Thermonuclear explosions of Type Ia supernovae (SNIa) involve turbulent deflagrations, detonations, and possibly a deflagration-to-detonation transition. A phenomenological delayed detonation model of SNIa successfully explains many observational properties of SNIa including monochromatic light curves, spectra, brightness – decline and color – decline relations. Observed variations among SNIa are explained as a result of varying nickel mass synthesised in an explosion of a Chandrasekhar mass C/O white dwarf. Based on theoretical models of SNIa, the value of the Hubble constant $H_o \simeq 67\text{km/s/Mpc}$ was determined without the use of secondary distance indicators. The cause for the nickel mass variations in SNIa is still debated. It may be a variation of the initial C/O ratio in a supernova progenitor, rotation, or other effects.

1. Introduction

Type Ia supernovae (SNIa) are important astrophysical objects which are increasingly used as distance indicators in cosmology. SNIa appear to be a rather well behaving group of objects. There are deviations in maximum brightness of $\sim 2\text{m}$ among SNIa, but they correlate with variations in the shape of SNIa light curves: less bright supernovae tend to decline faster. This is often expressed as a correlation between $m$ and $dm_{15}$, where $dm_{15}$ is the decrease in magnitude 15 days since maximum. Another correlation exists between SNIa color at maximum and postmaximum decline, $(B - V) - dm_{15}$ – less bright supernovae tend to be more red [1]. These two correlations can be used to account for variations in brightness of SNIa and for interstellar absorption. Using these has led to improved determinations of $H_o$ [2] and to new findings concerning $\Omega_m$ and $\Omega_\Lambda$ [3].

Are there exact and unique maximum brightness – postmaximum decline and color – postmaximum decline relations among SNIa? Are these relations the same for nearby and cosmological supernovae? Before these questions so important for $\Omega_m$ and $\Omega_\Lambda$ can be addressed from theoretical grounds, we would like the theory of SNIa to answer more general questions:

(1) Why do SNIa differ from each other?
(2) Why do some of SNIa characteristics correlate?

2. Pre-supernovae

It is believed that SNIa are thermonuclear explosions of carbon-oxygen (CO) white dwarfs (WD). However, evolutionary paths leading to SNIa are still a bit of a mystery [4]. Three major scenarios have been considered based on the evolution of binary stellar
systems: (1) a CO-WD accreting mass through Roche-lobe overflow from an evolved companion star [5]. The explosion is triggered by compressional heating near the WD center when the WD approaches the Chandrasekhar mass. (2) Merging of two low-mass WDs caused by the loss of angular momentum due to gravitational radiation [6]. Resulting merged configuration consists of a massive WD component surrounded by the rotationally supported envelope made of less massive, disrupted WD [7]. If ignition takes place at low densities, near the base of the rotating envelope, it will probably lead to slow burning and subsequent core collapse [8]. Otherwise, gradual redistribution of angular momentum may lead to a growth of a massive CO core which then ignites near the center when its mass approaches the Chandrasekhar limit. The exploding configuration will resemble an isolated $\sim 1.4M_\odot$ CO-WD, but with rotation and surrounded by an extended CO envelope. (3) a CO-WD accreting mass through Roche-lobe overflow as in (1), but the explosion is triggered by the detonation of an accumulated layer of helium before the total mass of the configuration reaches the Chandrasekhar mass [9]. Only the first two models appear to be viable. The third, the sub-Chandrasekhar WD model, has been ruled out on the basis of predicted light curves and spectra.

3. Phenomenological models of SNIa explosion

Many ingredients of the SNIa explosion physics such as equation of state and nuclear reaction rates are known well. However, flame propagation in a supernova is difficult to model from first principles due to an enormous disparity of spatial and temporal scales involved. One is forced to make assumptions about regimes of burning (detonation or deflagration), and about the speed with which the flame propagates in case of turbulent deflagration. Once the assumptions are made, an outcome can be calculated by solving the equations of fluid dynamics coupled with the (prescribed) nuclear energy release terms, and with terms describing self-gravity of the star.

Three major models of the explosion of a Chandrasekhar mass CO-WD have been considered: (1) detonation model [10], (2) deflagration model [11], and (3) delayed-detonation (DD) model [12-15]. The most detailed computations of SNIa explosion to date involve a hydrodynamic calculation of the thermonuclear explosion that includes a nucleosynthesis computation, a time-dependent radiation-transport computation that gives the light curve, including mechanisms for $\gamma$-ray and positron deposition, the effects of expansion opacity, and scattering, and NLTE spectra computations [16,17 and references therein].

It was found that purely detonation models do not fit observations because they do not produce intermediate mass (Si-group) elements which are so prominent in the spectra of SNIa around maximum light. Deflagration models produce intermediate mass elements, but typically in a too narrow velocity range, and also have difficulty explaining the variety of SNIa. Delayed detonation models are successful in reproducing the main features of SNIa, including multi-wavelength light curves, the spectral behavior, and the brightness – decline and color – decline correlations [16,18].

Delayed detonation models assume that burning starts as a subsonic deflagration and then turns into a supersonic detonation. The deflagration speed, $S_{\text{def}}$, and the moment of deflagration-to-detonation transition (DDT) are free parameters. The moment of DDT is conveniently parametrized by introducing the transition density, $\rho_{\text{tr}}$, at which DDT
happens. Initial central density and initial composition (C/O ratio) of the exploding WD must also be specified. To reproduce observations, deflagration speed should be a rather small fraction of the speed of sound $a_s$, say, $S_{\text{def}} < 0.1a_s$. Physical arguments why $S_{\text{def}}$ is small are discussed in the next section. The models are very sensitive to the variations of $\rho_{\text{tr}}$, but to a much lesser extent on the exact assumed value of the deflagration speed, initial central density of the exploding star, and the initial chemical composition.

A delayed detonation explosion is schematically illustrated in Figure 1. Because the speed of deflagration is less than the speed of sound, pressure waves generated by burning propagate ahead of the deflagration front and cause the star to expand. As a result, deflagration propagates through matter which density continuously decreases with time. After deflagration turns into a detonation, detonation wave incinerates the rest of the WD left unburned during the deflagration phase. Detonation produces Fe-group elements if it occurs at densities greater than $\rho \simeq 10^7$ g/cc. At lower densities it produces intermediate mass elements. At even lower densities around $\sim 10^6$ g/cc only carbon has time to burn. The outermost layers of a supernova will consist of products of explosive carbon burning such as O, Ne, Mg, etc. To reproduce observations, $\rho_{\text{tr}}$ must be selected in the range $\rho_{\text{tr}} \simeq (1 - 3) \times 10^7$ g/cc. Virtually no intermediate mass elements will be produced for larger values of $\rho_{\text{tr}}$. For lower $\rho_{\text{tr}}$, the WD expands so much that a detonation cannot be sustained. With $\rho_{\text{tr}}$ in the right range, the inner parts of the exploded star consist of Fe-peak elements and contain radioactive $^{56}$Ni. Outer parts contain intermediate group elements and products of explosive carbon burning (Figure 1).

The amount of $^{56}$Ni produced during the explosion is very sensitive to $\rho_{\text{tr}}$. Varying $\rho_{\text{tr}}$ in the range $(1 - 3) \times 10^7$ g/cc gives nickel mass in the range $\simeq 0.1 - 0.7 M_\odot$, respectively. The reason for such a sensitivity is the combination of an exponential temperature dependence of reaction rates and the dependence of the specific heat of a degenerate matter on density. Small differences in density at which burning takes place translate into small differences in burning temperature. These, however, translate into large differences in reaction rates, and into qualitative differences in the resulting chemical composition. The kinetic energy of the explosion, on the other hand, is very insensitive to $\rho_{\text{tr}}$. It depends on the total amount of burned material (Fe-group and Si-group together). This is because the difference in binding energies of Fe-group and Si-group nuclei is relatively small compared to the difference between binding energies of both Fe- and Si-group elements and the initial CO mixture. Thus, the delayed detonation model predict SNIa with significantly varying nickel mass but with almost the same kinetic energy and expansion velocities.

The above property of the delayed detonation model is the key to the explanation of the brightness – decline and color – decline relations among Type Ia supernovae. All delayed detonation supernovae expand with approximately the same velocity. Explosions with more nickel give rise to brighter supernovae. Also, because of more nickel decays, envelopes of these supernovae are heated better and stay hot and opaque. The result is a slow post-maximum decline and a blue color. Explosions with less nickel give rise to dim supernovae. Envelopes of these supernovae are cool and transparent because they contain less nickel. The result is a fast post-maximum decline and a red color$^1$.

As a representative example, Figure 2 shows results of numerical modeling of the

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$^1$ In deflagration models, the amount of nickel and kinetic energy of the explosion are...
bright SNIa 1994D [19]. The light curves of SN1994D are fit with the light curves of the best fit delayed detonation model M36, one of the models of the series of [16] with the initial central density $\rho_c = 2.7 \times 10^9$ g/cc and $S_{\text{def}} = 0.04a_s$. For the M36 model, the transition density was $\rho_{\text{tr}} = 2.4 \times 10^7$ g/cc. As can be seen, both optical and IR light curves are fit by M36 rather well, including the secondary maximum in R and I typical of normally bright SNIa. Models with other values of $\rho_{\text{tr}}$ led to much worse fits to observations.

Delayed detonation models have been used to predict a purely theoretical (without using Cepheid distances) value of the Hubble constant [20,16]. The idea is to fit a supernova with the model which best reproduces its light curves and spectra. The model then gives the absolute brightness of a supernova. The method takes into account both brightness variations among SNIa and possible interstellar absorption. The result is shown in Figure 3. Values of $H_o$ determined from individual supernovae show a large spread for close SNIa but converge to $H_o \approx 67 \pm 9$ km/s/Mpc with increasing $z$. This value is in agreement with $H_o$ found using Cepheid variables [21].

4. Three-dimensional SNIa

Three-dimensional effects in the propagation of turbulent flames and deflagration-to-detonation transition (DDT) must play a key role in SNIa in determining the actual speed of the flame propagation, energetics, and nucleosynthesis, and also are likely to translate initial differences in presupernova structure into the observed differences among SNIa.

Deflagration. — Laminar flame in a WD is driven by heat conduction due to degenerate electrons and propagates very subsonically with the speed $S_{\text{lam}} < 0.01a_s$ [22]. Such a slow flame cannot account for the explosion properties of SNIa. However, in the presence of gravity, the flame speed will be enhanced by the Rayleigh-Taylor instability [23]. Whether the Rayleigh-Taylor instability can itself sufficiently increase the flame speed to cause the explosion or whether deflagration just serves to pre-expand the star which is incinerated later by a supersonic detonation, has been a subject of numerous studies and 3D simulations[24,25,27,32 and references therein].

Simple scaling arguments show that turbulent flame subjected to a uniform gravity acceleration in a vertical column must propagate with a speed [24]

$$S_{\text{def}} \approx \alpha \left( gL \frac{\rho_0 - \rho_1}{\rho_0 + \rho_1} \right)^{1/2},$$

where $g$ is local acceleration, $L$ is the width of the column, $\rho_0$ and $\rho_1$ are densities ahead and behind the flame, respectively, and $\alpha < 1$ is a constant which depends on the column’s geometry and boundary conditions. Formula (1) is valid, of course, only when $S_{\text{def}}$ is much larger than $S_{\text{lam}}$. It tells that when the characteristic RT speed $\approx (gL)^{1/2}$ is greater than $S_{\text{lam}}$, the flame speed is determined by the turbulence on the largest scale, $L$,
independent of details of flame propagation on smaller scales. The reason for this behavior is self-similarity of the flame. Turbulent flame speed is the product of the area $A$ of the flame surface and the laminar flame speed, $S_{\text{def}} = A \cdot S_{\text{lam}}$. Turbulence tends to increase $A$ whereas intersections of different portions of the flame front tend to decrease $A$. The latter effect is proportional to $S_{\text{lam}}$. In equilibrium, the two effects balance each other, and $A \propto 1/S_{\text{lam}}$. The product of $A$ and $S_{\text{lam}}$ remains constant. Three-dimensional numerical simulations with varying $g$, $L$ and varying laminar flame speed confirm equation (1) including its independence of $S_{\text{lam}}$ and indicate $\alpha \simeq 0.5$ [24,26]. The results are consistent with high-gravity combustion experiments that used a centrifuge to study premixed turbulent flames at various $g$.

Equation (1) tells several important things. Near the WD center $g \simeq 0$. Thus, in the beginning the deflagration speed $S_{\text{def}} \simeq S_{\text{lam}}$ should be small. The speed will then tend to increase as the flame goes away from the center and the gravity increases. When the intensity of turbulence increases, the flame speed will become independent of the physics of burning on small scales. The latter conclusion is very important since it gives us a hope that SNII explosions can be modeled in three dimensions without resolving all small spatial and temporal scales. However, equation (1) is missing an important piece of physics. It is valid only in a uniform gravitational field and only when there is no global expansion of matter.

In a supernova explosion, burning causes a global expansion of a star. Equation (1) may be valid only on scales where the expansion velocity is less than the characteristic RT speed. On larger scales, expansion will tend to freeze the turbulence out. The net result will be a substantial decrease of the turbulent flame speed. A crude estimate of the scale $L_f$ at which the turbulence becomes frozen and of the effective deflagration speed limited by expansion can be obtained as follows. First, carry out a one-dimensional simulation assuming no turbulence freeze-out, that is, with the flame speed given by equation (1) with $L$ equal to the flame radius $R_f$. This gives the expansion rate. Then estimate $L_f$ as a scale at which the expansion velocity becomes comparable with the characteristic RT velocity. Finally, estimate the effective deflagration speed from equation (1) using $L = L_f$ [27]. The estimates are $L_f \simeq (\text{a few}) \times 10^7 \text{cm}$, and

\[
S_{\text{def}} \simeq 1.5 \times 10^7 \text{cm/s} \left( \frac{g}{10^9 \text{cm/s}^2} \right)^{1/2} \left( \frac{L_f}{10^8 \text{cm}} \right)^{1/2}.
\]  

Equation (2) shows that in conditions typical of the exploding white dwarf, a turbulent burning speed is a few per cent of the sound speed $a_s \simeq 5 \times 10^8 \text{cm/s}$. This is not enough to cause a powerful explosion. An additional effect that further limits the rate of deflagration is a deviation from the steady-state turbulent burning regime. A certain time is required

\[\text{There is a close analogy here with the self-similarity of an ordinary Kolmogorov cascade. In the Kolmogorov cascade, changes in the fluid viscosity lead to changes in the viscous microscale, but do not influence the amount of energy dissipated into heat. The rate of dissipation depends only on the intensity of turbulent motions on the largest scale.} \]

$S_{\text{lam}}$ plays the role of viscosity in a turbulent flame.
for a turbulent flame to reach a steady-state. This time is larger for larger scales. Scales of the order of $R_f \approx$ might never reach a steady-state during the explosion.

Figure 4 shows some results of a three-dimensional numerical simulation of the entire Chandrasekhar mass CO-WD exploding as a supernova. In this simulation, equation (1) has been used for the turbulent flame velocity on scales not resolved numerically. For regions of the “average” flame front not oriented “upwards” against gravity this formula most probably overestimates the local turbulent flame speed. Despite this, only $\approx 5\%$ of the mass has been burned by the time the star has expanded and quenched the flame, and the white dwarf has not even become unbound. These results show that spherical expansion is indeed important and that burning on large scales does not reach a steady state. Big blobs of burned gas rise and penetrate low density outer layers, whereas unburned matter flows down and reaches the stellar center. The model experienced an almost complete overturn. This has obviously important implications for nucleosynthesis and may cause an element stratification incompatible with observations if composition inhomogeneities are not smeared out during the subsequent detonation stage of burning. The results of 3D modeling indicate that the deflagration alone is not sufficient to cause an explosion. To make a powerful explosion, the deflagration must somehow make a transition to a detonation (delayed detonation model).

Deflagration-to-Detonation Transition. – In terrestrial conditions detonation may arise from a non-uniform explosion of a region of a fuel with a gradient of reaction (induction) time via the Zeldovich gradient mechanism [28]. The region may be created by mixing of fresh fuel and hot products of burning, as in jet initiation, or it may be created by multiple shocks, etc. The same gradient mechanism can operate in supernovae [29-31]. There exist a minimum, critical size of the region capable of generating a detonation, $L_i$. This parameter is determined by the the equation of state and nuclear reaction rates and is mainly a function of the density of the material. $L_i$ is much much less than the size of a WD for all but very low densities $\rho < 10^7 \text{g/cc}$ [30].

Why then DDT does not happen in supernovae at high densities? Why does it have to wait until the WD expands significantly? The explanation may be this. The critical size $L_i$, however small, is still several orders of magnitude larger than the thickness of a laminar flame. To mix fresh fuel with products of burning, the surface of the flame must be disrupted. But this is difficult to achieve unless the turbulence on a scale of a flame front is larger than the laminar flame speed. Only at very low densities, where reactions slow down, the width of the laminar flame becomes very large, and its speed becomes very small, the turbulence may have a chance to create the right conditions for DDT [30,31].

In addition to mixing fuel and products inside an active deflagration front, another mechanism for creating the right conditions for DDT may be as follows. As mentioned above, turbulence in a SNIa will be limited by the expansion. The conditions for DDT during the expansion of a star may not be fulfilled at all. But when deflagration speed is small, deflagration quenches due to expansion before the WD becomes unbound. This happens, in particular, in the simulation shown in Figure 4. The star will then experience a pulsation and collapse back. During the expansion and contraction phases of the pulsation, the high entropy ashes of dead deflagration front will mix with the fresh low entropy fuel again to form a mixture with the reaction time gradients. Mixing will be facilitated during
the contraction phase due to the increase of turbulent motions due to the conservation of angular momentum (like a skating ring dancer increase his rotation by squizing his arms). The estimate of the mixing region formed during pulsation is $\simeq 10^6 - 10^7$ cm, much larger than $L_i$. Is was also shown that as soon as only a few per cent of hot ashes are mixed with a cold fuel, the mixture cannot be compressed to densities higher than $\simeq (a few) \times 10^7$ g/cc. Further compression will lead to a burnout on time scales much shorter than the pulsation time scale. As soon as this mixture returns to high enough densities $\simeq 10^7$ and re-ignites, the detonation will be triggered [13,33,30].

It should be noted at this point that three-dimensional theory of flame propagation and DDT in supernovae is far from being finished, and remains a subject of an active research. In particular, it was speculated recently that DDT may be caused by a sudden acceleration of a quasi-spherical deflagration front, due to the Landau-Darrehus or some other yet unknown internal instabilities of the flame; that a suddenly accelerated deflagration might keep propagating with the speed of sound without turning into a detonation, etc. [32]. Whether any of these can actually happen should be either tested in appropriately scaled terrestrial experiments or demonstrated in three-dimensional simulations. Further work is required, and it will undoubtedly improve our understanding of SNIa explosions.

It may also be possible to distinguish between different multi-dimensional explosion mechanisms on the basis of observations. One of the amazing properties of SNIa is their apparently small deviation from spherical symmetry. We do not expect all three-dimensional models to have this property. For example, pure deflagration models are expected to be clumpy (Figure 4) and asymmetric with large blobs of Si and Fe group elements embedded in the unburned CO envelope. Delayed detonation models, on the other hand, should be more symmetric. A supersonic detonation mode of burning that follows deflagration will tend to homogenize the ejecta. Rotation of the progenitor may impose a global, low order asymmetry on the ejecta. Viable models can be limited by computing the polarization of the emerging radiation and comparing the predictions with the existing [34] and planned observations.

5. Discussion

We described a phenomenological delayed detonation model of SNIa based on the explosion of a Chandrasekhar mass carbon-oxygen white dwarf. The model assumes that the explosion starts as a subsonic deflagration and then turns into a supersonic detonation mode of burning. The model is successful in reproducing the main features of SNIa, including multi-wavelength light curves, the spectral behavior, and the brightness – decline and color – decline correlations. It was argued that an apparently low deviations of SNIa from spherical symmetry (low polarization of SNIa) may be attributed in delayed detonation models to the homogenizing effect of the detonation phase of an explosion.

The model interprets existing brightness – decline and color – decline relations among SNIa as a result of varying nickel mass synthesised during the explosion. Major free parameters of the model are the deflagration speed $S_{\text{def}}$, the transition density $\rho_{\text{tr}}$ at which deflagration turns into a detonation, and also initial density and composition (C/O ratio) of the exploding WD. The variation of nickel mass in the model is caused by the variation of $\rho_{\text{tr}}$. Strong sensitivity of the nickel mass to $\rho_{\text{tr}}$ is probably the basis of why, to first
approximation, SNIa appear to be a one-parameter family. Nonetheless, variations of the other parameters also lead to some relatively small variations of the predicted properties of SNIa, which indicate that the assumption of a one-parameter family may not be strictly valid.

To fit observations, the delayed detonation model requires low values of $S_{\text{def}} < 0.1a_s$ and low values of $\rho_{\text{tr}} \simeq (1 - 3) \times 10^7$ g/cc. In Section 4 it was argued that slow deflagration is the result of an expansion of a star caused by the deflagration itself. The expansion tends to freeze the turbulence and, thus, limits the deflagration speed. The actual rate of deflagration in a supernova is determined by the competition of the Rayleigh-Taylor instability which is the turbulence driving force, the turbulent cascade from large to small scales, and the turbulence freeze-out. Two possible mechanisms that lead to a low $\rho_{\text{tr}}$ were discussed – one related to the disruption of an active deflagration front by the existing turbulence, and the other related to quenching of deflagration, mixing of the low-entropy fuel with high-entropy burning products, and its subsequent compression.

It may seem unusual that the two apparently different mechanisms predict almost the same low values for $\rho_{\text{tr}}$, these same low values that are required to fit observations in phenomenological delayed detonation models. Note, however, that predictions of low transition density by both DDT mechanisms and the very reason why low $\rho_{\text{tr}}$ is needed to fit SNIa observations stem from the same two fundamental facts: (1) specific heat of matter in supernovae depends on density; (2) nuclear reactions depend on temperature exponentially. The resulting dependence of burning timescales on density is very steep. Numbers are such that at densities above $10^7$ g/cc nuclear burning timescales are much shorter than the sound crossing time ($\simeq$ explosion timescale) of a WD. At densities below $10^7$ g/cc the timescales become much longer than the sound crossing time. That is why a laminar flame front can be disrupted by turbulence only below approximately $10^7$ g/cc – flame width is proportional to a burning timescale and at higher densities it is much much shorter than any other relevant spatial scale of a WD. That is why a mixture of cold fuel and hot products cannot be compressed to densities much higher than $10^7$ g/cc – at higher densities it will react faster than it is being compressed. And that is also why intermediate mass elements can be synthesised in an SNIa only at densities around $\sim 10^7$ g/cc – at higher densities reactions will have enough time to reach a nuclear statistical equilibrium and, thus, to burn CO into Ni-group elements.

What may cause the variations of $\rho_{\text{tr}}$ among SNIa? There are several possibilities. One is differences in the initial C/O ratio. If less carbon is present near the WD center, less energy will be released by burning, and this will affect both the buoyancy of burning products and the rate of expansion of a WD. This, in turn, will affect the speed of deflagration, and will lead to different conditions for DDT. Variations of initial C/O ratio among SNIa has been recently studied in the framework of one-dimensional phenomenological delayed detonation models in [35-37]. The effect of varying C/O ratio may result in small but noticeable variations in the rise time to maximum and in some other variations in light curve behavior. This is a potential source of systematic evolutionary effects, and has obvious implications for using SNIa in cosmology. However, in one-dimensional models one has to assume how changes in C/O influence the deflagration speed and $\rho_{\text{tr}}$, and the predictions then depend on these assumptions. Three-dimensional modeling is required in
order to predict the actual influence of C/O ratio on the outcome of the explosion.

Another possibility is the influence of rotation if SNIa are the result of a merger of low-mass CO-WD. Rotation will undoubtedly influence the turbulent deflagration phase which, in turn, will affect DDT. Merger configurations may also differ in their mass, so that slightly super-Chandrasekhar mass WD explosions are probable. Could they be responsible for unusually bright SN1991T-like events? An extended CO envelope around a merger WD may manifest itself in SNIa light curves and spectra. Further work is needed to answer these questions.

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References

1. Phillips, M. M. 1993, ApJ, 413, L105
2. Riess A.G., Press W.H., Kirshner R.P. 1996, ApJ, 473, 588
3. Schmidt, B. et al., 1998, ApJ, 507, 46; Perlmutter, S. et al. 1999, ApJ, 517,565.
4. Livio, M. 2000, in The Largest Explosions Since the Big Bang: Supernovae and Gamma-Ray Bursts, eds. M. Livio, K. Sahu, & N. Panagia, in press.
5. Nomoto, K. & Sugimoto, D., 1977, PASJ, 29, 765; Nomoto, K., 1982, ApJ 253, 798.
6. Webbink R.F. 1984, ApJ, 277, 355; Iben I.Jr., Tutukov A.V. 1984, ApJS, 54, 335.
7. Benz, W., Bowers, R.L., Cameron, A.G.W, Press, W.H., 1990, ApJ, 348, 647.
8. Mochkovitch R., Livio, M. 1990, A&A, 236,378.
9. Nomoto K. 1980, ApJ ,248, 798; Woosley S.E., Weaver T.A., Taam R.E. 1980, in: Type I Supernovae, eds. C.Wheeler, Austin, U.Texas, p. 96.
10. Arnett W.D. 1969, Ap. Space Sci., 5, 280; Hansen C.J., Wheeler J.C. 1969, Ap. Space Sci., 3, 464.
11. Nomoto K., Sugimoto S., & Neo S. 1976, ApSS, 39, L37.
12. Khokhlov A.M. 1991, AA, 245, 114.
13. Khokhlov A.M. 1991, AA, 245, L25.
14. Yamaoka H., Nomoto K., Shigeyama T., Thielemann F.-K. 1992, ApJ, 393, 55.
15. Woosley, S. E., Weaver, T. A. 1994, in Les Houches, Session LIV, Supernovae, ed. S. A. Bludman, R. Mochkovich, & Zinn-Justin (Amsterdam: North-Holland), 63
16. Höflich, P., Khokhlov, A.M. 1996, ApJ, 457, 500
17. Nugent, P. et al. 1997, ApJ, 485, 812
18. Höflich, P.; Khokhlov, A.; Wheeler, J. C. 1995, ApJ, 444, 831; Höflich, P.; Khokhlov, A., Wheeler, C.J., Phillips, M.M., Sunzeff, N.B., Hamuy, M. 1996, ApJ, 472, L81; Wheeler et al. 1998, ApJ, 496, 908, and references therein.
19. Höflich, P. 1995, ApJ, 459, 307.
20. Müller, E., Höflich, P.A. 1994, A&A, 281, 51.
21. Sandage, A. 2000, in The Largest Explosions Since the Big Bang: Supernovae and Gamma-Ray Bursts, eds. M. Livio, K. Sahu, & N. Panagia, in press.; Riess, A.,
Nugent, P., Filippenko, A.V., Kirshner, R., Perlmutter, S., 1998, ApJ, 504, 935; Ferrarese, L. et al. 1999, ApJ, in press.
22. Timmes F.X., Woosley S.E. 1992, ApJ 396, 649.
23. Nomoto K., Sugimoto S., & Neo S. 1976, ApSS, 39, L37
24. Khokhlov, A.M., 1995, ApJ, 449, 695.
25. Livne, E., Arnett, W.D. 1993, ApJ 415, L107; Arnett, W.D., Livne, E. 1994, 427, 314.;
26. Khokhlov, A.M. Oran, E.S., Wheeler, J.C. 1996, Combustion & Flame, 105, 28
27. Khokhlov, A.M., Oran, E.S., Wheeler, J.C., 1995, in Type Ia Supernovae, proc. of the NATO conference, Barcelona, Spain, 1995.
28. Zeldovich, Ya. B., Librovich, V. B., Makhviladze, G. M., & Sivashinsky, G. L. 1970, Acta Astron., 15, 313; Lee, J. H. S., Knystautas, R., & Yoshikawa, N. 1978, Acta Astron., 5, 971.
29. Blinnikov, S.I., Khokhlov, A.M. 1986, Soviet Astron. Lett., 12, 131.
30. Khokhlov, A.M., Oran, E.S., Wheeler, J.C. 1997, ApJ, 478, 678.
31. Niemeyer, J.C., Woosley, S.E. 1997, ApJ, 475, 740.
32. Niemeyer, J.C., 1999, ApJ, 523, L57.
33. Arnett, D., & Livne, E. 1994, ApJ, 427, 330.
34. Wang, L., Wheeler, J.C., Höflich, P. 1997, ApJ, 476, 27.
35. Domínguez, I., Höflich, P.A., 1999, ApJ, in press (astro-ph/9908204); Höflich, P.A., Domínguez, I., 2000, in The Largest Explosions Since the Big Bang: Supernovae and Gamma-Ray Bursts, eds. M. Livio, K. Sahu, & N. Panagia, in press.
36. Umeda, H., Nomoto, K., Kobayashi, C., Hachisu, I., Kato, M., 1999, ApJL, in press
37. Höflich, P.A., Nomoto, K., Umeda, H., Wheeler, J.C., 1999, ApJ, in press.
Figure captions

1. Schematics of the delayed detonation explosion. Ignition takes place in a dense, Chandrasekhar mass carbon-oxygen white dwarf. Flame propagates from the center as a subsonic turbulent deflagration. Deflagration-to-detonation transition (DDT) takes place in a significantly expanded star after only a small fraction of mass has been burned. Detonation incinerates the rest of the white dwarf. The resulting configuration consists of the inner core of Fe-group elements including $^{56}\text{Ni}$ surrounded by a massive envelope of Si-group elements.

2. Comparison of observed (SN1994D) and theoretical (M36) B, V, R, I light curves [19].

3. Direct determination of the Hubble constant ($H_0 = 67 \pm 9\text{km/s/Mpc}$) using delayed detonation models [16]. Values of $H_0$ are plotted for individual SNIa based on distances determined by fitting their light curves and spectra with theoretical models.

4. Three-dimensional simulation of an explosion of a Chandrasekhar mass CO-WD [24]. The figure shows density distribution during the deflagration phase of the explosion.
Ignition

Deflagration (speed - parameter)

DDT

Detonation (speed - known)

Free expansion

Carbon-Oxygen

Si-group

Fe-group
The diagram shows a plot of $H$ [km/sec Mpc] versus $v$ [km/sec]. The data points are labeled as follows:

- **H (indiv. SN Ia)**: Individual supernova Ia measurements.
- **H (mean)**: The mean value of $H$.
- **2σ range**: The 2 standard deviation range around the mean.

The plot indicates a relationship between $H$ and $v$, with error bars illustrating the uncertainty in each measurement.
