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Creating Stars, Supernovae, and the Big Bang in the Laboratory: Nuclear Astrophysics with the National Ignition Facility

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A nontechnical summary prepared for the ACS News Service

Summary

This talk has been prepared for the *Symposium on Novel Approaches to Nuclear Astrophysics* hosted by the ACS Division of Nuclear Chemistry and Technology for the San Diego ACS meeting. This talk indeed describes a truly novel approach. It discusses a proposal for the construction of the National Ignition Facility which could provide the most powerful concentration of laser energy yet attempted. The energy from such a facility could be concentrated in such a way as to reproduce, for the first time in a terrestrial laboratory, an environment which nearly duplicates that which occurs within stars and during the first few moments of cosmic creation during the big bang. These miniature versions of cosmic explosions may allow us to understand better the tumultuous astrophysical environments which have profoundly influenced the origin and evolution of the universe.

Nuclear astrophysics is a discipline which seeks to understand the unseen interiors of stars and the first few moments of cosmic expansion during the big bang. In these environments the temperatures exceed tens of millions of degrees while matter can be compressed to thousands of times the density of material which one finds on earth. Under such conditions nuclear reactions occur. It is the release the energy from such reactions which keeps stars like the sun shining. Indeed, a continual chain of nuclear reactions associated with various stages in the life cycle of stars is believed to account for the presence of most of the elements in the universe. Some of the isotopes of hydrogen, helium, and lithium, however, are thought to have been produced by nuclear reactions occurring during the birth of the universe in the big bang.

One important question which could be addressed using these mini-cosmic explosions is that of the opacity of stellar material. Opacity is a measure of the efficiency of the flow of heat through a star. The opacity of material in stellar interiors plays a key role in determining how stars evolve, i.e. what the maximum mass of a stable star is, how hot and how bright the star is while it burns its nuclear fuel, how it may flicker in what are called pulsational instabilities, whether it loses much of its outer envelope in outbursts of one kind or another, and at what stage of its evolution it might explode as a supernova. A determination of the opacity for stellar material, however, is very complex, and has stood as a formidable challenge to theoretical atomic physics. With these new experiments it may be possible to directly measure stellar opacities.

Stellar structure and evolution is also governed by what is called the equation of state. The equation of state describes the relations between the density and temperature of the material, and its pressure (and other properties like internal energy, specific heats, etc.). In the very centers of stars, particularly those in later stages of their evolution, the equation of state is difficult to model theoretically. It may be measurable, however, in these mini-cosmic explosions.

A study of nuclear reactions in stars is another possibility which we are considering. Although nuclear reactions can be studied in terrestrial accelerator laboratories, it is seldom the case that the nuclear reactions can be measured at the actual energies at which they occur in stars. This is because the rates of the nuclear reactions at stellar energies are too slow. Although a slow reaction rate is a good thing for us, since it keeps stars like the sun burning for a long time, it is frustrating to the experimenter who must measure the reactions at high energy (where they occur faster) and then carefully extrapolate that rate to lower energies. This extrapolation process can introduce uncertainties.

We are studying the possibility that enough nuclear reactions might occur during the proposed laser-powered mini-cosmic explosions at the National Ignition Facility (NIF) to allow for an examination of nuclear reactions at the actual energies and densities at which they occur in stars and the big bang. Although such experiments would be difficult they may allow new insight into the nuclear processes of stellar interiors.

During the big bang the universe is believed to have undergone a complicated evolution as it cooled from billions down to millions of degrees during a time interval from about one second to several minutes after the initial big bang. During this time the evolution of the universe is thought to have been characterized not only by nuclear reactions, but also by the presence numerous matter and anti-matter electronic pairs. Indeed, such electron-positron plasmas are expected to have played an important role not only in the big bang but other explosive astrophysical environments such as supernovae, pulsars, and the distant quasars. Such matter-antimatter pair plasmas represent a new state of matter with unique properties different from ordinary matter. Under the right conditions, the NIF may produce some electron-positron pairs in a way which is analogous to the way in which such pairs are formed in astrophysical environments. By studying the formation and annihilation of these pairs one can hope to better understand the astrophysical environments in which such pairs are a dominant influence.

The way in which the Department of Energy's National Ignition Facility would work follows from an upgrade of existing technology such as that developed for facilities like the Nova laser at Lawrence Livermore National Laboratory. If the NIF facility is built, it will focus hundreds of trillions of watts of laser power onto a small capsule for a few billionths of a second. The ensuing explosion could compress matter within the capsule to very high density while heating it to hundreds of millions of degrees. By carefully selecting the laser and capsule design, it should be possible to reproduce conditions that occur within the stars, supernovae, and the big bang, although only for a tiny fraction of a second.

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