H\text{Si5972}, and H\text{Si5972} + H\text{Si4130} correlate with \( \Delta m_{15}(B) \). It is clear that at \( t \approx -10 \) d, H\text{Si5972} + H\text{Si4130} has the tightest relation with \( \Delta m_{15}(B) \). Figure 13 also compares \( t \approx -10 \) d H\text{Si5972} correlation with \( \Delta m_{15}(B) \) to that at \( t \approx +3 \) d. It is clear that the correlation is much tighter at \( t \approx +3 \) d than at \( t \approx -10 \) d (see discussions in §4.2).

4.6 Line competition

Since every element has a limited abundance, there could be a competition of two features from the same element. And, the competition could be more intense when these two features have similar energy levels, as they could be closely related in the radiation transport (e.g., Sim et al. 2013; Sim 2017). Below we show some spectral behaviors that could be related to line competition.

As noted in §3.1 and §3.2, Si II \( \lambda 5972 \) behaves quite differently compared to other features. For example, as shown in Figure 3 (here we focus on NV SNe), during the epoch from \(-13 \) to \(-2 \) d, Si II \( \lambda 5972 \) weakens with time, while Si II \( \lambda 4130 \) strengthens with time. This is hard to explain with temperature effect or abundance difference, as these two features are both from Si II feature and have very similar energy levels.

A possible explanation is that Si II \( \lambda 5972 \) may have serious competition with Si II \( \lambda 4130 \), forcing the later to be located in a much deeper layers. This also explains the fact that at early times Si II \( \lambda 5972 \) has a much higher velocity than Si II \( \lambda 4130 \) (see Figure 2). At maximum light, the competition may be less intense due to relatively high luminosity (and thus more abundant photons), leading to a much smaller velocity difference between Si II \( \lambda 5972 \) and 4130. Then after maximum light, as the luminosity decreases, the competition may be intensified, causing a rebound of the velocity difference. Similarly, line competition may help explain the great difference between the line strengths of Si II \( \lambda 5972 \) and 4130. For example, at phases

\[
 t \approx -14 \text{ to } -10 \text{ d}, \quad \text{pEW}_{\text{Si5972}} \approx \frac{1}{2} \text{pEW}_{\text{Si4130}}, \quad \text{while near maximum light,} \quad \text{pEW}_{\text{Si5972}} \approx \text{pEW}_{\text{Si4130}},
\]

as shown in Figure 3. A competition between Si II \( \lambda 5972 \) and 4130 may also help explain the complicated correlation between strength-ratio H\text{Si5972}/H\text{Si4130} and \( \Delta m_{15}(B) \) (see §10).

A similar case is between the two components of S II W-trough, i.e. S II \( \lambda 5454 \) and S II \( \lambda 5620 \), which originate from almost the same levels (\( E_{\text{bind}} = 13.73 \) eV vs. 13.70 eV, \( E_{\text{esc}} = 2.21 \) eV vs. 2.27 eV). As shown in Figure 3, before \( t \approx -10 \) d the redder component has almost twice the strength of the bluer component. While near maximum light, the two components have almost the same strengths. A possible explanation is that there is a competition between the two components. The other possible reason is the saturation effect, as some of the lines from a singly-ionized ion may be saturated for an increasing abundance of the singly-ionized state.

5 CONCLUSIONS

The key to improving the cosmological distance measurements with SNe Ia is to correct for their intrinsic diversity as revealed in the spectral diversity. The aim of this paper is to better understand the physics of the SN Ia features, which would provide a basis for quantitative correction of the intrinsic diversity. We examined four important features of Si II and S II for 554 spectra of 76 SNe Ia, and investigated the time evolutions of their velocities and line strengths, their velocity-differences and depth-ratios, their correlations with \( \Delta m_{15}(B) \), and the diversity among the subclasses. Below is a summary of our major findings:

1. **Velocity**: Line velocities generally decrease with time.
as expected, but an exception is the velocity of Si II λ5972, which somehow after −2 d and even surpasses the velocity of Si II λ6355 after +2 d. Faster-decliners tend to have faster declining velocities, possibly resulting from faster decrease of temperature.

2. Line strength: Before −7 d, line strengths of the two longer-wavelength features, i.e. Si II λ5972 and 6355 decrease with time, while line strengths of the two shorter-wavelength features, i.e. Si II λ4130 and S II trough, increase with time. After −7 d, the line strengths of all features increase with time, and reach a flat maxima or plateau near maximum light, except the strength of Si II λ5972 which reaches a minima near maximum light. A possible reason for the mysterious behavior of Si II λ5972 might be its competition with other Si II features.

3. Velocity-pEW correlation: The overall correlation between velocity and pEW is positive. But for different subclasses at different phases, the correlation can be very different. For example, for HV and 91T/99aa-like objects at −6 d, V_{Si6355} appears to be positively correlated with pEW_{Si6355}. While for NV objects at +3 d, V_{Si6355} appears to be anti-correlated with pEW_{Si6355}.

4. Δm15(B)-dependence of the velocity: There is an overall trend of increasing velocity for the brighter SNe. But this trend is only significant near +3 d, and is almost nonexistent within NV subclass.

5. Δm15(B)-dependence of the line strength: Among the NV SNe, there is a trend of stronger Si II and S II features for faster decliners, possibly a result of lower degree of ionization and more remained IMEs in the ejecta of dimmer ones. Among the 91T/99aa-like SNe, on the contrary, slower decliners appear to have stronger Si II and S II absorptions.

6. Velocity-difference: There is an overall trend of larger V_{Si6355} − V_{SW} for fainter objects at early times. But within 91T/99aa-like SNe the trend is reversed, possibly due to an effect of ionization. The absolute values of the velocity-differences between different features increase with time after maximum light, suggesting an accelerating separation of the ejecta layers.

7. Depth-ratio: Depth-ratios of a longer wavelength feature to a shorter wavelength feature show positive correlations with Δm_{15}(B), though the correlations weaken quickly with time after maximum light. The only exception is the H_{Si6355}/H_{Si5972}, which is anti-correlated with Δm_{15}(B), possibly due to the saturation of Si II λ6355. Time-evolutions of the depth-ratios are slower than the evolutions of velocity-differences, especially for H_{Si6355}/H_{SW}, suggesting relatively stable element abundances in the ejecta.

8. Luminosity indicator: Less affected by line-blendings, the absorption depths may be better indicators of the luminosity than the corresponding pEWs. Near maximum light, H_{Si5972} shows the strongest correlation with Δm_{15}(B), while at early times H_{Si4130} + H_{Si5972} shows the strongest correlation with Δm_{15}(B).

The results of this study are very suggestive, but require further investigation. This would require an even larger spectral sample that covers extensive observations of all subtypes. The results of this paper may also help constrain the explosion models (e.g., help determine the abundances of burning products at different phases through the line strengths), or be used to improve the accuracy of SNe Ia as distance indicators. Further theoretical analysis or modeling would be very helpful to better understand the results we obtain here.

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DATA AVAILABILITY

The authors confirm that the data supporting the findings of this study are available within the article and its supplementary materials.

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