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### Journal

Astrophysical Journal, 906(1)

### ISSN

0004-637X

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### Publication Date

2021

### DOI

10.3847/1538-4357/abcccc

Peer reviewed

## Nebular Models of Sub-Chandrasekhar Mass Type Ia Supernovae: Clues to the origin of Ca-rich transients

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(Received October 27, 2019)

Submitted to ApJ

### ABSTRACT

We use non-local thermal equilibrium (NLTE) radiative transport modeling to examine observational signatures of sub-Chandrasekhar mass double detonation explosions in the nebular phase. Results range from spectra that look like typical and sub-luminous Type Ia supernovae (SNe) for higher mass progenitors to spectra that look like Ca-rich transients for lower mass progenitors. This ignition mechanism produces an inherent relationship between emission features and the progenitor mass as the ratio of the nebular [CaII]/[FeIII] emission lines increases with decreasing white dwarf (WD) mass. Examining the [CaII]/[FeIII] nebular line ratio in a sample of observed SNe we find further evidence for the two distinct classes of SNe Ia identified in Polin et al. (2019) by their relationship between SiII velocity and B-band magnitude, both at time of peak brightness. This suggests that SNe Ia arise from more than one progenitor channel, and provides an empirical method for classifying events on based on their physical origin. Furthermore, we provide insight to the mysterious origin of Ca-rich transients as we show that only a small mass fraction of Ca (1%) is required to produce a nebular spectrum that cools primarily through forbidden [CaII] emission.

*Keywords:* supernovae: general— radiative transfer— hydrodynamics— methods: numerical

### 1. INTRODUCTION

A popular sub-Chandrasekhar model for Type Ia SNe consists of a carbon-oxygen white dwarf (C/O WD), below the Chandrasekhar mass limit, which ignites through the aid of an accreted helium shell. The helium ignition sends a shock wave into the center of the C/O WD causing a detonation near the core of the star followed by thermonuclear runaway. This process, known as the double detonation scenario, has been theorized as a possible path to SNe Type Ia, initially for WDs with large helium shells (Woosley & Weaver 1994; Nomoto 1982a,b; Livne 1990) and later for WDs with only a small amount of helium on their surfaces (Bildsten et al. 2007; Shen & Bildsten 2014; Fink et al. 2007, 2010; Sim et al. 2010). Current simulations show that the latter can be a promising path to normal and

sub-luminous Type Ia's (Shen et al. 2018a; Polin et al. 2019; Townsley et al. 2019).

Evidence increasingly points towards sub-Chandrasekhar mass white dwarfs being responsible for a significant portion of SNe Type Ia. Recently the discovery of SN2018byg (ZFT18aaqaeasu) provided strong evidence for a sub-Chandrasekhar mass explosion triggered by a massive helium shell ignition (De et al. 2019). De et al. (2019) fit this peculiar Type I SN with a model derived from Polin et al. (2019) concluding that the early flux excess exhibited by SN2018byg was due to the radioactive decay of elements in the outermost ejecta which were produced during the initial helium shell burning. The spectrum at peak was also completely line blanketed for wavelengths less than 5000 Å which was fit well by optically thick helium shell ashes in the outermost ejecta. This event lends credence to the ability of the double detonation scenario to lead to the explosion of a WD.

Other rare transients may also relate to WDs accreting helium shells. Ca-rich gap transients, so called because their peak luminosity lives in the “gap” between that of novae and SNe, are a class of astrophysical transients identified by their nebular spectra which are dominated by [CaII] emission (Kasliwal et al. 2012). The origin of these transients is still unknown, but helium shell ignitions have been suggested as a possible progenitor (Dessart & Hillier 2015). These events all exhibit a fast photospheric evolution, rising in  $\sim 15$  days, with photospheric velocities  $\sim 6,000$ - $10,000$  km/s. They reach the nebular phase very quickly, in 1-3 months, indicating a small ejecta mass. Furthermore, Ca-rich transients tend to occur offset from their host galaxies indicating an origin from an old stellar population (Lunnan et al. 2017).

While peculiar transients may arise from WDs with a large amount of helium on their surface, studies have shown that smaller helium shells allow for normal and sub-luminous Type Ia events (Polin et al. 2019; Townsley et al. 2019). Polin et al. (2019) points to a population of Ia’s distinguished by the relationship between their peak luminosity and SiII velocity as likely candidates for originating from a sub-Chandrasekhar mass double detonation, a delineation that was further supported by the examination of spectropolarimetry measurements of this population in Cikota et al. (2019). Furthermore, the new discovery of fast Gaia WDs have been pointed to as the potential surviving companions of a very thin helium shell ignition occurring during a dynamical merger of two WDs, known as the D6 mechanism (Shen et al. 2018b).

While studies show promising results when comparing double detonation models to SNe Type Ia during the photospheric phase there has yet to be a comprehensive examination of what these models look like in the nebular phase when the ejecta becomes fully optically thin. This study aims to examine the observational consequences of the double detonation mechanism once the ejecta reaches the nebular phase. Using the ejecta profiles produced in Polin et al. (2019) we perform one-dimensional NLTE radiative transfer simulations to examine, systematically, the observational signatures of double detonations in the nebular phase.

In section 2 we describe the methods used to model nebular spectra and detail the parameter space of models we explore. We examine the synthetic spectra and qualitatively compare them to the trends of Type Ia SNe in section 3. In section 4 we discuss the strong [CaII] emission and discuss the consequences for the understanding of Ca-rich transients. We compare the models to an existing set of observed nebular SNe Type Ia in

section 5 and discuss the overarching implications of this study in section 6.

## 2. METHODS

We begin with the homologous ejecta profiles produced in Polin et al. (2019) and use the NLTE radiative transport code developed for Botyánszki & Kasen (2017) to produce synthetic spectra in the nebular phase.

### 2.1. Initial Ejecta Profiles

Polin et al. (2019) explored a parameter space of double detonation models and their observational signatures in the photospheric phase. We begin with the ejecta models that were produced using the massively parallel compressible hydrodynamics code CASTRO (Almgren et al. 2010). We examine all models from  $0.7$ - $1.2 M_{\odot}$  WDs with  $0.01$ - $0.1 M_{\odot}$  He shells (35 models in total) and perform NLTE radiative transport calculations to produce synthetic spectra in the nebular phase. We then compare our results to data by using some of the photospheric properties simulated in Polin et al. (2019) using the radiative transport code, Sedona (Kasen et al. 2006).

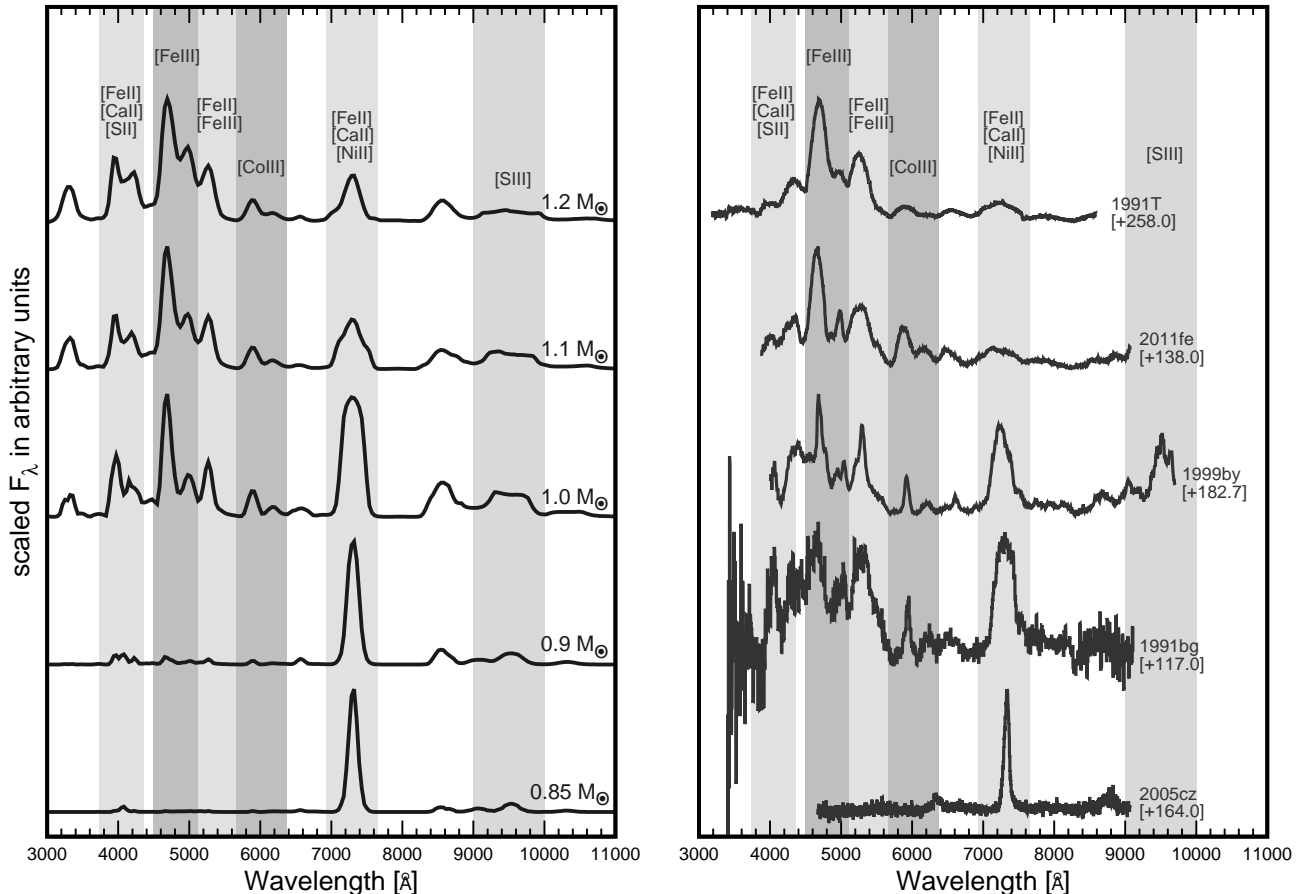
### 2.2. NLTE Radiative Transport Methods

Botyánszki & Kasen (2017) have developed a 3D, NLTE, radiative transfer tool to model nebular spectra. The process involves first using the radiative transport code, Sedona (Kasen et al. 2006), to model the gamma ray transport of radioactive decay products to determine the energy deposition rate over time. We then use the nebular code to solve the full NLTE rate equations while taking non-thermal excitations and ionizations into account. Then, assuming homologous expansion, the line emission is integrated along the chosen line of sight to find the wavelength-dependent flux.

Some physical assumptions are made during this process. First, we assume that the gas temperature and level populations have reached equilibrium on a timescale much shorter than the expansion timescale. Next, we assume that by the epochs considered, the entire ejecta has become optically thin. This is a safe assumption for wavelengths of interest at epochs  $\gtrsim 100$  days after explosion, although the ejecta may remain optically thick in the ultraviolet for a longer time (Botyánszki & Kasen 2017).

## 3. NEBULAR SPECTRA

In this section we explore the spectral series produced by our simulations and discuss a qualitative comparison to the observed population of SNe Type Ia in the nebular phase.



**Figure 1.** *Left:* Nebular spectra of all models with  $0.01 M_{\odot}$  He shells at 150 days after explosion. Models are arranged in decreasing mass from top to bottom, with labels on the right indicate the mass of the underlying WD for each. Strong [CaII] emission appears in all models. For models that produce less Ni-56 (and thus less [FeII] and [FeIII] emission) the [CaII] line at  $7290 \text{ \AA}$  is the predominant feature, reminiscent of Ca-rich transients. *Right:* Observed sequence of nebular Type Ia’s ordered from the most luminous (1991T) to the least luminous (1991bg) as well as an example Ca-rich transient (2005cz) at the bottom.

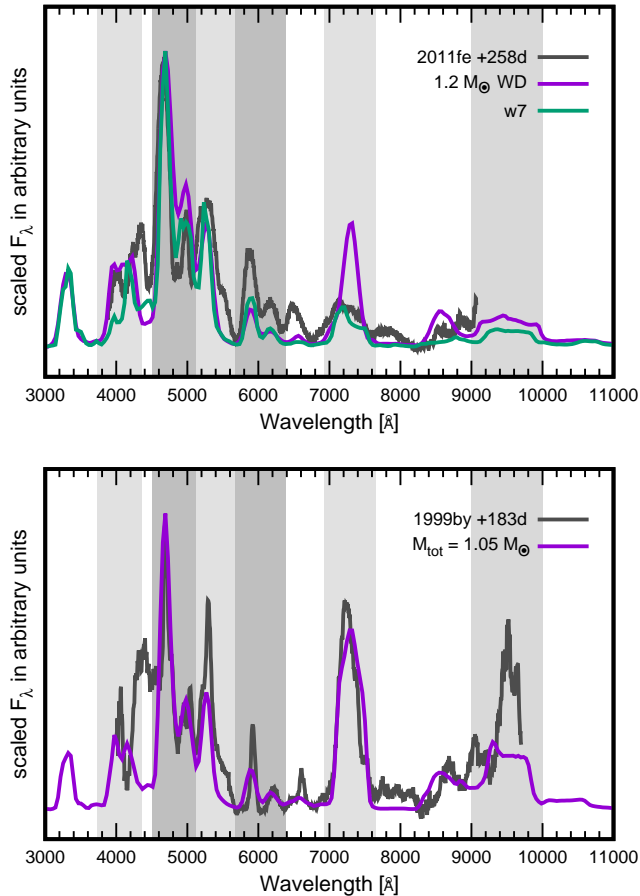
### 3.1. Summary of Results

We take each model from Polin et al. (2019) and produce spectra for 150-450 days from explosion in increments of 50 days.

The left panel of Figure 1 shows example spectra at 150 days from explosion, ranging from our most massive WD,  $1.2 M_{\odot}$ , and decreasing in mass to a  $0.85 M_{\odot}$  WD at the bottom, all with  $0.01 M_{\odot}$  of helium on their surface. We first note that the spectra lack features that distinguish the mass of the helium shell. This result is not entirely surprising as nebular spectra are probes of the internal structure of the SNe ejecta, and the inner ejecta of the double detonation models is primarily a function of the total mass of the progenitor ( $M_{WD} + M_{He}$ ). Instead we focus on features that arise as we vary the total mass of the system.

Qualitatively the produced sequence reflects the trends seen in observed nebular SNe Type Ia (see the right panel of Figure 1). The more massive progenitors

produce spectra with strong Fe lines ( $\sim 4500\text{-}5600 \text{ \AA}$ ), while also showing [CoIII] emission lines ( $\sim 5800 - 6200 \text{ \AA}$ ). However, even our brightest model over produces [CaII] emission at  $7290 \text{ \AA}$  when compared to the brightest Type Ia’s (1991T and 2011fe). As we examine models with lower masses the spectra show increasingly weaker and narrower Fe emission until, for low enough mass progenitors, the majority of the cooling is through the forbidden [CaII] emission line at  $7290 \text{ \AA}$ . This too is a trend we see reproduced in the observed SNe Type Ia. Fe emission lines grow narrower for lower luminosity events (Mazzali et al. 1998), and the sub-luminous, 1991bg-like, Type Ia’s show strong emission features around  $7290 \text{ \AA}$  that can reach comparable strengths to their Fe emission (see 1991bg and 1999by in the right panel of Figure 1). Our lowest mass models are reminiscent of the nebular spectrum of a Ca-rich transient. We further examine the implications of the [CaII] emission in section 4.



**Figure 2.** *Top:* The normal Type Ia SN 2011fe at 258 days from peak (Mazzali et al. 2015) compared with our most luminous (and most massive) model ( $1.2 M_{\odot}$ ) in purple and the w7 model (Nomoto et al. 1984) in green. While our model produces a reasonable match to the strength and ratios of the Fe emission lines our model over produces Ca emission when compared to normal Type Ia’s. The w7 model which contains far less  $\text{Ca}^{40}$  in its ejecta is a better fit.

*Bottom:* 1999by (a sub-luminous, 91bg-like Type Ia) compared with our model for a progenitor with a total mass of  $1.05 M_{\odot}$ . Our model reproduces the strength of the emission feature at  $7290 \text{ \AA}$ .

### 3.2. Normal Type Ia SNe

In Figure 2 we compare our most massive (and most luminous) model to the normal Type Ia 2011fe and the w7 pure deflagration model for Type Ia SNe (Nomoto et al. 1984). At a glance the w7 model is a much better fit for a normal Type Ia SN than the double detonation model. While both models reproduce the strength and width of the Fe emission lines in the  $4500\text{--}5500 \text{ \AA}$  range neither model perfectly reproduces the emission feature at  $7290 \text{ \AA}$ . This result is not surprising as the w7 model is a decent match to the peak and stretch of normal Type Ia’s (Nomoto et al. 1984) while

our double detonation models also showed some discrepancies with the observed properties in the photospheric phase (Polin et al. 2019).

Our results are mostly consistent with previous modeling of 2011fe performed in Mazzali et al. (2015). This study also notes an overproduction of [CaII] emission seen in nebular spectra produced by a sub-Chandrasekhar model in Mazzali et al. (2015). Mazzali et al. (2015) propose successful model for the nebular signatures of 2011fe originating from a Chandrasekhar mass object with the inner most ejecta populated by stable Fe group species. This stable Fe is required to reproduce the observed [FeII]/[FeIII] ratio (as seen in the relative strengths of the  $5270 \text{ \AA}$  and  $4658 \text{ \AA}$  Fe emission lines respectively). The sub-Chandrasekhar mass model is further ruled out by its density profile, which would be less dense in the central regions during burning and produce very little stable Fe, and thus under produce [FeII] emission. While we agree that the [CaII] emission is in conflict with the sub-Chandrasekhar model for 2011fe it is important to note that our models do produce the relative strengths of the  $5270 \text{ \AA}$  and  $4658 \text{ \AA}$  lines without this stable Fe present in the ejecta.

The  $7290 \text{ \AA}$  feature is very sensitive to [CaII] emission, but not exclusively. The double peaked nature of this emission feature in the w7 model (and in 2011fe) indicates there is very little contribution from [CaII], but rather the feature is dominated by [FeII] and [NiII], while the gaussian shape of the emission from our double detonation model at this wavelength indicates it is dominated by [CaII], which only is resolvable as a doublet for low ejecta velocities.

Recently Flörs et al. (2019) performed a study of nebular spectra produced by one zone NLTE models, where the ejecta was composed of varying ratios of Fe, Ni and Co. When fitting to a sample of normal Type Ia SNe they find that they can fit the feature at  $7290 \text{ \AA}$  in normal Type Ia’s with only [FeII] and [NiII] emission, and no contribution from [CaII]. While this is likely the case for normal Ia’s, the inferred masses of Ni and Fe indicated by the fits points to a sub-Chandrasekhar origin (by comparing to the nucleosynthetic yields of Ni and Fe for the sub-Chandrasekhar mass models in Shen et al. (2018a)). However, we find that the  $^{40}\text{Ca}$  present in such models will produce a flux in this region, which is not seen in these normal Ia’s<sup>1</sup>. See section 4 for a more detailed discussion on the Shen et al. (2018a) models.

<sup>1</sup> Here we define normal Ia’s as 2011fe-like objects of magnitudes  $-19 \text{ mag}$  and normal velocities ( $v_{SiII} \sim 11,000 \text{ km/s}$ ). See section 5 for more details.



### 3.3. Sub-Luminous Type Ia SNe

The double detonation model provides a better fit to the nebular Ca emission seen in sub-luminous, or 91bg-like, SNe Type Ia. The bottom panel of Figure 2 shows a model comparison to 1999by (Silverman et al. 2012), a 91bg-like SN. We choose 1999by over 1991bg because of its better signal to noise ratio, particularly for wavelengths less than 6000 Å where the Fe emission features are prominent. Our model naturally produces the strength and width of the [FeII] and [FeIII] emission peaks as well as the strength of the 7290 Å [CaII] emission feature.

Mazzali & Hachinger (2012) investigates the nebular spectra of 1991bg using tomographic methods to determine an abundance and density profile for the ejecta. This study shows that lower central densities are required to reproduce the narrow Fe line emission features seen in this sub-luminous event, and these densities are consistent with both a sub-Chandrasekhar mass model and a WD merger model. However, the sub-Chandrasekhar model is ruled out due to a poor photospheric match to 1991bg. Our models, however, are a good fit for sub-luminous Ia’s in the photospheric phase (Polin et al. 2019) likely because we are comparing spectra for a lower mass object than the one chosen in Mazzali & Hachinger (2012).

It is worth also discussing the discrepancies in this fit. Two emission features are under-produced by our models, one at  $\sim 4400$  Å and one at  $\sim 9500$  Å. The 4400 Å emission is due to [FeII] with a small contribution from [SII]. The fact that our models under produce flux at this wavelength could be due to the stable Fe arguments made for 2011fe (see section 3.2). However, this feature is also under represented in the Chandrasekhar mass models produced in Mazzali et al. (2015). More likely this discrepancy is a result due to a limitation in the atomic data. The feature at 9500 Å is more puzzling. The emission in this region is primarily due to forbidden [SIII] emission (Botyánszki & Kasen 2017). It is unclear why we under produce this emission. It is possible that this is due to too little sulfur produced at the requisite densities in the ejecta, however we do note that past studies have been successful in modeling the strength of the [SIII] emission of 1999by with a sub-Chandrasekhar mass model, ignited as a pure central detonation with no helium on its surface, however those models also over produced the [CaII] emission at 7290 Å (Blondin et al. 2018).

### 3.4. SN2018byg

SN2018byg (ZTFaaqasu) (De et al. 2019) was a peculiar Type I SN found in the outskirts of its host

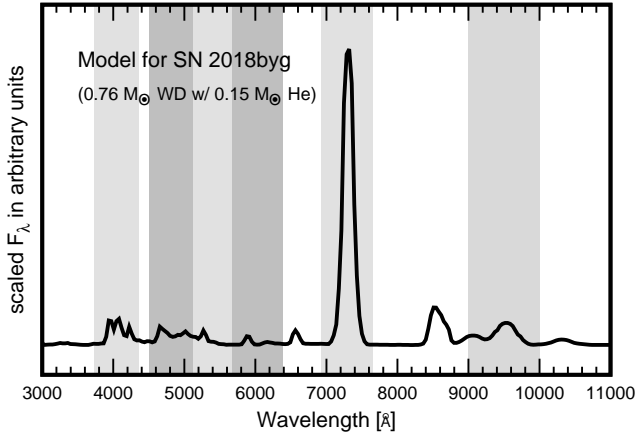
galaxy. Features in both the light curve and spectra distinguished this as an unusual event. The light curve exhibited a rapid rise that turned out to be an excess in flux over the first few days post explosion. Spectra taken during this time show a blue continuum with some broad absorption features bluer than 5000 Å. At peak the r-band photometry reached a maximum brightness of  $-18.27 \pm 0.04$  mag, sub-luminous for a Type Ia, but typical for a 91bg-like Type Ia. The spectra at peak best serve to distinguish this event as unusual. The blue part of the spectrum exhibited extreme line blanketing, nearly extinguishing all flux for wavelengths less than 5000 Å, and wavelengths red of this sharp cutoff exhibit absorption features from SiII and a broad CaII absorption feature. These were all features predicted by Polin et al. (2019) as “smoking gun” signatures of a double detonation resulting from the ignition of a thick helium shell.

De et al. (2019) presented a custom model which was created following the methods of Polin et al. (2019) which showed all of these peculiarities for a  $0.76 M_{\odot}$  WD with a  $0.15 M_{\odot}$  helium shell. In the model the early flux excess was produced by the radioactive decay of elements produced during the burning of the massive helium shell, and the extreme line blanketing was caused by those same optically thick helium ashes which reside in the outer most SN ejecta. The velocity and strength of the CaII absorption feature was well modeled, with the  $0.035 M_{\odot}$  of  $^{40}\text{Ca}$  produced during nucleosynthesis.

In Figure 3 we show the consequences of running the model for SN2018byg into the nebular phase. The total mass of the model ( $0.9 M_{\odot}$ ) places it in the [CaII] dominated regime. While no nebular spectra were taken for this event, we propose that the result would have categorized this event as Ca-rich. We predict that the next such 18byg-like event should exhibit strong [CaII] emission features in the nebular phase.

## 4. [CAII] EMISSION AND CA-RICH TRANSIENTS

Here we examine the striking feature in the synthesized nebular spectra: the [CaII] emission line at 7290 Å. Figure 4 shows how the ratio of [CaII] to [FeIII]<sub>4658</sub> emission lines varies systematically with WD mass. The results can be fit with a sum of two exponentials, one representing a region of parameter space where the spectra are dominated by Ca emission (models with a total mass  $\lesssim 0.98 M_{\odot}$ ) and one describing the Fe dominated spectra (models with a total mass  $\gtrsim 1.1 M_{\odot}$ ). The transition between the two regimes occurs where the amount of intermediate mass elements produced by the progenitor is comparable to the mass of  $^{56}\text{Ni}$  produced. This occurs for a progenitor  $\sim 1.0 M_{\odot}$  (see Figure 2 in Polin et al.



**Figure 3.** The Polin et al. (2019) model used to fit SN 2018byg (ZTFaaqasu) in the photospheric phase followed through to the nebular phase. We predict that this peculiar event would fall into the regime where the nebular spectrum is dominated by [CaII] emission.

(2019)). For progenitors with masses greater than  $1.0 M_{\odot}$  the gains in  $^{56}\text{Ni}$  are no longer exponentially increasing with the total mass and the relationship between Fe and Ca emission stays nominally constant.

The left panel of Figure 4 shows an example of this fitting process for all models at 150 days after explosion. The right panel of Figure 4 shows the compiled fits across all nebular times with the thickness of the line being bound on top by the fit at day 450 and the bottom by day 150 post explosion. The shaded grey region represents an estimate of uncertainties in the modeled spectra due to uncertainties in atomic data (Botyánszki & Kasen 2017). We show only small variations in this modeled ratio over nebular times, making this measurement a good quantity to compare to data, as some flexibility in observational epoch may be allowed.

How much to trust this prediction boils down to how confident we are about the quantities of Ca and Fe group elements in the modeled SN ejecta. In Figure 5 we compare our ejecta models to those of Shen et al. (2018a) who used a sophisticated nuclear network to post-process yields for the detonations of bare sub-Chandrasekhar mass WDs (which lack helium on their surface and are ignited by a central detonation). We plot the ratio of  $^{40}\text{Ca}$  to  $^{56}\text{Ni}$  in the ejecta vs the V-band magnitude at time of V-band peak for all of our models (grey circles) and the Shen et al. (2018a) models (colored triangles). We choose V-band for this comparison because it is most similar to the bolometric magnitude and it is free from any line blanketing effects caused by the helium shell ashes in our models, so we are free to

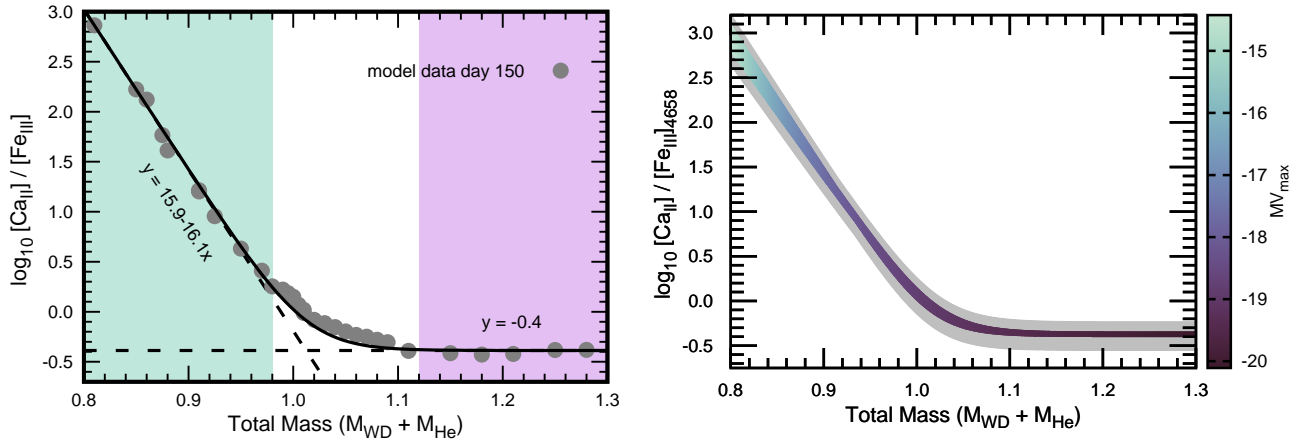
compare them to the Shen et al. (2018a) models which lack helium shells. We see that the Shen et al. (2018a) models fall onto the relationship we map out relating the photospheric signatures ( $M_V$ ) to the ejecta variables that control the [CaII] emission in the nebular phase (the masses of  $^{40}\text{Ca}$  and  $^{56}\text{Ni}$ ). The masses of these models do not perfectly align (the Shen et al. (2018a)  $0.85 M_{\odot}$  model looks like our  $0.9 M_{\odot}$  model) as mentioned in Polin et al. (2019). However, the overall relationship is consistent. Given the mass ratios of  $^{40}\text{Ca}$  and  $^{56}\text{Ni}$  in the Shen et al. (2018a) models we expect to see this strong [CaII] emission feature even for updated nuclear networks. Due to the close agreement shown in Figure 5 we expect to see similar nebular spectra from models in both studies that correspond to the same peak luminosity.

#### 4.1. Implications for Ca-Rich Transients

Here we examine the implications of our results for Ca-rich transients.  $^{40}\text{Ca}$  is produced via the double detonation mechanism in quantities greater than a standard Chandrasekhar mass model for a Type Ia SN. For example the w7 model has  $0.01 M_{\odot}$   $^{40}\text{Ca}$  whereas our models can produce up to a factor of four times that amount. Figure 6 shows the mass of  $^{40}\text{Ca}$  produced as a function of total model mass. Whether or not a model would be categorized as a Ca-rich SN if observed during the nebular phase is dependent on two parameters: the amount of  $^{40}\text{Ca}$  in the ejecta, and the amount of Fe group elements. It is not sufficient to have Ca in the ejecta, in fact it is more important that the ejecta lack Fe group elements through which to cool.

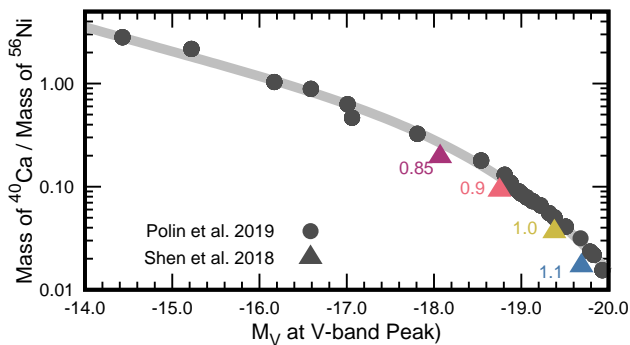
Our understanding of Ca-rich transients is limited by the small number of observed events, however current constraints made by fitting light curve shapes place ejecta mass estimates of order  $\sim 0.5 M_{\odot}$  (Kasliwal et al. 2012). The question remains: how rich in Ca do these events need to be? The prototype event, SN2005E was originally modeled with an ejecta mass of  $0.3 M_{\odot}$  and  $0.14 M_{\odot}$  of  $^{40}\text{Ca}$  in the ejecta ( $X_{Ca}=0.47$ ) (Perets et al. 2010). More recently Dessart & Hillier (2015) modeled a helium shell detonation model (one where the shell burning does not cause an ignition of the underlying WD) and showed that the nebular spectra appeared Ca-rich with an ejecta mass of  $0.2 M_{\odot}$  having produced  $0.03 M_{\odot}$  Ca ( $X_{Ca}=0.15$ ) and showed that the nebular spectrum continued to cool through [CaII] when that mass fraction was halved.

While the models focused on in Polin et al. (2019) are not a good match to Ca-rich transients in the photospheric phase, they provide important insight into the puzzle of the origin of such events. When we examine



**Figure 4.** *Left:* The relationship between  $[\text{CaII}]/[\text{FeIII}]$  to the total mass of the progenitor. Grey points show data for all models at 150 days after explosion. The two exponential fits delineate two regions of parameter space: one dominated by  $[\text{CaII}]$  emission (shaded in green) and one with strong  $[\text{FeII}]$  and  $[\text{FeIII}]$  emission features (shaded in purple).

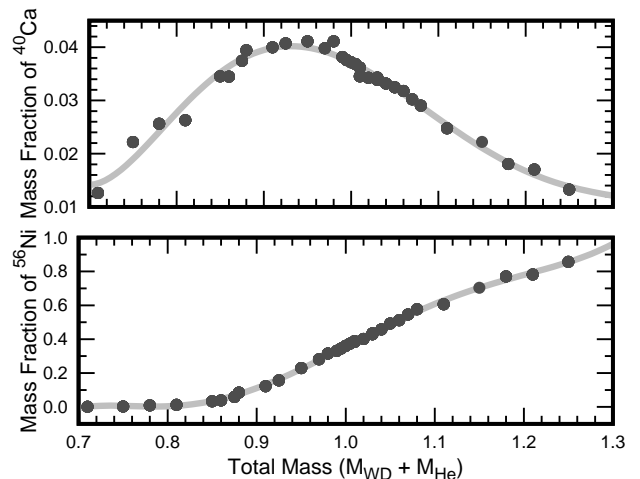
*Right:* The results of the same fits but for all nebular times. The width of the colored line represents the variation over modeled times. The curve is bounded on the bottom by models at 150 days after explosion and on top at day 450. The grey region represents the error bars due to uncertainties in atomic data, which is reported to be  $\sim 30\%$  in Botyánszki & Kasen (2017). Only a small variation in this ratio is measured over nebular times.



**Figure 5.** The ratio of the masses of  $^{40}\text{Ca}$  to  $^{56}\text{Ni}$  as a function of V-band magnitude for the Polin et al. (2019) and Shen et al. (2018a) models. show good agreement in composition yields when comparing models of similar peak brightness.

our double detonation models which would be characterized as Ca-rich (those with a total mass less than  $\sim 0.9 M_{\odot}$ ) we see spectra that primarily cool through  $[\text{CaII}]$  emission with a significantly smaller ratio of Ca required. Figure 6 shows that as little as  $0.02 M_{\odot}$   $^{40}\text{Ca}$  (or  $0.01$  by mass fraction) can produce a Ca-rich event. This is an order of magnitude less than the percentages provided in previous literature.

Very low mass ( $\lesssim 0.7 M_{\odot}$ ) double detonation progenitors were not explored in Polin et al. (2019), so we cannot rule out the low mass part of this parameter space as a possible progenitor for some Ca-rich gap transients. This region of double detonations is worth exploring, however, NLTE radiative transport calculations would



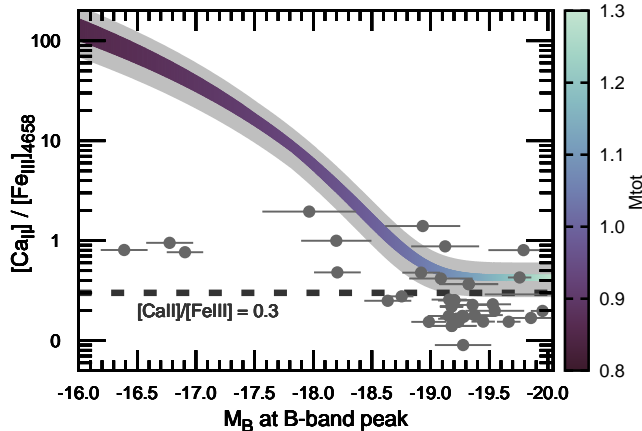
**Figure 6.** Mass fractions of  $^{40}\text{Ca}$  (top) and  $^{56}\text{Ni}$  (bottom) summed from the modeled ejecta masses. Nebular spectra appear Ca-rich for mass fractions as high as  $X_{\text{Ca}} = 0.04$  and as low as  $X_{\text{Ca}} = 0.01$ .

be required throughout the photospheric phase to determine if features such as He absorption seen in many of the Ca-rich population can be explained by this model. We leave it as a future exercise to examine if very low mass double detonations (should they disrupt their underlying C/O WD) can act as potential progenitors for these Ca-rich transients.

## 5. COMPARISON TO DATA

In this section we compare our model parameters to a set of 37 observed nebular SNe, and determine how





**Figure 7.** The modeled relationship between  $[\text{CaII}]/[\text{FeIII}]_{4658}$  and  $M_B$  (at time of B-band peak) plotted with the nebular SNe data. The modeled relationship fits a family of SNe with magnitudes brighter than  $-19.0$  mag, but no less luminous SNe fall on the modeled region. However, we do see a rise in the strength of the  $[\text{CaII}]$  line (with respect to the  $[\text{FeIII}]$  line) occurring between for SNe with magnitudes less than  $-19.0$  mag matching the predicted behavior. The dashed line represents the minimum value for  $[\text{CaII}]/[\text{FeIII}]$  expected from our models while considering the grey error regions.

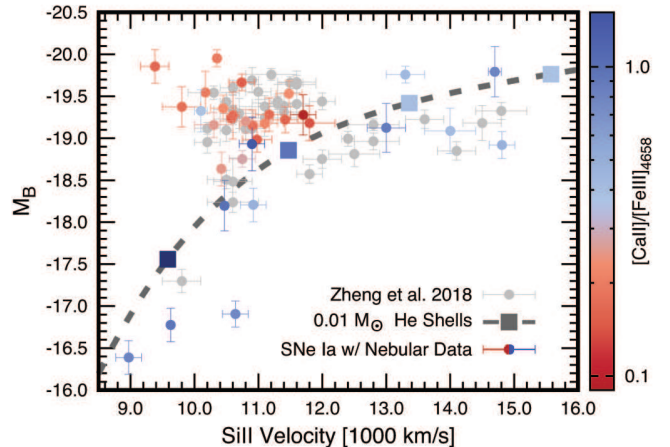
the nebular phase can further help to identify SNe as deriving from double detonation progenitors.

### 5.1. Population of Observed Nebular SNe

We select a population of Type Ia SNe observed in the nebular phase by searching WISEREP, a public repository of SNe photometry and spectra (Yaron & Gal-Yam 2012), and selecting all Type Ia’s observed between 120 and 320 days after peak. We include all Types of Ia’s (e.g. 91T-like, 91bg-like and peculiar) as well as normal Ia’s. We also searched the open supernova catalog (Guillochon et al. 2017) for any remaining SNe with nebular spectra from the population in Zheng et al. (2018). The result is 37 SNe Type Ia observed in the nebular phase, all of which are plotted in figures 7 and 8. See Table 1 for a table of all SNe and associated references.

### 5.2. $[\text{CaII}]/[\text{FeIII}]$ Ratio as a Function of Magnitude

In Figure 7 we compare the observed SNe data to our models by plotting the  $[\text{CaII}]/[\text{FeIII}]$  ratio as a function of B-band magnitude at B-band peak. We convert between total mass of our models and the B-band magnitude according to the results of the thin helium shell magnitudes modeled in the photospheric phase in Polin et al. (2019).



**Figure 8.** B-band magnitude vs SiII velocity (both at B-band peak) for a observed population of SNe Type Ia. Polin et al. (2019) suggested that this relationship is evidence of two classes of SNe Ia; those that follow the modeled relationship may be identified as sub-Chandrasekhar mass progenitors and those that lie in the cluster as Chandrasekhar mass origin. All of the SNe that follow the modeled relationship have a stronger contribution of  $[\text{CaII}]$  emission than those in the cluster, supporting the hypothesis that these are the SNe Type Ia originating from a double detonation mechanism. The colorbar transition from red to blue is placed at a value of  $[\text{CaII}]/[\text{FeIII}]=0.3$ , corresponding to the minimum expected value from our models.

Again the grey region represents the errors in atomic data from Botyánszki & Kasen (2017). The results show a trend in the increase of  $[\text{CaII}]$  emission for magnitudes  $\lesssim 0.98 M_{\odot}$  as predicted by our models. The magnitude of the  $[\text{CaII}]$  features is over predicted by our models at these lower magnitudes. For brighter SNe (magnitudes brighter than  $-19.0$ ) we see examples of SNe with comparable and even more extreme  $[\text{CaII}]/[\text{FeIII}]$  ratios than our models predict. On the low luminosity end we over predict the strength of the  $[\text{CaII}]$  line compared to the observed SNe Type Ia.

### 5.3. SiII Velocity Relationship: Which Ia’s are Double Detonations?

Here we examine the consistency of our nebular predictions with the population of SNe Type Ia that Polin et al. (2019) point to as the likely candidates for sub-Chandrasekhar mass double detonations. This population is identified by their relationship between SiII velocity and B-band magnitude, both at time of B-band peak. Polin et al. (2019) identifies two distinct populations of SNe Type Ia. One group follows the relationship modeled by the double detonation models, and contains SNe at both high and low SiII velocities. These are the SNe Type Ia that may originate from a sub-Chandrasekhar mass double detonation progeni-

tor. The other group clusters tightly around -19.5 mag and 11,000 km/s outside of the allowed relationship for double detonations. Recently [Cikota et al. \(2019\)](#) examined this relationship using an additional population of SNe Ia's and show this trend persists in their data, although the outliers are not as easily identifiable around the Chandrasekhar mass cluster. Furthermore, when they examine spectropolarimetry measurements of the SiII line polarization they yet again find a distinction between the cluster (which have lower polarization measurements) and the SNe that follow the predicted sub-Chandrasekhar mass relationship (which have higher polarization measurements).

We reproduce this plot in Figure 8 with all of our nebular data colored by [CaII]/[FeIII] emission. Grey data represents the [Zheng et al. \(2018\)](#) data for which no nebular were available. We see that this trend of outliers is further delineated by their nebular features. All of the SiII velocity outliers that lie along the modeled sub-Chandrasekhar mass sequence show a [CaII]/[FeIII] ratio greater than 0.3 while the majority of the SNe in the cluster show a weaker [CaII] contribution. This cut-off is the same as indicated by the minimal expected value for the ratio of [CaII]/[FeIII] (see the dashed line in Figure 7). The  $0.01 M_{\odot}$  helium shell models are plotted as squares along a spline fit to the model data shown as a dashed grey line. From left to right the plotted models are  $0.9 M_{\odot}$ ,  $1.0 M_{\odot}$ ,  $1.1 M_{\odot}$ , and  $1.2 M_{\odot}$  WDs. The  $0.9 M_{\odot}$  model, having [CaII]/[FeII]  $\sim 10$  does over produce [CaII] emission when compared to any observed SNe Type Ia, however higher mass models are consistent with the data. We stress that these objects are now delineated by four different features: velocity, color ([Polin et al. 2019](#)), polarization ([Cikota et al. 2019](#)), and nebular [CaII] emission. We are confident that we now distinguish two distinct classes of SNe Type Ia's that differ by their physical origin.

## 6. DISCUSSION

In this study we performed a systematic survey of double detonation models in the nebular phase. We showed that these models can qualitatively reproduce sub-luminous SNe Ia spectra in the nebular phase, but over produce [CaII] emission compared to most normal Type Ia's. The ratio of [CaII] to [FeIII] emission as a function of total mass can be used as a diagnostic to de-

termine if a SN Ia can result from a sub-Chandrasekhar mass progenitor. When we examine this ratio compared to the peak B-band magnitude of our models it further supports the conclusions of [Polin et al. \(2019\)](#) that a population of SNe Type Ia with sub-Chandrasekhar mass double detonation progenitors can be identified by their relationship between SiII velocity and B-band magnitude. This is now the fourth axis by which these groups differentiate from each other, which strongly indicates that two distinct classes of SNe Type Ia can be identified by this relationship.

Furthermore our study gives important insight into the progenitors of Ca-rich transients as we show that very little Ca is needed in the SN ejecta to produce a nebular spectrum that cools predominantly through the forbidden [CaII] emission line. We predict that future events like SN2018byg could be classified as Ca-rich in the nebular phase and caution the use of this diagnostic to group SNe as the photospheric spectra can be wildly disparate.

Nebular spectra are a powerful probe of the internal structure of SNe, including any asymmetries in the geometry of the ejecta. This study has been performed with 1D hydrodynamic models and we plan to perform future studies to examine the consequences of any asymmetries that may be present in multidimensional simulations.

We would like to thank Ken Shen for useful discussions and access to the ejecta profiles from [Shen et al. \(2018a\)](#). We would like to thank the National Energy Research Scientific Computing Center, which is supported by the Office of Science of the U.S. Department of Energy under Contract No. DE-AC02-05CH11231, for providing staff, computational resources, and data storage for this project and the Computational HEP program in The Department of Energy's Science Office through Grant #KA2401022. This work was supported in part by the U.S. Department of Energy, Office of Science, Office of Nuclear Physics, under contract number DE-AC02-05CH11231 and DE-SC0017616, and by a SciDAC award DE-SC0018297. This research benefited from collaboration supported by the Gordon and Betty Moore Foundation through Grant GBMF5076.

*Software:* SedoNeb ([Botyánszki & Kasen 2017](#)), Sedona ([Kasen et al. 2006](#)), Castro ([Almgren et al. 2010](#))

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**Table 1.** List of SNe with Nebular Spectra.

SN	Figures	Database	Citation(s)
SNe in the Zheng et al. (2018) sample with Nebular spectra:			
2000cx	7,8	OSC	Silverman et al. (2012), Li et al. (2001)
2001ep	7,8	OSC	Silverman et al. (2012)
2002bo	7,8	OSC	Blondin et al. (2012), Matheson et al. (2008)
2002dj	7,8	OSC	Pignata et al. (2008)
2002er	7,8	WiSeREP	Kotak et al. (2005)
2002fk	7,8	OSC	Hicken et al. (2009)
2003cg	7,8	OSC	Elias-Rosa et al. (2006)
2004dt	7,8	OSC	Silverman et al. (2012)
2004eo	7,8	WiSeREP	Pastorello et al. (2007)
2005cf	7,8	WiSeREP	Wang et al. (2009)
2005ki	7,8	WiSeREP	Folatelli et al. (2013)
2006X	7,8	WiSeREP	Wang et al. (2008)
2007af	7,8	WiSeREP	Silverman et al. (2012)
2007le	7,8	OSC	Silverman et al. (2012)
Additional Nebular SNe Type Ia:			
1986G	7,8	WiSeREP	Cristiani et al. (1992)
1990N	7,8	WiSeREP	Gómez & López (1998)
1991T	1,7,8	WiSeREP	Gómez & López (1998)
1991bg	1,7,8	OSC	Turatto et al. (1996)
1994ae	7,8	WiSeREP	Silverman et al. (2012)
1995D	7,8	WiSeREP	Blondin et al. (2012)
1996X	7,8	WiSeREP	Salvo et al. (2001)
1998aq	7,8	WiSeREP	Branch et al. (2003)
1998bp	7,8	WiSeREP	Silverman et al. (2012)
1998bu	7,8	WiSeREP	Matheson et al. (2008)
1999aa	7,8	WiSeREP	Silverman et al. (2012)
1999by	1,2,7,8	WiSeREP	Silverman et al. (2012)
2000E	7,8	WiSeREP	Blondin et al. (2012)
2002cs	7,8	WiSeREP	Silverman et al. (2012)
2002dp	7,8	WiSeREP	Silverman et al. (2012)
2003du	7,8	WiSeREP	Anupama et al. (2005)
2003hv	7,8	WiSeREP	Leloudas et al. (2009)
2005ke	7,8	WiSeREP	Folatelli et al. (2013)
2006D	7,8	WiSeREP	Silverman et al. (2012)
2007if	7,8	WiSeREP	Blondin et al. (2012)
2008A	7,8	WiSeREP	McCully et al. (2014)
2008Q	7,8	WiSeREP	Silverman et al. (2012)
2011fe	1,2,7,8	WiSeREP	Mazzali et al. (2015)
Additional Spectra:			
2005cz (Ca-rich transient)	1	OSC	Kawabata et al. (2010)

NOTE—The OSC refers to the Open Supernova Catalog (Guillochon et al. 2017), and the figures column refers to the figure in which the spectrum or data taken from the spectrum appear.

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