Angela V, J Phys Res Appl 2021, 5:3

Journal of Physics Research and Applications

Editorial

A SCITECHNOL JOURNAL

The Role of Mixing in Astrophysics

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Received date: May 09, 2021; **Accepted date:** May 16, 2021; **Published date:** May 30, 2021

Editorial

The role of hydrodynamic mixing in astrophysics is reviewed, emphasizing its connections with laser physics experiments and inertial confinement fusion. Computer technology now allows us to use twodimensional simulations, with complex microphysics, of stellar hydrodynamics and evolutionary sequences, and it holds the promise of simulations in three dimensions. Careful validation of astrophysical methods by laboratory experiment, by the critical comparison of numerical and analytical methods, and by observation is necessary for the development of simulation methods with reliable predictive capabilities. The recent and surprising results from isotopic patterns in presolar grains, from twodimensional hydrodynamic simulations of stellar evolution, and from laser tests and computer simulations of Richtmeyer-Meshkov and Rayleigh-Taylor instabilities will be discussed in relation to stellar evolution and supernovae.

In astronomy, mixing is important in two widely different situations. First, there is the mixing of chemically discrete materials. Here we consider the interstellar medium and the sufficiently cold environments where solid particles (grains) may survive (Clayton 1982). This area is exciting now because of the direct experimental identification of presolar grains (see Anders & Zinner 1993, Huss et al. 1994, Bernatowicz & Zinner 1997, and references therein). The second situation involves the mixing of plasma that differs in its isotopic composition; this is vital to the evolution of stars, which produce isotopic and nuclear variations by thermonuclear burning (Clayton 1968; Arnett 1996). Thermonuclear burning is analogous to chemical combustion in many ways and may be as complex. Mixing becomes important in determining whether a flame can spread to new fuel or whether it is choked by the buildup of ashes. Mixing, even to a small degree, can provide indications of ashes that can be used to diagnose burning conditions.

We sometimes forget that stars are really very large. Let us make an order-of-magnitude estimate of diffusion timescales in a dense stellar plasma. It is the nuclei and not the electrons that define the composition. The Coulomb cross section for pulling ions past each other is of order p B10~16 cm2. For a number density NB 1024 cm~3, this implies a mean free path j \ 1/pNB 10~8 cm. For a particle velocity cm s v ~1, this gives a diffusion time d B108 q d \ (*r)2/jv s cm~2. For a linear dimension of stellar d B(*r)2 size, *r \ 1011 cm and yr (or 3000 Hubble q d \ 3] 1014 times!). While one may quibble about the exact numbers used, it is clear that pure diffusion is ineffective for mixing stars, except for extreme cases involving extremely long timescales and steep gradients. Actually, we all know from common experienceÈsuch as stirring cream into coffee (tea)Èthat this discussion is incomplete. To diffusion must be added advection, or stirring. Stars may be stirred too. For example, rotation may induce currents, as may accretion, and pertubations from a binary companion. However, the prime mechanism for stirring that is used in stellar evolutionary calculations is thermally induced convection. The idea is that convective motions will stir the heterogeneous matter, reducing the typical length scale *r to a value small enough so that diffusion can ensure microscopic mixing. For our stellar example above, this would require a reduction in scale of (j/*r)1@2B 10~8. Convection is not perfectly efficient so that the actual mixing time would still be definite. Given that such a limit exists, we must examine rapid evolutionary stages to see if microscopic mixing is a valid approximation. For presupernovae, the approximation is almost certainly not correct so that these stars are not layered in uniform spherical shells as conventionally assumed but are heterogeneous in angle as well as radius. In a discussion of stellar evolution, one encounters the topics of rotation, convection, pulsation, mass loss, micro-turbulence, sound waves, shocks, and instabilities (to name a few), which are all just hydrodynamics. However, the direct simulation of stellar hydrodynamics is limited by causality. In analogy to light cones in relativity, in hydrodynamics one may define space time regions in which communication can occur by the motion of sound waves. To correctly simulate a wave traveling through a grid, the size of the time step must be small enough so that sound waves cannot “jump” ÏÏ zones. Thus, the simulation is restricted to short time steps-an awkward problem if stellar evolution is desired.

Ultimately, simulations must be well resolved in three spatial dimensions. One of the great assets of computers is their ability to represent complex geometries. If we can implement realistic representations of the essential physics, then simulations should become tools to predict È not “post dict“ ÏÏ-phenomena. An essential step toward that goal is the testing of computer simulations against reality in the form of experiment (Remington et al. 1995). This is a venue in which we can alter conditions (unlike astronomical phenomena) and thereby understand the reasons for particular results. Experiments are intrinsically three dimensional, with two-dimensional symmetry available with some effort, so that they provide a convenient way to assess the effects of dimensionality. For Rayleigh-Taylor instabilities, the Nova experiments not only sample temperatures similar to those in the helium layer of a supernova, but they hydrodynamically scale to the supernova as well (Kane et al. 1997; Ryutov et al. 1999). In the same sense that aerodynamic wind tunnels have been used in aircraft design, these high-energy density laser experiments allow us to reproduce precisely a scaled version of part of a supernova. The Nova laser is physically imposing. The building is larger in area than an American football field ; the lasers concentrate their beams on a target about the size of a small ball bearing. This enormous change in scale brings home just how high these energy densities are. Preliminary results show that the astrophysics code (PROMETHEUS) and the standard inertial confinement fusion code (CALE) both give qualitative agreement with the experiment. For example, the velocities of the spikes and bubbles are in agreement with both experiment and analytic theory, which is applicable in this experimental configuration (Kane et al. 1997). The two codes give similar but not identical results. These differences will require new, more precise experiments to determine which is most nearly correct. Great At least for explosive events (such as supernovae, novae, and gamma-ray bursts), there is much overlap in interests between the astrophysics community and those interested in the physics that now can be realized in high-energy density laser facilities. Collaborative efforts are already fruitful and promise to be even more productive.