Experimental and Numerical Study of the Unconfined Deflagration-to-Detonation Transition in Thermonuclear Type Ia Supernovae

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The nature of stellar progenitors and the associated explosion mechanism of Type Ia supernovae (SNIa) - thermonuclear incinerations of compact, degenerate, white dwarf (WD) stars - remains one of the major open questions in astrophysics. Virtually all existing theoretical models, in particular the single-degenerate Chandrasekhar-mass and sub-Chandrasekhar-mass scenarios as well as the double-degenerate merger model, require formation of a supersonic detonation wave capable of providing nearly complete combustion of the stellar material. The mechanism of detonation initiation in unconfined systems, such as the interior of a WD, remains poorly understood not only in astrophysics but also in the context of terrestrial chemical systems. Furthermore, modern large-scale numerical models of SNIa are unable to capture detonation formation from first principles due to the extreme range of dynamical scales in the system, and instead are forced to trigger detonations artificially. As a result, the time and location of detonation initiation are free parameters present in every existing SNIa model.

Prior study by Poludnenko et al. (2011) [1] suggested a mechanism of the spontaneous deflagration-to-detonation transition (DDT) in unconfined systems based on the direct numerical simulations (DNS) of chemical turbulent flames. Here we present the first experimental confirmation of this process in terrestrial H_2-air flames. Next, we present DNS of unconfined turbulent thermonuclear flames in a degenerate ^{12}C stellar plasma. These calculations for the first time show that under conditions representative of those inside a WD during a SNIa explosion, this DDT mechanism can also result in the formation of strong shocks, which can subsequently lead to detonation ignition.

Finally, we briefly discuss the general theory of turbulence-induced DDT and use it to determine the criteria for detonation initiation in the classical single-degenerate Chandrasekhar-mass model. We show that DDT can occur at densities in the range 10^7 - 10^8 g/cm^3 with the maximum probability at $\rho_{DDT} \approx 3 \times 10^7$ g/cm^3. These results open path for the new generation of SNIa models, in which detonation initiation conditions can be determined self-consistently.

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[1] A.Y. Poludnenko, T.A. Gardiner, E.S. Oran, *Spontaneous transition of turbulent flames to detonations in unconfined media.* Phys. Rev. Lett. (2011) v.107, p.054501.