A New Approach to Supernova Standardization using the Si II Line Velocity

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ABSTRACT

Type Ia Supernovae (SNe Ia) are used in cosmological analysis such as determining the expansion rate of the Universe since their intrinsic peak luminosity, colours and light curves relate to distance. This relation is expressed in Standardization which uses the isotropicity of SNe Ia peak luminosities to estimate distances. Recent work on SNe Ia has indicated a split in the population based on the velocity of the Si II 6355 Å spectral line, resulting in SNe Ia having different luminosities and hence standardization. **This project attempts to consolidate the standardization of the two populations by analysing a sample of SN siblings from the Zwicky Transient Facility (ZTF)**. Although we find the current sample to be too small to provide conclusive results, we successfully validate our methodology by matching theoretical predictions on the velocity gradient of the Si feature within 3σ.

INTRODUCTION

A **type Ia Supernova (SN Ia)** is the thermonuclear explosion of a carbon-oxygen (C/O) white dwarf (WD) in a binary system.

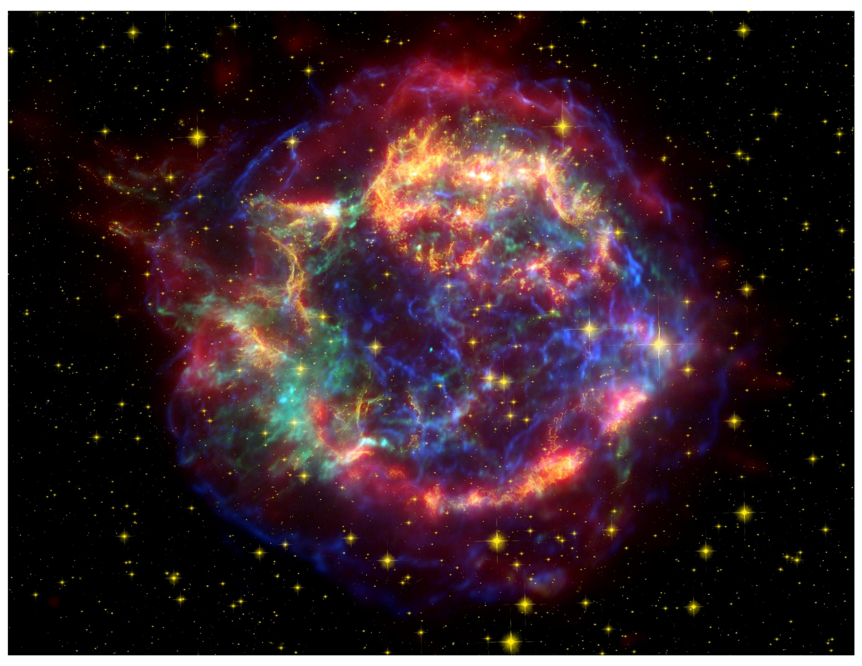

Figure 1. Cassiopeia A (Supernova Remnant)[2]

Type Ia SNe are characterized from other Supernova (SN) subtypes by the presence of a **strong singly ionized Silicon (Si II) absorption line in the SN spectrum**. By analyzing the spectrum we can obtain the velocity of Si II in the ejected material. **Recent studies have shown that high-velocity SNe (velocity of Si II $\gtrsim$ 12,000 km/s) have different properties and hence different standardization as compared to low-velocity SNe**. The current standardization assumption of a population-consistent peak luminosity is no longer accurate and may be the source of current cosmological problems such as the Hubble Tension. **Thus we need to redefine the standardization relation**. We do so by analyzing pairs of **SN siblings** which are SNe in the same host galaxy as this method is independent of cosmology, redshift, and global systematics.

Standardization Relation (SALT2 Model)

Current Standardization Relation for a Supernova:

$$\mu = m_B + \alpha x_1 - \beta c - M_B - \delta_{hos}$$

Proposed Standardization Relation for Supernova Siblings:

$$\Delta\mu = \Delta m + \alpha\Delta x_1 - \beta\Delta c - \Delta v$$

where μ is the distance modulus. The other terms are parameters relating to the colour and brightness of the SN. Notice that the proposed relation is for a pair of supernova siblings and hence is the difference in distance modulus, $\Delta\mu$, rather than μ for a single supernova. The new relation demonstrates the advantage of using siblings as some parameters cancel out as a result of siblings having common properties. This allows us to introduce and solve for a new parameter Δv, the "velocity-step", to account for the high-low velocity SN population split.

METHODOLOGY

The methodology is split into two parts:

- **Velocity Gradient**: This part involves identifying and resolving the Si II feature in SN spectra from the **Carnegie Supernova Project (CSP)** and extracting the associated Si II velocity.

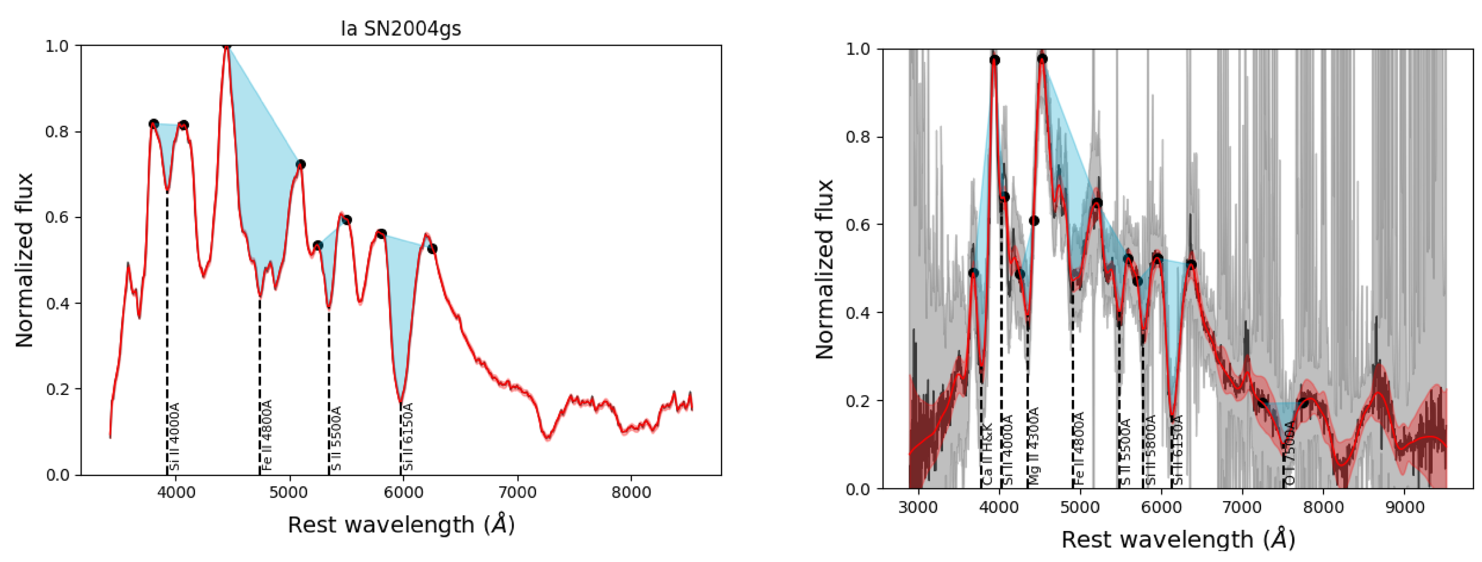

Figure 2. Left: Processed CSP Spectra, Right: Processed ZTF Spectra

Since CSP data has the same SN recorded at several epochs we can get the velocity at each of those epochs and then plot the **velocity evolution curve** for each SN. The final step in this part is to find the **velocity gradient** or the rate of change of Si II velocity with epoch from this plot.

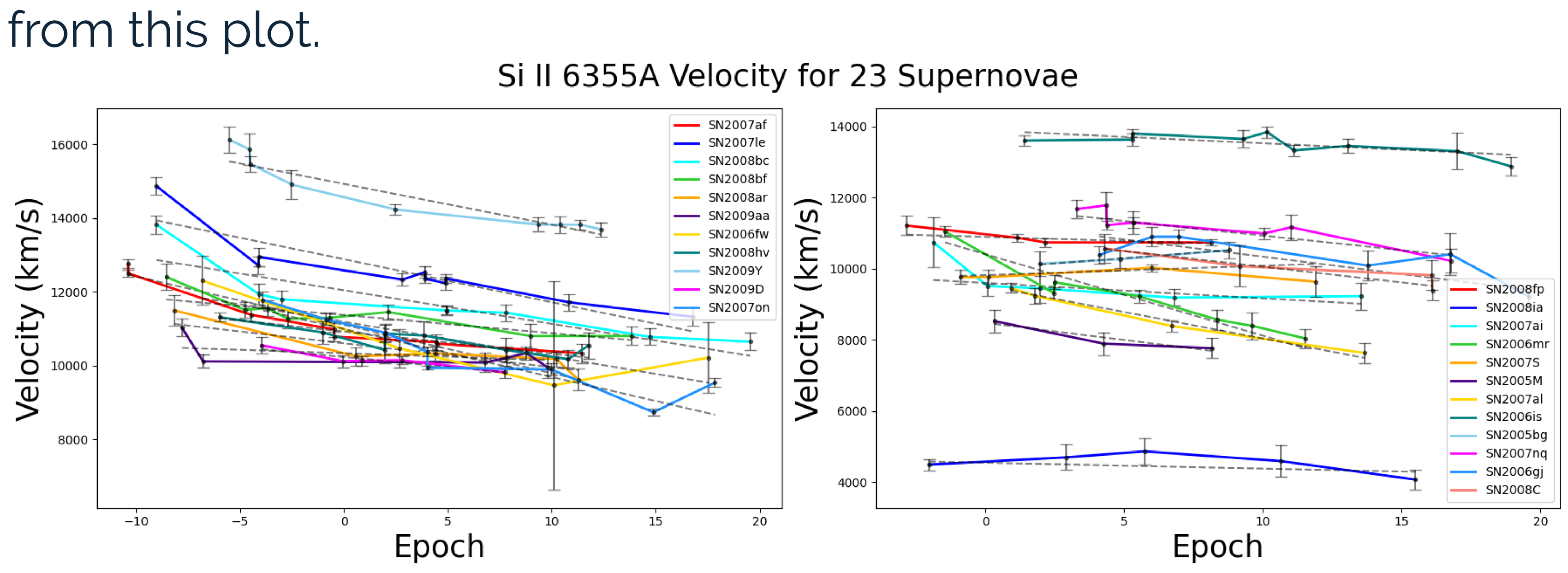

Figure 3. Velocity Evolution Curves (23 CSP SNe split across 2 subplots)

- **ZTF Correction**: We repeat the velocity extraction for SN siblings from the Zwicky Transient Facility (ZTF) dataset and use the velocity gradient we got previously to **correct** the velocities from their recorded epochs to a **reference epoch** which is chosen to be at **peak luminosity (Epoch = 0)**. Since the ZTF spectra differ in quality, we estimate the signal-to-noise ratio (SNR) from the Si II line depth and make some selection cuts. The final step is to run an algorithm called MCMC to fit Δv given the velocity at the peak for pairs of siblings, twice for the high and low-velocity populations respectively.

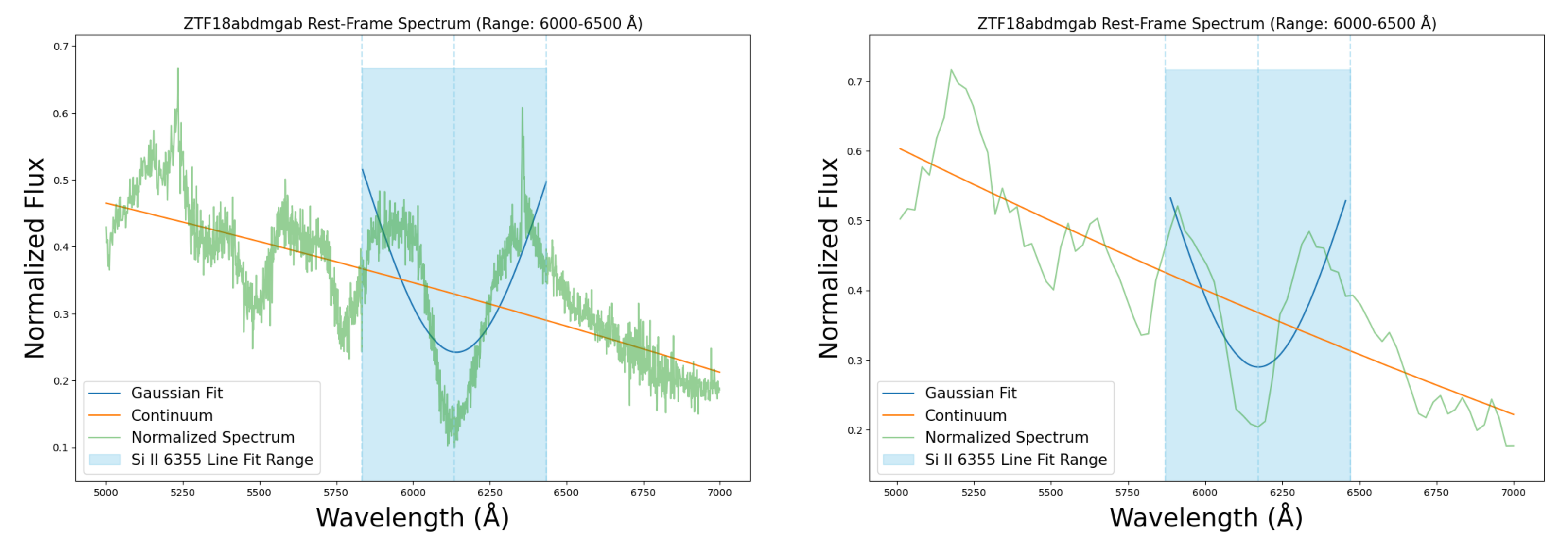

Figure 4. SNR Estimating Plots for bad (left) and good (right) spectra (Gaussian Fit to the Si II line and a linear fit to the continuum to calculate their difference at the Si II wavelength)

RESULTS

1. By fitting splines to the velocity evolution curve data points, we find the shape of the curve to be **linear** as predicted by theory within 3σ highlighting the competence of this method.

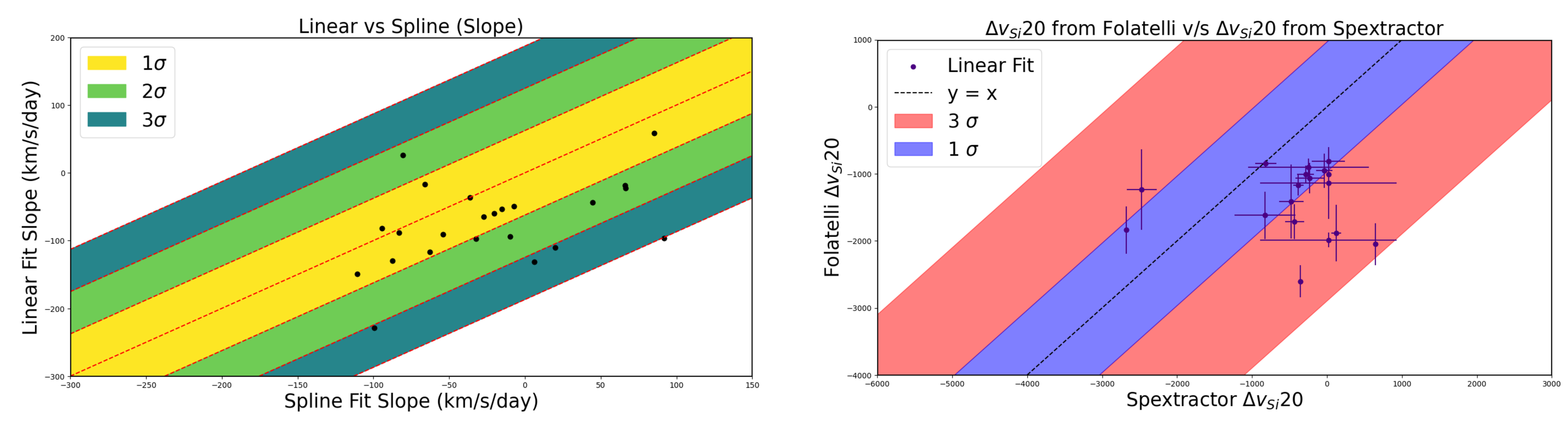

Figure 5. Left: Linear v/s Spline Fit, Right: Spextractor Velocity Gradient v/s Folatelli Velocity Gradient

2. We find the **mean velocity gradient** to be within **3 σ** of the value obtained by another paper by Folatelli[1] using a different method, adding further credence to this method.
   Spextractor Δv = -73.668 $\pm$59.549 km/s/day
   $Folatelli\ \Delta v = -75.587 \pm 42.015$ km/s/day
3. Due to the low number of data points (only 3 siblings or 6 SNe in the final analysis), Δv is **not well constrained** for both the high and low-velocity populations but the pipeline will be useful in the future.

ACKNOWLEDGEMENTS

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REFERENCES

[1] Gastón Folatelli, Nidia Morrell, Mark M. Phillips, Eric Hsiao, and Campillay. Spectroscopy of Type Ia Supernovae by the Carnegie Supernova Project., 773(1):53, August 2013.
[2] Image Credit: NASA/SAO