Asymmetric Explosions of Type Ia Supernovae

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ABSTRACT

The burning speed of a thermonuclear supernova front could be described by the fractal model of combustion. We have examined the effects of magnetic fields on the fractalization of the front considering a white dwarf with a nearly dipolar magnetic field and found an intrinsic asymmetry on the velocity field of the expanding plasma. For white dwarf’s magnetic fields of $10^8 - 10^9$ G at the surface, and assuming a field roughly 10 times greater near the center, we have found asymmetries in the velocity field > 10 – 20% at $\rho \sim 10^8$ g cm$^{-3}$, produced between the magnetic polar and the equatorial axis of the remnant. This effect may be related to the asphericities inferred from spectro-polarimetric observations of very young SN Ia remnants (for example: the SN 1999by).

In the present work, we analyse the dependence of the asymmetry with the composition of the white dwarf progenitor.
1. Introduction

The explosion of a type Ia supernova begins with the combustion at the center of a Chandrasekhar mass white dwarf of carbon-oxygen (C+O) or oxygen-neon-magnesium (O+Ne+Mg) fuels. The heat is transported mainly by conduction due to degenerate and completely relativistic electrons as a subsonic deflagration wave propagating outwardly of the star. The deflagration front born laminar is subject to several hydrodynamic instabilities such as Landau-Darrieus (LD) and Rayleigh Taylor (RT) instability (Arnett & Livne 1994, Khokhlov 1993) that produce an increment of the area at which the nuclear reactions take place. This causes an increase of the nuclear energy generation rate and consequently an acceleration of the front.

The combustion front is stabilized by the merging of cells, the formation of cusps, and the expansion of the exploding star. This leads to the formation of a cellular structure at microscopic scales. The bubbles that grow due to RT instability are also subject to Kelvin-Helmoltz (KH) or shear instability when nonlinear stabilization fails. The onset of the KH instability marks the transition to the fully developed turbulence regime at the lower scales. During this, fluid motions are characterized by the formation of a turbulent cascade in the inertial scales where viscous dissipation is not important. This turbulence can be described by the Kolmogorov’s scaling law.

The fractal model for the combustion (e.g., Timmes & Woosley 1992, Niemeyer & Woosley 1997) has achieved some success on describing the acceleration of wrinkled flames both in experiments and also in numerical simulations. The velocity of the flame in this case is given by:

\[
v_{frac} = v_{lam}(L/l_{min})^{D-2}
\]  

(1)
Where \( v_{\text{frac}} \) is the effective fractal velocity and \( v_{\text{lam}} \) is the laminar velocity of the flame; \( L \) and \( l_{\text{min}} \) are the greatest and minimum scales, respectively, of preturbations which are R-T unstable; and \( D \) is the fractal dimension of the front. The derivation of the value of \( D \) for a turbulent combustion regime has given \( D = 2.25 - 2.5 \) (see Ghezzi, de Gouveia Dal Pino & Horvath 2001), which is in agreement with previous numerical results (Blinnikov, Sasorov & Woosley 1995).

2. Magnetic field effects on the fractalization of the combustion front

We have incorporated the effects of magnetic fields on the fractal growth of the combustion front assuming that the progenitor star of a SN Ia is a magnetized white dwarf with a centered dipolar magnetic field with strengths at the surface \( 10^8 - 10^9 \) G (see Jordan 1992) and roughly 10 times greater near the center. Using the fractal model described above we have found that the presence of the magnetic field causes the effective velocity of the flame at the magnetic poles (\( v_{\text{pol}} \)) to be larger than that at the equator of the star thus producing an asymmetry in the explosion of the SN Ia (Ghezzi, de Gouveia Dal Pino & Horvath 2001):

\[
\frac{v_{\text{pol}}}{v_{\text{eq}}} = \left( \frac{B^2/8\pi + \rho v_{\text{lam}}^2/2}{\rho v_{\text{lam}}^2/2} \right)^{D-2}. \tag{2}
\]

For the evaluation of this equation we have used a fractal dimension \( D = 2.5 \), and taken the remaining data from Timmes & Woosley (1992). We note that our analysis is applicable only for densities \( \rho \geq 10^7 \) g cm\(^{-3} \), since the turbulent motions could destroy the corrugated flamelet regime for lower densities (Niemeyer & Woosley 1997), and in this case the fractal model is no longer applicable.

Figure 1 displays the percentage of asymmetry in the velocity field as a function of
the internal magnetic field strength at a middle radial distance $\sim 8 \times 10^7$ cm from the center of the star (where the fuel density is $\rho \sim 10^9$ g cm$^{-3}$) for white dwarfs with different compositions. For example, for a composition of $X(^{12}\text{C}) = 0.2$ and $X(^{16}\text{O}) = 0.8$, we have used $v_{l,am} = 0.415 \times 10^5$ cm s$^{-1}$. We see that the asymmetry is sensitive to the composition of the progenitor. Heavier progenitors show higher asymmetries since their laminar velocities are smaller, so that the kinetic energy term becomes less dominant with respect to the magnetic energy term in the asymmetry equation above.

Figure 2 shows the asymmetry on the combustion front at a density $\rho = 10^8$ g cm$^{-3}$. The total asymmetry increases with increasing radius (or decreasing density) and is larger for progenitors with heavier compositions.

3. Conclusions

An asymmetry in the velocity field is developed by the presence of a dipolar magnetic field during the fractal growth of the deflagration front of a type Ia supernova that can lead to the formation of a prolate remnant. The magnetic field introduces an effective surface tension in the equator of the white dwarf progenitor that reduces the velocity of the combustion front at the equator, $v_{eq}$, with respect to the velocity at the poles, $v_{pol}$, so that $v_{pol} > v_{eq}$. The asymmetry is larger for heavier progenitors\footnote{In this work we calculated the "instantaneous asymmetry values" at a given density, as we will show (see Ghezzi et al. 2002, and Ghezzi 2002) integrating the effect over the explosion leads to higher asphericity of the remnant.}. In particular, for progenitors with a composition $X(^{12}\text{C}) = 0.2$ $X(^{16}\text{O}) = 0.8$, $\Delta \rho/\rho = 0.415$, and surface magnetic fields $\sim 10^8$ G, a 10 to 20% asymmetry has been found at a middle distance from the center of the star (see Fig. 2).
As only a small fraction of the observed white dwarfs are inferred to have magnetic fields higher than about $10^8$ G, asymmetries are not expected to occur very frequently. Nonetheless, recent spectropolarimetric observations have revealed a linear polarization component in the radiation of very young SN Ia remnants, which suggests that prolate atmospheres with asymmetries > 17% are producing it (see Leonard, Filippenko, & Matheson 1999, Wang, Wheeler & Höflich 1997 and Howell, Hoeflich, Wang & Wheeler 2001). The model presented here offers a plausible explanation for such observations.

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Figure Caption

Figure 1. Asymmetry percentage in the field velocity for progenitors with different initial compositions at $\rho \simeq 10^9$ g cm$^{-3}$, as a function of the central magnetic field strength. The asymmetry has lower values at higher densities. So this figure represent the lower values for the asymmetry, since the central density values of the progenitors are of the order of $\sim 10^9$ g cm$^{-3}$. From this figure is possible to see that heavier compositions show higher asymmetry values.

Figure 2. Asymmetry percentage for two different progenitors with compositions $X(^{12}\text{C}) = 0.2 \ X(^{16}\text{O}) = 0.8$, for the full line and $X(^{12}\text{C}) = 0.5 \ X(^{16}\text{O}) = 0.5$, for the dotted line. The calculation were made at a density of $\rho = 10^8$ g cm$^{-3}$. 
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