High-velocity Feature as the Indicator of the Stellar Population of Type Ia Supernovae

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Abstract

Although Type Ia supernovae (SNe Ia) are very useful in many astrophysical fields, their exact nature is still unclear, e.g., the progenitor and explosion models. The high-velocity features (HVF) in optical spectra of SNe Ia could provide some meaningful information to constrain the nature of SNe Ia. Here, I show strong evidence that the SNe Ia with a strong Ca II infrared triple (Ca II IR3) HVF around maximum brightness are associated with a relatively younger population than those with a weak Ca II IR3 HVF, e.g., the SNe Ia with a strong Ca II IR3 HVF tend to occur in a late-type galaxy or in an early-type galaxy with significant star formation. In addition, using pixel statistics, I find that the SNe Ia with a strong maximum-light Ca II IR3 HVF show a higher degree of association with the star formation index, e.g., H\textalpha or near-UV emission, than those with a weak Ca II IR3 HVF. Moreover, I find that the strength of the Ca II IR3 HVF is linearly dependent on the difference of the absorption-weighted velocities between the Ca II IR3 and Si II 6355.5 nm absorption lines, which then is a good index for diagnosing whether there is a high-velocity component in the Ca II IR3 absorption feature in the spectra of SNe Ia. I finally discuss the origin of the HVFs and the constraints from our discoveries on the progenitor model of SNe Ia.

Unified Astronomy Thesaurus concepts: Type Ia supernovae (1728); White dwarf stars (1799); Circumstellar matter (241)

1. Introduction

As the best distance indicator, the observation of Type Ia supernovae (SNe Ia) leads to the discovery of an accelerating-expansion universe, which implies that there is a mysterious dark energy in the universe and that the evolution of the universe is dominated by the dark energy (Riess et al. 1998; Perlmutter et al. 1999). Now, SNe Ia are becoming the center of a kind of scientific industry, such as measuring the equation of dark energy (Sullivan et al. 2011; Meng et al. 2015; Abbott et al. 2019), and constraining the cosmological model and basic physics via comparing the Hubble constant value from SNe Ia with the value from the Planck satellite (Riess et al. 2016; Planck Collaboration et al. 2018). The cosmological utility of SNe Ia as distance indicators is dependent on one property of SNe Ia, i.e., their luminosity may be standardized by the shape of their light curves (Phillips 1993; Riess et al. 1996; Perlmutter et al. 1997).

Although SNe Ia are so important for cosmology and basic physics, the exact nature of SNe Ia is still unclear. Generally speaking, SNe Ia arise from the thermonuclear explosion of carbon–oxygen white dwarfs (CO WDs) in binary systems (Hoyle & Fowler 1960), but we still do not have an exact understanding on the explosion physics and the evolution of the WDs toward explosion, i.e., various explosion and progenitor models are proposed, but no single model can explain all the properties of SNe Ia (Hillebrandt & Niemeyer 2000; Goobar & Leibundgut 2011; Wang & Han 2012; Hillebrandt et al. 2013; Maoz et al. 2014). Spectral features may provide clues for diagnosing the explosion and progenitor models of SNe Ia (Jha et al. 2019), e.g., a variable or blueshift sodium line in early spectra indicates that at least a part of SNe Ia may originate in the single-degenerate systems (Patat et al. 2007; Sternberg et al. 2011), and a signature of the global asymmetry in the innermost ejecta from later spectra implies an off-center ignition in an exploding WD (Maeda et al. 2010; Maguire et al. 2018). Detailed spectroscopic analysis usually focuses on the absorption features of silicon with minima that may indicate typical photospheric velocities (the so-called “photospheric-velocity feature”, PVF), and be proposed as a diagnostic tool for inspecting the subcases of SNe Ia (Benetti et al. 2005; Branch et al. 2009; Wang et al. 2009). Another interesting feature in early SN Ia spectra is the “high-velocity feature” (HVF), whose velocity is higher than the normal PVF by 6000–13,000 km s\textsuperscript{−1} (Mazzali et al. 2005a; Childress et al. 2013; Maguire et al. 2014; Zhao et al. 2015). Since the first suggestion of an HVF was made by Hatano et al. (1999), it has been found that almost all SNe Ia show an HVF in their early spectra (Mazzali et al. 2005a). The HVFs of SNe Ia are often seen in Ca II H&K, Si II λ6355, and Ca II infrared triplet features (hereafter Ca II IR3). They appear strong in their early spectra, and become weak with time (Parrent et al. 2012; Marion et al. 2013; Childress et al. 2014; Zhao et al. 2015). In addition, numerous spectropolarimetric observations show that the line-forming region for the HVFs is physically distinct from that for PVFs, and that it is substantially asymmetric (Wang et al. 2006; Wang & Wheeler 2008; Patat et al. 2009; Maund et al. 2013).

The HVFs in SNe Ia have received increasing attention, and some recent studies have found some correlations between different observable quantities. For example, the strength of the HVFs was discovered to correlate with the light-curve width of SNe Ia, i.e. the SNe Ia with strong HVFs tend to have a wide light curve, while the SNe Ia with narrowest light curve favor a weak HVF (Maguire et al. 2012, 2014; Childress et al. 2014). However, although there is an indication that the Ca II H&K velocity correlates with the stellar mass of the host galaxy (Maguire et al. 2012), the strength of HVFs from a larger
Regarding the origin of the HVFs, at least one of the following phenomena must be present: an abundance enhancement, a density enhancement, or an ionization effect in a high-velocity region (see the detailed discussion in Mazzali et al. 2005b).

However, although the samples of SNe Ia on the HVFs become increasingly larger, no determining constraint on the progenitor and explosion models of SNe Ia is obtained by studying the HVFs. The question remains, in particular, why no correlation between the strength of the HVFs and the population of SNe Ia has been discovered since the strength correlates with the width of the light curve (the width is an index to represent the brightness of an SN Ia; Phillips 1993; Riess et al. 1996; Perlmutter et al. 1997), while it has long been established that bright SNe Ia favor a young stellar population and dim SNe Ia tend to belong to an old stellar population (Hamuy et al. 1996; Wang et al. 1997; Howell 2001; Sullivan et al. 2006). In this paper, I show strong evidence that SNe Ia with strong HVFs belong to a relatively young population, while those with weak HVFs favor a relatively old population.

In Section 2 I describe some definitions and the data that I use in this paper. I present my results in Section 3, and discuss the origin of the HVFs and the constraints of my discoveries on the progenitor models of SNe Ia in Section 4. In Section 5 I summarize my main conclusions.

2. Data

All the data used in this paper have been published or can easily be obtained from the NASA/IPAC Extragalactic Database (NED). The majority of the SNe Ia used here are from the Berkeley SN Ia Program (BSNIP) and have been published in Silverman et al. (2012a). In this paper, I mainly discuss whether the strength of an HVF correlates with other observable quantities. If there is a high-velocity component in an absorption feature, the absorption feature may be fit by two Gaussian profiles, i.e., one is the HVF and the other is the PVF. Following the definition in Childress et al. (2014), the strength of the HVF may be described by the ratio of the pseudo-equivalent width (pEW) of the HVF absorption component to the PVF absorption component, i.e.,

\[
R_{\text{HVF}} = \frac{\text{pEW(HVF)}}{\text{pEW(PVF)}}.
\]

Generally, the strength of the HVFs decreases with time, and around maximum light, the HVFs for some SNe Ia become very weak and even disappear, while the other SNe Ia still show very strong HVFs. So, I choose the \(R_{\text{HVF}}\) value around maximum light as the indicator of the HVF strength for one SN Ia, following Childress et al. (2014). The Ca II IR3 absorption line in the spectra of an SN Ia usually shows the most remarkable HVF and is widely studied. Therefore, I only focus on the Ca II IR3 line, and the \(R_{\text{HVF}}\) values of Ca II IR3 lines for different SNe Ia are from Silverman et al. (2015) and Zhao et al. (2015).

Meng et al. (2017) found that all SNe Ia may follow a universal polarization sequence, i.e., the polarization of the Si II 635.5 nm absorption feature increases with a relative equivalent width (REW), where the REW is defined as the ratio of the pEW to the relative depth (\(a\)) of an absorption feature, i.e.,

\[
\text{REW} = \frac{\text{pEW}}{a}.
\]

Meng et al. (2017) suggested that the REW of the Si II 635.5 nm absorption line could be an indicator for diagnosing the explosion model of SNe Ia because the REW reflects the distribution of an element in supernova ejecta. They found that the distribution of the REW of Si II 635.5 nm around maximum light may be well fit by a Gaussian with an average value of 157.9 Å, and then they suggested that their discovery could mean that all SNe Ia share the same explosion mechanism, and only the delayed-detonation model might have the ability to explain their discovery at present. Here, following Meng et al. (2017), I determine whether there is a correlation between the REW of the Si II 635.5 nm absorption line and the strength of the HVF of the Ca II IR3 line around maximum light, where the values of pEW and \(a\) for different SNe Ia are mainly from Silverman et al. (2012b).

Childress et al. (2014) defined an average absorption-weighted velocity and found that the difference of the absorption-weighted velocity between the Ca II IR3 and Si II 635.5 nm lines correlates with the decline rate \([\Delta m_{15}(B)]\) of the light curve of SNe Ia, where the absorption-weighted velocity is defined as

\[
\bar{v} = \frac{\int v \times a(v)dv}{\int a(v)dv},
\]

where \(a(v)\) is the normalized absorption profile in velocity space. Childress et al. (2014) presented the absorption-weighted velocities of the Si II 635.5 nm, Ca II IR3, and Ca II H&K lines around maximum light for 58 SNe Ia, and I study whether the absorption-weighted velocities correlates with other properties of SNe Ia.

In this paper, I also check whether the strength of the Ca II IR3 HVF around maximum light correlates with the stellar population or stellar environment. The stellar environment at the location of the supernova explosion may reflect information on the stellar population of SNe Ia, and this can be tested by checking the SN positions in their host galaxies and the global properties of the host galaxies (Wang et al. 2013; Anderson et al. 2015b). The global parameters of the SN host galaxies, e.g., the physical size and near-ultraviolet (NUV) absolute magnitude, are obtained from the NED4, and the position information of SNe Ia in their host galaxies are from Wang et al. (2013) and Anderson et al. (2015a).
Zhao et al. (2015) found that the decay rate of \( R_{\text{HVF}} \) measured 7 days before maximum brightness roughly correlates with \( \Delta m_{\text{B}}(B) \) and \( V_{\text{max}}^{\text{Si II}} \) (the maximum-light photospheric velocity measured for the Si II 635.5 nm absorption line). Here, I also check whether the decay rate of \( R_{\text{HVF}} \) of the Ca II IR3 line around maximum light correlates with the host galaxy morphology, the REW value of the Si II 635.5 nm absorption line, and the strength of the Ca II IR3 HVF around maximum light, where the decay rate of \( R_{\text{HVF}} \) around maximum light is calculated by

\[
R_{\text{HVF}} = \frac{\Delta R_{\text{HVF}}}{\Delta t},
\]

where \( \Delta R_{\text{HVF}} \) is the difference of the \( R_{\text{HVF}} \) value of Ca II IR3 line in two spectra between before and after maximum light. Here, I only chose those SNe Ia whose Ca II IR3 \( R_{\text{HVF}} \) must have a value higher than 0 before maximum light, and the spectrum phases must be within 5 days around maximum brightness. The \( R_{\text{HVF}} \) values of the Ca II IR3 lines for different SNe Ia are from Silverman et al. (2015).

### 3. Result

#### 3.1. The Distribution of \( R_{\text{HVF}} \) for the Ca II IR3 Line

Silverman et al. (2015) provided a very large sample of SNe Ia from BSNIP, and 132 SNe Ia have a spectrum with a Ca II IR3 absorption feature around maximum light (within 5 days of the \( B \)-band maximum brightness). In their Table A4 they list the strength of the HVF of the Ca II IR3 absorption line for the sample, as defined in Equation (1). In Figure 1 I show the distribution of the strength of the Ca II IR3 HVF (\( R_{\text{HVF}} \)) around maximum light,\(^5\) where the distribution shows a peak at low value and follows a long tail until \( R_{\text{HVF}} > 2.0 \), i.e., the stronger the Ca II IR3 HVF, the lower the frequency for an SN Ia to occur. Following the definition in Childress et al. (2014), i.e., \( R_{\text{HVF}} > 0.2 \) means a strong HVF, about 55% of SNe Ia still present a strong HVF in the Ca II IR3 absorption feature around maximum brightness, and some even show a very strong HVF (\( R_{\text{HVF}} > 0.8 \)). One question then arises, i.e., what factor(s) leads to the different strength of the HVF between different SNe Ia. In the following sections, I present possible answers for the question.

#### 3.2. The Relation between \( R_{\text{HVF}} \) and REW

The Si II 635.5 nm absorption line is the most remarkable feature in the optical spectra of an SN Ia around maximum brightness, and the REW of Si II 635.5 nm line could be an index reflecting the key free parameters in the delayed-detonation model (Meng et al. 2017). Figure 2 presents the relation between the \( R_{\text{HVF}} \) of the Ca II IR3 absorption line and the REW of the Si II 635.5 nm absorption feature around maximum light. At first glance, no clear correlation appears to be between the \( R_{\text{HVF}} \) and the REW, but the SNe Ia with weak maximum-light Ca II IR3 HVFs are mainly distributed between REW = 140 and 200, while those with a strong Ca II IR3 HVF have a wide REW distribution. Especially the SNe Ia with very strong Ca II IR3 HVF (i.e., \( R_{\text{HVF}} > 0.8 \), Zhao et al. 2015) seem to disfavor the medium REW value.

In Figure 3 I show the number distributions of the REW for the SNe Ia with a weak and a very strong Ca II IR3 HVF around maximum light. The distributions are quite different, i.e., the SNe Ia with a weak Ca II IR3 HVF focus on a value of the REW between 150 and 180, while those with a very strong Ca II IR3 HVF are relatively rare in this region. A Kolmogorov–Smirnov (K–S) test shows that the probability that the two subsamples are from the same mother sample is only \( 1.1 \times 10^{-3} \). Meng et al. (2017) found that all types of SNe Ia follow a universal polarization sequence, i.e., the polarization of an SN Ia increases with the REW of the Si II 635.5 nm absorption line, and then the authors suggested that all SNe Ia could share the same explosion model, regardless of their progenitors. If this holds true, the different distributions in Figure 3 indicate that another factor might affect the strength of the HVFs in SNe Ia, e.g., different progenitors (Wang et al. 2013), rather than the explosion model itself.

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\(^5\) In the sample of Silverman et al. (2015), the value of \( R_{\text{HVF}} \) is set to be 0 if \( R_{\text{HVF}} < 0.2 \). So, I set the distribution of \( R_{\text{HVF}} < 0.2 \) into one large bin in Figure 1, which shows 60 SNe Ia.
When I check the Branch type of the SNe Ia (Branch et al. 2009), those with a weak Ca II IR3 HVF around maximum light favor the core normal (CN) and cool (CL) SNe Ia, while those with a very strong Ca II IR3 HVF tend to be the shallow-silicon (SS) and broadline (BL) SNe Ia. Generally, 1991T-like SNe Ia belong to the SS group, and 1991bg-like SNe Ia belong to the CL group (Branch et al. 2009). In the sample of Silverman et al. (2015), all of the eight 1991T-like SNe Ia have a very strong Ca II IR3 HVF around maximum light (i.e., $R_{\text{HVF}} > 0.8$), while of the seventeen 1991bg-like SNe Ia, only 2002dk shows $R_{\text{HVF}} = 0.38$ and the others present a weak or no Ca II IR3 HVF around maximum brightness. This discovery is consistent with previous results, i.e., the SNe Ia with a fast-evolving light curve tend to show weak HVFs, and the SNe Ia with strong HVFs usually have a slowly evolving light curve (Maguire et al. 2012, 2014; Childress et al. 2014). It is well established that 1991T-like SNe Ia arise from a relatively young stellar population and 1991bg-like SNe Ia belong to an old stellar population (Howell 2001; Johansson et al. 2013b; Fisher & Jumper 2015). This result implies that the strength of the maximum-light Ca II IR3 HVF could correlate with the stellar population of SNe Ia. I address this probability in the following sections.

### 3.3. The Relation between Absorption-weighted Velocities and REW

Childress et al. (2014) showed the dependence of the absorption-weighted velocities for Si II 635.5 nm ($\bar{v}_{\text{Si}}$), Ca II IR3 ($\bar{v}_{\text{Ca}}$), and Ca II H&K ($\bar{v}_{\text{HI}}$) features and the difference between $\bar{v}_{\text{Ca}}$ and $\bar{v}_{\text{Si}}$ on $\Delta m_{15}(B)$ to verify that the correlation between the strength of the Ca II IR3 HVF and $\Delta m_{15}(B)$ is not an artifact. In Figures 4 and 5 I also show the dependence of these properties on the REW of the Si II 635.5 nm absorption line around maximum brightness. Figure 4 shows that $\bar{v}_{\text{Ca}}$ and $\bar{v}_{\text{Si}}$ do not significantly depend on the REW, while $\bar{v}_{\text{Si}}$ seems to slightly increase with REW, i.e., no significant physical correlation exists between the absorption-weighted velocities and the REW of the Si II 635.5 nm line. However, Figure 5 presents a clear trend that the larger the difference between $\bar{v}_{\text{Ca}}$ and $\bar{v}_{\text{Si}}$, the smaller the REW of the Si II 635.5 nm absorption line. Especially the SNe Ia with smaller REW (or with a larger difference between $\bar{v}_{\text{Ca}}$ and $\bar{v}_{\text{Si}}$) tend to have a stronger HVF of the Ca II IR3 line, as indicated in Figure 2. In addition, Figure 5 already indicates the fact that the strength of the Ca II IR3 HVF would depend on the difference between $\bar{v}_{\text{Ca}}$ and $\bar{v}_{\text{Si}}$.

In Figure 6 I show the correlation between the strength of the Ca II IR3 HVF and the difference between $\bar{v}_{\text{Ca}}$ and $\bar{v}_{\text{Si}}$ around maximum brightness. There is a very good linear relation between the strength of the HVF and the velocity difference, i.e., the larger the velocity difference, the stronger the Ca II IR3 HVF [$R_{\text{HVF}} = -0.198 + 3.013 \times 10^{-4}(\bar{v}_{\text{Ca}} - \bar{v}_{\text{Si}})$]. This relation arises mainly from the fact that all SNe Ia have a similar absorption-weighted velocity of the Si II 635.5 nm absorption line around maximum brightness, and then the strength of the Ca II IR3 HVF is mainly dominated by its absorption-weighted velocity, as shown in Figure 7, which presents the relation between the $R_{\text{HVF}}$ of the Ca II IR3 line and the absorption-weighted velocity $\bar{v}_{\text{Ca}}$ and $\bar{v}_{\text{Si}}$. Figure 7 also shows a linear

![Figure 3](image3.png)

**Figure 3.** The number distributions of the relative equivalent width of the Si II 635.5 nm line for SNe Ia with a weak (solid line) and a very strong Ca II IR3 HVF (dashed line) around maximum light.

![Figure 4](image4.png)

**Figure 4.** Absorption-weighted velocities for the Si II 635.5 nm, Ca II IR3, and Ca II H&K features ($\bar{v}_{\text{Si}}$, black asterisks; $\bar{v}_{\text{Ca}}$, red triangles; and $\bar{v}_{\text{HI}}$, green stars) vs. the REW of the Si II 635.5 nm absorption line around maximum light. The absorption-weighted velocity data are from Childress et al. (2014), while the REW data are from Silverman et al. (2012b). The cross represents the typical error of the data.

![Figure 5](image5.png)

**Figure 5.** The difference between $\bar{v}_{\text{Ca}}$ and $\bar{v}_{\text{Si}}$ vs. the REW of the Si II 635.5 nm line around maximum brightness. Different points represent the different range of the Ca II IR3 $R_{\text{HVF}}$. The absorption-weighted velocity data are from Childress et al. (2014), while the REW data are from Silverman et al. (2012b). The cross represents the typical error of the data.
relation between the strength of the Ca II IR3 HVF and \( \tau_{C1} \), but the scatter of the linear fit is much larger than that in Figure 6, i.e., the difference between \( \tau_{C1} \) and \( \tau_{Si} \) is an indicator for measuring the strength of the Ca II IR3 HVF.

In addition, Figure 6 shows that some SNe Ia with \( R_{HVF} = 0 \) have a high value of \( (\tau_{C1} - \tau_{Si}) \), even higher than 2000 km s\(^{-1}\). Based on the linear relation found in Figure 6, these SNe Ia would show \( R_{HVF} \sim 0.2 - 0.5 \). Similarly, some SNe Ia without Ca II HVF also significantly deviate from the linear fit in Figure 7. These SNe Ia may also have a line-forming region for HVFs in the supernova ejecta, but the region overlaps with or is not distinct from the PVF region, which could be the reason why these SNe Ia show a significantly higher photospheric pEW value than other SNe Ia with a weak Ca II IR3 HVF, e.g., SN 2000dk, 2006X, 2006gt, 2007ba, and 2007fr (see Table 2 in Childress et al. 2014). A piece of evidence supporting this idea is from SN 2006X. In Childress et al. (2014), the pEW of the photospheric Ca II IR3 line in the maximum-light spectrum of SN 2006X is \( 320 \pm 1 \) Å, without the HVF, but in Silverman et al. (2015), the pEW of the photospheric Ca II IR3 line in the same spectrum is \( 166.6 \pm 5.3 \) Å, with a very strong HVF, i.e., \( R_{HVF} = 0.89 \pm 0.03 \) (see also Zhao et al. 2015). Such a different result could be derived from a fact that Silverman et al. (2015) have a series of spectra on SN 2006X from a very early phase to a phase after maximum light, while Childress et al. (2014) only analyze one spectrum at \( t = 2 \) day. Based on the evolution of the spectra, it would be relatively easy for Silverman et al. (2015) to judge whether there is a high-velocity component in the Ca II IR3 absorption feature, and to estimate the possible strength of the HVF. So, based on the result in Figure 6, the difference between \( \tau_{C1} \) and \( \tau_{Si} \) becomes a very good indicator that may be helpful to judge whether there is a Ca II IR3 HVF in the spectrum of an SN Ia, i.e., if the difference is larger than 1000 km s\(^{-1}\), it is likely that there is a high-velocity component in the Ca II IR3 absorption feature, even if a single-Gaussian profile may fit the feature.

### 3.4. The Distribution of \( R_{HVF} \) for HVG and LVG SNe Ia

Observationally, the photospheric velocity decreases with time, but with a different temporal velocity gradient. Based on the different velocity gradient, Benetti et al. (2005) divided normal SNe Ia into two subgroups, i.e., high-velocity gradient (HVG) and low-velocity gradient (LVG) SNe Ia. The different velocity gradients could reflect the viewing angle relative to an asymmetric explosion center, i.e., LVG SNe Ia are viewed from the direction of the off-center initial sparks, while HVG SNe Ia are viewed from the opposite direction (Maeda et al. 2010). In Figure 8 I show the distributions of the \( R_{HVF} \) of Ca II IR3 line around maximum brightness for HVG and LVG SNe Ia. The two distributions look similar to the distribution shown in Figure 1, i.e., a peak at low \( R_{HVF} \) and a long tail of high \( R_{HVF} \). Similarly, the difference of the cumulative percent distributions of the \( R_{HVF} \) between HVG and LVG SNe Ia are not significant either. A K-S test shows that the probability that the two subsamples are from the same mother sample is as high as about 60%. Then, the strength of the HVF of Ca II IR3 line around maximum brightness cannot depend on the viewing angle to the asymmetric explosion center if the velocity gradient reflects the viewing angle. This result could indicate
that the HVFs in the spectra of SNe Ia cannot be derived from the explosion mechanism of SNe Ia.

3.5. The Dependence of \(R_{\text{HVf}}\) on the Host Galaxy Type

Zhao et al. (2015) checked the potential dependence of the number distributions of SNe Ia with strong and weak HVFs on their host galaxy morphologies, the K-band absolute magnitude of the host galaxies, and the normalized radial distance of the SNe Ia in their host galaxies, and did not find a significant dependence on these parameters. This result seems to suggest that there is no correlation between the strength of HVFs and the stellar population (but see Pan et al. 2015). However, the number distribution cannot completely reflect the intrinsic dependence of the strength on the stellar population. Here, I check the potential dependence again in another way, i.e., by directly studying the relation between the strength of HVFs and the parameters indicating the stellar population of SNe Ia. In Figure 9 I show the \(R_{\text{HVf}}\) of SNe Ia and the number fraction of the SNe Ia with weak maximum-light Ca II IR3 HVF (\(R_{\text{HVf}} = 0\)) as a function of host galaxy morphology. In a host galaxy with a morphology later than S0, the number fractions of the SNe Ia with weak maximum-light Ca II IR3 HVF are not significantly different from each other within the errors, which is a similar result to that found in Zhao et al. (2015). However, the number fraction of the SNe Ia with weak maximum-light Ca II IR3 HVF in elliptical galaxies seems to be higher than that in later type galaxies, which implies that the SNe Ia with weak Ca II IR3 HVF favor an old stellar population. Most of the SNe Ia with strong maximum-light Ca II IR3 HVF tend to occur in later type galaxies, in which the star formation rates are generally high. Although a high star formation generally favors core-collapse SNe, arising from short-lived progenitors, it may also increase the birth rate of SNe Ia relative to the genuinely old stellar population (Della Valle & Livio 1994; Navasardyan et al. 2001). Then, the result here could indeed imply that SNe Ia with strong HVFs belong to a relatively young population.

Regardless of these ideas, some SNe Ia still present a strong Ca II IR3 HVF around maximum brightness in elliptical and lenticular galaxies, e.g., SN 1995D, 1998es, 2000dn, 2005cf, 2007gi, and 2007on. Generally, elliptical and lenticular galaxies are passively evolving and do not contain young stars. However, we should keep in mind that many early-type galaxies present recent star formations (Salim et al. 2005; Schawinski et al. 2007). Then, I checked the detailed circumstance of these SNe Ia. SN 2005cf has the highest maximum-light Ca II IR3 \(R_{\text{HVf}}\) of all SNe Ia that are hosted in lenticular galaxies, and its host galaxy is the peculiar lenticular galaxy (MCG -01-39-003), which interacts with its neighbor. There is a tidal bridge between MCG -01-39-003 and its neighbor, and SN 2005cf is located close to the tidal bridge (Pastorello et al. 2007). It is widely known that the interaction between galaxies may enhance the star formation rate. In addition, the blue ultraviolet color of the galaxy from the Galaxy Evolution Explorer (GALEX) also indicates a high star formation rate in MCG -01-39-003 (Smith et al. 2010). Then, SN 2005cf would be associated with a relatively young population.

SN 2007gi is another supernova with very high maximum-light Ca II IR3 \(R_{\text{HVf}}\) in a lenticular galaxy. Strictly speaking, the host galaxy of SN 2007gi (NGC 4036) is not a typical lenticular galaxy, but has a morphology between S0 and Sa, with strong activity, which is another index for triggering star formation in a galaxy (Véron-Cetty & Véron 2006; Ann et al. 2015). Interestingly, SN 2007gi is located very close to the inner activity region (Zhao et al. 2015). For SN 1998es, although the morphology of its host galaxy (NGC 0632) is classified as S0, the star formation phenomena in the galaxy are very strong and it is a starburst galaxy (Balzano 1983). The case of SN 2007on is also very interesting, i.e., its host galaxy (NGC 1404) interacted with its neighbor galaxy (NGC 1399) about 1.2 Gyr ago, and there is much intracluster medium between these two galaxies (Sheardown et al. 2018). Now, NGC 1404 is falling into the center of the Fornax cluster and interacts with the intracluster medium to form a sharp leading edge. SN 2007on is located very close to this edge (Su et al. 2017; Gall et al. 2018). The host galaxies of SN 1995D (NGC 2962) and 2000dn (IC 1468) have rings or arms around their main bodies that are significantly bluer than their main bodies, which indicates star formation activities or a relatively young stellar population in the galaxies (Marino et al. 2011). These two SNe Ia are located either at the end of an arm or close to one of the rings (Zhao et al. 2015, see also the image in SIMBAD)\(^6\). Based on this detailed check, I find that these SNe Ia with strong maximum-light Ca II IR3 HVF in early-type galaxies are also correlated with star formation activity or a relatively young stellar population (see also Pan et al. 2015). When these SNe Ia that are correlated with a young stellar population are eliminated, the number fraction of the SNe Ia with weak maximum-light Ca II IR3 HVF in lenticular galaxies would also be significantly higher than that in later type galaxies, as shown in elliptical galaxies, i.e., the SNe Ia with weak maximum-light Ca II IR3 HVF favor an old stellar population.

\(^6\) http://simbad.u-strasbg.fr/simbad/sim-fbasic
3.6. The Dependence of $R_{\text{HVF}}$ on the Global Parameters of the Host Galaxies

Zhao et al. (2015) checked the potential dependence of the number distribution of SNe Ia with different $R_{\text{HVF}}$ on the $K$-band absolute magnitudes of the host galaxy, and no significant difference between strong and weak HVF samples was found. Here, I also check whether the $R_{\text{HVF}}$ value depends on the other global parameters of the host galaxies, e.g., physical sizes and NUV-band absolute magnitude. In Figure 10 I show the Ca II IR3 $R_{\text{HVF}}$ value of SNe Ia around maximum brightness as a function of the physical size (major axis) of their host galaxies, but I do not find any potential correlation between $R_{\text{HVF}}$ and the major axis, i.e., the number distributions of the physical size of the host galaxies for the SNe Ia with weak and strong maximum-light Ca II IR3 HVFs are indistinguishable.

In Section 3.5 I find a clue that the Ca II IR3 $R_{\text{HVF}}$ value of SNe Ia around maximum brightness might be correlated with their stellar population, but the number distribution of SNe Ia with different $R_{\text{HVF}}$ does not rely on the $K$-band absolute magnitudes of their host galaxies (Zhao et al. 2015). This inconsistency might be caused by the fact that the $K$-band absolute magnitude of a host galaxy is not a good index for reflecting the star formation in the galaxy, and the $K$-band light in a galaxy is generally dominated by old stellar populations (Mannucci et al. 2005). However, the ultraviolet absolute magnitude of a host galaxy would be a better index in the galaxy (Salim et al. 2005; Schawinski et al. 2007). I obtained the GALEX NUV absolute magnitudes of the host galaxies of SNe Ia in the sample of Zhao et al. (2015) and Silverman et al. (2015) from the NED to check the potential correlation between the maximum-light Ca II IR3 $R_{\text{HVF}}$ value of SNe Ia and the NUV absolute magnitudes of their host galaxies (Figure 11). Again, the distributions of NUV absolute magnitudes of the host galaxies of the SNe Ia with strong and weak Ca II IR3 HVF are indistinguishable, i.e., a K–S test shows that the subsamples with $R_{\text{HVF}} > 0.2$ and $R_{\text{HVF}} < 0.2$ have a probability of 46% to be from the same mother sample. However, it seems that most SNe Ia are located in a declining zonal, as the dotted lines show. The results in this section seem to be inconsistent with the result discovered in Section 3.5, which could be derived from the fact that the global parameters of a host galaxy are not a good tracer of the stellar population at the site of a supernova explosion. The global parameters of a host galaxy only represent the average information of the stellar population in the host galaxy, and could erase the intrinsic relation between SN Ia properties and their stellar populations.

3.7. Pixel Statistics

The most direct method to determine the progenitor nature of an SN Ia is to investigate its pre-explosion image (Li et al. 2011; McCully et al. 2014). Such cases are rare and therefore the statistics remain low because it is only possible for events in very nearby host galaxies. Another way is to investigate how the properties of SNe Ia vary with different global parameters of their host galaxies, as discussed in Section 3.6. However, this method could erase the intrinsic relation between SN Ia properties and the information of their stellar populations because the global parameters of a host galaxy may only represent average information of the stellar population in the host galaxy, which could be the reason why no correlation is found between the strength of the HVF and the global parameters of the host galaxies in Section 3.6 and in Zhao et al. (2015). An intermediate method to constrain the nature of SN Ia progenitors is to investigate the environments at the position of an SN Ia in its host galaxy, e.g., the statistical analysis of a fractional flux or a normalized cumulative rank (NCR) pixel value function of the host galaxies at the SN explosion site (Fruchter et al. 2006; Anderson & James 2008). Generally, core-collapse SNe trace the star formation region (light) in their host galaxies approximately linearly, while SNe Ia do not (Anderson et al. 2015a, 2015b). Here, I also use this method to check whether there is a difference in the environments between the SNe Ia with a strong and weak Ca II IR3 HVF around maximum light.

In Figure 12 I show the cumulative distribution of the fractional flux of the host galaxies at SN explosion site for

Figure 10. The Ca II IR3 $R_{\text{HVF}}$ around maximum brightness vs. the physical sizes (major axis) of the host galaxies, where the red points mean that the sizes are represented by the $B$-band light major axis at 25 mag arcsec$^{-2}$ isophote, and the green points are sizes represented by SDSS $r$-band major axis at 25 mag arcsec$^{-2}$ isophote. The $R_{\text{HVF}}$ data are from Silverman et al. (2015) and Zhao et al. (2015), and the physical sizes of the host galaxies are from the NED. The two dotted lines divide SNe Ia into weak ($R_{\text{HVF}} < 0.2$), strong ($R_{\text{HVF}} > 0.2$), and very strong ($R_{\text{HVF}} > 0.8$) subgroups.

Figure 11. The Ca II IR3 $R_{\text{HVF}}$ around maximum brightness vs. the GALEX NUV-band absolute magnitudes of the host galaxies. The cross shows the typical error of the data. The $R_{\text{HVF}}$ data are from Silverman et al. (2015) and Zhao et al. (2015), and the NUV-band absolute magnitudes of host galaxies are from the NED.
Figure 12. The cumulative distribution of the fractional flux of the host galaxies at the SN explosion site for SNe Ia with a strong (black solid line) and weak (red dashed line) Ca II IR3 HVF around maximum light in SDSS u’, g’, and r’ bands. The fractional flux data are from Wang et al. (2013).

Figure 13. The cumulative NCR distributions of the SNe Ia with a strong (black solid line) and weak (red dashed line) Ca II IR3 HVF around maximum light for the Hα band. The NCR data of the host galaxies at the SN Ia explosion site are from Anderson et al. (2015a).

Figure 14. The cumulative NCR distributions of the SNe Ia with a strong (black solid line) and weak (red dashed line) Ca II IR3 HVF around maximum light for the NUV band. The NCR data of the host galaxies at the SN Ia explosion site are from Anderson et al. (2015a).

The SNe Ia with a strong and weak Ca II IR3 HVF around maximum light in the Sloan Digital Sky Survey (SDSS) u’, g’, and r’ bands, where the fractional flux of an SN Ia represents the fraction of total host light in pixels fainter than or equal to the light in the pixel of the SN Ia site in its host-galaxy image (Fruchter et al. 2006). A young population traces the diagonal line in the plot, while an old population lies far away from the diagonal line. The figure shows that regardless of the SDSS band, the cumulative distribution of the SNe Ia with strong Ca II IR3 HVF is closer to the line that traces the star formation region than that of the SNe Ia with a weak HVF, although the distributions for g’ and r’ are similar. A 2D K–S test for the u’ and g’ bands or the u’ and r’ bands shows that the probability that the two subsamples are from the same mother sample is lower than 1.5%, i.e., the SNe Ia with strong maximum-light Ca II IR3 HVF are more likely to be from the relatively young stellar population, while those with weak maximum-light Ca II IR3 HVF tend to be from the relatively old stellar populations.

The cumulative distributions for the g’ and r’ bands are much closer to the diagonal line than those for the u’ band, especially for the SNe Ia with a weak Ca II IR3 HVF, which indicate that g’ and r’ band lights would not be good tracers for the star formation in a galaxy. However, the NUV and Hα bands are good choices (Anderson et al. 2015a, 2015b).

The definition of an NCR value is different from the fractional flux. The NCR value of a pixel is equal to the flux count ratio between this pixel and the pixel with the highest flux count within the image of a host galaxy. Then, an NCR value is between 0 and 1, where a value of 0 means that a pixel in the image is consistent with zero flux or sky values, while a value of 1 means that the pixel has the highest flux count in the image. Whether the distribution of the NCR value for a given band in a cumulative plot follows a diagonal one-to-one relation may provide constraints on the population and progenitor properties of SNe Ia, i.e., a very young population will trace the diagonal one-to-one relation, while an old population will be far away from the diagonal one-to-one relation. In another words, the closer the cumulative line to the diagonal one-to-one relation, the younger the population of the SNe Ia (Anderson et al. 2015a; Anderson & James 2008).

Figures 13 and 14 present the cumulative NCR distributions of the SNe Ia with a strong and weak Ca II IR3 HVF around maximum light for Hα and NUV bands, respectively. These figures show that regardless of whether the maximum-light Ca II IR3 HVF is strong or weak, or regardless of the band, the cumulative distributions of the NCRs do not trace the diagonal line, which indicates that the progenitors of SNe Ia do not belong to a very young population (see also Anderson et al. 2015a, 2015b). This also verifies that the SDSS g’ and r’ bands are not good tracers for star formation. However, the cumulative distribution for the SNe Ia with a strong maximum-light Ca II IR3 HVF is always closer to the diagonal line than the one for the SNe Ia with a weak maximum-light Ca II IR3 HVF for the Hα and NUV bands, which indicates that the populations of the SNe Ia with a strong maximum-light Ca II IR3 HVF are relatively younger than those with a weak maximum-light Ca II IR3 HVF. A 2D K–S test for the distributions of the NCR value for the Hα and NUV bands between the subsamples of the SNe Ia with a strong and weak Ca II IR3 HVF shows that the probability that the two subsamples are from the same mother sample is only 2.3%, i.e. they arise from different mother samples.
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3.8. Radial Analysis

The delay time\(^7\) of an SNe Ia to a great extent shares a similar meaning of its stellar population. An SN Ia with a long delay time belongs to an old population, and vice versa. Compared with the core-collapse SNe, SNe Ia have a significant delay time from star formation to explosion, and then they are very likely to explode at a position far away from their birth sites. Because a stellar population with a different age and metallicity in a galaxy is located at different characteristic galactocentric radial positions, I may further investigate the environments of SNe Ia by exploring the position of an SNe Ia with respect to the radial distribution of different stellar populations, e.g., a “Fr” fractional flux value may provide this information. Here, only the H\(\alpha\) band is considered (Anderson et al. 2015a). A value of Fr = 0 for an SN Ia means that the SN Ia is located at the central peak pixel in the H\(\alpha\)-band image of its host galaxy, while a value of Fr = 1 implies that the SN Ia exploded in an outer region of its host galaxy, where the H\(\alpha\)-band flux is even equal to the sky value (see details in Anderson et al. 2015a). Generally, in the cumulative plot for Fr, the cumulative fraction for a young population increases more quickly at a low Fr value than for an old population. In Figure 15 I present the cumulative distribution of the Fr value for the SNe Ia with a strong and weak Ca II IR3 HVF around maximum brightness. As said above, the cumulative value for the SNe Ia with a strong maximum-light Ca II IR3 HVF increases more quickly at low Fr value than for those with a weak maximum-light Ca II IR3 HVF, i.e., the distributions indicate that the SNe Ia with a strong maximum-light Ca II IR3 HVF belong to a relatively younger population than those with a weak maximum-light Ca II IR3 HVF. A K–S test for the distributions of the Fr value shows that the probability that the two subsamples are from the same mother sample is only 3.7%, i.e., they are from different mother samples.

Here, the sample size of the SN Ia with a weak maximum-light Ca II IR3 HVF is much smaller than that with a strong maximum-light Ca II IR3 HVF, which is probably due to the fact that all the host galaxies in Anderson et al. (2015a) are star-forming galaxies. When the small sample of the SN Ia with a weak maximum-light Ca II IR3 HVF is combined, this fact is another piece of evidence to support our discovery, i.e., that the SNe Ia with a strong maximum-light Ca II IR3 HVF are more likely to correlate with a relatively young population.

3.9. Decay Rate of \(R_{\text{HVF}}\)

The previous sections have shown that the SNe Ia with a very strong Ca II IR3 HVF around maximum light tend to occur in later type host galaxies, and some statistical analysis also showed that these SNe Ia correlate with relatively younger stellar population than the SNe Ia with weak Ca II IR3 HVF. Because I only check the dependence of the \(R_{\text{HVF}}\) values of SNe Ia at maximum brightness on their exploding environments, our results might imply that SNe Ia in relatively young environments have a slower decay rate of \(R_{\text{HVF}}\) than those in old environments. By calculating the average value of the various measurable parameters of SNe Ia, Zhao et al. (2015) found that the decay rate of the HVFs roughly correlates with \(\Delta m_{15}(B)\) and \(V_{\text{max}}\). So, because it is widely known that the bright SNe Ia favor late-type galaxies (Hamuy et al. 1996; Wang et al. 1997), we would expect that the decay rate of the strength of the Ca II IR3 HVF correlates with the host galaxy morphology.

In Figure 16 I show the decay rate of \(R_{\text{HVF}}\) for the Ca II IR3 absorption line (\(R_{\text{HVF}}\)) around maximum brightness as a function of the host galaxy morphology. Here, I do not find any potential correlation between \(R_{\text{HVF}}\) and the host galaxy morphology. The difference from the result in Zhao et al. (2015) might arise because they measured their decay rate at 7 days before maximum brightness, while I measured it around maximum brightness here. However, the statistical error bars of the average values in Zhao et al. (2015) are so large that it could also mean that the decay rate of \(R_{\text{HVF}}\) does not depend on \(\Delta m_{15}(B)\) and \(V_{\text{max}}\), which is consistent with my result here.

To confirm this conclusion, I still need to justify that \(R_{\text{HVF}}\) is independent of \(R_{\text{HVF}}\). I present the plot of \(R_{\text{HVF}}\) versus the decay rate of \(R_{\text{HVF}}\) for the Ca II IR3 absorption line around maximum brightness in Figure 17. The figure shows that there is no potential correlation between \(R_{\text{HVF}}\) and \(R_{\text{HVF}}\), as I

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\(^7\) The delay time is the elapsed time from the formation of the primordial system to the supernova explosion.
expected. In addition, I do not find any potential correlation between $R_{\text{HVF}}$ of the Ca II IR3 absorption line and the REW of Si II 635.5 nm absorption line around maximum brightness either. For simplicity, I do not show the plot again here. So there is indeed a correlation between the strength of the Ca II IR3 HVF around maximum light in SNe Ia and their stellar population.

In Figures 16 and 17, I note that some SNe Ia have a maximum-light $R_{\text{HVF}}$ value higher than 0, i.e., the strength of Ca II IR3 HVF becomes stronger after maximum. For example, $R_{\text{HVF}} = 0.62 \pm 0.07$ at $t = -3.9$ day and $R_{\text{HVF}} = 1.17 \pm 0.02$ at $t = -3.0$ day for SN 1999dq, and $R_{\text{HVF}} = 0.39 \pm 0.05$ at $t = -4.5$ day and $R_{\text{HVF}} = 0.87 \pm 0.10$ at $t = 2.3$ day for SN 2006bt (see Table A4 in Silverman et al. 2015). In general, the HVFs appear strongest in early-time spectra and become weak with time, but some well-observed SNe Ia show interesting HVF evolutions. As one of the best observed SNe Ia, i.e., SN 2011fe, the strength of the Ca II IR3 HVF statistically significantly increases with time during the first week after the supernova explosion, and then it decreases with time after it reaches a maximum value (Childress et al. 2014). The evolution of the $R_{\text{HVF}}$ of the Ca II IR3 line in SN 2006X also shows a similar behavior to SN 2011fe (see Table A4 in Silverman et al. 2015). In addition, some SNe Ia show a plateau in the evolution curve of $R_{\text{HVF}}$, e.g., SN 2004dt, SN 2009ig, and SN 2012fr (Childress et al. 2014; Zhao et al. 2015). Especially SN 2005cf presents both these behaviors (Zhao et al. 2015). These behaviors on the evolution of the strength of the Ca II IR3 HVF provide another constraint on the origin of HVFs.

4. Discussion

4.1. Origins of the HVFs

In this paper, based on the published data of Ca II IR3 HVF around maximum light in the literature, I found that the SNe Ia with a strong Ca II IR3 HVF tend to occur in later type host galaxies or in early-type galaxies with significant recent star formation, and some statistical analysis also show that these SNe Ia are correlated with a relatively younger stellar population than those with a weak Ca II IR3 HVF. So, my discoveries provide very strong constraints on the origins of HVFs, even on the progenitor and explosion models of SNe Ia.

Generally, there are three popular scenarios to explain the origins of the HVFs shown in the spectra of SNe Ia, i.e., the abundance enhancement (AE), density enhancement (DE), and ionization effect (IE) scenarios (Mazzali et al. 2005b; Tanaka et al. 2008; Blondin et al. 2013). Combined with previous results in the literature, I discuss which scenario is more plausible to explain my discoveries in the following sections.

4.1.1. AE Scenario

For the AE scenario, the outer layers of supernova ejecta are dominated by Si and Ca, which implies that the outer layers of the progenitor WD are significantly burned, or the significantly burned materials in the inner region are brought up to the outer part of the supernova ejecta during the explosion phase (Mazzali et al. 2005b).

Several mechanisms could contribute to this abundance structure. For the delayed-detonation model (Khokhlov 1991), the first deflagration phase may lead to an asymmetry for the distribution of the detonation ignition point, which could burn C/O into Si/Ca in some directions (Blondin et al. 2013; Seitenzahl et al. 2013). A detonation in the violent merger of two WDs or a gravitationally confined detonation on the surface of a WD could also produce a similar situation, i.e., a detonation in one side may produce more high-velocity Si/Ca than in the other side (Plewa et al. 2004; Kasen & Plewa 2005; Pakmor et al. 2012). Theoretically, the convection or a high accretion rate before the explosion may naturally lead to an off-center ignition in a WD, and then to an asymmetric explosion (Kuhlen et al. 2006; Chen et al. 2014). It has been suggested that the evolution of the photospheric velocity may reflect the fact of an asymmetric explosion, i.e., LVG SNe Ia are observed along the off-center-ignition side, while HVG SNe Ia are observed from another side (Maeda et al. 2010). Polarization observations show that supernova ejecta is not spherically symmetric (Wang & Wheeler 2008). Especially it is found that the higher the REW value of the Si II 635.5 nm absorption line, the higher its polarization, which may be explained by the delayed-detonation mode (Meng et al. 2017). However, it is still unclear how the asymmetric explosion affects the HVFs in SNe Ia. In particular, we did not find a difference of the $R_{\text{HVF}}$ distribution between LGV SNe Ia and HVG SNe Ia (see Figure 8), which indicates that the asymmetric explosion could not affect the HVFs in an SN Ia.

If the HVFs in SNe Ia are from the mechanisms described above, our discoveries indicate that the progenitor population of an SN Ia would affect its explosion, and they require that the explosion from a relative young population is more likely to produce Si/Ca at the outer layers of supernova ejecta, and the layers have a higher velocity (see Figures 6 and 7), or that a relatively young population leads to a more asymmetric explosion. At present, it is still unclear how the progenitor population of an SN Ia affects its final explosion, although in principle, the initial condition of an exploding CO WD would be determined by its progenitor. The cooling time of the initial WD before the onset of accretion or the initial WD mass in a single-degenerate system might play some role (Chen et al. 2014; Meng & Han 2018).

An alternative possibility is the double-detonation model, in which a He detonation initiated near the WD surface may also produce AE in this region and then show HVFs in the spectra of SNe Ia (Woosley & Kasen 2011; Maguire et al.
This mechanism may naturally explain the fact that the line-forming regions for HVF and PVF are detached. The companion of the exploding CO WD may be a helium star or a helium WD. Generally, the systems with helium star companions belong to the relatively young population, and the systems with helium WDs tend to be old populations (Wang et al. 2013; Meng & Han 2015). So, if the abundance-enhanced Si/Ca from the double-detonation model is the origin of the HVFs in SNe Ia, our discoveries imply that the systems with helium star companions would produce the more energetic SNe Ia with strong HVFs, while the systems with helium WDs would lead to those with weak HVFs. However, the current double-detonation model does not provide this result, and no evidence shows that the detonations from helium stars and helium WDs are different. This merits careful investigation in the future (Tanikawa et al. 2019), however.

Another recently explored possibility is that a helium-shell flash on a WD with a mass close to the Chandrasekhar mass limit could build up a layer enhanced in silicon or calcium before the SN explosion, where the helium shell is from the accretion of hydrogen or helium from a non-degenerate companion in a single-degenerate system (Kato et al. 2018). The Si/Ca-rich material should be located in the outermost layers of the supernova ejecta, which would be physically separated from the photospheric silicon layers. This might explain the correlation between $R_{\text{HVF}}$ and $\Delta \tau_{\text{II}}$, but it cannot explain the SNe Ia with $R_{\text{HVF}} = 0$ and a high value of $\Delta \tau_{\text{II}}$. However, it is unclear how this mechanism would be related to the stellar population of SNe Ia. Might there be a difference in the helium flash between young and old populations?

In summary, although the AE scenario may provide a natural way to produce the HVFs, it is completely unclear how this scenario is correlated with the stellar population of SNe Ia. In particular, the strength of the HVFs from the AE scenario should decrease with time because the supernova ejecta become increasingly thinner with time, and it is quite difficult to explain the increase and plateau behaviors in the $R_{\text{HVF}}$ evolution curve with time presented in some well-observed SNe Ia, e.g., SN 2011fe, SN 2005cf, and SN 2006X (Childress et al. 2014; Silverman et al. 2015; Zhao et al. 2015). So, the origin of the HVFs in SNe Ia is more likely to be from a mechanism that is related to the progenitor models of SNe Ia, rather than explosion models.

### 4.1.2. DE and IE Scenarios

In the DE scenario, the HVFs originate from a high-density or density bump shell (equivalent to adding mass) at outer layers, in which the abundance is a typical value in the expanding ejecta (Mazzali et al. 2005b; Tanaka et al. 2008; Mulligan & Wheeler 2017, 2018). Generally, two mechanisms are suggested to produce the density variation. One is from an asymmetrical explosion, as discussed in the above section. Then, the ejecta in some directions may be affected by burning differently from other directions. As discussed in Section 4.1.1, this mechanism has difficulties to explain the correlation between the strength of the maximum-light Ca II IR3 HVF and the stellar population of SNe Ia, and it is difficult to explain the increase and plateau behavior of the strength evolution of the Ca II IR3 HVF shown in some SNe Ia. Another mechanism to achieve a density bump shell may be the interaction between supernova ejecta and the relatively dense CSM around the progenitor system (Mulligan & Wheeler 2017, 2018).

In the IE scenario, a low amount of hydrogen is mixed at the outermost layer as a source of free electrons. Because Ca is mostly doubly ionized in the outermost layer, the increased free electron density suppresses the ionization status of Ca by recombination, and then the fraction of Ca II is increased (Mazzali et al. 2005b; Tanaka et al. 2008). The hydrogen may be from a contamination of hydrogen on the WD surface in a single-degenerate system, or from the interaction between supernova ejecta and relatively dense CSM as in the DE scenario.

Both DE and IE scenarios have a potential ability, or play a role together, to explain the correlation between the strength of HVFs and the stellar populations of SNe Ia, if the HVFs are from the interaction between the supernova ejecta and the CSM. The interaction between supernova ejecta and the CSM may contribute to the Ca II IR3 HVF in the following three ways: (I) adding mass at the highest velocity region of supernova ejecta by the accumulation of CSM, (II) changing the ionization degree of calcium by increasing the free electron density from hydrogen, and (III) increasing the residence time of photons in the hydrogen shell by a higher scattering-off probability of photons from a higher electron density. All these effects contribute to an increased line absorption at the highest velocity region of supernova ejecta, and then an HVF is presented in the absorption line of the Ca II IR3 line in the early optical spectrum of an SN Ia. Because the Ca II line is the most remarkable feature in the optical spectrum of an SN Ia, it is also most significantly affected by the interaction between supernova ejecta and the CSM (Mazzali et al. 2005b; Tanaka et al. 2008). Generally, young SNe Ia tend to have a dense CSM, while the environments around old SNe Ia are relatively clear, e.g., 1991T-like SNe Ia just belong to a relatively young population, while no CSM is discovered around old 1991bg-like SNe Ia (Johansson et al. 2013a; Fischer & Jumper 2015). These two scenarios in particular might explain the evolution of the strength of the HVFs with time. Here, the dominant factor is the decreasing density of supernova ejecta with time, which leads to the global decrease in the strength of the HVFs with time. However, the CSM structure around SNe Ia may vary, depending on the mass-loss histories of their progenitors, e.g., a wind or a shell structure, as some SNe Ia show (Patat et al. 2007; Dilday et al. 2012), which could result in different evolution behaviors of the HVF strength.

Two particular types of SNe Ia must receive more attention if the HVFs stem from the interaction between the supernova ejecta and the hydrogen-rich material, e.g., 2002cx-like and SN Ia-CSM objects (Foley et al. 2013; Silverman et al. 2013). Both types of objects belong to a relatively young population and have a much denser CSM than normal SNe Ia (Chomiuk et al. 2016; Lyman et al. 2018; Szalai et al. 2019). Meng & Podsiadlowski (2018) even suggested that these two peculiar subclasses of SNe Ia share the same origin, i.e., from the hybrid CONe WD + MS system, based on a newly developed version of the single-degenerate model (common-envelope wind (CEW) model, Meng & Podsiadlowski 2017). However, the Ca II IR3 absorption features in the spectra of these peculiar SNe Ia are quite different from the normal SNe Ia. For SNe Ia-CSM, the Ca II IR3 features are strong and broad emission features, rather than absorption lines in normal SNe Ia (Silverman et al. 2013). This difference between SNe Ia-CSM and the normal SNe Ia...
could arise from the amount of hydrogen-rich material. To form the HVFs in normal SNe Ia, a few $10^{-3} M_\odot$ hydrogen-rich materials are enough, but the CSM around SNe Ia-CSM is much more massive than this value. For example, the CSM around SN 2002ci (the prototype of SNe Ia-CSM, Hamuy et al. 2003) may be as massive as 0.5–6 $M_\odot$ (Chugai & Yungelson 2004; Kotak et al. 2004; Wang et al. 2004). For 2002ci-like SNe Ia, no significant HVF is discovered, but a significantly lower maximum-light expansion velocity than normal SNe Ia becomes a typical character (Foley et al. 2013). The low expansion velocity could result in an overlap or mixed line-forming region between the HVFs and PVFs, as shown in some normal SNe Ia with high pEW of the photospheric component, but without the high-velocity Ca II IR3 lines (see the discussions in Section 3.3). However, no definitive evidence supports or refutes these ideas at present, although SN 2006X provides a clue for the ideas (see Section 3.3). Especially, it is still unclear how a large amount of hydrogen-rich CSM affects the Ca II IR3 lines. Then, more efforts on these subjects are needed in the future.

If the HVFs in SNe Ia arise from the interaction between supernova ejecta and hydrogen-rich CSM and the CSM is massive enough, the SNe Ia with very strong HVFs would show a variable sodium absorption lines in their early spectra, as did SN 2006X (Patat et al. 2007; Blondin et al. 2009; Simon et al. 2009; Ferretti et al. 2016). Recently, Wang et al. (2019) provided a sample of SNe Ia with a variable sodium absorption line, including SN 2006X, and these SNe Ia indeed present a strong Ca II IR3 HVF. For example, SN 2006X, the prototype of an SNe Ia with a variable sodium line, has a maximum-light value of $R_{\text{HVF}} = 1.14 \pm 0.07$ (also for SN 1999dq, 2002bo, and 2002cd, see Table A4 in Silverman et al. 2015 and Table 2 in Wang et al. 2019). In addition, SN 2002dj presents a quickly variable sodium line around 8 days before maximum light (Figure 2 in Wang et al. 2019). Interestingly, SN 2002dj also shows a very strong Ca II IR3 HVF at the same epoch, i.e., $R_{\text{HVF}} = 1.17 \pm 0.06$ (Table A4 in Silverman et al. 2015). The CSM around SNe Ia may present itself in another way, i.e., the CSM may redden the color of SNe Ia and then lead to a color excess, e.g., $E(B−V)$. Recently, Bulla et al. (2018) found that some SNe Ia show time-variable $E(B−V)$, and these SNe Ia prefer the SNe Ia with a variable sodium line, e.g., SN 2002bo, 2002cd, and 2006X, which also show a very strong maximum-light Ca II IR3 HVF. Another interesting fact is that the distribution of the $R_{\text{HVF}}$ of the maximum-light Ca II IR3 HVF is quite similar to the distribution of the $E(B−V)$ of SNe Ia around maximum brightness, i.e., a low-value peak of $R_{\text{HVF}} [E(B−V)]$ with a long tail (Reindl et al. 2005; Meng et al. 2009).

4.2. Progenitor of SNe Ia

The correlation between the strength of the maximum-light Ca II IR3 HVF and the stellar population of SNe Ia may provide meaningful constraints on the progenitor models of SNe Ia. In particular, combined with the results in the literature, our discoveries seem to favor the hypothesis that the HVFs in SNe Ia arise from the interaction between supernova ejecta and the CSM around SNe Ia. This is also helpful for distinguishing between different progenitor models of SNe Ia. Generally, the progenitors of SNe Ia are categorized into three main scenarios based on the companion nature of the exploding CO WDs and on the explosion mechanism, i.e., the single-degenerate (SD, Whelan & Iben 1973; Nomoto et al. 1984), double-degenerate (DD, Iben & Tutukov 1984; Webbink 1984), and the Chandrasekhar double-detonation (D-DT) models (Woosley & Weaver 1994; Livne & Arnett 1995; Shen et al. 2013). In the following sections, I discuss which model more likely explains all the observations of the HVFs in SNe Ia.

4.2.1. SD Model

In the SD model, the companion of the exploding CO WD may be a main-sequence (MS), a subgiant (SG), a red giant (RG), or a helium star. The accreted hydrogen-rich or helium-rich material is burned on the surface of the CO WD into carbon and oxygen, and then deposited onto the WD. When the WD mass reaches a value close to the Chandrasekhar mass limit, an SN Ia may be produced. After the supernova explosion, the companion may survive (Wang & Han 2012; Maoz et al. 2014; Meng et al. 2015). If the correlation between the strength of the HVFs and the stellar population arises from the interaction between supernova ejecta and the hydrogen-rich CSM, the SD model might explain the origin of the HVFs, where the CSM is from the outflow or wind from the binary system. For a given initial WD, the amount and density of the CSM is then mainly determined by the initial companion mass, i.e., the more massive the companion, the more likely it is to form a dense CSM by a wind (e.g., the common-envelope wind, Meng & Podsiadlowski 2017). In addition, the age of an SN Ia from the SD channel is also dominated by the companion mass, i.e., the more massive the companion, the younger the SN Ia. So, a relatively younger SN Ia means a relatively denser CSM, and then stronger HVFs, i.e., in principle, the SD model may explain my discoveries in this paper. Because the CSM structure may vary depending on the detailed mass-loss histories, the SD model may in principle also explain the increase or plateau behaviors in the Ca II IR3 $R_{\text{HVF}}$ evolution with time. In addition, based on the SD model, in principle, the CSM may exist anywhere from the vicinity of the progenitor system of an SN Ia to a distance of more than 300 pc to the system, depending on the specific way that the CSM is formed (Meng & Podsiadlowski 2017, 2018), as deduced from observations (Broersen et al. 2014; Bulla et al. 2018).

A symbiotic system with a low-mass RG could also be the progenitor of an SN Ia (Li & van den Heuvel 1997; Hachisu et al. 1999; Chen et al. 2011). Such a system belongs to an old population, but may also have a relatively dense CSM, which seems to be inconsistent with our discovery. A spin-up/spin-down mechanism might be required (Justham 2011; Di Stefano & Klic 2012). For this mechanism, the CO WD will not explode as an SN Ia immediately for a rapid rotation, spun up by the accretion, even if its mass reaches or exceeds the Chandrasekhar mass limit. The fast-rotating WD must experience a spin-down phase to explode, although the spin-down timescale is quite uncertain (Di Stefano et al. 2011; Meng & Podsiadlowski 2013). During the spin-down phase, the environment around the progenitor system may become very clean and the RG companion may become a dim helium WD or an sdB star (Justham 2011; Meng & Li 2019). The initial WD mass might play a key role for the spin-down timescale (Meng & Han 2018). If so, the SD model is not inconsistent with our discoveries.
The interacting CSM may emit at radio and X-ray, but no SN Ia has been detected in radio or in X-ray bands, even for the two most well-observed SNe Ia, e.g., SN 2011fe and SN 2014J (Chomiuk et al. 2012; Margutti et al. 2012, 2014; Pérez-Torres et al. 2014). These negative results indicate a very low CSM density around the exploding SNe Ia, which is consistent with the required amount of the hydrogen-rich CSM to explain the HVF of SNe Ia, but without hydrogen emission lines in the spectra of SNe Ia (e.g., a few times $10^{-3} M_\odot$, Mazzali et al. 2005b; Tanaka et al. 2008). If the hydrogen-rich CSM is massive enough, the hydrogen emission line would be expected, as shown in the spectra of SNe Ia-CSM (Hamuy et al. 2003; Dilday et al. 2012; Silverman et al. 2013).

4.2.2. DD Model

In the DD model, a binary system consisting of two CO WDs loses its orbital angular momentum by gravitational radiation, and finally merges. If the total mass of the binary system exceeds the Chandrasekhar mass limit, the merger may explode as an SN Ia. However, the merger will be disrupted completely and no surviving companion exists after the supernova explosion (Wang & Han 2012; Maoz et al. 2014; Meng et al. 2015).

The CSM might also be formed from a DD system, but it is deficient in hydrogen and helium, i.e., it mainly consists of carbon and oxygen, where the CSM could arise from a super wind during the merging process (Soker 2013). For example, although they are very rare, the so-called “super-Chandrasekhar” SNe Ia are suggested to be a Chandrasekhar-mass WD that exploded inside a dense carbon or oxygen envelope that is the remains of the WD–WD merger (Howell et al. 2006; Scalzo et al. 2014; Taubenberger et al. 2013, 2019). If this type of CSM plays a role in forming the HVFs in SNe Ia, the origin of HVFs would be the DE scenario.

It was suggested that younger more massive stars produce more massive white dwarfs, and then a more massive carbon and oxygen envelope is formed during the merging process (Howell 2011; Maoz & Mannucci 2012), which could contribute to the correlation between the HVFs of SNe Ia and their stellar population. However, a detailed binary population synthesis shows that the distribution of the total masses of the DD systems is rather uniform within the whole delay-time interval because the delay time of SNe Ia from the DD systems is mainly determined by gravitational wave radiation, rather than their progenitor evolutionary time (Meng & Yang 2012), which indicates that the remains of the WD–WD merger would be the same regardless of whether the progenitors of SNe Ia belong to a young or to an old stellar population. As required in the SD model, a spin-down timescale and a magnetic field might be required, i.e., for young SNe Ia, the magnetic field of the merger is stronger, and then the spin-down timescale is shorter to form a relatively denser carbon/oxygen CSM (Ilkov & Soker 2012). However, it is completely unclear why younger DD systems would form a merger with a stronger magnetic field and then experience a shorter spin-down timescale.

The remains of the WD–WD merger could have another geometric structure, e.g., the disk-originated CSM, depending on the merger timescale (Levanon et al. 2015; Levanon & Soker 2019). The less massive WD is tidally destroyed by its more massive companion and forms an accretion disk around the more massive companion. A bipolar wind or jet might be blown off to form the CSM that originates in the disk, which is also deficient in hydrogen and helium. If the interaction between supernova ejecta and the CSM that originates in the disk is the reason for the HVFs in SNe Ia, the DE scenario would be the origin of the HVFs. However, similar to the above discussions, many efforts are needed to explore why young SNe Ia have this CSM that originates in the disk, while old SNe Ia do not, although the distribution of the total mass of the DD systems leading to SNe Ia is rather uniform throughout the whole delay-time interval (Meng & Yang 2012).

Both the SD and DD models together might produce SNe Ia, but with different age populations, e.g., the SD model mainly produces relatively young SNe Ia and the DD model mainly produces old SNe Ia, because some evidence showed that different SNe Ia may stem from different populations (Wang et al. 2013). For this combination of different progenitor models, the IE scenario would be the origin of the HVFs in SNe Ia to explain the correlation between the strength of HVFs and the stellar population of SNe Ia. However, the combination scenario has difficulties to explain why almost all SNe Ia show the HVF in a very early phase if the IE scenario is the origin of the HVFs.

As a special case of DD model, the core-degenerate (CD) model, may also be able to explain the correlation between the maximum-light Ca II IR3 HVF and the stellar population of SNe Ia, where the hydrogen-rich CSM is from the common envelope formed by merger between a CO WD and an AGB star with a CO core (Kashi & Soker 2011). Similar to the SD model, a spin-down timescale is also necessary to explain the correlation found in this paper, where a magneto-dipole radiation torque dominates the spin-down timescale (Ilkov & Soker 2012). However, it is completely unclear why a young merger tends to have a strong magnetic field, and then lead to a short spin-down timescale (Ilkov & Soker 2012). In addition, the CD model is less able to contribute to the majority of SNe Ia (Meng & Yang 2012; Wang et al. 2017), although the argument on the contribution exists (Ilkov & Soker 2013).

4.2.3. D-DET Model

The D-DET model is also frequently discussed, in which the companion of the CO WD is a helium WD or a helium star. The companion fills its Roche lobe and a stable mass transfer occurs. If the mass-transfer rate is not high enough for the helium-rich material to burn stably, the helium will gradually accumulate on the CO WD. When the helium layer is thick enough, a detonation is ignited at the bottom of the helium shell, where the inward supersonic detonation wave may lead to the second detonation in the center of the CO WD. After the supernova explosion, a hypervelocity companion may survive (Geier et al. 2015; Shen et al. 2018).

The D-DET model could contribute to the HVFs in three different ways. (I) There is a thin hydrogen-rich layer on a helium WD that is transferred onto the WD before the He core is tidally disrupted. Finally, this hydrogen-rich material is ejected from the binary system in a way similar to a classical nova to form the CSM (Shen et al. 2013). The interaction between supernova ejecta and the CSM could contribute to the HVFs in SNe Ia. A key problem for this scenario is whether the amount of the CSM is sufficient because the hydrogen-rich layer on a He WD is generally only $2 \times 10^{-4} M_\odot$ and a part of hydrogen-rich material is consumed during the classical nova explosion phase, while $(4–5) \times 10^{-3} M_\odot$. 

4.3. Origin of the Relation between $R_{\text{HVF}}$ and $(\tau_{\text{CI}} - \tau_{\text{Si}})$

In Section 3.3 I found a very good linear relation between $R_{\text{HVF}}$ and $(\tau_{\text{CI}} - \tau_{\text{Si}})$, and suggested $(\tau_{\text{CI}} - \tau_{\text{Si}})$ as an indicator for whether the Ca II IR3 absorption line contains a high-velocity component. This relation could provide important clues on the explosion mechanism of SNe Ia and on the origin of the HVFs in SNe Ia.

Figures 6 and 7 show that the Ca II IR3 line usually has a higher absorption-weighted velocity than the Si II 635.5 nm line. When we consider that different elements are located in different layers in supernova ejecta (Filippenko 1997; Mazzali et al. 2007), these results indicate that calcium layer has a higher average velocity than the silicon layer. As discussed in the previous sections, some mechanisms, e.g., asymmetric explosion and double detonation, could contribute to the results, but they appear to have difficulties in explaining the correlation between the strength of the Ca II IR3 HVF and the population of SNe Ia. In other words, these mechanisms have greater or lesser difficulties to simultaneously explain why $R_{\text{HVF}}$ linearly increases with $(\tau_{\text{CI}} - \tau_{\text{Si}})$ and why $R_{\text{HVF}}$ depends on the stellar population of the SNe Ia.

However, there might be a very simple explanation for the relation in Figure 6, i.e., the silicon and calcium layers have a similar velocity distribution in the velocity space of supernova ejecta, but the IE is the origin of Ca II IR3 HVF. Because calcium has a much lower number density than silicon in the forming region of HVF and the calcium ion is more likely to be affected by free election from hydrogen than silicon, a small amount of hydrogen could lead to a more significant HVF in the Ca II IR3 line than in the Si II 635.5 nm line, i.e., the weighted mean absorption velocity of the Ca II IR3 line becomes higher than that of the Si II 635.5 nm line (see the discussion in Mazzali et al. 2005b). At the same time, the strength of the Ca II IR3 HVF increases. This simple explanation can also relatively easily explain why the Ca II IR3 absorption line usually shows a more significant HVF than the Si II 635.5 nm line. More detailed efforts are required to verify this idea, however.

5. Conclusions

Although many data on the HVFs of SNe Ia have been published, the origin of the HVFs is still unclear. In particular, no definitive constraint on the progenitor or explosion model was obtained from HVF observations. In this paper, based on the data published in the literature, I found strong evidence that the strength of the Ca II IR3 HVF around maximum brightness correlates with the stellar population of SNe Ia, and the main results are as follows:

1. SNe Ia with strong Ca II IR3 HVF around maximum brightness tend to occur in late-type galaxies. Some lenticular galaxies also host SNe Ia with a strong Ca II IR3 HVF, but all of these lenticular galaxies show the signature of recent or ongoing star formation, and the SNe Ia with a strong maximum-light Ca II IR3 HVF are located at or close to the star formation regions in their host galaxies.

2. In the sample of Silverman et al. (2015), all of the eight 1991T-like SNe Ia have a very strong Ca II IR3 HVF around maximum light, while of the seventeen 1991bg-like SNe Ia, sixteen present weak or no Ca II IR3 HVF around maximum brightness. It is well established that 1991T-like SNe Ia arise from a young stellar population and that 1991bg-like SNe Ia belong to old stellar population.

3. By pixel statistics, I found that the SNe Ia with a strong Ca II IR3 HVF around maximum brightness show a higher degree of association with the star formation index, e.g., H$\alpha$ or NUV emission, than those with a weak maximum-light Ca II IR3 HVF.

4. Because all the host galaxies are star-forming galaxies in the sample of Anderson et al. (2015a), the sample size of SNe Ia with a weak maximum-light Ca II IR3 HVF is much smaller than that with a strong maximum-light Ca II IR3 HVF (see Section 3.8).

5. The distribution of the REW of Si II 635.5 nm around maximum brightness between the SNe Ia with a strong and weak Ca II IR3 HVF are quite different, i.e., SNe Ia with a strong maximum-light Ca II IR3 HVF favor small or larger REW, while those with a weak maximum-light Ca II IR3 HVF tend to have a medium value of the REW.

6. I found that the strength of the Ca II IR3 HVF around maximum brightness is linearly dependent on the difference of the absorption-weighted velocities between the Ca II IR3 and Si II 635.5 nm absorption lines in the same phase. Then, I suggest that the difference of the absorption-weighted velocities may be helpful to judge whether the Ca II IR3 feature in the spectra of SNe Ia contains a high-velocity component.

Based on these results, I conclude that the SNe Ia with a strong Ca II IR3 HVF around maximum brightness favor a relatively younger stellar population than those with a weak maximum-light Ca II IR3 HVF, which provides meaningful constraints on the explosion and progenitor models. Although a spin-up or spin-down mechanism is necessary, the SD model can relatively naturally explain the correlation between the strength of the HVFs and the stellar population of SNe Ia discovered here, while more efforts are required for the DD and D-DET models. Although my results cannot give a definitive conclusion on the origin of the HVFs, the discoveries here seem to disfavor the AE scenario as the origin of the HVFs, and the HVFs are less likely to arise from the explosion of an SN Ia itself. In contrast, the interaction between supernova ejecta and the hydrogen-rich CSM could be a natural origin of the HVFs.
in SNe Ia, where the DE and IE scenarios together could play a role.

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