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I. Introduction

The current front-runner for the mechanism of core-collapse supernovae is that advanced by J. Wilson (1985) in a series of papers starting in 1983. The essence of this mechanism is neutrino energy deposition in the semi-transparent shocked outer mantle at hundreds of kilometers over a period long ($\sim$ 100's of milliseconds to seconds) compared with dynamical times ($\sim$ milliseconds). The stalled accretion shock is eventually reenergized as the ram pressure of the infalling material subsides, the protoneutron star is fattened, and its envelope becomes radiation-dominated (Bethe & Wilson 1985; Lattimer & Burrows 1984). Precursor pulsations and the accretion luminosity itself figure prominently in this scenario. Recently, Bruenn (1992) has achieved explosions via a similar "second chance." However, both Wilson's and Bruenn's explosions are anemic ($\leq 0.5\times10^{51}$ ergs) and problematic, depending on details in an uncomfortable way.

In parallel with the development of the delayed mechanism has been the realization that a number of hydrodynamic instabilities should operate both early in the core (Burrows 1987) and later near the shock wave (Bethe 1990). Whether these "convective" motions are curiosities or are central to many of the crucial remaining questions of supernova and neutron star birth theory is not known. In this short note, we assume the latter and list some of the new ideas

and possibilities that follow from violations of spherical symmetry. We have just completed a series of 2D hydrodynamic simulations of the early mantle ($\lesssim$ 150 kilometers) instability during the first 30 milliseconds after core bounce (Burrows and Fryxell 1992) and have discovered some interesting phenomena that deserve further investigation. In addition, Herant et al (1992) have recently studied "hot bubble" convection (Bethe 1990) driven by neutrino heating at larger radii (> 200 kilometers) and at later times (> 100's milliseconds). Furthermore, Mayle and Wilson (1988) and Mayle (1985) have championed "salt-finger-" like instabilities in the core whose mixing motions they suggest might enhance the core neutrino fluxes that drive the otherwise spherically symmetric delayed explosion. Wilson believes that the 20% boost in the neutrino luminosity (L_ν) that obtains is crucial to the mechanism. We believe that the mantle instability driven by negative entropy gradients, if it persists, is much more important in boosting L_ν and that, if salt-fingers form, their effect is swamped by standard Raleigh-Taylor-like mantle overturn and the subsequent convection. The Herant et al (1992) hot bubble convection operates, if it operates, still later and stands in the wings if earlier phenomena fail to launch the supernova. Nevertheless, whether early or late, deep or in the bubble, instabilities must be addressed in a new multi-dimensional world of supernova theory.

II. The Early Mantle Instability

Since it is quite natural for the bounce shock and neutrino transfer to impress exotic composition (lepton or electron number) and entropy profiles during the violent dynamics of neutron star birth and a supernova, one should not be surprised that the residue is unstable via the Ledoux criterion in a substantial fraction of its volume. Negative entropy gradients and negative lepton gradients (akin to positive molecular weight gradients) are created that drive Raleigh-Taylor-like

overturning motions. When the bounce shock forms, its progress creates a positive, stabilizing entropy gradient that turns into a negative, unstable entropy gradient as it stalls near an interior mass of 1.0 $M_{\odot}$.

Thus, the inner core is stabilized against immediate overturn, while the mantle near a radius of 80–100 kilometers experiences almost immediate ($\leq$ 10 milliseconds) interchange. This is what we have termed mantle or "shock-spike" convection and is on what we focus here. We caution that a great deal remains to be done concerning the nature, consequences, and duration of this instability and that we have merely taken a short and tentative step towards understanding it.

The first generation of papers concerning convection in core-collapse supernovae began with the paper of Epstein (1979), in which the possibility of lepton-driven microconvection was aired. This was followed by a series of papers in which explosive core overturn (Colgate and Petschek 1980; Livio, Buchler, and Colgate 1980), instability-driven pistons (Smarr et al 1981), or neutrino-driven explosion via lepton-driven overturn (Bruenn, Buchler. and Livio 1979) were advanced. These works, while stimulating, suffered from a variety of short-comings, foremost among which were unrealistic equations-of-state, unrealistic initial models, and crude simulation techniques. They all believed that it was the negative lepton gradient that drove the instabilities. After the paper of Lattimer and Mazurek (1981), it was realized that the shock spike stabilized the negative lepton gradient and that total core overturn did not occur. However, the potential of the outer, negative entropy gradient to drive interesting motions was starting to be appreciated (Arnett 1987; Burrows 1987; Burrows and Lattimer 1988).

The character of the early development of mantle convection can be understood with simple

back-of-the-envelope arguments. The Brunt-Väisälä frequency is given by,

$$\begin{aligned} N^2 &= -g\left(\frac{\partial \ln \rho}{\partial r} - \frac{1}{\gamma}\frac{\partial \ln P}{\partial r}\right) \\ &= -\frac{g}{\gamma P}\frac{\partial P}{\partial S}\bigg|_{\rho,Y}\left[\frac{\partial S}{\partial r} - \frac{\partial S}{\partial Y_\ell}\bigg|_{\rho,P}\frac{\partial Y_\ell}{\partial r}\right] , \end{aligned} \tag{1}$$

where all the symbols have their standard meanings. Eq. (1) makes clear that entropy and composition gradients can make N imaginary and, hence, can drive instability. For a representative set of numbers in the stalled shock context $\left(\gamma \sim \frac{5}{3}\ ,\ g \sim 10^{12}\,\mathrm{cm/s^2}\ ,\ \frac{\partial(S/R)}{\partial r} \sim 0.1/\mathrm{km}\right)$, we find that N $\sim$ 300–1000 rads/s and can derive turnover times of $\sim$ 3–5 milliseconds, velocities of $1 - 3 \times 10^9$ cm/s (Mach # $\sim$ 1), kinetic energies in the overturning mantle of 10^{51} ergs, and hydrodynamic powers of 10^{53} ergs/s. It is interesting to note that the kinetic energy in the convecting mantle is approximately equal to the energy that was required to dissociate the nuclei in its $\sim$ 0.1–0.2 solar masses.

Normally in astrophysical problems that don't involve accretion disks, viscosities are negligible. The Reynolds numbers are too high for shear forces to compete with inertial terms. However, in the early protoneutron star context, neutrino viscosities can be appreciable (Burrows & Lattimer 1988). (The product of the neutrino energy density and mean free path is large.) Estimates yield for the kinematic viscosities (ν) in the mantle values of 10^{9-14} cm^2/s and for the dynamical viscosity (μ) values near 10^{22} gm/[cm $\cdot$ s]. Thelatter is comparable to that in the Earth's crust! As peculiar is the Prandtl number $\left(\frac{\nu}{\chi} = \frac{\text{viscosity}}{\text{heat conduction}}\right)$, which for the sun ranges between 10^{-6} and 10^{-9}, but for a young neutron star is near 10^{-2}. This value is comparable to those for liquid sodium and liquid mercury. With a viscosity like that in the Earth's mantle and a Prandtl number like that of molten metal, the protoneutron star is indeed an exotic beast. One derives initial Reynolds numbers in the convecting mantle of 10^{1-3} and an inertial range ($\sim$ Re$^{3/4}$) of

30–200. This implies a dissipation scale of kilometers (see, however, Thompson and Duncan 1992 for a discussion of a "double cascade"). The calculations we have performed ignore viscosity and radiative transfer and are meant to stimulate and goad the theoretical community into a serious consideration of the multi-dimensional nature of protoneutron stars. However, the problems that will be encountered when viscosity and transfer are included promise to be fascinating and unique.

We choose not to display here in detail the results of our first series of calculations and refer the interested reader to Burrows and Fryxell (1992). However, Figures 1 and 2 depict in qualitative terms the violent and dramatically aspherical nature of the mantle instability. Figure 1 is the entropy distribution at 12.5 milliseconds employing a grayscale to bring out the features. Figure 2 depicts a similar electron fraction distribution at 20 milliseconds. While the inner core remains stable, the outer mantle between 30 and 160 kilometers is involved in large-scale motions. there is deep penetration beyond the linearly unstable region and significant overshoot. High Mach numbers ($\lesssim 1.3$) are achieved. The composition profile is interestingly modified. The neutrinospheres are breached. The latter is important in as much as an enchancement in the neutrino luminosity is implied. However, whether these motions are transient or will continue and affect by accelerating, energizing, or enabling the delayed explosion mechanism is yet to be determined. We do see that there is no appreciable piston effect and that flickering and hot spots are expected. We surmise that the enhancement in L_ν may be important for the delayed supernova explosion and will dwarf any salt-finger enhancements. However, does convection persist during the early protoneutron star cooling phase ($\lesssim 500$ ms)? Will it effect r-process nucleosynthesis? Will it influence pulsar B-fields or pulsar kicks? Is it generic? Does it seed hot bubble convection? These and other questions are for the future.

Another parallel set of questions involves the neutrino opacities in high-density matter. If Wilson needs a 20% enhancement in L_ν over 100's of milliseconds to get an explosion, why not achieve it by modifying the opacities? Do we really know the mean-free-paths of all neutrino species to better than 20%? I suspect not. Though this possibility may undercut the need for a convective boost, it is sufficiently important to demand closer attention. Fermi-liquid corrections to the opacities due to the $\nu n \rightarrow \nu n$ and $\nu_e n \rightarrow e^- p$ processes and the renormalization of g_A^2 due to the Δ resonance (see Burrows and Lattimer 1986 and references therein), as well as ion-ion correlations and polarization effects (Leinson, Oraevsky, and Semikoz 1988), might provide the missing flux.

III. B-Fields, Pulsar Kicks, and Gravitational Radiation

Whether there is mantle convection or hot bubble convection, such motions will modify the magnetic field structure of the young neutron star. Thompson and Duncan (1992) have recently suggested that mantle convection can power high-Rossby number (not α–Ω) dynamo action. Even if there is no dynamo in young pulsar mantles, any magnetic flux frozen into the core prior to collapse will be rearranged due to convective motions (magnetic diffusivity $\sim 10^{12-14}$ cm^2/s). At the very least, the multipolarity structure and flux distribution will be effected by both mantle and hot bubble convection, if they in fact arise. Since the inner core of the protoneutron star is thought not to undergo such motions, dynamo action in only its mantle may restrict B-fields to the mantle. This would bear on the possible ohmic, etc. decay of pulsar fields inferred from the pulsar data (see e.g. Chanmugan 1992).

One of the most intriguing consequences of convective motions in protoneutron stars may be the impulsive kicks such motions can impart to the residual pulsar. A 1% asymmetry in the

mass motions can give a neutron star a recoil speed near 100 km/s. A 1% net asymmetry in the neutrino emissions can impart a $\sim$ 300 km/s kick. If the turnover time is τ_c, the turbule scale at a radius R is ℓ, and the cooling time is τ, the mean-square anisotropy (A) is roughly $\left(\frac{\tau_c}{\tau}\right)^{1/2} \frac{\ell}{2R}$ (see also Thompson & Duncan 1992). Putting reasonable numbers in gives for A $\sim \frac{1}{2}$%, implying kick speeds of $\sim$ 150 km/s. These numbers are near those derived from pulsar proper motion surveys (Cordes 1986).

The large mass-energy currents suggest that mantle convection will be an interesting source of gravitational radiation. An estimate of the power that might be expected in such waves can be obtained by using $L_{GR} \sim L^2/L_0$ where $L_0 = c^5/G = 3.63 \times 10^{59}$ ergs/s and L is the kinetic energy luminosity in the overturning motions. One obtains $L_{GR} \sim 10^{46-47}$ergs/s($\equiv 10^{-8}\, M_\odot$/s) and $\int L_{GR} dt \sim 10^{-9}\, M_\odot$, a source that if galactic might be detected by LIGO (cf Schutz 1986). Hot bubble convection could also be a source, though the characteristic time would be longer ($\times$10), the luminosity would be lower ($\times \frac{1}{100}$), and the total energy might be lower ($\times \frac{1}{10}$). Note that neither source depends upon rotation.

IV. Conclusion

The thesis of this communication is that protoneutron stars are unstable at birth and that these instabilities might influence the supernova mechanism, puslar kicks, neutron star B-fields, and all major questions that attend stellar collapse. We have presented results from a purely hydrodynamic study of shock-spike or mantle overturn that suggest high Mach numbers, deep penetration, and the violation of the neutrinospheres. It would seem that spherically-symmetric models are not adequate to handle young neutron stars and the early supernova phenomenon and that some of the future of the field lies in multi-dimensional simulation.

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Figure Captions

Figure 1. The entropy distribution 12.5 milliseconds after the shock stalled, shown in grayscale. The inital model was taken from the same source as in Burrows and Fryxell (1992), the zoning was $300(r) \times 200(\theta)$, periodic boundary conditions were used at $\theta = 0$ and $\theta = 90°$, and a random velocity perturbation of 5% of the local speed of sound was imposed initially on a zone-by-zone basis.

Figure 2. The same as Figure 1, but for the electron distribution at 20 milliseconds after the shock stalled ($\sim$ 10 milliseconds after bounce).

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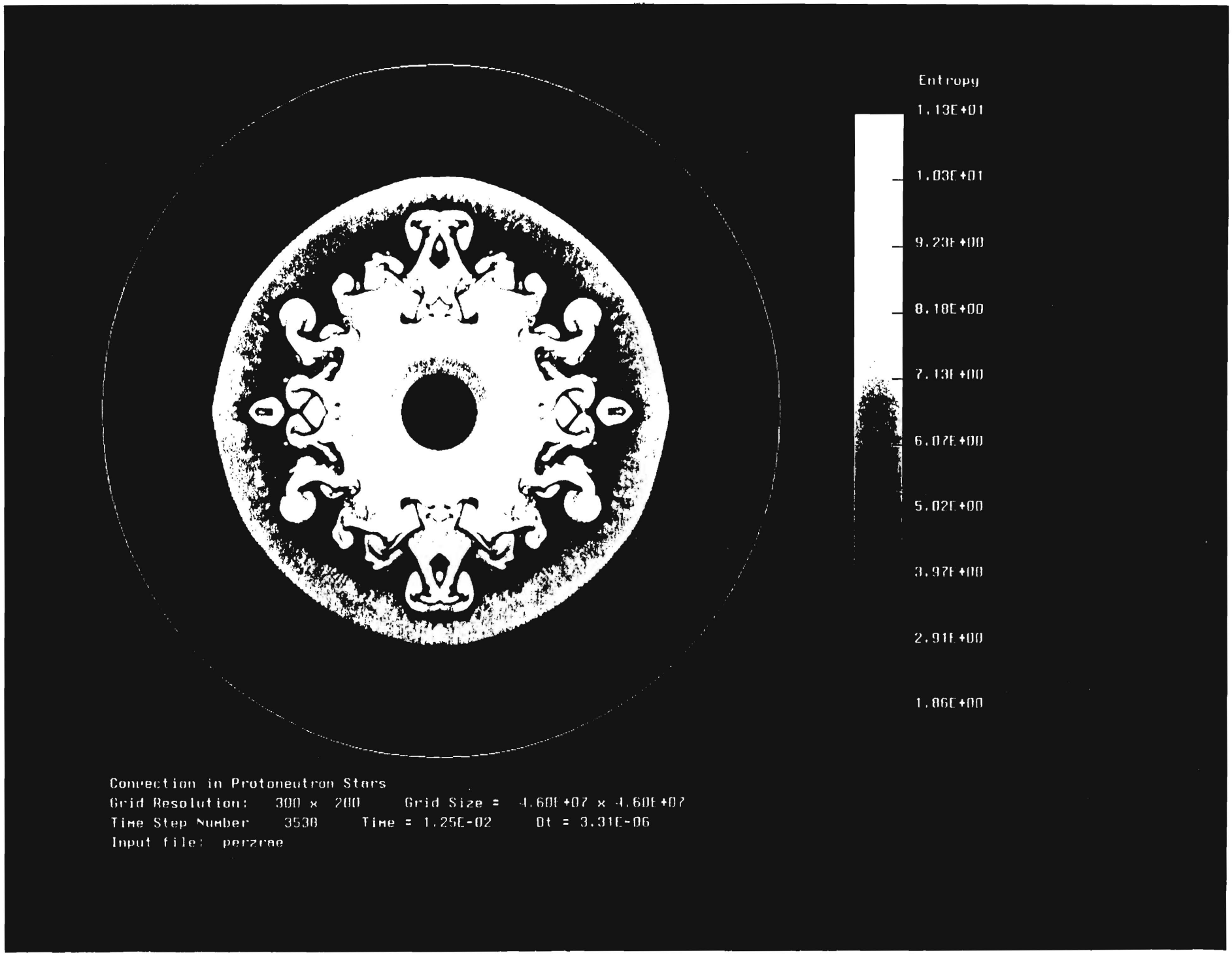
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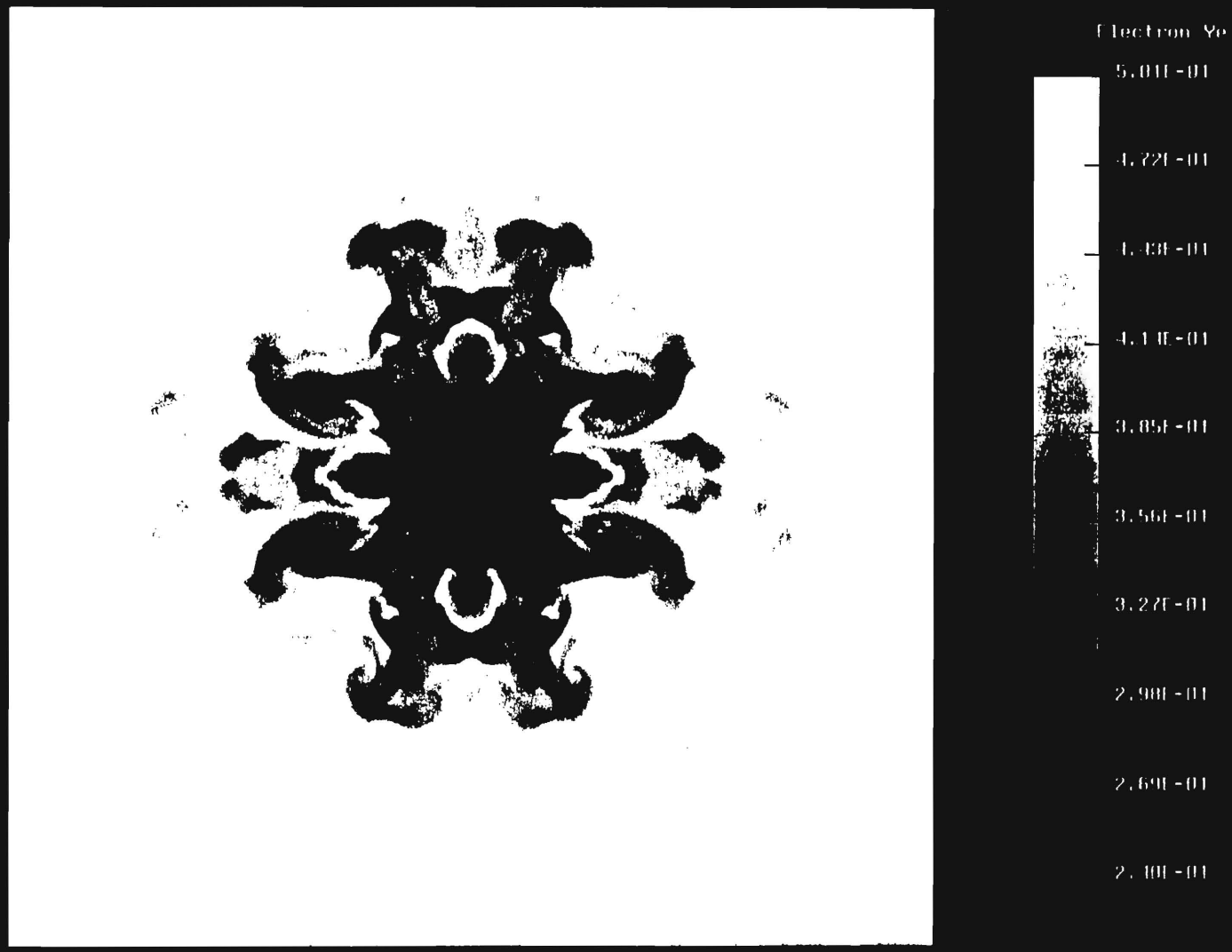
1.03E+01
9.23E+00
8.18E+00
7.13E+00
6.07E+00
5.02E+00
3.97E+00
2.91E+00
1.86E+00
Convection in Protoneutron Stars
Grid Resolution: 300 x 200 Grid Size = 4.60E+07 x 4.60E+07
Time Step Number 3538 Time = 1.25E-02 Dt = 3.31E-06
Input file: perzrae

FIGURE 1



Convection in Protoneutron Stars
Grid Resolution: 300 x 200 Grid Size = 4.60E+02 x 4.60E+02
Time Step Number 5884 Time = 2.00E-02 Dt = 3.13E-06
Input file: perzrab

FIGURE 2