CAN DEFLAGRATION-DETONATION TRANSITIONS OCCUR IN TYPE Ia SUPERNOVAE?

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ABSTRACT

The mechanism for a deflagration-detonation transition (DDT) by turbulent preconditioning, which has previously been used to explain the possible occurrence of delayed detonations in Type Ia supernova explosions, is argued here to be conceptually inconsistent. It relies crucially on diffusive heat losses of the burned material on macroscopic scales. Regardless of the amplitude of the turbulent velocity fluctuations, the typical gradient scale for the temperature fluctuations is shown to be of the order of the laminar flame width or smaller rather than the homogeneity scale required for DDT, which is larger by more than a factor of 1000. Furthermore, thermonuclear flames cannot be fully quenched in regions that are much larger than the laminar flame width as a consequence of their simple “chemistry.” Possible alternative explosion scenarios are briefly discussed.

Subject headings: hydrodynamics — supernovae: general

1. INTRODUCTION

The delayed detonation scenario for Type Ia supernova (SN Ia) explosions asserts that a slowly accreting Chandrasekhar mass C + O white dwarf undergoes a thermonuclear explosion in two distinct modes: an initial turbulent deflagration (flame) phase that preexpands the star, allowing the abundant production of intermediate-mass isotopes observed in SN Ia spectra, followed by a detonation that accounts for the high material velocities and for the strength of the explosions (Khokhlov 1991; Woosley & Weaver 1994). Both modes are assumed to be linked by a deflagration-detonation transition (DDT) that occurs either during the first expansion phase or after a partial recollapse of the star (Arnett & Livne 1994). The background density of the DDT, \( \rho_s \), is often referred to (Hofflich et al. 1996; Nomoto, Iwamoto, & Kishimoto 1997) as the leading candidate for the physical parameter that corresponds to the observed correlation of peak luminosity and light-curve shape (Pskovskii 1977; Phillips 1993).

Despite the apparent success of one-dimensional delayed detonation models in reproducing many features of observed SN Ia spectra and light curves (Hofflich et al. 1996), a quantitative investigation of DDTs in supernovae has begun only recently. Both dimensional analysis and numerical simulations indicate that a turbulent thermonuclear flame front driven on large scales by the Rayleigh-Taylor (RT) instability falls short of sonic propagation by at least 1 order of magnitude (Niemeyer & Hillebrandt 1995; Khokhlov 1995; Reinecke, Hillebrandt, & Niemeyer 1999a), making early proposals for DDT by direct shock formation seem implausible. An alternative route to detonations in supernovae involving local flame quenching and microscopic turbulent mixing was recently proposed (Khokhlov, Oran, & Wheeler 1997b; Niemeyer & Woosley 1997). It is based on the induction time gradient mechanism (Zeldovich et al. 1970), which was first applied to detonations in supernovae by Blinnikov & Khokhlov (1986, 1987; Woosley 1990; Niemeyer & Woosley 1997). Owing to the absence of walls or obstacles, which are the preferred locations for DDT in confined systems, preconditioning in supernova explosions can only be attributed to mixing in an unconfined turbulent flow field. It will be shown in § 3 that under these conditions, successful preconditioning entails a degree of synchronicity that is irreconcilable with subsonic turbulence.

In this Letter, it will be argued that turbulent mixing in large systems does not, in general, give rise to uniform gradients on large scales (§ 3). Furthermore, even if locally isolated regions are considered, the robustness of thermonuclear flames with respect to turbulent quenching disfavors the emergence of sufficiently well-mixed regions for DDT. We conclude that unless we are missing an important piece of information, the physics of unconfined turbulent thermonuclear flames appears to allow transitions to a detonation only in the case of rare fluctuations instead of providing a robust framework for DDT. Some alternative explosion scenarios will be outlined in § 4.

2. PREREQUISITES FOR DDTs IN SUPERNOVAE

Assuming that there are no natural sources of shocks in the turbulent flame brush of a supernova explosion (for a possible exception, see the description of active turbulent combustion [ATC] in § 4), such as the corners or obstacles in terrestrial combustion experiments, the only way to create a pressure spike that turns into a detonation is by burning a certain critical volume, \( V_c \sim l_c^3 \), of fuel within a time comparable to or less than its sound-crossing time, \( t_c(l_c) \sim l_c/\omega_s \). This can be achieved in two very different ways. On the one hand, turbulent deformation of the flame surface can, in principle, create a sufficiently large flame surface area to burn a given volume in an arbitrarily short time. This idea is the motivation behind the fractal model (Woosley 1990). However, a simple argument shows that this can only occur in rare fluctuations as long as

released by the burning wave may form a self-sustaining reaction-shock complex, i.e., a detonation. Note that no microscopic transport or high fluid velocities are needed for the runaway to detonation. Instead, the problems of those proposals for DDT that need supersonic turbulent flame speeds are now entirely passed on to the preconditioning of the gradient region. It is well known that the gradient mechanism is very sensitive to even small-temperature nonuniformities (Blinnikov & Khokhlov 1986, 1987; Woosley 1990; Niemeyer & Woosley 1997). Owing to the absence of walls or obstacles, which are the preferred locations for DDT in confined systems, preconditioning in supernova explosions can only be attributed to mixing in an unconfined turbulent flow field. It will be shown in § 3 that under these conditions, successful preconditioning entails a degree of synchronicity that is irreconcilable with subsonic turbulence.

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the steady state turbulent flame velocity, \( S_f \), is subsonic since the statement of burning \( V_f \) within \( t_f \) is equivalent to \( S_f \approx u_f \) if \( S_f \) is evaluated on the scale \( l_c \). Given that in the flamelet regime, the turbulent flame speed scales with the turbulent velocity fluctuations on each scale, \( S_f(l) \sim v(l) \), and that the latter is bound from above by the (subsonic) terminal rise velocity of buoyant RT bubbles, it is clear that this mechanism is an unlikely candidate for a robust DDT scenario (Niemyer & Woosley 1997).

On the other hand, detonations might be created via the well-studied induction time gradient mechanism (Zeldovich et al. 1970; Lee, Knystautas, & Yoshikawa 1978), whereby a combustion wave moving along a preconditioned temperature gradient coherently builds up a pressure wave that—for sufficiently large preconditioned volumes—eventually turns into a detonation (for a recent discussion, see Khokhlov et al. 1997a, 1997b). The minimum size \( l_c \) of the preconditioned region that gives rise to a detonation in white dwarf matter was derived numerically by Niemyer & Woosley (1997) and Khokhlov et al. (1997b). It sensitively depends on the composition and density of the fluid; however, for the purpose of this Letter, it is sufficient to note that in all cases, \( l_c \) is larger than the laminar flame width \( \delta \) by more than 3 orders of magnitude.

So far, the problem has merely been shifted from the fine-tuning of the flame surface area within the critical region to that required to precondition the temperature field. In both cases, the only tool naturally available is subsonic buoyancy-driven turbulence. However, as pointed out by Khokhlov et al. (1997a, 1997b) and Niemyer & Woosley (1997), it is possible in principle that for a given laminar flame speed and width, there exists a critical turbulence intensity such that turbulent mixing can locally extinguish, or quench, the nuclear reactions within the flame. If this were the case, turbulence might be able to mix burned and unburned material and establish an appropriately smooth temperature field. The details of this mixing process, however, were not investigated in previous studies.

Niemyer & Woosley (1997) and Khokhlov et al. (1997a, 1997b) used the Gibson length \( l_g \), defined as the scale where the turbulent eddy velocity is equal to the laminar flame speed, \( v(l_g) \approx S_f \), to postulate the necessary conditions for flame quenching: if \( l_g \approx \delta \), the burning regime changes from “flamelet” to “distributed” burning, and turbulence begins to affect appreciably the diffusion-reaction structure of the flame. Only in the distributed burning regime can local flame quenching take place. The above criterion was later shown to be equivalent to a definition of the flamelet regime based on the relative strengths of turbulent and thermal diffusivities (Niemyer & Kerstein 1997). Note that for Prandtl numbers below unity, where the Prandtl number is defined as the ratio of viscosity to thermal conductivity, \( Pr = \nu/c_p \), this criterion is in conflict with conventional flamelet theory (Peters 1984), which relies on a comparison of the Kolmogorov length and \( \delta \); according to this definition, thermonuclear flames with \( Pr \approx 1 \) would never be anywhere near the flamelet regime. Recent numerical experiments favor the modified flamelet definition as opposed to the conventional one (Niemyer, Bushe, & Rutesc 1999).

Intriguingly, the transition from flamelet to distributed burning, and hence the first chance for turbulence to create large islands of preconditioned material, approximately takes place at the right transition density for DDT, \( \rho_d \approx 10^7 \, \text{g cm}^{-3} \), inferred from one-dimensional explosion models (Niemyer & Woosley 1997). It could therefore provide the switch that triggers detonations in the late phase of supernova explosions, replacing a free model parameter with a physical one. To conclude this section, the combination of the gradient mechanism for DDT and the transition from flamelet to distributed burning at a density of \( \approx 10^7 \, \text{g cm}^{-3} \) may explain the bulk of SN Ia observations, but it crucially hinges on the existence of a mechanism for turbulent preconditioning of a region much larger than the laminar flame width at that density.

3. FAILURE OF TURBULENT FLAME QUENCHING AND MACROSCOPIC PRECONDITIONING

Consider first an infinite fluid dynamical system, containing a passive scalar field that changes from zero to a finite value across the domain of interest and is subject to self-similar turbulent mixing in the center of the domain. Assuming for now that turbulence or expansion manages to extinguish nuclear burning completely, this is a reasonable description of the temperature field \( T \) in the turbulent flame brush, since the length scales we are interested in, \( l \approx l_c \), are much smaller than the stellar radius and since the turbulence on these scales had ample time to establish a self-similar cascade. Under these conditions, the temperature-fluctuation amplitudes obey Kolmogorov scaling, \( T(l) \sim l^{1/3} \). The temperature field becomes a smooth function at the heat diffusion scale given by \( l_d \approx Re^{3/4} Pr^{-1/4} \) for \( Pr < 1 \), where \( Re \) is the Reynolds number and \( L \) is the integral scale of the turbulence. Under conditions, which are typical for the onset of distributed burning in SN Ia models, \( L \approx 10^7 \, \text{cm} \), \( Re \approx 10^{14} \), and \( Pr \approx 10^{-4} \), the heat diffusion scale is \( l_d \approx 10^{-1/2} \, \text{cm} \approx \delta \approx l_c \). Evidently, increasing the intensity of the turbulence (and thus \( Re \)) decreases, rather than increases, the largest length scale where \( T \) can be considered smooth. Regardless of the amplitude of large-scale turbulent velocity fluctuations, turbulent mixing is inherently unable to provide uniformly mixed regions on macroscopic scales \( l_c \). Dropping the simplification of treating \( T \) as a passive scalar further strengthens this statement, since burning strongly enhances temperature fluctuations on scales \( \approx \delta \approx l_c \).

The question of DDT in the presence of temperature fluctuations was recently investigated numerically by Montgomery, Khokhlov, & Oran (1998). It was found that perturbation amplitudes of \( 10\% - 15\% \) are sufficient to divide the gradient region into subregions, each of which would need to have the size of the unperturbed critical length \( l_c \) in order to give rise to a detonation. However, this study optimistically assumed that a constant temperature gradient of order \( l_c^{-1} \) exists initially and is subsequently perturbed by turbulent fluctuations on smaller scales. As argued above, these initial conditions are inconsistent with a self-similar turbulent mixing region.

One may also drop the assumption of self-similarity by looking at the special case of a locally isolated fluid element, recognizing that while these are not typical regions of a turbulent flow, a small number of them may be realized on statistical grounds. Consider, for instance, a single large eddy of size \( l_e \) with little or no entrainment of material from the outside. In this case, the passive scalar is mixed microscopically over the entire region after approximately one eddy turnover time \( \tau_{edd}(l_e) \). This situation would, in fact, give rise to suitable preconditioning for DDT if burning could be inhibited during the mixing process; otherwise, small-scale fluctuations on the scale \( \delta \) are continually resupplied. The remaining question is thus: can turbulence quench nuclear reactions in a region as large as \( l_e \gg \delta \)? More specifically, can the burning products contained in \( V_f \) be cooled sufficiently such that the burning time-scale \( \tau_e \approx \delta^{-1} \), where \( \delta \) is the fuel consumption rate, is larger than \( \tau_{edd}(l_e) \) everywhere within \( V_f \)?
The answer is no, provided that heat loss to the environment is negligible and the flow is subsonic. For simplification, we shall concentrate on carbon burning alone, since it represents the fastest reaction and its extinction is a necessary (and sufficient) condition for flame quenching. Ignoring the small density change across the flame, the carbon-burning rate \( \dot{w}_{c+c} \) depends only on temperature and a carbon mixture fraction. Note further that because of electron degeneracy, heat diffuses many orders of magnitude more rapidly than nuclei, so that we can safely assume that carbon is nondiffusive. Consequently, flame quenching can only occur by diffusive cooling (pdV-cooling is irrelevant because the flow is to a very good approximation incompressible). Turbulence affects the efficiency of diffusion by straining the flame and thus steepening the temperature gradients. For temperature gradients of order \( \delta^{-1} \), the diffusion timescale, \( \tau_d(\delta) \sim \delta^{-1} \kappa \), is by definition of \( \delta \) comparable to the burning timescale \( \tau_b \sim \dot{w}_{c+c}^{-1} \). For gradients larger than \( \delta^{-1} \), diffusion is faster than burning throughout most of the flame. However, it can lead to full extinction only if the entire region of burning products that it is connected with is also smaller than \( \sim \delta \), in which case heat can leak out to all sides and the products can be cooled sufficiently to satisfy \( \tau_d \ll \tau_b \). Otherwise, if the flame is connected to a heat bath of burning products larger than \( \delta \), the temperature at the interface of fuel and ash always remains fixed at the final product temperature, keeping \( \tau_d \) small in its immediate vicinity, regardless of the strain rate experienced by the flame. The total burning rate may drop with respect to the flamelet regime, but fast nuclear burning is never fully extinguished within the whole volume.

According to these arguments, the only conceivable way to quench the flame in a large volume \( V \) is to stretch it into a thin filament with thickness \( \lesssim \delta \) and curl it up such that it fills \( V \). In order to prevent unquenched burning in any part of \( V \), before the onset of the spontaneous runaway, this curling has to be completed in a time \( t \ll \tau_b(\delta) \). Interestingly, we now face the same problem as the fractal model described in the previous section: the eddy velocity has to be supersonic in order to prepare the runaway region before it is burned. Again, we are limited by the fact that a subsonic process cannot set up conditions that are later supposed to burn with a supersonic phase velocity.

The above line of argument is supported by numerical (Ponsot, Veynante, & Candel 1991) and experimental (Shy, Jang, & Ronney 1996) evidence that premixed chemical flames can only be quenched in the presence of heat losses or complicated thermochemical effects, both of which are absent in thermonuclear combustion. Further confirmation was obtained with a one-dimensional calculation of a thermonuclear flame that was subject to discrete multiscale remappings representing turbulent eddies (Lisewski et al. 1999). The interaction of simple diffusion-reaction flames with turbulence on the scale of the flame width was studied by Niemeyer et al. (1999), demonstrating that local flame propagation is nearly unaffected by turbulence even if the turbulent velocity fluctuations are comparable to the laminar flame speed.

4. ALTERNATIVE SCENARIOS

If the initial deflagration phase fails to release enough energy to unbind the star and no DDT takes place during the expansion, the star pulses and eventually recontracts, revitalizing the turbulence by compression (Arnett & Livne 1994; Khokhlov 1995). During the pulse, the cutoff scale for temperature fluctuations \( l_s \) can grow extremely large because turbulence is essentially frozen in. At very low densities, the flame width \( \delta \) is macroscopically large, allowing the formation of fluid regions that—if they survive the recontraction phase without disruption—may be suitably preconditioned for DDT later on. However, turbulent entrainment of hot and cold material during the collapse will again raise the amplitude and lower the cutoff scale of temperature fluctuations. It is impossible to say a priori whether the fluid is more likely to reignite in the deflagration or detonation mode. While the extensive mixing period during the pulse probably helps to create favorable conditions for DDT, its benefits may well be erased by the enhanced intensity of the turbulence during the recontraction. Moreover, the extremely finely-tuned time synchronization required for the gradient mechanism for DDT seems to be as unnatural in the pulsational mode as in the direct one.

An additional problem of the pulsational delayed detonation scenario was pointed out by Niemeyer & Woosley (1997): if a large pulse is needed to achieve the required degree of homogeneity, what are the observational counterparts of those events that barely unbind the star but do not detonate? One may evade this problem by assuming that turbulent deflagrations reliably fall short of releasing the binding energy of the white dwarf. This, however, is in conflict with the latest two-dimensional simulations that indicate a clear trend toward higher energy release with increased numerical resolution (Hillebrandt, Reinecke, & Niemeyer 1999). These simulations employ a flame-capturing algorithm based on the level set method (Reinecke et al. 1999b) that shows the emergence of more and more flame structure as the grid resolution is improved. For certain initial conditions, the star clearly becomes unbound, yet no convergence of total energy generation with respect to resolution has been achieved so far. Should this trend continue, and ultimately be confirmed in three-dimensional calculations, there is a realistic possibility that turbulent deflagrations alone are sufficient to power the explosions without the need for detonations.

The simulations by Niemeyer, Hillebrandt, & Woosley (1996) and Reinecke et al. (1999a) further demonstrate that the role of the initial conditions for flame ignition has not yet been fully explored. If the explosion is sparked off at many disconnected points, the complexity of the flame surface later on may easily exceed the surface area derived from the nonlinear growth of an initially smooth, RT unstable interface (the “dandelion model”; Niemeyer & Woosley 1997). One-dimensional SN Ia models are unable to represent such effects adequately.

Finally, we can consider alternative routes to detonations that do not rely on large-scale preconditioning. One such possibility is the ATC (Kerstein 1996; Niemeyer & Woosley 1997), a runaway process of turbulent combustion that may occur as a consequence of flame-generated turbulence on multiple scales. Scaling arguments show that in the absence of an effective mechanism for stabilization, a runaway must ensue in any unconfined turbulent flame brush (Kerstein 1996). It is possible that the nonlinear stabilization mechanism of the Landau-Darrieus (LD) instability by cusp formation (Zeldovich 1966) is unstable with respect to finite-amplitude perturbations excited by turbulent fluctuations, giving rise to an increasingly more violent acceleration of the flame front that ends only when the compressibility effects become important. Cusp stabilization of the LD instability may also break down at a critical expansion ratio of burned and unburned material, as suggested by Blinnikov & Sasorov (1996). Practically, the consequences of the ATC would involve either nearly sonic turbulent com-
bustion or direct DDT by shock formation ahead of the combustion front. While undoubtedly speculative, the ATC is a promising mechanism for powerful SN Ia explosions without the need for fine-tuning. Numerical experiments designed to measure the relevance of the ATC for thermonuclear flames are underway.

5. CONCLUSIONS

This Letter argues that the gradient mechanism for DDTs, previously believed to be the most realistic candidate for explaining delayed detonations in SN Ia, is inconsistent with the phenomenology of turbulent mixing and combustion. Combining the inability of turbulence to provide microscopic mixing over macroscopic length scales with the robustness of thermonuclear flames with respect to quenching, the establishment of sufficiently large regions with a nearly constant temperature gradient is shown to be very unlikely. Both of these effects can (and must) be verified by means of direct numerical simulations on small scales. Work in this direction is in progress; first results of flame-turbulence interactions on small scales can be found in Niemeyer et al. (1999). The argument above holds as well for pulsational explosions, although here the long intermediate period of diffusion-dominated mixing may slightly facilitate the preconditioning needed for DDT.

Why, then, do one-dimensional explosion models with a slow deflagration phase followed by a delayed detonation so successfully fit the majority of SN Ia observations? Either we are missing an important effect that robustly leads to a DDT or at least to a very fast turbulent flame late during the explosion—a noteworthy, albeit speculative, possibility is the ATC—or one-dimensional models get the right answer for the wrong reasons because they cannot accurately represent important multi-dimensional effects. An example for the latter is the impact of multipoint ignition on the development of the flame surface complexity, an effect that may well lead to a strongly enhanced burning rate in the deflagration mode as compared with the standard scenario. In any case, the success of both the direct and pulsational modes for DDT hinges on a deflagration phase that is much slower than indicated by recent results of two-dimensional simulations.

On the other hand, there is a trend toward higher energy release by the turbulent flame if the numerical resolution is increased. So far, no convergence of the total energy generation has been attained. If this trend continues and is confirmed by three-dimensional calculations with realistic subgrid-scale modeling, the possibility that the bulk of Type Ia supernovae explode without ever detonating must be taken more seriously.

To summarize, our analysis suggests that detonations may never take place in SN Ia explosions. If they do, they probably need to be preceded by a nearly sonic turbulent deflagration, in which case it may not be possible to distinguish clearly deflagrations from detonations observationally. ATC, multipoint ignition, higher than anticipated energy release in the turbulent flame brush, or any combination thereof may provide the required energy output to power the explosion.

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