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Frontier HED Science accessible on NIF

B. A. Remington, D. D. Ho

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Bruce A Remington and Darwin Ho

Lawrence Livermore National Laboratory, USA

Abstract:

With the advent of high-energy-density (HED) experimental facilities, such as high-energy lasers and fast Z-pinch pulsed-power facilities, millimeter-scale quantities of matter can be placed in extreme states of density, temperature, and/or velocity. With the commissioning of the NIF laser facility in the very near future, regimes experimentally accessible will be pushed to even higher densities and pressures. This is enabling the emergence of a new class of experimental science, wherein the properties of matter and the processes that occur under the most extreme physical conditions can be examined in the laboratory. Areas particularly suitable to laboratory astrophysics include the study of opacities relevant to stellar interiors, equations of state relevant to planetary interiors, strong shock-driven nonlinear hydrodynamics and radiative dynamics relevant to supernova explosions and subsequent evolution, protostellar jets and high Mach number flows, radiatively driven molecular clouds, nonlinear photoevaporation front dynamics, and photoionized plasmas relevant to accretion disks around compact objects such as black holes and neutron stars. In the area of materials science and condensed matter physics, material properties such as phase, elastic coefficients such as shear modulus, Peierls stress, and transport coefficients such as thermal diffusivity can be accessed at considerably higher densities and pressure than any existing data. In the field of nonlinear optical phenomena, NIF will be an unparalleled setting for studying the nonlinear interactions of a "statistical ensemble" of 100 high power beams in large volumes of plasma. In the area of nuclear physics, nuclear reaction rates in dense, highly screened plasmas and on ignition implosions, reactions from excited nuclear states via multi-hit reactions should be possible. A selection from this frontier HED science accessible on NIF will be presented.

Modern high power lasers and magnetic pinch facilities produce energy densities in millimeter-scale volumes large enough to access phenomena that otherwise appear only in energetic astrophysical systems. Examples of areas that can be studied include strong shock phenomena; high Mach number jets; strongly coupled plasmas; compressible hydrodynamic instabilities; radiation flow; photoevaporation front hydrodynamics; and fundamental properties such as opacities and equations of state. [Remington 2006; Takabe, 2001]. Consequently, a new field of research is emerging – high energy density laboratory astrophysics. Examples where experimental work has started include experiments relevant to planetary interiors, core-collapse supernova explosion hydrodynamics, protostellar jet dynamics, and accretion disk photoionized plasmas. With the NIF laser at LLNL soon to be commissioned, it is timely to look at examples of frontier laboratory astrophysics at the most extreme states that can be accessed on NIF.

Figure 1 is one representation of HED astrophysics and HED laboratory astrophysics. [Davidson, 2003] A density-temperature plot is only one of many ways to parameterize laboratory systems. The rectangles overlap most of the extreme conditions for typical stars (stars of 60 and 1 solar mass are shown; the 60-solar-mass star is both burning helium [at the center] and hydrogen [in a shell], while the 1-solar-mass star is a model of the present-day Sun), and a significant fraction of the extreme conditions found in the interior of giant planets and brown dwarfs. This figure has been extended slightly from its original form, to reflect the realization that several unique radiative conditions at lower matter densities, fall below the 10^{12} erg/cm^3 boundary discussed in [Davidson, 2003], yet these very important regimes can only be accessed on HED experimental facilities, such as high power lasers or Z-pinches. Examples that fall in this regime correspond to photoionized plasmas found in the vicinity of accreting black holes and neutron stars, stellar envelope opacities, supernova remnant radiative shocks, radiatively driven molecular clouds and photoevaporation front dynamics, and protostellar jet dynamics. Comprehensive review of the field of HED laboratory astrophysics can be found in [Remington, 2006; Takabe, 2001; Drake, 1999; Woolsey, 2007]

Figure 2 pictorially represents several of the more interesting astrophysics regimes and phenomena that fall under HED astrophysics. Examples include (a) the interiors of the giant gaseous planets, (b) hypervelocity impacts, such as depicted by the impact of comet Shoemaker-Levy into Jupiter at 60 km/s, (c) ultrafast lattice dynamics due to shock or ramp wave compression [Lorenzana, 2006], (d) photoevaporation (ablation) front dynamics in radiatively driven molecular clouds, such as the Eagle Nebula, (e) protostellar jets, such as the well known Herbig-Haro-47 jet, (f) stellar envelope dynamics and evolution, such as the dramatic Eta Carinae, (g) supernova explosions and subsequent evolution into supernova remnants, (h) photoionized plasmas around accreting black holes, and (i) double-hit nuclear reactions from the intense burst of 10^{19} neutrons in ~100 ps from a "point" source in an ICF ignition capsule.

One of the most difficult regimes to experimentally access in the laboratory are the very high pressure, dense, relatively cool regimes found near the cores of giant planets. We show a unique experimental design for NIF designed to reach 10 Mbar pressures or greater at conditions very similar to a room temperature adiabat. [Ho, 2005] The laser is used to drive a very strong shock (40-50 Mbar) through a sacrificial "reservoir", which unloads across a vacuum gap. When this unloading stagnates on a carefully shielded and tamped metal sample, quasi-isentropic conditions at pressures of ~10 Mbar can be achieved, with the samples predicted to stay factors of several below their melt temperature, hence, remaining in the solid state condition. It is hoped that the very high pressure phase diagram of a number of astrophysically relevant materials can be examined in such an experimental configuration. A similar design using a hohlraum drive is also discussed in [Park, 2007]

In summary, on modern HED experimental facilities, including the new NIF laser, a wide variety of very interesting planetary and astrophysical conditions can be accessed, and the properties of matter studied under extreme conditions of density and temperature. Examples include the EOS at very dense, very high-pressure conditions relevant to planetary interiors [Jeanloz, 2007]; new phases of matter and ultrafast lattice response in high pressure, solid-state matter [Lorenzana, 2006; Shigemori, 2007; Park, 2007; Koniges, 2007]; transport coefficients in strongly coupled, degenerate WDM conditions [Glenzer, 2007; Gregori, 2007]; stellar evolution: stellar envelope opacities; molecular cloud dynamics; protostellar jets: high-M-#, radiative, MHD or hydrodynamic jets [Lebedev, 2007[; core-collapse supernovae, strong shock hydrodynamics, and turbulent hydrodynamics [Ohnishi, 2007; Iwakami, 2007]; supernova remnants dynamics, radiative shocks, and shock processing of the ISM [Woolsey, 2007; Drake, 2007]; and black hole accretion disk dynamics, photoionized plasmas, (e^+, e^-) pair fireball generation and evolution [Takabe, 2001; Remington, 2007].

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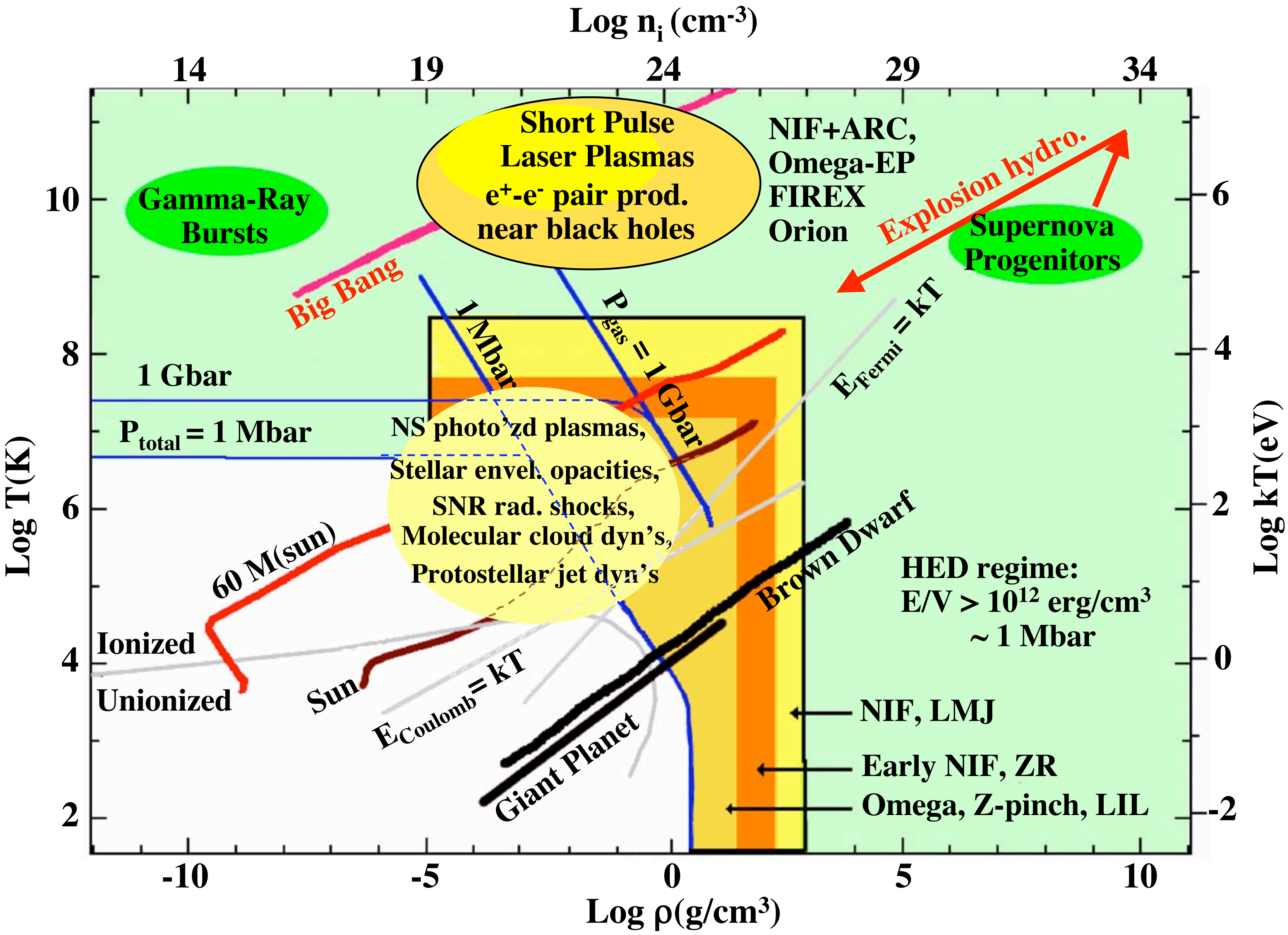
Figure captions:

Figure 1. HED facilities allow matter to be studied under extreme conditions of temperature and density. The gray curves correspond to separation between ionized and unionized matter, ideal gas vs. the strongly coupled regime where the Coulomb

interactions are significant, and classical gas vs Fermi degenerate plasma where quantum effects are significant. Modified from Fig. 1.1 in Davidson et al., National Academies Press (2003), "Frontiers in High Energy Density Physics: the X-Games of Contemporary Science".

Figure 2. HED facilities open up a unique experimental window into the physics of the universe. (a) planetary interiors, (b) hypervelocity impacts, (c) ultrafast lattice dynamics, (d) radiatively driven molecular clouds, (e) protostellar jets, (f) stellar dynamics, (g) core-collapse supernovae, and supernova remnants, (h) accreting black holes and neutron stars, and (i) excited state nuclear reactions in ignition experiments.

Figure 3. Simulation results for a 900 GPa (9 Mbar) peak pressure, solid-state design for a Mo sample as a candidate experiment for the National Ignition Facility (NIF). (a) Initial target density profile for this design. The sample corresponds to a 160 μm Be ablator, backed by a 290 μm CH(6% I) radiation shield, then a 550 μm carbon foam graded density region (in 9 steps). Next follows a 1.2 mm vacuum gap, followed by a 30 μm CH(2% Br) heat shield, the 100 μm Mo sample, and finally a 400 μm vanadium tamper. The laser pulse assumed in the 1D simulation was $I_L = 3.8 \times 10^{13}$ W/cm^2 for 49 ns at 1/3 μm wavelength. (b) Pressure (in Mbar) vs time (in nanoseconds) at depths of 5, 10, 20, and 40 μm into the Mo sample, for a design based on a 1D simulation, assuming laser intensity of $I_L = 3.8 \times 10^{13}$ W/cm^2 for 49 ns. If we assume that 50% of the laser energy is contained in the useful 3.4 mm diameter spot, this design corresponds to a total laser energy of 0.34 MJ. If we assume a laser energy of 0.83 MJ, of which 50% is absorbed in a 3.4 mm diameter spot at an intensity of $I_L = 9.3 \times 10^{13}$ W/cm^2 for 49 ns, this gives a peak pressure greater than 20 Mbar at $T_e/T_{melt} < 1/2$.



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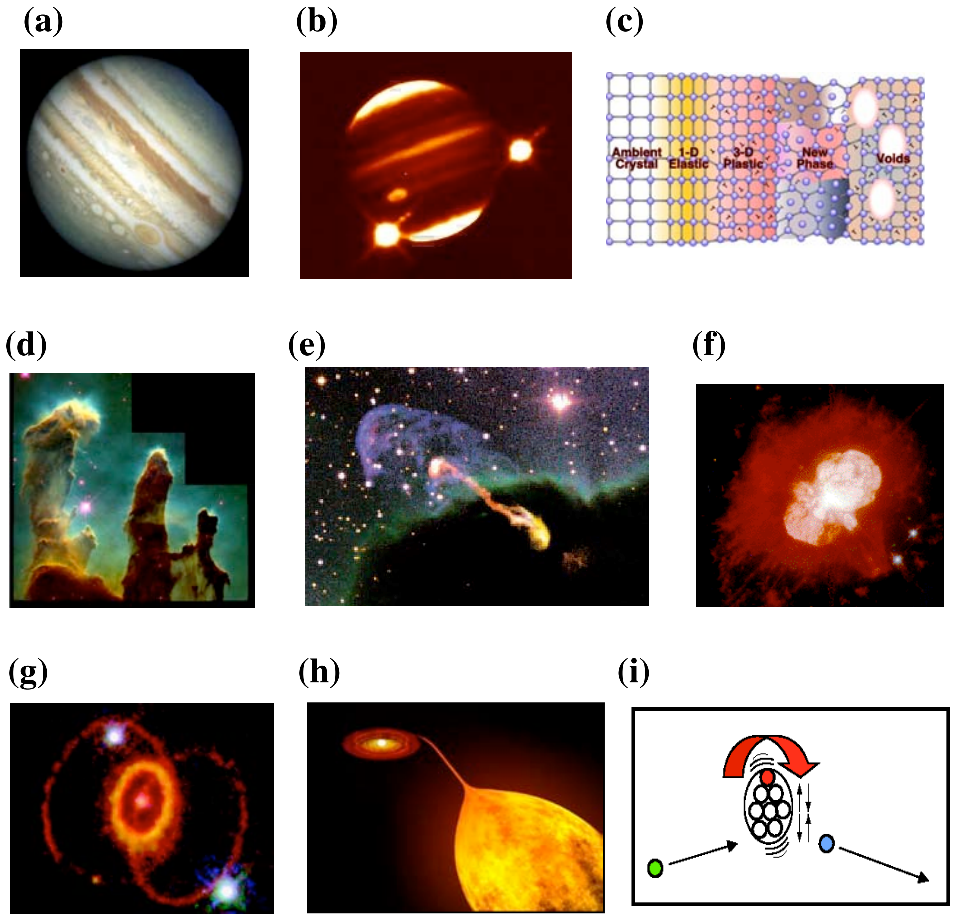

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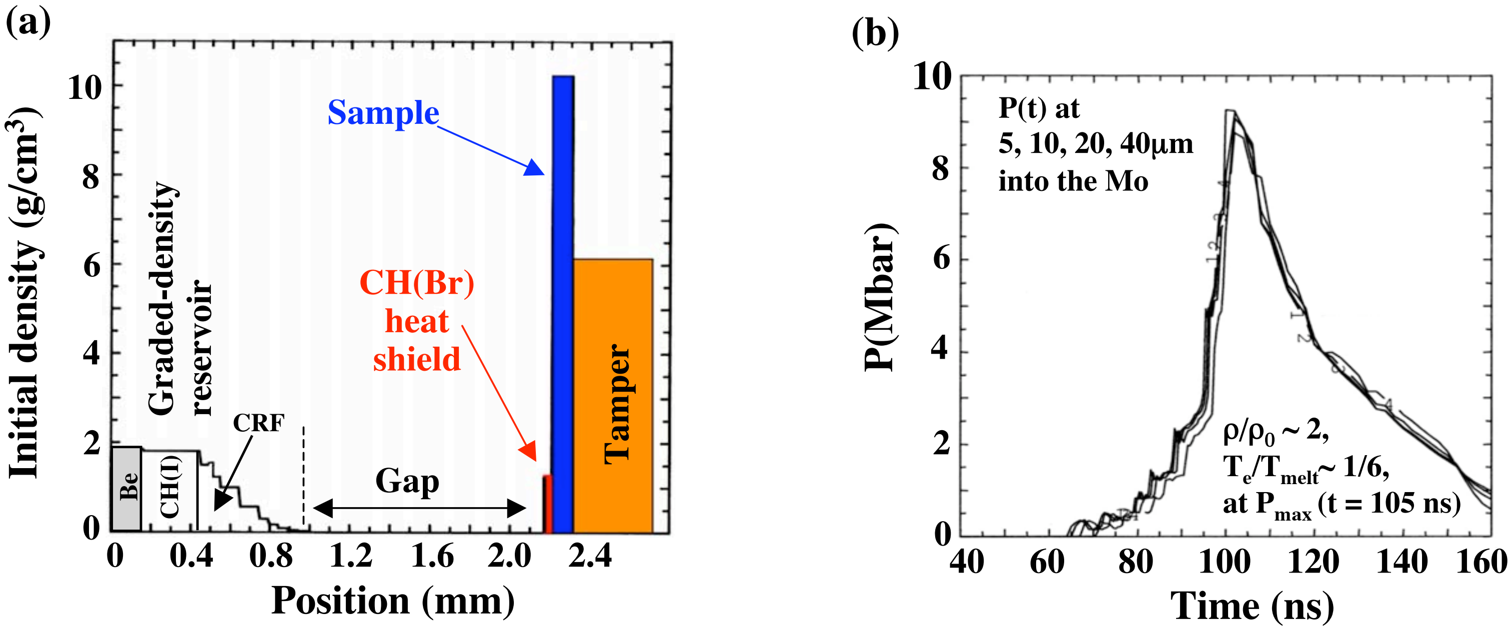

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