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Turbulence in the First Stars

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Abstract. We present preliminary results of 2-D simulations of the effects of turbulence in the mixing of Pair Instability Supenovae. We make use of the FLASH code to evolve initial 1-D models of post-bounce PISNe and seed turbulence in form of velocity perturbations. We identify the energetic and spatial scale for the turbulence to have mixing effects on the metal shells inside the star. Under the conditions we examine, we observe some mixing but the onion structure of the metal distribution is not disrupted.

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DUST FORMATION IN PRIMORDIAL ENVIRONMENTS

The transition between the first and the second generation of stars is one of the most intriguing and challenging topics of the field, whose relevance has been pointed out again in this conference (and stressed by the suggestion of adopting a non-trivial terminology). The effects of metals and dust in the process of stellar formation is still a non totally explored ground and the main current problems have also been summarized in these proceedings [1]. It has been shown [2], [3], and more recently in [4], that dust can induce fragmentation in extremely metal-poor environments, namely with metallicities as low as $Z=10^{-5\pm1}Z_{\odot}$. Understanding and quantifying dust formation and propagation in the post-First Star environment is of crucial importance in drawing the picture of the "IMF-transition". Several papers have studied these processes with semianalitical models, examining the environment of Supernova ejecta and how the dust formation proceeds. In particular [5] developed a model to estimate the amount of dust formed in Supernova ejecta, which they tested against 1987A observation; more recently this method has been reviewed and applied to Pair Instability Supernovae, [6]. These models rely on the assumption that the innermost part of the star, from the central part up to the base of the helium shell, gets totally mixed while the shock gets to the surface of the star, or in the very early times after the explosion, on timescales negligible with respect to the ejecta evolution ones. This means that metals are assumed to be entirely mixed when dust formation becomes efficient and nucleation reactions can take place in an environment where all reactants are at contact. What happens if reactants are separated, namely if the shells do not run into each other and the metals are not well-mixed? In these proceedings we present preliminary results on the efficiency of purely hydrodynamical effects in mixing the elemental shells during the explosion phase of a PISNe. We aim to check whether during the shock propagation up to the surface of the star, and later during the first phases of the SN ejecta expansion, instability driven perturbations are able to mix the inner part of the star, and to which extent. This may put sounder basis to the assumptions underlying the studies in dust formation, or raise the possibility that the initial assumptions might have to be reconsidered.

OUR MODEL

For the preliminary results presented in these proceedings we use an initial 1-D model of zero-metallicity, $200M_{\odot}$ kindly provided by A. Heger. The model is taken at t_0=100s after the bounce over the maximum central density of the core, and the material is expanding outward with velocities up to $v_{exp} \approx 10^9$cm/s in the inner parts of the star ($R<10^{12}$cm), while it is still collapsing towards the center in the outer part. We have mapped the initial model into a 2-D space and run it with the FLASH code in cylindrical coordinates. Owing to the extreme sensitivity of the problem to thermodynamic properties we have test our results against the original 1-D model, and found that an adiabatic equation of state fails to reproduce the correct results in the first 1000 seconds after the bounce; we therefore use an Helmholtz EoS.

The method adopted in these proceedings is a naive but very efficient one in exploring the sensitivity of the problem to numerical diffusion, spatial and energetic scale. Namely, we set turbulence in the form of velocity perturbations of our initial radial profile; they are set at a uniform local energy (or velocity module v_p) all over the volume of the star within a well defined

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radius R_p, and are spatially randomly oriented. Within such radius we impose a constant resolution, thus being able to keep constant the dimension of the cell, and therefore of the spatial scale on which the perturbation is applied. First, given the nature of the problem, we have carefully checked the spatial scale in order to exclude that the effects we observe are due only to numerical diffusion from the grid, and second to understand the spatial scale on which perturbations starts being effective in mixing the material. Indeed, in our study numerical diffusion is actually negligible: we have tested our model by running it on different resolutions, with no initial perturbations, and found the profile remained spherical up to the end of our run ($t_{max} \approx 10^5$s after the bounce). For the rest of our runs we have set our perturbations within a radius $R_p = 10^{12}$cm, thus including in the "perturbed" region both the shocks and the bottom of the helium shell, above which hydrogen and helium are the only components of the stellar model we study. Within this region we have set a uniform resolution and applied the velocity perturbation on each cell, thus simulating uniform "bubbles" of gas of the size of the cell, which move coherently at the time we start the simulation; the perturbations are set only on the first step, then the gas is set free to evolve. We have also tested the energetic scales on which the perturbations start affecting the mixing, noticing that only perturbations approaching the sound-speed regime may sensitively affect the hydrodynamics; namely we have found that some effects start to be observable when $v_p = 1/10$ of the local sound speed, c_S. We have also performed tests by running perturbations whose intensity was gaussianly distributed around a central value, reporting the same conclusions as above.

In Table 1 we show the density profiles at $t = 10^4$s after the bounce, with the perturbation applied on different scales. As it could be naively expected, perturbations set initially on bigger scales do create more consistent effects. However, even in the case of bubbles initially set on scales of 10^{10}cm, no disruption of the shock is observed, and the explosion of the star proceeds almost unperturbed.

In Table 2 we show the effects of perturbations with ($v_p = 1/10\ c_s$) seeded on the smallest scale we are able to reproduce $L \approx 10^8$cm on the elemental shells in the inner part of the star. We do observe some mixing, although that is mostly driven by the turbulence at the boundary between different shells, and the shells are not entirely disrupted. It can be seen that the oxygen shell retains its shape, although some minor mixing occurs at the boundaries. At the stage we are able to simulate such process we do not observe total mixing of the metals inside the star.

CONCLUSIONS

The 2-D simulations described here show that under peculiar conditions at the center of the star, initial perturbations can drive some mixing within the inner shells of an exploding star. We have seen that perturbations with an initial velocity $v_p \approx 1/10$ of the local sound speed in the innermost regions (adding an energy injection still negligible with respect to the total energy of the gas) can drive mixing, whose magnitude does anyway depend on the spatial scale of the turbulent bubble. We have not seen total mixing of the elements.

These results can be seen as a lower limit to the mixing before the explosion of the star; similar conclusions are obtained in the case of normal Core Collapse Supernovae [7], although conditions in the center of exploding "normal" CC Supernovae are extremely different from the ones encountered in PISNe. However, turbulence will not happen on a single spatial nor energetic scales, our results will be used to further investigate the effects of mixing driven on scales correlated with physical instabilities at the time of the bounce.

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TABLE 1. Logarithmic density profiles at t=10^4s after the bounce (the scale in the lower left panel is in g/cm^3). Perturbations with v_p=c_S/10, have been initiated on a uniform scale L≈$10^{10/9/8}$cm, clockwise from top left; the size of the box shown is B=8×10^{12}cm, half the radius of the star.

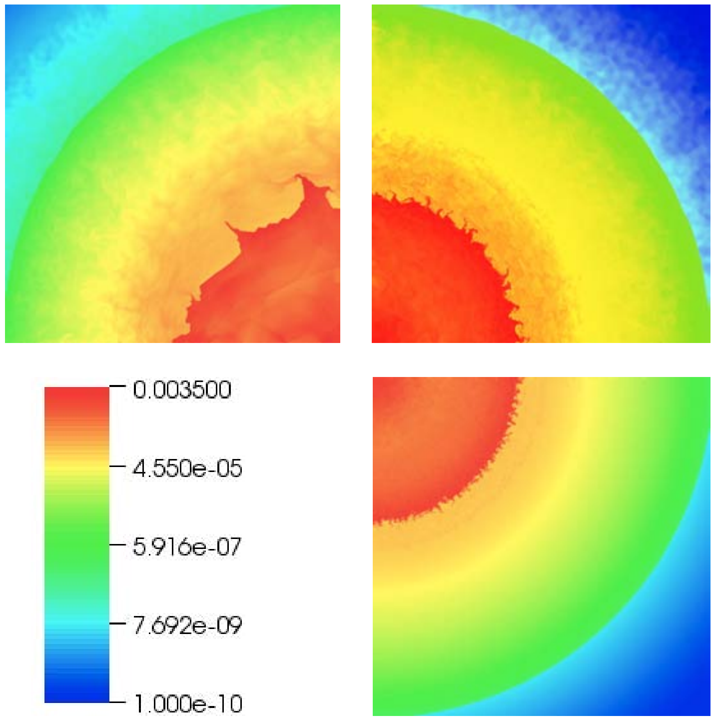

TABLE 2. Elemental abundances at t=10^4s after the bounce. Perturbations with v_p=1/10 of the local sound speed, c_S, have been initially applied on a uniform scale L≈10^8cm. In the left figure: the oxygen shells; in the right one: inner and colored ^{56}Ni and outer in grey, ^{4}He. The size of the box shown is B=4×10^{12}cm.