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Laboratory Astrophysics on High Power Lasers and Pulsed Power Facilities

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LABORATORY ASTROPHYSICS ON HIGH POWER LASERS AND PULSED POWER FACILITIES*

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INTRODUCTION

Over the past decade a new genre of laboratory astrophysics has emerged, made possible by the new high energy density (HED) experimental facilities, such as large lasers, z-pinch generators, and high current particle accelerators. (Remington, 1999; 2000; Drake, 1998; Takabe, 2001) On these facilities, macroscopic collections of matter can be created in astrophysically relevant conditions, and its collective properties measured. Examples of processes and issues that can be experimentally addressed include compressible hydrodynamic mixing, strong shock phenomena, radiative shocks, radiation flow, high Mach-number jets, complex opacities, photoionized plasmas, equations of state of highly compressed matter, and relativistic plasmas. These processes are relevant to a wide range of astrophysical phenomena, such as supernovae and supernova remnants, astrophysical jets, radiatively driven molecular clouds, accreting black holes, planetary interiors, and gamma-ray bursts. These phenomena will be discussed in the context of laboratory astrophysics experiments possible on existing and future HED facilities.

SUPERNOVAE

Supernovae (SNe) represent one of nature's most spectacular moments, the explosive death of a massive star. (Arnett, 1996) A quantitative description of these stellar explosions relies upon an understanding of macroscopic matter under extreme conditions, involving the equation of state (EOS) of bulk nuclear matter, particle physics, general relativity, hydrodynamic instabilities and turbulence, atomic physics, opacities, and radiation transport. Furthermore, there are different types of SNe, with very different mechanisms of energy release and explosion dynamics.

At peak luminosity, a SN can outshine its entire host galaxy. The light that is detected from the SN comes not from the core, where the energy release has occurred, but from the photosphere, which corresponds to the visible "surface" of the SN. Energy is transported from the core to the photosphere by a complex combination of hydrodynamic flows and radiative transport. Correlating the energy release in the core with the observed light curve evolution requires an accurate description of radiative transport and sophisticated opacity models. Laboratory experiments both on lasers and on z-pinch facilities have already made significant contributions in this area by providing direct opacity measurements under relevant conditions. (Rogers, 1994; Perry, 1991; Springer, 1997)

There are several additional areas related to SN dynamics that could benefit from laboratory experiments. One is the laboratory simulation of compressible turbulent flows relevant to SN explosions. Three-dimensional (3D) effects are paramount here, and successful 3D experiments relevant to the dynamics triggered by a core-collapse SN have already been demonstrated. (Robey, 2001) The scale transformation relating these experiments to the SN has also been described. (Ryutov, 2000; 2001)

With the two next generation "mega-lasers" on the horizon, the NIF in the U.S. and the LMJ in France, it may become possible in the future to experimentally address questions of thermonuclear ignition and burn physics relevant to Type 1a SNe. It may also prove feasible in laboratory ignition experiments, which will produce intense outbursts of neutrons, to measure rare nuclear reactions relevant to nucleosynthesis of the heavy elements. It may even be conceivable to implode a rotating "core", to observe the resulting rotational plasma dynamics. (Baldwin, 1995)

SUPERNOVA REMNANTS

Supernova remnants (SNRs) are the end result of SN explosions. These remnants evolve for centuries if not millennia, producing observable structures through the interaction of the expanding stellar ejecta from the SN explosion with the surrounding or circumstellar environment. (McCray, 2001) In addition, SNRs are widely believed to produce most of the cosmic rays that irradiate the Earth. Despite our ability to observe a number of SNRs in considerable detail, their structure and evolution continue to challenge our understanding. Laboratory experiments can help improve our understanding of several of the mechanisms present in SNRs, and can test aspects of the computational models developed to interpret their behavior.

Some SNRs, such as the Crab nebula, (Hester, 1996; Sankrit, 1997; Weisskopf, 2000) may have inherited their structure from the supernova explosion itself. Yet observations of Cassiopeia A, which is just over 300 years old, reveal an object within which there is an amazing array of knots, filaments, and flocculi. (Hughes, 2000) Of particular interest in Cas-A is the observation that the core materials appear to have out run the envelope materials from the original progenitor star, in a core-envelope inversion. In other words, the ejecta from the exploded star has turned inside out. Hydrodynamic modeling can give a qualitative description of these dynamics, but a quantitative description is not yet possible.

Experiments on HED facilities can address uncertainties in the SNR dynamics in several areas. Experiments relevant to the hydrodynamics of the young SNR phase have already been demonstrated (Drake, 1998; Grun, 1991), including the effects of a strong shock on clumps and scaled circumstellar rings. (Klein, 2000; Kang, 2001) The Sedov-Taylor phase dynamics has also been accessed in laboratory experiments, (Grun, 1991; Ripin, 1990) and several experiments have demonstrated that aspects of the radiave-phase can be accessed. (Keiter, 2001; Koenig, 2002; Bozier, 1986; Shigemori, 2000) Radiative MHD experiments relevant to some aspects of SNR evolution may also be possible. (Woolsey, 2001) Finally, collisionless shocks represent one of the fundamental unsolved mysteries of SNR dynamics, and particle acceleration relevant to cosmic rays. Some progress has been made experimentally in this area (Zakharov, 1996; Bell, 1988; Woolsey, 2001), and the scaling issues have also been addressed in a careful experimental design study (Drake, 2000).

ASTROPHYSICAL JETS

Galactic and extragalactic jets present us with some of the most visually captivating images encountered in astronomy and astrophysics. (Livio, 1999) These jets span an enormous range of spatial scale, from 10^{17} cm for protostellar jets from young stellar objects (YSO) to 10^{24} cm for jets associated with active galactic nuclei (AGN) harboring massive black holes. The class of stellar jets known as Herbig-Haro objects correspond to collimated bipolar outflows emerging from accretion disks during the star formation process. Typical velocities of the protostellar jets are a few hundred km/s, giving Mach numbers of 10-50, and typical density contrasts >> 1. Due to the high densities and high Mach numbers, these jets are thought to be strongly radiatively cooled, which significantly alters their morphology. Another class of bipolar jet is associated with planetary nebula and proto-planetary nebula. These systems represent stars in the late stages of stellar evolution, as they leave the asymptotic giant branch stage, enroute to becoming a white dwarf. On a much larger scale reside the extragalactic radiojets, thought to arise from massive black holes at the center of AGNs. These relativistic jets of predominantly electrons have velocities and spatial extents of 0.9c and 10^{24} cm with density contrasts of << 1, making these the largest known continuous structures in the universe.

Experiments on high Mach number, hydrodynamic jets (Foster, 2002; Logory, 2000) and radiatively collapsing jets (Farley, 1999; Shigemori, 2000 Lebedev, 2002) have been demonstrated both on lasers and on pulsed power facilities. The purely hydrodynamic jets of Foster and Logory had internal Mach numbers M < 10, whereas the strongly radiatively cooled jets of Farley and Shigemori had Mach numbers as high as 50-60. (Mizuta, 2002) Finally, a new class of very energetic proton jets has been observed on ultra-high intensity, short-pulse lasers. (Snavely, 2000; MacKinnon, 2001; Maksimchuk, 2000; Norreys, 1999) The mechanism behind their formation is still being debated, but their existence at energies of up to 100 MeV is well established. (See the gamma-ray burst section below for more discussion.)

In the ultra-relativistic regime, possibly relevant to the jets emanating from AGN, an experiment has been conducted using a 30 GeV beam of electrons propagating through a substantial length of low density plasma at SLAC. (Hogan, 2000; Lee, 2000) (See also the gamma-ray burst section below.)

RADIATIVELY DRIVEN MOLECULAR CLOUDS

Cold dense molecular clouds illuminated by bright, young, nearby massive stars serve as the stellar incubators of the universe. The intense stellar radiation incident on the cloud creates a high pressure source at the surface by photoevaporation (ablation), augmented by the ram pressure from the stellar wind. The result is that the cloud is shock compressed, and subsequently accelerated, as the star clears away the cloud out of which it was born. Well known examples of such systems are the Eagle Nebula, (Hester, 1996; Pound, 1998) the Horsehead Nebula, (Zhou, 1993) the Rosette Nebula, (Schneps, 1980) and NGC 3603. (Brandl, 1999) Interest in dense molecular clouds in the vicinity of bright young stars is due in part to the hypothesis that these clouds serve as "cosmic nurseries," harboring and fostering regions of active star formation.

The Eagle Nebula is intriguing because of its famous columns, the so-called "pillars of creation". These "elephant trunk" structures arise possibly as a result of hydrodynamic instabilities such as the Rayleigh-Taylor (RT) instability acting at the photoevaporation front, as first suggested 50 years ago (Spitzer, 1954; Freeman, 1954). An alternative explanation, the so-called "cometary tail" model, attributes the columns to the flow of photoevaporated plasma from and around pre-existing dense clumps of matter embedded in the molecular cloud, much like the dynamics that lead to the plasma tail of comets.

Experimentally, aspects of the dynamics of radiatively driven molecular clouds can be tested in the laboratory. Using the radiation emitted from tiny radiation cavity "point sources" on large lasers and pulsed power facilities, it appears possible to reproduce the dominant photoevapration-front hydrodynamics of radiatively driven molecular clouds. (Remington, 2002; Kane, 2000; Ryutov, 1998; Glendinning, 2000) Also, the strong shock launched into the dense molecular is likely to encounter density inhomogeneities, triggering localized regions of shock-induced turbulent hydrodynamics. These hydrodynanics can also be reproduced in scaled strong-shock experiments on lasers (Klein, 2000; Robey, 2002) and on Z-pinch facilities (Dannenberg, 2001). The shock launched into the dense molecular cloud is thought to be radiative. Progress on producing radiative shocks in the laboratory has also been demonstrated on several facilities. (Keiter, 2001; Koenig, 2002; Shigemori, 2000) A magnetic field embedded in the cloud may be a key component to the dynamics, adding "stiffness" to the compressibility of the cloud. Strong shock MHD experiments may also be possible on lasers and pulsed power facilities. (Woolsey, 2001; Peyser, 1992; Mostovych, 1989) The possibility to form an integrated program of theory, modeling, test-bed laboratory experiments, and astronomical observations presents itself, and several groups are moving in that direction.

ACCRETING BLACK HOLES

One of the most exciting areas of modern astronomy and astrophysics is the study of accretion powered compact objects. (Kahn & Liedahl, 1994) These correspond to binary systems where one of the members is a collapsed object such as a neutron star or black hole, in the case of an x-ray binary, or a white dwarf, in the case of a cataclysmic variable. At the extreme end lie the active galactic nuclei and quasars. Their enormous luminosities are thought to result from the energy conversion of matter falling into supermassive black holes at the center of galaxies. The intense x-ray emissions from these compact objects produces photoionized plasma conditions in the infalling accretion disk. One of the ultimate goals of high energy astrophysics is to understand the dynamics of these black hole-accretion disk systems. The most promising observational tool to put to this task is high resolution spectroscopy of the emerging x-ray emissions. Two new space-based x-ray observatories, Chandra and XMM, currently in orbit are acquiring impressively high quality data of just such x-ray emissions. (Paerels, 2000; Kaastra, 2000) Turning these data into a better understanding of the dynamics of accreting black holes, however, will require a better understanding of photoionized plasmas, both in equilibrium and possibly in nonequilibrium conditions.

Models for photoionized plasmas exist, but these complex codes differ in their predictions, and have not been directly validated, due to a lack of relevant laboratory data. Modern Z-pinches and large lasers are now capable of generating intense bursts of photoionizing x-rays. Experiments on the "Z" pulsed-power facility have shown that astrophysically relevant, equilibrium photoionized plasmas can be created and diagnosed. (Heeter, 2001; Bailey, 2001) It may also be possible to access photoionized plasma conditions on large laser facilities. (Morita, 2001). These new HED laboratory capabilities will allow complex x-ray photoionization theories and models to be tested under relevant conditions, thereby serving as a critical component in the effort to understand the dynamics of accreting black holes.

PLANETARY INTERIORS

The discovery of extrasolar planets and brown dwarfs represents one of the most exciting new astronomical developments of the decade. (Guillot, 1999) The newly discovered planets tend to be giant gas planets with small, highly eccentric orbitals. These new "hot giants" raise many questions about our models for planetary formation, and planetary interiors. Models for the interiors of the extrasolar planets, as well as the solar planets exist. (Guillot, 1999) Yet these models rely upon a quantitative understanding of cold, dense matter at extreme pressures. At such high pressures, the matter is pressed so closely together that the outer electronic orbitals overlap, causing pressure ionization. This serves as an energy sink, which affects the compressibility. Such coupled quantum mechanical-thermodynamic effects are notoriously difficult to calculate theoretically.

Experimental techniques are being developed on pulsed power facilities (Knudson, 2001; Asay, 1999), lasers (da Silva, 1997; Collins, 1998; Evans, 1996; Mostovych, 2000; Koenig, 1999), gas guns (Nellis, 2001; Gupta, 1997), and diamond anvil cells (Yoo, 1995) to probe the properties of matter under extreme conditions of pressure and compression. The conditions achieved to date cover pressure ranges of 0.1 – 40 Mbar in EOS measurements (Asay, 1999; Cauble, 1998), planar shock pressures of up to 750 Mbar in a proof of principle demonstration experiment, (Cauble, 1993) and ~10 Gbar at the core of an imploding spherical capsule. (Meyerhofer, 2001) In the coming decade, with the advent of the NIF and LMJ lasers, this parameter space will be filled in and extended. These laboratory conditions correspond to the interiors of terrestrial and giant gas planets, brown dwarfs, average mass stars, and the envelopes of white dwarfs.

GAMMA RAY BURSTS

Gamma-ray bursts (GRB) are the greatest enigma in contemporary astrophysics (Fishman 1995; Piran, 1997; Waxman, 2000). Detected at a rate of more than one per day from random directions in the sky, GRBs have typical burst durations of a few seconds, but signal variability as short as ~1 msec, at photon energies of 0.1-100 MeV. At least some of the GRBs are at cosmological distances of several billion light years, and their total source energies of 10^{51}-10^{53} ergs/burst appear to be emitted from very compact sources. Their power law spectral shape is often interpreted as suggesting that the source plasma is optically thin to the radiation observed.

The fireball scenario is perhaps the most widely discussed model of GRBs. (Piran, 1997; Waxman, 2000; Rees, 1992). Here, an initial release of ~10^{52} ergs of energy into a volume of spatial extent ~10^7 cm creates a relativistically hot fireball of photons and leptons, with a small admixture of baryons. This initial fireball of electrons, positrons, and photons at an initial temperature of 1-10 MeV expands relativistically. A small admixture of baryons is also accelerated to relativistic velocities, thereby transferring the fireball thermal energy to the kinetic energy of the radially expanding baryons. The baryons sweep into the ISM, creating a system of forward shock and several reverse shocks, with the observed GRB emission coming from the reverse shocks. The much longer lived x-ray afterglow then comes from the forward shock in the ISM.

In the laboratory, the most promising means for accessing these relativistic plasma dynamics and flows are with experiments done on ultra-intense, short-pulse lasers. Experiments on such lasers have reached intensities of ~10^{20} W/cm^2 (Key, 1998; Tatarakis, 2002), and have yielded many fascinating results. Jets of protons with energies of 10's of MeV have been created in a very well colimated "beam". (Snavely, 2000; Hatchett, 2000; MacKinnon, 2001; Maksimchuk, 2000) Also, less colimated directional outflows of electrons and positrons with energies of up to 100 MeV have been generated. (Key, 1998; Cowan, 1999; Norreys, 1999) In terms of an effective temperature, the high energy electrons have a "slope parameter" of 1-10 MeV, making these plasmas thermally relativistic, with $T_e > m_e c^2$, corresponding to a "laboratory micro-fireball". Similar temperatures are inferred from a fireball analyses of GRBs. (Piran, 1997; Rees, 1992) Another intriguing observation in these ultraintense laser experiments was the generation of ultrastrong magnetic fields. Strong magnetic field generation (>100 MegaGauss) has been experimentally observed on such ultraintense laser experiments, (Tatarakis, 2002) with simulations predicting fields of up to 1 GigaGauss or more. (Lasinski, 1999; Pegoraro, 1997) Such extreme conditions, albeit over small volumes and exceedingly short times, may overlap with aspects of the relativistic fireball dynamics thought to occur in GRBs. One conceptual design already exists for a experiment using several ultra-intense lasers incident on opposite sides of a thin Au foil to generate an electron-positron fireball, with observable numbers of positrons. (Liang, 1998) This design is meant as a first step towards demonstrating that aspects of GRB physics can be reproduced in the laboratory.

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