The question of the nature of the progenitor of Type Ia supernovae (SNe Ia) is important both for our detailed understanding of stellar evolution and for their use as cosmological probes of the dark energy. Much of the basic features of SNe Ia can be understood directly from the nuclear physics, a fact which Gerry would have appreciated. We present an overview of the current observational and theoretical situation and show that it not incompatible with most SNe Ia being the results of thermonuclear explosions near the Chandrasekhar mass.

Keywords: Type Ia supernovae, Synthetic spectra
1. Introduction

I have been fascinated listening to all of the talks and the remembrances of Gerry. It is especially interesting to see the wide scientific range of all of the Nuclear Theory Group alumni. My relationship with Gerry was complex. Unlike most of Gerry’s students whom he actively recruited, when I asked Gerry if I could work with him, he was noncommittal. I had done just okay in Tom Kuo’s Quantum Mechanics course and poorly on the QM section of the qualifier and I’m sure he used that as a filter to decide which students to take on. Nevertheless, Gerry did give me a chance and he helped me through many of the bewildering aspects of graduate school. Actually, once I joined the Nuclear Theory Group as a graduate student I worked much of the time with Jerry Cooperstein (Coop) and our work preceded quite well. When a promised fellowship fell through, I had to scramble to find my first postdoc. I returned to the Nuclear Theory Group for my second postdoc. In a weak economy, finding a permanent position was difficult and Gerry worked hard on my behalf. In the end, Gerry always came through for me. Gerry’s strong sense of fair play that many of us have remarked on, definitely worked on my behalf.

I also want to take a minute to discuss our collaborators on the supernova problem during my time at Stony Brook. First I want to mention the role that Coop played in both my and Gerry’s scientific work on the core collapse problem. Gerry trusted Coop implicitly. If Coop said it then Gerry took it seriously. And while Gerry was my thesis adviser, my day-to-day interactions were with Coop. It is indeed a shame that Coop couldn’t make it to this meeting.

The other person to mention is, of course, Hans Bethe. Gerry’s collaboration with Hans was really important to him. He was proud that Hans was his collaborator. Gerry, Hans, Coop, and I certainly enjoyed the January “breaks” at Caltech, Santa Barbara, and Santa Cruz (Fig. [1]).
2. SNe Ia Basics

Type Ia supernovae as observational phenomena are exceedingly regular, particularly when compared with the much more diverse class of core collapse supernovae. In astronomer’s units the maximum brightness of SNe Ia in the B band, $M_B$ is -19.25 with a 1-σ dispersion of 0.50 mag. For ordinary SNe IIP $M_B = -16.75$ with a 1-σ dispersion of 0.98 mag [88]. This regularity led quickly to the understanding that the progenitors of SNe Ia were likely the thermonuclear explosion of near Chandrasekhar mass white dwarfs [20].

In fact the energy source of the visible display of SNe Ia and that of traditional core-collapse supernovae are very different. In core collapse the underlying energy source is gravitational potential energy, which is released during the collapse of the iron core of a massive star to become a proto-neutron star. From an astronomical viewpoint, the core collapse display, that is the observed light curve and spectra in the UV+Optical+IR (UVOIR) is for the most part powered by energy deposited by the shock and stored in the thermal and ionization energy of hydrogen and other elements.

In thermonuclear supernovae, SNe Ia, the explosion energy is provided by the thermonuclear fusion of the C+O white dwarf to iron group and intermediate mass elements. The rough structure that any model for a SN Ia must reproduce is shown in Figure 2. However, the optical display seen by astronomers is not due to the thermal energy produced by the thermonuclear fusion of the explosion. While this energy unbinds the star and produces the kinetic energy of the explosion, the initial high density and compact radius of a white dwarf means that it is opaque to radiation until it has expanded in radius by about a factor of a million. This means the volume has increased by $10^{18}$ and thus all the stored thermal energy has been exhausted in $pdV$ work. Thus, the optical display for SNe Ia comes not from the fusion itself, but rather from the radioactive decay of $^{56}$Ni, where the $\gamma$-rays and positrons are thermalized and produce the optical light curves and spectra.

It is important to understand that the thermonuclear explosion of a nearly
Figure 2: The final element distribution of a classical deflagration to detonation model. This is a delayed-detonation model which reproduces the light curves and spectra for Branch-normal supernovae [33, 41, 43, 45]. The C/O white dwarf is from the core of an evolved 5$\odot$ main sequence star. Through accretion, this core approaches the Chandrasekhar limit. An explosion begins spontaneously when the core has a central density of $2.0 \times 10^9$ g cm$^{-3}$ and a mass close to 1.37 $M_\odot$ [40]. The transition from deflagration to detonation is triggered at a density of $2.3 \times 10^7$ g cm$^{-3}$. Adapted from Baron et al. [4].
Chandrasekhar white dwarf induces a form of stellar amnesia due to the nuclear physics of the initial progenitor. At high densities the material will burn to the iron group, producing $^{56}$Ni, or, if the densities are high enough, electron capture will be significant and non-radioactive iron group elements will be produced in the central regions.

In addition, the explosion itself is complex, in all scenarios it begins with a subsonic burning phase (deflagration). However, Rayleigh Taylor instabilities will lead to a well-mixed distribution of the elements in contrast to what is observed in SNe Ia spectra. This behavior is shown in Figure 3. The favored solution to this problem is the deflagration to detonation transition (DDT) scenario, where the explosion begins as a deflagration, allowing the material to pre-expand, but the deflagration transitions to a detonation at some density. The detonation shock wave travels both forward and backward through the star burning any mixed unburned material and producing a layered structure. Figure 4 shows one realization of the DDT model. Several variations on this scenario exist, including the gravitationally confined detonation and the pulsating reverse detonation. While the deflagration to detonation transition occurs in terrestrial situations where the burning occurs in a confined region, with walls for the pressure waves to reflect off of, it is unknown if it naturally occurs in the unconfined stellar medium, but see Ref. 86.

At first glance, SNe Ia seem remarkably homogeneous in their observational characteristics. Nevertheless, observations carried out since the 1980’s have increasingly revealed a widespread diversity in spectra and light curves requiring a whole new understanding of the field. Empirically, considerable order was brought to the understanding of SNe Ia with the development of the Phillips relation, which is understood as due to a variation in the total amount of radioactive nickel produced in the supernova causing higher temperature and hence opacity variations which leads to variations in the diffusion time. The correlation in the brightness (nickel mass) and the diffusion time leads to the Phillips relation. Yet, while the light curve shape relation allows...
Figure 3: 3-D models: Pure deflagration leads to low energy explosion, and lots of clumps of unburned material particularly near center. Adapted from Gamezo et al. [31].

Figure 4: 3-D models: Delayed detonation, the initial deflagration phase allows the star to pre-expand. The detonation “sphericizes” the incomplete burning left from the deflagration. Adapted from Gamezo et al. [30].
us to use SNe Ia as standard candles, it does not explain all of the observed diversity.

This diversity observed on top of the Phillips relation is sometimes generically referred to as the second parameter problem, and is partially captured in the work of Branch et al. \[8-12\] who plotted pseudo-equivalent widths of the Si II $\lambda 6355$ and 5970 features against each other (see Fig 5). Branch et al. used this diagram to group SNe Ia into four classes: core normals (CN), cools (CL), shallow silicon (SS), and broad line (BL). Using a different approach Benetti et al. \[5\] arrived at similar classes: Faint (overlapping with CL), High Velocity Gradient or “HVG” (overlapping with BL), and Low Velocity Gradient or “LVG” (overlapping with CN and SS). Some of this variation has been ascribed to asymmetrical explosions \[66, 72\], and asymmetric distributions of both iron group elements (including radioactive nickel) as well as of intermediate mass elements are possible.

Since the total amount of radioactive nickel production generally explains the
Phillips relation, it may not be too far afield to expect that variations in the zero age main sequence mass (ZAMS) of the progenitor, its primordial metallicity and the history of the binary system, may well account for much of the “second parameter” diversity described above.

In spite of the detailed diversity of SNe Ia, they remain important cosmological probes and their basic layered structure well reproduces the observed detailed spectra for normal SNe Ia. Figure 6 shows a detailed non-local thermodynamic equilibrium (NLTE) spectral calculation of the parameterized W7 model compared to the observed spectrum of the core normal SN 1994D and Figure 7 shows an extremely detailed NLTE calculation of a standard delayed detonation model compared to the full UV–IR spectrum of the nearby, normal SN 2011fe.

Observations in the 21st Century have seen the discovery of an uncomfortably large number of peculiar “classes” of SNe Ia identified by their prototypes:
Figure 7: Detailed NLTE spectrum of delayed detonation model compared to the maximum light spectrum of SN 2011fe. The observed spectrum covers the entire wavelength range from the UV to the IR. Adapted from Baron et al. [4].

2000cx (rare, photometrically-peculiar events that do not follow the Phillips relation, showing a rise time typical of a SN Ia, but with an unusually slower decline and high photospheric temperature [16, 64, 97]); 2001ay (a BL-HVG event with an extremely slow decline rate but with an apparently modest $^{56}$Ni yield of 0.6 solar masses [4, 58]); 2002cx (events that are spectroscopically similar to normal SNe Ia, but have lower maximum-light velocities, low luminosities for their decline rates, yet generally hotter photospheres [28, 63, 83]); 2002ic (SNe Ia-like events with a strong CSM interaction [6, 13, 21, 23, 36, 37, 57, 101]); and 2006bt (SNe Ia with broad light curves like a hot, luminous event and lacking a prominent secondary maximum in the near-IR, but displaying spectra at maximum similar to those of low-luminosity SNe Ia [27, 67]). Moreover, several SNe Ia (2003fg, 2006gz, 2007if, 2009dc) have been observed whose brightness and light curve shape have led them to be classified as super-Chandrasekhar explosions [39, 46, 47, 77, 94, 96, 100] which may be due to double degenerate explosions where the mass of the binary exceeds a Chandrasekhar mass, or possibly due to supermassive white dwarfs due to rotational support [104, 105].

In fact this wide range of diversity has led to the suggestion that the param-
eter responsible for the second parameter variation is the mass ejected in the explosion itself. This is due either to dynamical mergers of binary white dwarfs [24, 78, 80] or due to pure deflagration leading to a bound remnant with low ejected mass [26, 49, 60].

While these paths may in fact exist in nature, even among the wide variety of observed supernovae, there is opportunity for the Chandrasekhar mass scenario to explain some of the observed diversity. Particularly, pulsational delayed detonations (PDDs) allow for variation in the $^{56}$Ni distribution that explain deviations from the Phillips relation.

For example, SN 2001ay, the slowest known decliner, was significantly underbright for its decline rate [3, 58]. By increasing the C/O ratio, and assuming a PDD we were able to move the nickel distribution further out, increasing the kinetic energy and thus, the amount of $pdV$ work done, leading to a slow decline ratio, normal brightness, and the observed fast spectra [3]. The bolometric light curve of the model is shown in Figure 8 and the detailed NLTE synthetic spectrum is compared to the observations in Figure 9.
Similarly, the SN Iax class supernova 2012Z, can be explained by a PDD in a Chandrasekhar mass white dwarf, where the burning to the iron group takes place almost exclusively during the deflagration phase, leading to a central non-radioactive core, some $^{56}$Ni mixing during the fallback of the bound shell, but the layered structure characteristic of a detonation in the intermediate mass elements, as well as for the low velocity spectra with narrow lines, indicating a small differential spread in velocities [99]. Figure 10 shows the mean half widths of the 1.6$\mu$m Fe II feature for a variety of normal and SNe Iax supernovae.

Both the models of SN 2001ay and SN 2012Z, show that while the primary understanding of the Phillips relation is the correlation of the total mass of $^{56}$Ni produced in a Chandrasekhar mass explosion, additional variation can be accommodated by variations on the spatial distribution of $^{56}$Ni, leading to Chandrasekhar mass explosions that do not obey the Phillips relation.

There does remain a question of whether there are enough white dwarfs in binary systems to grow to the Chandrasekhar mass. Calculations of supernovae rates suggest that including both the single degenerate channel and the double
Figure 10: Mean Half Width, MHW, for the 1.6μm feature for SNe Ia (blue) and SN 2012Z (red). In addition, the MHW is given for theoretical models of the series 5p0a22 with (left line) and without mixing (right line) [45]. Adapted from Stritzinger et al. [99].

Figure 11: Gerry Brown and Hans Bethe relaxing in the San Gabriel Mountains during a 1982 visit to Caltech. Photo credit: Jerry Cooperstein.

degenerate channel still produces too few supernovae compared to the observed galaxy-cluster rate [19]. Chandrasekhar mass WD explosions are triggered by compressional heating near the WD center. Because the compressional heat release increases rapidly towards the Chandrasekhar mass, exploding stars should have a very narrow range in masses [42]. The donor star may be either a red giant or a main sequence star, a helium star, or the accreted material may originate from a tidally disrupted WD [84] [103]. We differentiate between dynamic merger models where a prompt explosion occurs on a dynamic timescale due to heating of merging material [often called violent mergers [61] [79] [80] and a secular merger in which the matter of the disrupted companion is accreted by the primary WD on a quasi-hydrostatic time-scale. The former leads to an ex-
plosion of a relatively low density configuration. The latter might share many characteristics with the standard high-density, single-degenerate $M_{\text{Ch}}$ explosion models. Efforts have been made to expand the progenitor distribution by including sub-Chandrasekhar explosions [90–93]. Sub-Chandrasekhar mass explosions are triggered by helium detonation which produce iron group elements at the surface making the spectra either too blue [44, 76] or too red [59, 78, 98]. Others have studied channels where two white dwarfs collide in globular clusters or multiple systems [24, 32, 38, 62, 87, 89]. While there is some evidence that the classical red giant mode of the single degenerate channel may be rare [17, 25, 65, 95] there are uncertainties on the nature of the environment as well as uncertainties on the nature of the progenitor white dwarf [22]. Additionally, there is some solid evidence for the single degenerate scenario [23, 73]. The study of delay time distributions (DTD) also somewhat favors the double degenerate scenario [68–70] in that the observed DTD seems to be proportional to $t^{-1}$. In the single degenerate scenario, the DTD should decline sharply after a few billion years since for longer times the primary will have smaller main sequence mass and hence produce lower mass white dwarfs. However the evidence based solely on delay times is not conclusive [35, 71]. Thus, while the total mass ejected in the explosion may be a parameter in some SNe Ia events, it is interesting to see just how much of the observed diversity may be explained within the Chandrasekhar mass scenario by variations in the $^{56}\text{Ni}$ distribution.

3. Conclusions

While the Phillips relation implies strong homogeneity, which is well accounted for in the Chandrasekhar mass model combined with fundamental nuclear physics, it is unclear just how much of the observed diversity can be accommodated in the Chandrasekhar mass paradigm. Nevertheless, some peculiar SNe Ia that don’t obey the Phillips relation can in fact be modeled within the Chandrasekhar mass paradigm and fit many of the observations. This does not mean that nature does not take advantage of other channels available.
Finally, Figure 11 shows Gerry and Hans as I fondly remember them.

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