THE NATURE OF THE Si\textsc{ii} 6150Å, Ca\textsc{ii} HK, CA\textsc{ii} IR-TRIPLET, AND OTHER SPECTRAL FEATURES IN SUPERNOVA TYPE Ia SPECTRA

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ABSTRACT
Spectra of Supernovae of type Ia (SN Ia) are commonly interpreted as a continuum with absorption features. The pseudo equivalent width (pEW) and Doppler shift of absorption features like Si\textsc{ii} 6150Å, Ca\textsc{ii} HK 3750Å, and the Ca\textsc{ii} IR-triplet 8150Å measures which are commonly interpreted as the optical thickness and the velocity of a shell of corresponding absorbing material, form the basis of common SN Ia spectral interpretation and classification schemes.

In this paper, we examine the nature of spectral features in SN Ia spectra using W7 model spectra, and show that Si\textsc{ii} 6150Å and many other features are largely emission dominated instead of absorption dominated. We show that apparent absorption features (like Si\textsc{ii} 6150Å) are frequently just coincidental troughs between two (or more) uncorrelated emission features. The pEW measured between such emission peaks is then only little related to true strength of the presumed absorption feature. It shows how the concepts of “absorption troughs” and “continuum” can be misleading and should be used with care. Furthermore, using the same model spectra, we demonstrate for different times post explosion how spectral features overlap each other and how together they compose the total spectrum. This overlap distorts individual line profiles and affects measured absorption velocities.

With an explosion model atmosphere that is tuned to match specific observations, the method presented in this paper can in principle be used to quantify all these effects and improve the interpretation and informative value of observed SN Ia spectra.

Subject headings: stars: Supernovae: general - radiative transfer - methods: numerical

1. INTRODUCTION

Supernovae of Type Ia (SN Ia) generally show very similar spectral and photometric behavior (e.g., Filippenko 1997). Because of this interesting homogeneity (and the fact that these objects become extremely bright) SNe Ia have proven to be very useful objects to study the universe at large distances (Kissel et al. 1998; Perlmutter et al. 1999). Yet despite the general similarity, there is an even more interesting diversity among SNe Ia, both photometrically and spectral. Whereas photometric diversity has long been studied (Phillips 1993; Wang et al. 2003), good spectroscopic data have only recently become available in large numbers (CIA SN Program; Blondin et al. 2012; Berkeley SN Ia Program; Silverman et al. 2012).

One step towards understanding spectroscopic diversity is finding similarities and defining classes. A number of spectral classification schemes for SN Ia have been proposed in literature. These are based on measurements performed on conspicuous Si\textsc{ii} and Ca\textsc{ii} absorption features present in all “normal” (Branch et al. 1993) SN Ia. These absorption feature measurements are:

1. The feature strength, expressed as pseudo equivalent width (pEW, see Folatelli 2004; Branch et al. 2006); 2. The line blue-shift, expressed as expansion velocity (Wang et al. 2009); 3. The rate of change in blue-shift, expressed as velocity gradient (Bennerti et al. 2005).

It is well known that atomic transition lines formed in a rapidly expanding atmosphere, like SN Ia, form P-Cyg profiles (Lamers & Cassinelli 1999). P-Cyg profiles generally show a superposition of an emission wing that is more or less symmetric around the transition’s rest wavelength plus an absorption wing that is blue shifted. But the precise shape of P-Cyg profiles in relativistically expanding atmospheres, and specifically the ratio of emission to absorption, strongly depends on details of the atmosphere (Hutsemekers 1993): 1) The radial extension of the line forming region; 2) The velocity gradient across the line forming region; 3) The wavelength dependence of the “continuum” and its change across the line forming region.

Parameterized models of SN Ia atmospheres, like SYNOW (Fisher 2000; Branch et al. 2009) or SYNAPPS (Thomas et al. 2011), have proven to be very powerful and rewarding tools for the interpretation of SN Ia spectra. Specifically, these models made it possible to identify lines and study the composition of observed SN Ia. However, these models do not account for the geometrical extension of the line forming regions nor the velocity gradients and change of the “continuum” flux across the line forming regions involved in shaping the P-Cyg profiles. Therefore, such models can not be expected to give accurate and physically realistic profile shapes, even though the large number of free parameters usually enables a rather precise reproduction of observed spectra.

Another fact that complicates the interpretation of SN Ia spectra is the large number of transition lines that leave their signature in the spectrum in an indistinguishable way (i.e., smeared out by the large expansion velocities of SN Ia atmospheres). Kusen (2006) have shown that many millions of transitions are needed to calculate the SN Ia opacity accurately. Even though some of these lines are stronger than others, the background opacity...
formed by the millions of weaker lines is definitely not constant (see Kased 2000) and will leave its signature on the profiles of those stronger lines.

Clearly, the line profiles in SN Ia spectra contain a large amount of information about the detailed atmospheric conditions and understanding their nature is the key to elevate the use and yields of spectroscopic observations to a higher level. In this paper we will demonstrate that Si ii 6150Å and many other features are in fact emission dominated and that commonly used measures like the pEW and the absorption velocity are little related to the actual properties of the these features.

2. METHODS

As described in the previous section, a realistic reproduction of P-Cyg profiles requires model atmospheres that describe the run of physical conditions over the geometrical extent of the line forming region. In this paper we do not aspire to attain perfect reproductions of observed P-Cyg profiles but rather focus on understanding the general nature of spectral features as they are observed for SNe Ia. For this purpose we calculate spectra from model atmospheres in which different atomic transition lines are removed from the opacity and compare them with spectra calculated using the full, unaltered opacity. The direct comparison between altered and unaltered opacity spectra shows what the signature of the removed atomic transition line(s) on the full spectrum is.

Because the differences between spectra are often small compared to the normal flux level it is important that the model spectra are calculated to very high precision. Monte Carlo methods for solving the radiation transport problem generate spectra in a statistical way, leading to spectra that are inherently noisy (Lucy 1999; Kasen et al. 2000; Kromer & Sim 2009) and consequently are not adequate for this purpose. Instead, we use PHOENIX, a state-of-the-art, general purpose stellar atmosphere code (Hauschildt 1999, 2004, 2006). This code solves the special relativistic radiation transport problem with very high accuracy using characteristic rays and operator splitting methods (Olson & Kunasz 1987). The time evolution of SN Ia atmospheres can be self-consistently calculated with PHOENIX using the radiation energy balance (REB) method (van Rossum 2012). PHOENIX with the REB method can in principle calculate SN Ia atmospheres in NLTE, however the challenging treatment of the huge number of lines that play a role for SNe Ia is work in progress (van Rossum, in preparation). Therefore, in this paper we use the LTE approximation.

Determining the atmospheric stratification of SN Ia ejecta from explosion models has been a highly active field of research for decades. Since W7, the very successful phenomenological 1D explosion model by Nomoto et al. (1984), explosion models have continued to improve in physical and numerical respects (Khokhlov 1991; Plewa et al. 2004; Kasen et al. 2009). Yet these improvements have not necessarily made the model end products look more similar to typical SNe Ia. Therefore, over time, W7 has become an established 1-dimensional (1D) reference model that is known to reproduce qualitatively the observed spectral properties of SNe Ia, from a few days to months after the explosion (Kasen et al. 2006; Kromer & Sim 2009; van Rossum 2012), making this a good starting point for studying the nature of spectral features.

Note that with the limitations of W7 (e.g. being 1D and not specifically tuned to match one certain SN Ia) it can not be expected to perfectly reproduce observations. For this reason, we will also not compare results to spectra of individual objects but rather to the Hsiao et al. (2007) (hereafter Hsiao07) spectral templates.

3. RESULTS

We examine the signature of individual lines (or groups of lines) by excluding these lines from the opacity and comparing the resulting spectrum to the full, unmodified spectrum. Figure 1 shows the W7 model spectrum compared to the Hsiao07 templates at four different times post explosion (pe). The peak template luminosity is aligned with the peak model luminosity at day 18pe. A single scaling factor is applied to the unit-less template flux (simultaneously for all times) to globally match the model flux. Apart from these two tightly constrained parameters, there is no freedom in the comparison. The colored patches indicate the difference (Delta) between spectra calculated with the lines of a certain chemical element removed from the opacity and the full spectrum (with unmodified opacities). In order to visualize all contributions at once the patches (Deltas) are stacked (starting with the low-Z elements), emission deltas are stacked below the dashed line and absorption deltas above. Patches below (above) the dashed full spectrum curve represent features in emission (absorption).

Figure 2 zooms in on the Si ii 6150Å feature in Figure 1 although shown at different times post explosion to complement the information. In Figure 3 the same deltas are shown as in Figure 1 but now plotted relative to the flux maximum (of the full spectrum) instead of stacked on top of the full spectrum and on top of each other. As a reference, it also shows the Bessell (1990) UBVRI filter functions, arbitrarily normalized.

The effects of line blending on the absorption velocity of the Si ii 6150Å trough are demonstrated in Figure 1. Figure 5 presents the true equivalent width (EW) values for the isolated Si ii 6355Å, Ca ii IRT, and Ca ii HK features, calculated versus the true continuum.

3.1. Absorption features

Si ii 6150Å absorption—On day 10pe, the absorption trough around 6150Å is dominated by Si ii (see also Figure 2). On day 20pe, the Si ii feature has mostly changed to emission and is significantly supported by Co emission. This trend continues on day 30pe, before Fe emission (at nearly the same wavelength) completely takes over at day 40pe.

Si ii “W” absorption—On day 10pe, the absorption trough around 5700Å is clearly dominated by Si ii. On day 20pe, it is heavily blended with Co and Fe emission, and on day 30pe Si ii has vanished.

Mg ii absorption—On day 10pe, the Mg ii absorption around 4300Å is blended with Si, S, and Fe absorption. On day 20pe, Fe absorption and Co emission dominate Mg ii, and on day 30pe Mg ii has vanished.
Figure 1. W7 model spectra (dashed) are compared to the Hsiao07 SN Ia spectral templates (solid) at different times post explosion (pe). The comparison uses only one free parameter to simultaneously match the template fluxes. The colored patches represent the signature of all atomic transitions of a single chemical element for each color. The signatures are individually calculated and subsequently stacked on top of the original spectrum. The colored areas above (below) the dashed curve show the absorptive (emissive) contributions. Apparently, SN Ia are largely emission dominated longwards of 5500 Å and absorption features are generally much smaller than a pEW evaluation would suggest. The famous Si II 6355 Å “absorption” feature is poorly described by the model, especially at day 30pe. The W7 model (and other models, see text) seem to miss an important emission feature around 5800 Å. More care should be taken with the interpretation and designation of the 6150 Å trough.

Figure 2. Zoom in on the Si II 6150 Å feature of Figure 1 although for different times post explosion: day 6, 8, 12, and 16pe. The spectral template flux level is omitted in this plot. The true absorption signature of this famous Si II feature is much smaller than the total depth of the trough, and decreases over time. In these early epochs, the emission wing on the blue side of the 6150 Å trough is mainly affected by O, Si, S, Fe, and Co. The emission wing on the red side sees contributions from C, Mg, Si, and Co. The wavelength of the trough minimum depends not only on the velocity of the Si II 6355 Å line but also on how other features are blended in (including emission from the Si II 5972 Å line).
Figure 3. Spectral features of different chemical elements normalized to the unmodified flux peak level in the W7 model (see also Figure 1). Emission and absorption features are plotted as positive and negative deltas, respectively. The dashed curves show the UBVRI Bessell 1990 band filter functions.

The famous Si\textsc{ii} 6150Å and Ca\textsc{ii} HK features, and many others, show emission wings that are stronger than their absorption counterparts. pEW definitions that are based on measuring the depth of presumed feature troughs may misrepresent the true feature strength.

The Ca\textsc{ii} HK feature (like many others) does not present itself isolated but is contaminated with contributions from Si, Co, Ti, and S. This complicates both the feature strength and velocity analysis. In all four epochs shown here, the B-band (more than other bands) contains contributions from many different elements. This possibly makes the flux in the B-band more robust against signature strength (abundance) variations between individual SNe Ia.

Figure 4. The absorption velocity of the Si\textsc{ii} 6150Å feature measured in three ways: 1) in the model spectrum calculated with full, unmodified opacities (black curve), 2) in the Si curve of the Delta plot in Figure 3 (dashed pink curve), and 3) in a Delta plot created by removing the Si\textsc{ii} 6355Å feature only (solid pink curve).

The solid pink curve is the most ideal measure of Si absorption velocity as it describes an isolated single feature. The dashed pink curve shows that the emission wing of the neighboring Si\textsc{ii} 5972Å line (the strength of this line is correlated to the 6355Å line) reduces the apparent absorption velocity, although the effect is small. After day 28pe, the Si\textsc{ii} trough disappears in the model spectra. The black curve does not follow the observed, gradually declining velocity evolutions because of the 5800Å emission feature missing in the model.

The shape of the Si line profile is independent of the presence or absence of that feature, so that the solid pink curve still shows a realistic run of the true (as opposed to observed) Si absorption velocity.

Figure 5. The evolution of the true equivalent widths (EW) of three spectral features over time. Each of the three features has a positive and a negative curve corresponding to absorption and emission, respectively (note the flipped vertical axis).

The EWs are computed using the Deltas from individual lines, i.e. the line profiles are evaluated versus the true run of the continuum flux level over each line profile.

Both the Si\textsc{ii} 6355Å and the Ca\textsc{ii} IRT line profiles are emission dominated after the first ∼10 days pe. The Ca\textsc{ii} HK line profile is absorption dominated before day 44pe.
4. DISCUSSION AND CONCLUSIONS

4.1. Absence of an important emission peak

Generally, W7 provides a reasonably good fit to the Hsiao07 templates. There is, however, one very serious mismatch. The model does not describe the 5800Å emission peak observed on day 20, 30, and 40pe. (Note that this finding is in agreement with results from W7 calculated with other radiation transport codes (e.g., Kasen et al. 2006; Kromer & Sim 2009).) This is a serious problem since this emission peak is responsible for the blue side of the Si II 6150Å trough and thus affects the Si II pEW measurements.

What makes this problem even more serious is that other SN Ia explosion models do not describe this emission peak either (e.g., Kasen et al. 2006, Figure 2b; Röpke et al. 2012, Figure 3). There are two possible reasons for this emission peak to be absent from the models: 1) the chemical element(s) responsible for this observed peak is under-represented in the explosion models, 2) the opacity data for the elements present in the models is missing one or more important transition lines. Note that NLTE effects do affect the shape of SN Ia spectra (Baron et al. 1999, van Rossum, in preparation) but are unlikely to explain discrepancies as big as this missing emission peak.

Since the origin of this observed emission line is unknown and it does shape the blue side of the Si II 6150Å absorption trough, special care must be taken with the interpretation of the pEW of this famous trough.

4.2. Blended features

Line features are known to strongly blend in SN Ia spectra but still it is common to speak of identified features, named after the predominant contributor. Figure 1 and 3 show the degree of blending in the model spectra, and the way it changes over time, for each feature in its own way. Note that the detailed degree of blending depends on the atmospheric conditions, which vary between SN Ia objects. The W7 results presented here provide a qualitative picture of the blending effects. A SN Ia model atmosphere tuned to fit a certain observation would allow to quantify the degrees of blending using the Delta method presented in this paper. This would be a very effective way to increase the informative value of observed SN Ia spectra.

4.3. The Si II 6150Å feature

Since this is the most widely used feature in the characterization and classification of SN Ia spectra it deserves extra discussion.

The absorption velocity of the Si II 6355Å line versus the 6150Å trough is demonstrated in Figure 1. It compares the velocity of isolated Si with the value measured in the full spectrum. At early times, the Si II 6150Å trough is filled from the blue side by emission from the next blue Si II line leading to lower velocities, although the effect is small (a few percent).

Figure 4 shows that from day 26pe on the Si II emission gradually declines. At the same time the peak is seamlessly taken over by Fe II emission at a similar but slightly higher wavelength. This not only affects the pEW but also makes the Si II velocity at late times appear lower (and its gradient higher) than it really is.

The run of the full spectrum curve in Figure 5 does not match the observed, gradually declining behavior (e.g., Blondin et al. 2012, Figure 15). Also, the 5800Å emission feature, that is missing in the model (see previous subsection), causes the Si II absorption trough to disappear after day 28pe. This missing feature apparently plays a key role in run of the absorption velocity.

For these reasons, using the Si II 6150Å velocity at late times (e.g., Howell et al. 2006; Blondin et al. 2012) is potentially problematic. The same problems might affect the velocity gradient definition in Benetti et al. (2005). The “improved” velocity gradient definition of Blondin et al. (2012) limits using Si II 6150Å velocities to day 10 post maximum brightness (approx. day 28pe for W7) and thus partly avoids these problems.

4.4. The nature of spectral features in SN Ia spectra

In this subsection we explain how the concepts of “absorption troughs” and “continuum” can be misleading and should be used with care.

Misinterpretation of “absorption troughs” — The identified features commonly used for interpretation and classification of SN Ia spectra describe the apparent “absorption troughs”, with apparent “continuum” in between of those troughs. However, many of the features in SN Ia spectra are predominantly in emission. Figure 4 shows that for wavelengths larger than 5400Å the spectral features generally are emission dominated (except possibly Si II at very early times), and on day 20pe (close to peak luminosity, day 18pe) emission contributes significantly to the flux level down to wavelengths as low as 3800Å. The widths and depths of these “absorption troughs” largely depend on the strengths and separation of the enclosing emission features.

Misinterpretation of “continuum flux level” — Estimating a realistic pseudo continuum from a SN Ia spectrum is not trivial. But since line emission is strong, a “maximum” continuum level that connects observed flux peaks is definitely unrealistic for many features at most evolution times.

1 In the scope of this work, we have verified the opacity data used by PHOENIX against recent atomic data from R.L. Kurucz (http://kurucz.harvard.edu/).
Redefinition of SN Ia feature strength — A SN Ia model atmosphere tuned to fit a certain observation would in principle allow to determine the pseudo continuum for any spectral feature using the method presented in this paper. Yet such atmospheres are not generally available.

Therefore, instead of the common pEW method, we suggest to measure the strength of spectral features using the height difference of P-Cyg profiles (at least in the region where emission is strong in SN Ia spectra, see above). The strength is defined as difference in flux levels at the trough minimum and the peak maximum on the red side of the trough normalized to the mean of these levels. The emission peak on the blue side of the trough, the strength of which is unrelated to the strength of the feature of interest, can thus be excluded, potentially giving a more accurate strength measure. Note that this new definition is a dimensionless quantity, not taking into account the width of the feature, which is loosely related to the absorption velocity. Thus the strength and the velocity measures become potentially more independent. Application of this redefined strength measure to large SN Ia spectral datasets will show whether this measure improves correlations to other spectroscopic or photometric properties, and how it will affect classification schemes based on line strengths.

In future work we will take the method presented in this paper to a higher level by using model atmospheres that are tuned to match observed SN Ia spectra. This will be parametrized atmospheres, based on W7 and more modern explosion models. This way, the details of the atmospheric structure can be directly inferred from observed SN Ia spectra in a physically self-consistent way.

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