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CONVECTION, NUCLEOSYNTHESIS, AND CORE COLLAPSE

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ABSTRACT

We use a piecewise parabolic method hydrodynamics code (PROMETHEUS) to study convective burning in two dimensions in an oxygen shell prior to core collapse. Significant mixing beyond convective boundaries determined by mixing-length theory brings fuel (^{12}C) into the convective regon, causing hot spots of nuclear burning. Plumes dominate the velocity structure. Finite perturbations arise in a region in which ^{16}O will be explosively burned to ^{56}Ni when the star explodes; the resulting instabilities and mixing are likely to distribute ^{56}Ni throughout the supernova envelope. Inhomogeneities in Y_e may be large enough to affect core collapse and will affect explosive nucleosynthesis. The nature of convective burning is dramatically different from that assumed in one-dimensional simulations; quantitative estimates of nucleosynthetic yields, core masses, and the approach to core collapse will be affected.

Subject headings: convection — hydrodynamics — nuclear reactions, nucleosynthesis, abundances — stars: abundances — stars: evolution — supernovae: general

1. INTRODUCTION

A problem central to modern astrophysics is the nature of the late evolution of massive stars and, in particular, that of the oxygen-burning shell. This region is important to our understanding of supernovae, as it is where radioactive sources for the supernova light curve (^{56}Ni and ^{57}Ni) are produced, most explosive nucleosynthesis occurs, and most thermonuclear energy is released. It is also here that the surface forms between the collapsed remnant (neutron star or black hole) and the ejected matter. The behavior of this region modifies the evolution before, during, and after the onset of core collapse.

Previous treatments of this region have been seriously flawed. Although the general properties of the evolution are constrained by thermal balance and quasi-hydrostatic equilibrium (Arnett 1972), the nature of convection is not determined by these general principles. Mixing-length theory (Prandtl 1925; Vitense 1953; Böhm-Vitense 1958) is the standard method by which the structure in convective regions is estimated. It successful use in stellar evolution calculations has been demonstrated in the reproduction of the properties of the Herzsprung-Russell diagram. However, mixing-length theory was never intended to describe convection as it occurs in oxygen shell burning (see Spiegel 1963). Here the sound travel time, the convective turnover time, and the nuclear burning time are all of the same order as the evolutionary time, and nuclear energy sources and neutrino cooling are ongoing in the convective flows. These environment characteristics are unlike those of any multidimensional convection simulation to date.

It has recently become possible to compute directly the hydrodynamic behavior of oxygen-burning shells (Arnett 1994); the evolution within a narrow sector ($\pi/10$ in colongitude angle θ) was examined at moderately high resolution. We improve and extend these methods and calculate the evolution of an oxygen-burning shell for several turnover times in a full range (2π radians) of colatitude angle ϕ. We find that the nature of such convective burning is dramatically different from the picture upon which the one-dimensional computations of the late stages of stellar evolution are based.

2. COMPUTATIONAL DETAILS

The code PROMETHEUS (Fryxell, Müller, & Arnett 1991; Müller, Fryxell, & Arnett 1991; Arnett 1994; Arnett & Livne 1994) was used. It is based upon the piecewise parabolic method (PPM) of Colella & Woodward (1984) and Woodward & Colella (1984). Details and further references may be found in these papers. We have improved the treatment of boundaries: (1) there is no significant loss of material from the computational grid, (2) we use the initial one-dimensional model to define the radial boundary conditions, and (3) we use periodic conditions in angle and a full range in angle rather than a small sector. This allows us to extend the computations to longer times and examine the behavior of the whole convective region, rather than a narrow wedge. There is a reduction in resolution of the flame zone itself, but both a comparison with Arnett (1994) and new calculations also having better resolution suggest that this does not affect the qualitative nature of the results.

The initial model is essentially the same as in Arnett (1994); it corresponds to a region containing the oxygen-burning shell in a helium core of 6 $M_\odot$ and is representative of stars of initial masses ranging from about 15 to 30 $M_\odot$. We note that rotation could affect the outcome of simulations such as ours; this complication would require full three-dimensional calculations. One expected result comes from a preliminary calculation, where long-lived vortices normal to the convective flow occur (Brummell, Hurlburt, & Toomre 1994).

3. RESULTS

As the evolution begins, there is a transient readjustment as the artificially imposed mixing-length convection is replaced by a self-consistent hydrodynamic flow. This new convective motion is subsonic (Mach number ~0.15) and strongly nonspherical. As Figure 1 shows, a steady state had not developed by the end of the calculation. What is evident, though, is the tendency toward a steady state, especially in the middle and upper portions of the convective region. However, the flux

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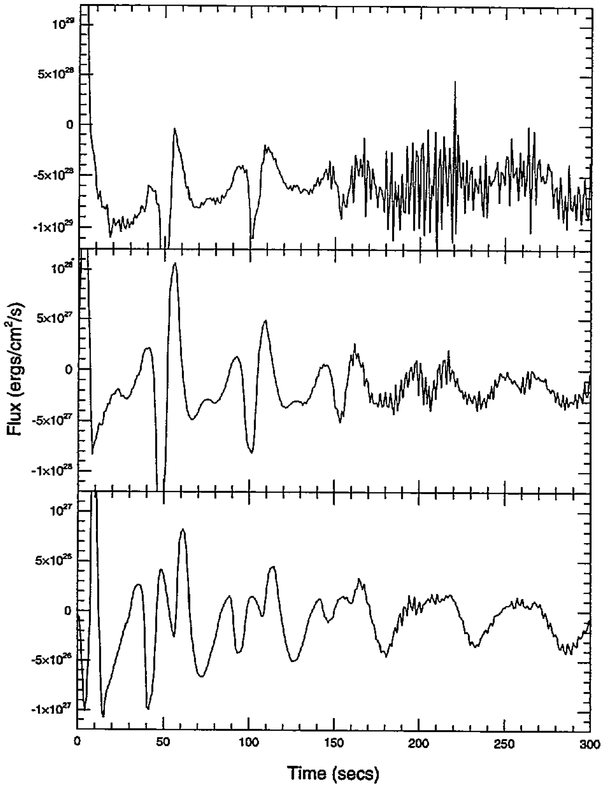

FIG. 1.—Total energy flux history near base of convective zone (*top*), in the middle of the convective zone (*middle*), and near the top of the convective zone (*bottom*).

history near the bottom of the convective zone shows a rich history of oscillations, which we believe is an indication of the interaction of the convective flow with neutrino cooling, which dominates the energy source term in this region and the oxygen-burning zone just below.

In fact, since the total duration of the calculation was approximately one-third of the estimated evolutionary time remaining, we feel that a steady state is unlikely to appear at all before core collapse. This also follows from the reasoning that our simulation covers no more than three mixing timescales (~100 s) and that the total time from beginning to end of shell oxygen-burning in the corresponding one-dimensional model (~1500 s) subtends no more than 15 mixing timescales. In two-dimensional box models (Hurlburt, Toomre, & Massaguer 1984), it was apparent that many more mixing timescales are needed to attain a steady state. An additional difference to consider is that these box models utilized a steady energy source, while in our case, reactions are coupled self-consistently to abundances of nuclear fuels and to thermodynamic conditions by the hydrodynamic flows. We clearly have a much more complex and dynamic problem.

A very important aspect of these calculations is that significant composition inhomogeneity arises due to incomplete mixing. This is shown in Figure 2, which displays 20 contours in nucleon fraction of Si-Ca, spaced by a factor of 5%. The velocity vectors show pronounced downdrafts which carry potential nuclear fuel (^{12}C) from stable regions toward the hotter regions of the convective zone. Such penetrative convection into stable regions is a hallmark of all multidimensional convection simulations (Hurlburt 1986 et al. 1986; Zahn 1991; Hurlburt et al. 1994) and is normally referred to in the stellar evolution community as "overshoot." As is evident here, penetrative convection is hardly spherical and is not easily related to the idea of spherical overshoot. In the entire convective region, spherical symmetry no longer exists. The descending plumes exhibit lowered entropy due to both neutrino cooling and the ambient entropy of material incoming from penetrated regions.

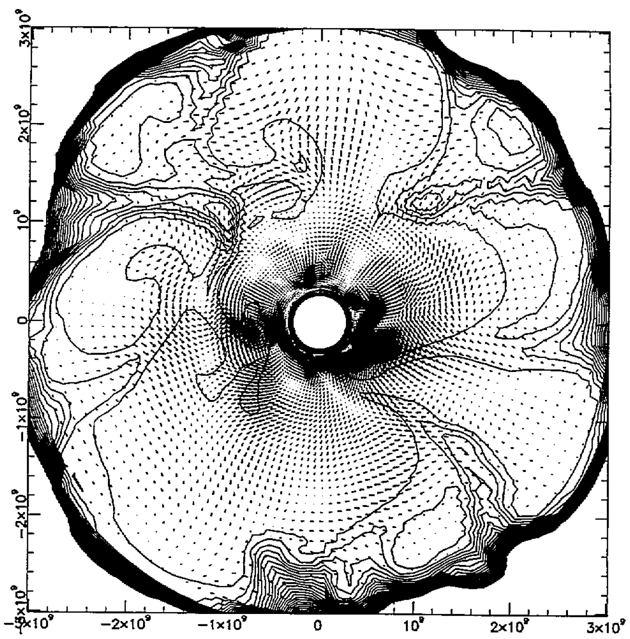

FIG. 2.—Silicon-calcium abundance

These velocity structures are reminiscent of those seen in two- and three-dimensional hydrodynamical simulations of convection (Hurlburt, Toomre, & Massaguer 1984; Cattaneo et al. 1991; Chan & Sofia 1989). However, quantitative comparison between such simulations and ours is difficult, as the former do not include the interaction between energy sources and sinks (i.e., nuclear burning and neutrino cooling) and the convective dynamics. An example of this interaction between flow and heating appeared in a simulation in which we attempted to impose periodic boundary conditions on a $\Delta\theta = \pi/2$ colongitude wedge. Impedance mismatches quickly fed back into the nuclear heating routines, resulting in an azimuthally travelling spiral shock.

As the downdrafts sink, and heat by compression, their fuels begin to burn, making hot spots and affecting the flow. This is seen in Figure 3, which shows contours of the rate of energy release by thermonuclear reactions. Several hot spots due to sinking matter are shown. A third hot spot occurs in the oxygen-burning shell itself; the burning in the shell is also strongly heterogeneous. In Arnett (1994), which resolved the flame zone of the oxygen shell more completely, we found that the burning was strongly coupled to the hydrodynamic motion and that much of the burning occurred outside the region of most rapid mixing. These calculations exhibited strong rising plumes from the flame zone; here we find dominant descending plumes of a more global nature. We expect that a high-resolution, full-angle computation would simply show both. Combining these results, we have a consistent picture in which the nature of the convective flow is qualitatively different from the steady, well mixed, discretely layered picture used in one-dimensional stellar evolution calculations.

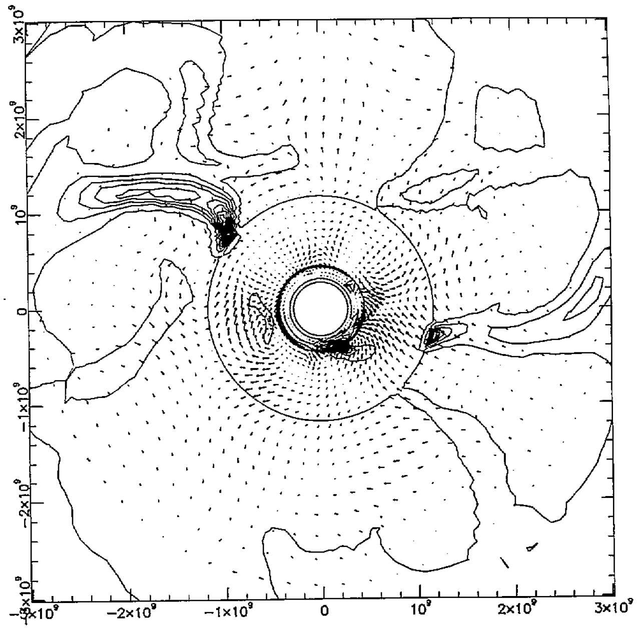

FIG. 3.—Hot spot burning

The inhomogeneity seen in the composition also occurs in other variables. Significant perturbations occur in density, temperature, pressure, and electron fraction; these are of order 5%, 1%, 3%, and 0.08%, respectively. In regions where Y_e equals 0.499, for example, this Y_e perturbation translates to a perturbation of 36% in neutron excess η. From this, we certainly expect inhomogeneities in isotopic abundances to develop during explosive nucleosynthesis, but not so much as to excessively pollute the interstellar medium with neutron-rich species (i.e., ^{58}Fe). While perturbations of the thermodynamic variables seem to have settled to a relatively constant average value, perturbations in composition may grow to larger values if calculations are taken to longer times.

4. IMPLICATIONS

To what extent do these results negate the extensive efforts made to predict nucleosynthesis yields from massive stars? The general features of the bulk yields will probably survive nicely. The constraints of (1) thermal balance in the convective region and (2) quasi-hydrostatic structure strongly restrict the conditions for shell burning and convective extent. The "glitchy" nature of the one-dimensional models with stellar mass is already smoothed by integration over an initial mass function. Quantitative yields from individual stars may well change, however.

The inhomogeneities in composition and the hot spot burning are likely to change the details of nucleosynthesis during this stage of stellar evolution. It is comforting that the range of variation seems to lie near that needed for synthesis of the solar abundance pattern, so that the new picture may be at least as successful as the old. We also expect that presupernova core masses will be modified from the results of one-dimensional calculations.

The perturbations which arise naturally from convection in the oxygen-burning shell have an amplitude and position which will enhance the mixing of ^{56}Ni; possibly solving the discrepancy with the observations of SN 1987A. We will discuss this in detail in a subsequent publication.

This particular model falls into a range of initial mass where the convective oxygen shell contains its greatest mass relative to the star. For initial masses both smaller and larger than our model (20 $M_{\odot}$), convective oxygen shells span a range of sizes. In subsequent work, we plan to examine how convective oxygen shells actually contribute a stellar evolution over the range of presupernovae massive stars.

In basing the convective aspects of oxygen burning on a better representation of the physical processes, we find that the nature of convective burning is dramatically different from the picture now used in one-dimensional computations of stellar evolution.

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