1. INTRODUCTION

Supernovae are luminous events that are explosions of a star at the end of its life. There are several types of supernovae based on spectroscopic and photometric observations, with the two major categories being Type I and II. Type II supernovae have hydrogen lines in their spectra, and are explosions of high mass stars. Type I supernovae do not have hydrogen lines in their spectra and are further split into subcategories of "a,b,c." In particular, "Ia" means that deep Si II absorption lines near wavelength 6150 Angstrom and strong blends of iron emission lines are present in their late-time spectra. (Nomoto et al. 1997) SN Type Ia are believed to be thermonuclear explosions of an accreting white dwarf (WD) in a binary system. They have nearly uniform light curves, which allows for distance measurements in cosmology, and can lead to more accurate measurements of the Hubble constant and other cosmological parameters like dark energy.

In a simplistic view, they each should explode at the same mass called the Chandrasekhar limit ($M_{\text{Ch}} = 1.46 M_\odot$) above which the star can no longer be supported by electron degeneracy pressure. If they all explode at the same mass and thus have the same absolute magnitude they should all have the same intrinsic light curves, which would provide a standard candle for measuring distances to the various events. In reality the measured light curves aren’t quite all the same, however corrections can be made to make them "standardizable" candles with various methods of using their light curves (Phillips 1993 decline rate relation), color corrections, and host galaxy mass relations. It has been suggested that possible reasons for these intrinsic differences in the SN are different metallicities of the initial stars, perhaps we don’t understand the detonation process of the explosion, or maybe the progenitor models need to be further studied. (Wang 2018)

I will be focusing on two main proposed progenitor models of SN, and the current progress of each of them. (1)The first model is called the single degenerate (SD) model, in which the white dwarf accretes material from a companion that is non-degenerate (main sequence star, red giant, etc.) and explodes when it has received sufficient material to have a mass near $M_{\text{Ch}}$. (2) The second model is the double degenerate (DD) model, and is described by a white dwarf merging with another degenerate white dwarf (due to angular momentum loss through gravitational wave radiation) to produce an explosion.

2. SINGLE DEGENERATE (SD) MODEL

The SD scenario was first modeled by Whelan and Iben (1973) and is probably what most people think of as a classical SN Type Ia. In this model, a white dwarf accretes material from a non-degenerate companion star (hence there is only a single degenerate star in the system) until its mass grows close to $M_{\text{Ch}}$. This model helps explain the similarities and almost uniformity of light curves of SN as they would all occur at around the same mass. The general process is shown in the diagram of Figure 1.

There are three theorized channels through which this scenario has been explored, each corresponding to a different type of companion star. The companion could be a normal main sequence (MS) star also called the "Supersoft" channel, red giant (RG) also called "Symbiotic" channel, or a helium star. I will mainly focus on the WD + MS channel to get an idea of how these situations would occur.

2.1. WD + MS or "Supersoft" Channel

It has been found that the MS donor scenario is one of the most efficient SD scenarios for producing SNe Ia. (Liu 2018) In this scenario, a WD accretes hydrogen-rich (H-rich) material from a MS or a slightly evolved subgiant (SG) companion star. The accreted H-rich material is burned into He, and then the He is converted to carbon and oxygen. When the CO WD increases its mass close to $M_{\text{Ch}}$, it explodes as an SN Ia. There are three further subchannels within this scenario depending on the evolutionary state of the primary star (which is defined to be the star that will accrete the mass and explode as a supernova) at the beginning of the first Roche lobe overflow (RLOF). All of the channels go through a different number of stages depending on how far along the primary star is in its evolution, but they all share the common phases of RLOF and common envelope (CE) phases. The general path is the primary star will evolve and expand, which leads to the RLOF and common envelope. The stars will then be ejected from the CE and the primary will continue to evolve until it is a white dwarf in binary with the main
sequence star, from which it will accrete material and then explode as a supernova.

2.2. Supporting Factors

There are of course many pros and cons of this model, a few of them listed below.

- Circumstellar material (CSM) is generally expected to exist around SN Ia progenitors as the result of mass transfer from the companion star, as well as from WD winds. Signatures of circumstellar matter (CSM) before SN explosion have been observed, along with wind blown cavities in some SN remnants.

- The model predicts that the companion star would be ejected from the system but should still be surviving out there somewhere. There have been measurements of high-velocity single stars that could be potential surviving companions. Hansen (2003) argued that the supersoft channel might potentially explain the properties of high-velocity WDs in the halo, which differs from others as they consist exclusively of single stars.

- Recently there have been possible pre-explosion images (McCully et al. 2014) Shown in Figure 3, the Hubbles images show a system S1 that they have identified as a probable progenitor system of SN Type Iax and have identified a young, blue MS donor. Type-Iax supernovae (SN Iax) are stellar explosions that are spectroscopically similar to some SN Ia at maximum light, except with lower ejecta velocities and lower luminosities. They are called “less successful” versions of Type Ia in that the explosion does not completely unbind the star. The source S1 could be the companion to an unseen white dwarf.

2.3. Challenges of the SD Model

A few challenges of the SD model, both observational and theoretical, are discussed below.

- A serious challenge is the non-detection of stripped H-rich material that is removed from the surface of the non-degenerate companion. The SN ejecta interacts with the companion star, removing material from its surface. If the removed companion material contains a large amount of H, some signatures of H would be shown in SN Ia nebular spectra. (Liu 2018) Simulations indicate the stripped material is always larger than 0.1 $M_{\odot}$ however no stripped H material has been detected in spectra.

- White dwarfs accreting mass at high rates should emit large amounts of radiation in the X-ray band, and they should appear as luminous supersoft X-ray sources but this is in conflict with the observed X-ray emission of elliptical galaxies and galaxy bulges. (Ruiz-Lapuente 2014)

- While there have been measurements of high-velocity single stars as potential candidates for surviving companions, one of the main challenges of this model is that no surviving companions have been confirmed.

- There are large uncertainties in the theoretical delay time distribution (discussed more in section 4).

3. DOUBLE DEGENERATE (DD) MODEL

In the DD model, the supernova is a result of two close WDs merging with a total mass greater than or equal to $M_{Ch}$. The merging is due to gravitational wave radiation, shown in Figure 4. In a merger of two typical-mass WDs at the conclusion of a slow in-spiral driven by gravitational-wave emission, the less-massive (and hence less dense) WD is expected to be tidally sheared into an accretion disc around the more-massive WD. The material of the less massive will be accreted onto the more massive until the total mass grows near or greater than $M_{Ch}$ and explode as a supernova. (Wang 2018)
Figure 1: Binary evolutionary scenarios of the WD + MS channel for producing SNe Ia.

Figure 2: Three subchannels within the Supersoft channel. Image courtesy of Wang and Han 2012.

Figure 3: Potential pre-explosion image of a SN Ia. Image courtesy of McCully et al. 2014.
Similarly to the SD model, there are 3 evolutionary paths within this model. They are less cleverly names but they all go through a certain number of CE phases and ejections and are therefore called the CE ejection scenarios.

3.1. CE Ejection Scenarios

Similarly to the SD model, each subchannel depends on the state of the initial stars when they go through the first RLOF. The initial state of the system could be an SG + MS system as shown in Case A of Figure 5, a TPAGB (thermally pulsing asymptotic giant branch) + MS as shown in Case B, or a TPAGB + He star as shown in Case C. The general process for each of these cases is as follows: one of the stars evolves, expands, and experiences RLOF onto the companion star that leads to a CE phase. The CE phase is not well understood and it is even possible the stars merge while in this phase, but for now we will assume they do not merge and are ejected from the envelope. Next the other star evolves, expands, goes through RLOF which leads to a CE phase and ejection. Depending on the initial states of the stars this process could happen multiple times, but they all lead to the system consisting of two WDs that merge and explode as a supernova.

3.2. Supporting Factors

A few supporting observations of the DD model are listed below.

- While light curves are nearly the same, there have been reported cases of higher or lower luminosities. Unlike the SD model, the DD model does not have a tight mass range. Exploding at a mass greater than $M_{\text{Ch}}$ could explain super-luminous SN that are calculated to have WD explosion masses $\geq 2 M_{\odot}$ (Wang 2018), and prompt detonations of sub-$M_{\text{Ch}}$ double WD merger could account for sub-luminous explosions in old stellar populations.

- Power law delay time distribution (DTD, discussed in more detail in section 4) closely matches observations.

- By design of the model there are no expected H and He lines in spectra of the SN Ia, as we have two CO white dwarfs merging.

- Also by design of the model, there is no need to search for evidence of surviving companion stars as both WDs would be destroyed in the merge.

- Theoretically predicted merger rate is quite high, consistent with observed SN Ia birthrate (Wang and Han 2012)

3.3. Challenges of the DD Model

A few challenges to the model are discussed below.

- While the range in masses is good for explaining anomalies, this model has difficulty explaining similar light curves, as this explosion mass has a wide range. There needs to be something unifying the physics of the supernova events as the observed properties are so similar.

- Merger could also result in formation of NS instead of SN Ia through accretion-induced collapse and not thermonuclear explosion. High accretion rate leads to off-center C burning which converts CO WD into O-Ne-Mg WD which could collapse to form a NS by electron capture. There have been theorized constraints in order for this not to happen, but many uncertainties remain. (Wang 2018)

- Difficult to directly observe because intrinsically faint systems. Many argue that we do not see them so maybe they are not there, however this may not be a suitable argument due to the severe observational difficulties.

3.4. Observational Complications

Finding close double-degenerate binaries is not straightforward since their spectra are virtually identical to those of single WDs. Hence, their identification has been mainly based on the detection of radial velocity variations, many of which carried out by SPY (ESO SN Ia Progenitor Survey). Identifying SNIa progenitors not only requires measuring the orbital periods but also the component masses of the two WDs in the system. The $H_\alpha$ line is typically used for identifying double-lined binaries, and the profiles are then used to measure the orbital periods and component WD masses to identify the system. In the Rebassa simulations (Rebassa-Mansergas et al. 2019), the percentage of progenitors expected to be identified are less than 5 %. The telescope needs to be large enough to achieve high SNR (signal-to-noise ratio) spectra and have high enough resolving powers to sample double-lined profiles. The orbital inclination plays also an important role for the detectability of the double lines. (Rebassa-Mansergas et al 2019) All of these complications combined, the probability for detecting a double WD SNIa progenitor in the Galaxy based on the detection of double-lined absorption profiles in the spectrum is extremely low. (Rebassa-Mansergas et al. 2019)

4. DELAY TIME DISTRIBUTIONS

Discussed briefly in both models previously, the DTD is an important measurement in supernova Type Ia modeling. The DTD is defined as the time interval between
Figure 4: Diagram of basic steps of DD model. Image courtesy of NASA/GSFC/D.Berry.

Figure 5: Three sub-cases within the DD model CE ejection scenarios. Image courtesy of Wang 2018.
the formation of the star and its explosion as a supernova. It is directly linked to the lifetimes (hence, the initial masses) of the progenitors and to the binary evolution timescales up to the explosion, and therefore different progenitor scenarios predict different DTDs. (Wang and Han 2012) A power-law DTD time dependence is generic to models (such as the DD model) in which the event rate ultimately depends on the loss of energy and angular momentum to gravitational radiation by the progenitor binary system.

Many methods have been derived to observe the DTD, primary among them is the use of galaxy clusters. As described by Maoz et al. 2012, the deep potential wells of clusters, combined with their relatively simple SFHs, make them ideal locations for measuring the DTD. It is assumed (through optical spectroscopy and multi-wavelength photometry) that peak star formation for galaxy clusters happened around redshift $z \sim 3$. If we assume we know when the star was formed and then go observe SN Ia rates of clusters at several redshifts, that is basically a direct measurement of the DTD.

There are other methods for observing the DTD, and as shown in Figure 7 they all nearly arrive at the same answer. It is clear that the DTD follows a power law of $t^{-1}$, which exactly matches the predictions of the theoretical DTD for the DD model. In contrast to the DD model, for the SD model there is a large variety of results among the predictions for the DTD. (Wang and Han 2012).

5. OTHER MODELS

There are, of course, other ideas aside from the main SD and DD models, each with their own pros and cons. I will briefly mention a few below.

5.1. Sub-Chandra Mass Model (Double Detonation)

This model is a variation of the SD model. A CO WD accumulates a substantial He-shell by mass accretion from a non-degenerate He star, with a total mass below $M_{Ch}$. The explosion is then triggered by detonation at the bottom of the helium shell: one detonation propagates out via the He shell and another propagates inward as a pressure wave compressing the CO core and leads to carbon ignition. (Wang 2018) Only double detonations occurring in a very limited range of ejecta mass produce spectra consistent with normal SN Ia. These could explain some fast-declining SN Ia well, but produce too much $^{56}$Ni to explain normal SN Ia outside of a narrow range of ejected masses. (Scalzo 2014) In summary, it is possible sub-luminous events are explained by this model, but it has difficulties in matching the observed light curves and spectroscopy of SN Ia.

5.2. Core Degenerate (CD) Model

This model is a variant of the DD model and involves the direct collision of two WDs. The WD number densities in globular clusters allow for this kind of situation, with ~10-100 times collisions between two WDs per year. (Wang and Han 2012) However there are other uncertainties such as resulting in an asymmetric explosion that does not match observations.

6. CONCLUSIONS

In summary, supernovae Type Ia are luminous events at the end of a low-mass star’s life in a binary system. This binary could consist of a non-degenerate star (in the case of the SD model), another degenerate star (in the case of the DD model), or a different option that is still being debated. There are observations and theory both in support and against each of these theorized models. As always, more high quality observations are needed and better theories to match them. In the upcoming years, the European Extremely Large Telescope (E-ELT), Great Magellan Telescope (GMT), and Thirty Meter Telescope (TMT) will allow observing to fainter magnitudes. LSST should identify large number of eclipsing WD binaries, and ESO SN Ia Progenitor Survey (SPY) is searching for double white dwarfs. Double WD binaries with certain orbital periods are expected to be detected through GW radiation by the Laser Interferometer Space Antenna (LISA).
Figure 6: Showing theoretical double WD spectra to identify DD systems. Image courtesy of Rebassa-Mansergas et al. 2019.

Figure 7: The first line shows the observed DTD from Maoz et al. 2012 (log units on right) from various methods of observing galaxies and galaxy clusters. The second line shows the theoretical DTDs from the SD model (left) and the DD model (right) from Wang and Han 2012. It can be seen that the DTD for the DD model matches the observed quite closely.
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