Quenching Processes in Flame-Vortex Interactions

M. Zingale*†, J. C. Niemeyer‡, F. X. Timmes*†, L. J. Dursi*†, A. C. Calder*†, B. Fryxell*†, D. Q. Lamb*†, P. MacNeice‖, K. Olson‖, P. M. Ricker*†, R. Rosner*†, J. W. Truran*†, and H. M. Tufo*

*Center for Astrophysical Thermonuclear Flashes[1], Chicago, IL 60637
†Department of Astronomy and Astrophysics, University of Chicago, Chicago, IL 60637
‡Max-Planck-Institut für Astrophysik, Garching, Germany 85748
‖Goddard Space Flight Center, Greenbelt Maryland 20771

Abstract. We show direct numerical simulations of flame-vortex interactions in order to understand quenching of thermonuclear flames. The key question is—can a thermonuclear flame be quenched? If not, the deflagration-detonation transition mechanisms that demand a finely tuned preconditioned region in the interior of a white dwarf are unlikely to work. In these simulations, we pass a steady-state laminar flame through a vortex pair. The vortex pair represents the most severe strain the flame front will encounter inside the white dwarf. We perform a parameter study, varying the speed and size of the vortex pair, in order to understand the quenching process. No quenching is observed in any of the calculations performed to date.

INTRODUCTION

The favored model for a Type Ia supernova begins as a flame deep in the interior of a Chandrasekhar mass white dwarf. At some point, the burning may undergo a deflagration-detonation transition (DDT). Some mechanisms for this transition require a preconditioned region in the star. As the flame propagates down the temperature gradient, the speed increases, and the transition to a detonation may occur [1,2]. For this to happen, the region must be free of any temperature fluctuations—any burning must be quenched.

A flame propagates by balancing thermal diffusion and nuclear burning. Heat diffuses from the hot ash to the cold fuel ahead of the burning front, raising its temperature to ignition. The width and speed of the burning front depends on how rapidly energy is released by nuclear burning, and how efficiently conduction can transport energy to the material ahead of the front. If a flame encounters a

1) The Center for Astrophysical Thermonuclear Flashes is supported by the Department of Energy under Grant No. B341495 to the University of Chicago

large rate of strain, the burning may not be able to keep pace with the increase in flame surface, and the flame can quench. Experiments and simulations involving chemical flames have observed flame quenching (see for example [3]).

FLAME-VORTEX SIMULATIONS

To study quenching processes in thermonuclear flames, we ran a grid of flame-vortex interaction simulations with the FLASH Code [4]. FLASH solves the compressible Euler equations with a nuclear energy generation source term and a realistic equation of state. FLASH uses an adaptive mesh, which concentrates spatial resolution at the complex features of the flow, greatly improving the efficiency of the simulation. For these simulations, FLASH was extended to include explicit thermal diffusion. The one-dimensional laminar flame speeds calculated by FLASH were compared to those computed by Timmes and Woosley [5] and found to be in excellent agreement.

For a typical white dwarf density of 5×10^8 g cm^{-3} and a pure carbon environment, the flame thickness is $\sim 4 \times 10^{-4}$ cm and the speed is $\sim 6 \times 10^6$ cm s^{-1} [5]. The radius of a white dwarf is $\sim 10^8$ cm, meaning a full direct numerical simulation of a supernova would need to span 13 orders of magnitude. We are interested in understanding the microphysics of flames, which will be necessary for sub-grid modelling for large calculations.

The calculation presented here was set up by mapping a steady-state flame solution onto a grid with a superposed vortex given by the stream function [3]:

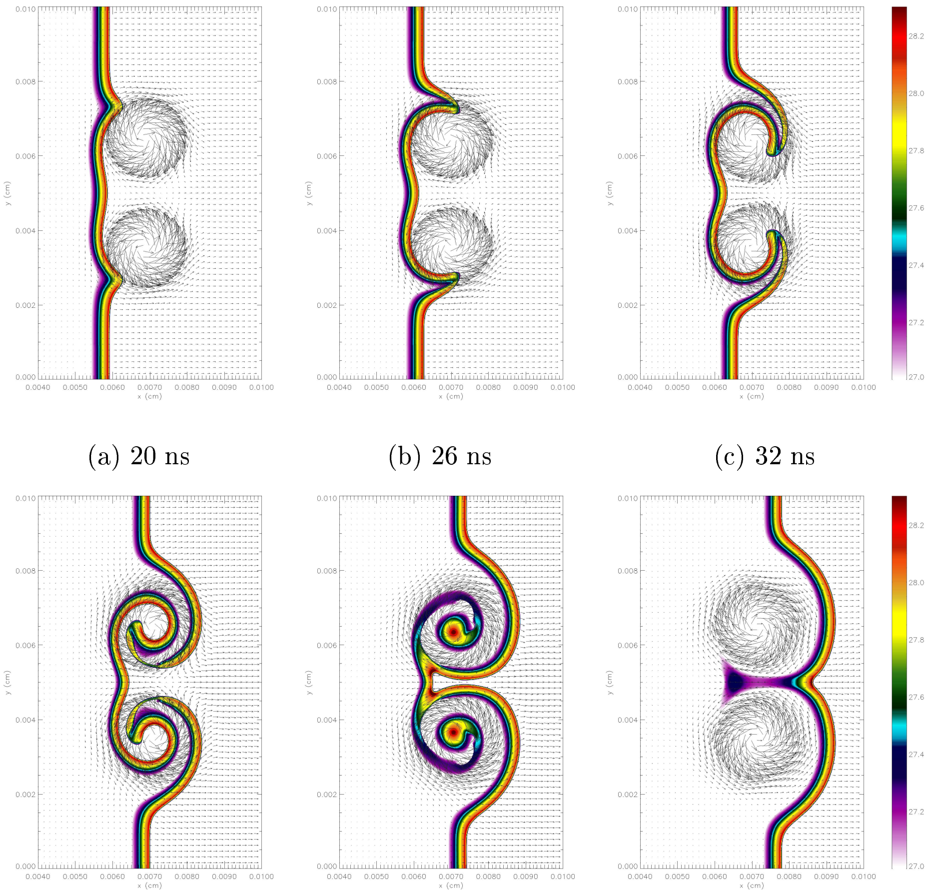
$$\Psi = Ce^{\left((x-x_{\rm ctr})^2+(y-y_{\rm ctr})^2\right)/2R_{\rm vortex}^2} \tag{1}$$

There are two free parameters: the vortex size ($R_{\rm vortex}$) and the amplitude (C). Additionally, the distance between the vortices must be chosen such that they do not overlap. The boundary conditions transverse to the direction of propagation are periodic, and they are zero-gradient along the direction of propagation.

We look at a single case here (see Fig. 1), where the vortex size is greater than the flame thickness ($R_{\rm vortex} = 5 \times 10^{-4}$ cm). The figures show the flame shortly after encountering the vortex pair. We see that the flame wraps around the vortices, but at no point is the flame disrupted. Additionally, no unburned fuel survives behind the front.

CONCLUSION

We have simulated a wide range of flame-vortex interactions, and no quenching has been observed. In contrast to the chemical cases, there is no heat loss to the walls of the system that help the quenching process. In none of the simulations does unburned fuel persist behind the flame front. A full anaylsis of these simulations will appear in Zingale *et al.* [6].



(a) 20 ns (b) 26 ns (c) 32 ns

(d) 38 ns (e) 44 ns (f) 50 ns

FIGURE 1. Time sequence of a flame encountering a vortex whose size is > the flame thickness. Log10 of nuclear energy generation rate is shown.

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