Study of Astrophysical Explosions with Intense and Ultra-intense Lasers

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Abstract: The author's original discipline, laser fusion, requires studying the physics of high-energy density (HED) plasmas. Modern astrophysics also needs the maturity of HED physics. I briefly describe the physics scenario of laser fusion and divide it to six subjects. They are (1)Laser plasma interaction, (2)Electron energy transport, (3)Hydrodynamics and strong shocks, (4)Hydrodynamic instability, (5)Atomic physics and X-ray transport, and (6)Laser-produced relativistic plasmas. The author proposed to introduce three views to consider and pick up model experiments for astrophysics suggested from each topics in laser fusion. They are (1)Sameness, (2)Similarity, and (3)Resemblance. The matrix made of six rows and three columns gave us at the present time 18 subjects of laser astrophysics. These 18 topics include, for example, the equation of state and opacity of the hot-dense plasmas, topics related to supernova explosions, and relativistic electron-positron plasma jets seen in active galactic nuclei. I hope that my presentation will motivate the listeners and/or readers to think and find a variety of new topics and the matrix table becomes black with many key words.

1. Introduction

The astrophysics aims at clarifying the evolution scenario from the Big Bang to the present structure of the universe. Therefore, if ambiguities in the physical processes in constructing the theories of galaxy formation, star formation, increase of heavy elements due to nuclear synthesis in supernovae, and so on can be clearer with model experiments, the entitled research will grow as a new research field for the fundamental physics. It is meaningless just to say that the laser-produced plasmas resemble those observed in the universe. We have to look for research scenarios with which a part of the critical issues for astrophysics can be solved with lasers.

When intense or ultra-intense lasers are irradiated on matters, high-density and high-temperature plasmas are produced. The physics of such plasmas, which is called HED (high energy density) physics [1], has the same base as the core physics of astrophysics. It was pointed out from the beginning of laser plasma research that the astrophysics is an important subject for laser plasma [2]. After 40 years from the beginning, the laser technology and laser plasma physics have come to the stage of maturity and the possibility of "laser astrophysics" has become realistic. It is beneficial for both scientists in fusion and astrophysics to study HED physics by modeling astrophysical phenomena with intense and ultra-intense lasers.

We can roughly divide the elements of astrophysics after the three minutes from the Big Bang into the following five.(I) Hydrodynamics and magneto-hydrodynamics, (II) Atomic physics, radiation transport, and radiation hydrodynamics, (III) Relativistic plasmas, (IV) Nuclear reactions, (V) Gravitational interactions

It is difficult to do some model experiments of the item (V) in the laboratory, while a variety of model experiments can be designed concerning the items (I) - (III) by use of intense and ultra-intense lasers. The ultra-intense lasers may be used to generate relativistic electron-positron plasmas. The item (IV) is principally possible to be studied with laser-produced fusion plasmas. For studying the detail of this physics, however, an extremely high temperature only achieved by thermonuclear reaction in an imploded fusion fuel is required. In this case, a big laser facility of multi-beam system such as National Ignition Facility (NIF) [3] or Laser-Mega-Joule [4] would be necessary. For studying magneto-hydrodynamics (MHD) phenomena such as collision-less shocks of Supernova remnants (SNRs) and magnetic reconnection phenomena observed in the solar flare, it is necessary to produce the plasma in external magnetic fields or laser-generated magnetic field.

2. Laser Experiments Related to Astrophysics

Based on the similarity transformation, the important physics such as hydrodynamic instabilities of supernova explosion and interaction between high Mach number shock wave and ISM (interstellar media) can be modeled in the laboratory to clarify controlling physics [5].

A model experiment for a strong blast wave has been carried out by Ripin et al [6] relating to SNRs and an instability of the blast wave front due to radiation cooling which is now called "Vishinac instability" has been observed [7]. The similarity and difference of the hydrodynamic instability in the supernova 1987A (SN1987A) were discussed by the author comparing it with that in laser-driven implosion [5]. Model experiments have been carried out in US regarding highly nonlinear stage of the R-T instability in supernova explosion [8]. These are summarized in a series of review papers written as a joint work with the author [9, 10, 11]

Line X-rays and γ-rays are good objects for new astrophysics research. For example, observational data with X-ray satellite "ASCA" are used to estimate the abundance in SNRs [12]. The line X-rays are emitted from SNRs, which is still in the ionizing phase even after 10^3 years from a supernova (SN) explosion. In order to calculate the material abundance of Si, Mg, and so on from the data, a rate equation solver to evaluate non local thermodynamic equilibrium (non-LTE) atomic state is necessary. Such numerical solver has to be checked by comparing it with well-defined experiments, and the laser-produced plasma can be a good candidate for this purpose. In this case, the temperature is almost same as SNR plasma, while the density and the time scale are very different. However, we can design a reasonable model experiment by adjusting the ionization parameter defined by the product of the density and time as will be discussed later. In addition, spectral opacity of relatively heavy elements with density and temperature near stellar surface or interior has been studied with the name of "opacity experiment" with a combination of laser heating and X-ray back-lighting by use of laser produced radiation.

3. Laser Fusion Plasmas

The physics scenario of laser fusion is briefly explained here. From the laser irradiation on a spherical target to the final fusion burn, we can roughly divide the physics issues to six. They are (1) Laser-plasma interactions, (2) Electron energy transports, (3) Hydrodynamics and strong shocks, (4) Hydrodynamic instabilities, (5) Atomic physics and X-ray radiation transports, (6) Laser produced relativistic plasmas

When an intense laser is irradiated on a target the physics of the item (1) should be studied. By laser-plasma interaction, most of laser energy is used to heat electrons and kinetics of electron energy transport becomes important. The electron energy is carried to the over-dense region and generates extremely high pressure over the surface of the target. Then, strong shock waves are generated and compressible hydrodynamics should be studied. Since the target shell is accelerated toward the center by the high-temperature, but relatively low-density ablating plasma, the ablation front becomes unstable to Rayleigh-Taylor instability. In addition, Richtmyer-Meshkov instability driven by shock wave also appears to be important in the implosion process. In order to control the density profile so as to reduce the growth of such instabilities, medium-Z material is doped in the target. Then, the x-ray transport becomes important issue to be studied. In addition, soft x-ray efficiently generated with intense laser irradiation on high-Z solid is also important in x-ray driven implosion [15]. The high-Z atom is in general not in local thermodynamic equilibrium. Therefore, complicated atomic physics and atomic process should be studied. Recently, the technical accomplishment of PW laser made the fast-ignition laser-fusion scheme [16] possible. In this fusion scheme, an ultra-intense laser is impinged at the edge of the compressed core. Then, the electric field of the focused beam becomes 10keV/Å and generated high energy electrons have energy in the range of 10 MeV. The relativistic plasma physics became one of the important issues to be studied in laser fusion recently.

4. Three Viewpoints

On the other hand, there are three view points which relate the laser-produced plasmas to astrophysics. They are (a) Sameness of physics, (b) Similarity of physical dynamics, (c) Resemblance of physics.

At first, it is easy to understand the meaning of the term (a). This means to produce plasma with the same temperature and density as the surface or interior of stars and to study, for example, the equation of state (EOS) and the emissivity and opacity of X-rays. In addition, if we are able to use a huge laser system like NIF (National Ignition Facility), we may also be able to study the cross sections and their density dependence of thermonuclear fusion reactions important inside stars.

The term (b) represents the study of physical evolution in time and space of compressible hydrodynamics, atomic processes etc. For example, we reproduce the physics of supernova remnants with the diameter of a few tens ly (light year) and the age of a few thousand years by reducing the scale of time and space by a factor 10^{20} in the blast wave driven by laser light. This concept is same as the design of aircraft by putting a small-scale model in a wind tunnel. In this case, the non-dimensional parameters, Reynolds number and Mach number, should be kept same as those for a real aircraft in flight. In the case of the wind tunnel, the scaling factor is about 10^3. The difference from the case of the wind tunnel is extremely large difference of the scaling factor. Another examples of the term (b) are very strong shock and matter interactions, hydrodynamic instabilities of the case where energy transports essentially modify the growth of the instabilities, non local thermodynamic equilibrium phenomena, radiation hydrodynamic phenomena and so on.

The term (c) represents the case where although scaling law is not found yet, physics and phenomena are very resemble each other. For example, it indicates the creation of anti-matter by use of ultra-intense lasers and electron-positron plasma formation. There are full of electron-positron plasmas near Black Hole and also in AGN (Active Galactic Nuclei). We plan to do an experiment where the generated electron-positron plasma collides with imposed magnetic field or matter. Such experiment may be an model experiment of expanding fire-ball believed to be important as the energy source of the gamma-ray bursts. At the same time, it is also interesting to study photo-nuclear reaction processes. The demonstration of possibility of X-ray laser astro-objects is also included in the term (c). It is reported that photo-ionized plasma is observed near the X-ray compact object, Cygnus X-3. The plasma with temperature roughly equal to 10-20 eV is under strong irradiation of hard X-ray coming from a companion black hole or neutron star. This low temperature plasma is photo-ionized to emit many strong line emissions from metal such as Si, Mg. By irradiating lasers in a gold cavity we can generate almost Planckian X-ray source with temperature up to about 300 eV[15]. By providing low temperature plasma at the same time, we can observe the atomic state distribution of photo-ionized plasma under the irradiation of this X-ray source. Systematic study of the photo-ionized plasma will lead us to clarifying the condition for photo-pumping X-ray lasing in the universe.

More details concerning to the topics 1-15 in Table 1 are described in Ref. [17].

5. Summary

In the present talk, I would like to review the topics to be studied with lasers. We can consider a variety of model experiments in the matrix mentioned already. At the present time, 18 subjects can be enumerated in my mind; some of them have already been studied experimentally. In my presentation, I would like to focus on proposing the possible model experiments in relation to a variety of explosion phenomena in astrophysics and would like to show the related simulation results so that the proposal is more quantitative.

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