Experimental Plasma Astrophysics Using a T^3 (Table-top Terawatt) Laser

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Lasers that can deliver immense power of Terawatt (10^{12} W) and can still compactly sit on a Table-Top (T^3 lasers) emerged in the 1990s. The advent of these lasers allows us to access to regimes of astronomical physical conditions that once thought impossible to realize in a terrestrial laboratory. We touch on examples that include superhigh pressure materials that may resemble the interior of giant planets and white dwarfs and of relativistic temperature plasmas that may exist in the early cosmological epoch and in the neighborhood of the blackhole event horizon.

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1 T^3 Laser

The dawn of the 1990s witnessed the emergence of a new class of lasers that are so compact that such a laser can sit on a Table-Top and yet so powerful that it can deliver high power exceeding Terawatts (10^{12} W) due to a revolutionary development of laser technology. Taking these three initial T's, this new class of lasers are often dubbed as T^3 lasers. In spite of the development of lasers applied to fusion etc., the progress in the peak power a laser can deliver has stagnated for twenty years since about 1970. However, what is occurring is a revolutionary development accompanied by a jump in the peak power by a few orders of magnitude due to (i) the invention of the CPA (chirped pulsed amplification) method that stretches in time prior to amplification instead of the conventional stretch in space; and to (ii) the discovery and development of high fluence solid-state lasing materials (such as Ti:Sapphire).

Using the CPA method, even if the laser might have no higher energy than large lasers of the conventional type, the CPA laser pulse becomes extremely shortened, thus acquiring the following salient characteristics:

(1) SHORT PULSE. The laser pulse length is compressed so that it is measured in femto (10^{15}) second (about $10^{-14} \sim 10^{-13}$ sec) and "ultrafast optics" has emerged as a new vibrant discipline. Such a timescale is atomic (or quantum) time, i.e. the time over which an electron circulates around an atom.

(2) ULTRAHIGH INTENSITY. Although the laser energy is not so high, the power exceeds terawatts and recently reaches a petawatt (10^{15} W), as the pulse length is extremely short. In addition its better focusibility than longer pulsed lasers allows immense intensity of the range of $10^{18} \sim 10^{23}$ W/cm^2. This corresponds to the laser electric field strength of $10^{11} - 10^{13}$ V/cm, which surpasses the atomic electric field.

(3) Wide bandwidth. Because the laser pulse is short, the spectral width is so wide to straddle the substantial range of optical wavelengths. This contributes to wide applicability.

(4) Compact size and price. Due to the principle that does not rely on the spatial expansion of beams to amplify, the gain media remain small and inexpensive. The whole system can sit compactly on a table top. Experiments in a single researcher's laboratory become possible.

(5) High repetition rate. The cooling time of lasing media is short because of its compact size. As compared with large lasers whose shots may come once in a few hours, this can operate with $10 - 10^4$ shots per second and can be suitable for precision experiments.

It is important to note that a T^3 laser satisfies not just one of the above five significant characteristics, but all five simultaneously. It is apparent that once such a laser makes a jump in the above physical quantities by a few orders of magnitude, it will open up new regimes of physics under extreme conditions. There are many attractive and exciting applications of this laser based upon the above major properties; fortunately, there have been some recent surveys,[1,2] the latter of which presents a particularly deep and thorough review. To these we can refer details and rather concentrate here on the physics under extreme conditions arising from its super intense irradiation relevant to astronomy and astrophysics.

The ultrahigh intensity of T^3 laser inverts the conventional atomic physics to turn into a nonperturbative (or inverted perturbational) atomic physics and also opens up the world of relativistic plasmas where the electronic energy in the field of photons is greater than the rest mass of an electron. It leads to high energy, high brightness emission of electrons, X-rays and γ-rays. Through these it is expected to have positron creation and nuclear matter excitation. According to a recent experiment[3] some tremendous electric fields of several hundred GeV/m have come within our grasp through the mechanism of the laser wakefield excitation.[4] In terms of magnetic fields, on the other hand, it is thought possible to generate $10^{10} - 10^{12}$ Gauss. As the laser electromagnetic field intensity of 10^{18} W/cm^2 sustains electron quivering energy of electron rest mass and enters in the relativistic regime, the laser intensity of $10^{23}\,\mathrm{W/cm^2}$ allows electron energies in excess of $100\,\mathrm{MeV}$. This is in the neighborhood of the meson rest mass (or the quark mass). In the language of the cosmological thermal (or plasma) history the laser irradiation at $10^{18}\,\mathrm{W/cm^2}$ corresponds to the electron-positron recombination epoch at about 1 second after the Big Bang, while that at $10^{23}\,\mathrm{W/cm^2}$ to the exotic plasma epoch with neutrinos and quarks in addition to electrons and positrons with energies beyond $100\,\mathrm{MeV}$ at about $10^{-3} - 10^{-4}$ second after the Big Bang. Such hot relativistic plasmas are relevant not only to the above cosmologically primordial Universe, but also to the physics of the blackhole atmosphere, active galactic nuclei (AGN), γ ray bursts etc. In addition, the pressure incurred by such intense electromagnetic radiation amounts to the neighborhood of TB (terabar), the highest currently available pressure terrestrially producible. Although it is difficult to control such high pressures experimentally, this will provide a new avenue to approach the conditions of the planetary and stellar interiors.

With creative applications of a T^3 laser it will become possible to terrestrially realize various physical conditions, albeit for a brief period of time, that are so astronomical that they have been deemed not possible to reproduce in a terrestrial laboratory. In addition to the above crude methods of exploiting the extreme conditions accessible by the T^3 laser, much more elegant and sophisticated methods will be invented to harness this laser for applications. For example, irradiating a T^3 laser pulse on heavy atoms to instantaneously ionize, one can study the precision QED through the interaction changes of inner shell electrons and the nucleus.[5] We expect innovative approaches by astronomers and physicists.

2 Advent of "Experimental Astrophysics"

In this manuscript let us introduce a few examples that even our poor imagination came up with of experimental astrophysics that become available by the utilization of a T^3 laser. Consider a simple experiment to irradiate a pulse of a T^3 laser on a surface of a solid. If the pulse is, as has been in the past laser pulses, longer than a pico (10^{-12}) second, the irradiation ionizes the surface of the solid and heats up the plasma, which spews out electrons from the surface, which in turn drags out ions. Thus as a result, the plasma as a whole jets out from the surface and leaves there a crater. On the other hand, if the pulse is shorter than a pico second, the interaction between light and matter completely changes and may be described as what we call "clean" interaction. That is, when the short pulse exceeds the intensity of $\sim 10^{14}\,\mathrm{W/cm}^2$, ionization can happen as light can rip electrons from an atom directly through the process of multiphoton ionization, instead of going through secondary processes of heat and collisions. In such a case since light is already gone by the time electrons experience secondary processes, the electronic energy is at best that of photons (i.e. about 1 eV). When the light intensity is a little bit stronger, the radiation can drill a hole in the Coulomb potential wall that confines electrons to an atom, leading to a leakage of electrons, which produces typically electrons of several eV (though the energy will depend on the intensity to an extent). Meanwhile, ions are unable to move due to their inertia as the pulse width of femto seconds is too short for ions. They, therefore, remain nearly stationary and near the room temperature initially. Upon this rapid injection of photons the several ionized eV electrons and ions form a relatively low temperature plasma, keeping its original solid surface "clean." At high intensity (nearly) all electrons are ionized by light so that the electron plasma density is as high as $10^{23} - 10^{24}\,\mathrm{cc}^{-1}$. How much photon energy is injected into the solid surface plasma depends on the parameters of the laser and the solid, but it is possible to have various scenarios. For example, it would be possible to have the plasma temperature beyond several eV. It is not yet clear how much higher density of a plasma can be created, utilizing the ultra intense light pressure of a T^3 laser.

It is probable that the plasma thus created at a relatively low temperature with a high density has unusual properties. Such a regime is that of a strongly coupled plasma. In Fig. 1 the phase diagram of hydrogen is shown. Suppose that we shine a short T^3 laser pulse on an iced solid (or liquefied) hydrogen tablet surface; then (although depending on scenarios) only the electron temperature rapidly rises, while the plasma remains nearly constant during the short irradiation period. After about a pico second the plasma begins to hydrodynamically expand due to the electron pressure. Thus in the phase diagram in Fig. 1 the temporary evolution of the plasma is horizontal (isochoric) first, and then as expansion ensues, the plasma follows the arrow shown in Fig. 1 toward lower density and lower temperature. The width of the arrow indicates the wide variation of evolution paths depending on the scenario. Along some of the paths it might be possible to pass by the conditions of Jupiter interior or a white dwarf. This wide arrow shows the case without compression by laser. However, if one can employ some clever method such as multiple shocks to compress the hydrogen target, the path may pass by different physical regimes of the phase diagram. We need to explore such methods. For example, if one can reach very dense (e.g. mass density of 10 g/cc) regimes at low temperature, it is thought[6,7] that the process called pycnonuclear (pressure-induced nuclear) reactions takes place rather than the thermonuclear process. This process is considered to be needed for the supernova explosion. Can one test experimental validation of such a process? (On the other hand, the thermonuclear regime is shown by the hatched area with ICF.)

Irradiation on elements other than hydrogen, such as carbon and silicon, is also astronomically meaningful. For example, the liquefaction of such an element and the question of its metallicity[8] are important questions for physical conditions of planetary and stellar interiors and can influence such astronomical problems as dynamo.[9] Irradiation on metallic elements is also important. Iron (Fe)'s phase diagram is shown in Fig. 2. Iron is an abundant element in the interior of well-evolved stars and our own Earth and plays prominently in evolution of the Universe. Again we show a broad arrow in Fig. 2 to indicate some scenarios of short pulse interaction of T^3 laser on the surface of iron. If we can inject a large amount of photons and can reach high temperatures, we might enter the regime of electron-positron pair creation.

When the laser intensity substantially exceeds 10^{19} W/cm^2 and enters the highly relativistic regime, electrons driven by laser with an iron nucleus as a catalyst can create a pair of ee$^+$ in a copious amount.[10] As enough positrons are created in a macroscopic amount, one can look to investigate not only properties of a positron as an individual particle, but also their collective properties, the electron-positron (-ion) plasma. So far only theoretically have we just scratched the surface as to its properties.[11,12] Such plasma properties might be relevant to the pulsar atmosphere.[13] In the future will such a research of materials and plasma physics become a part of astronomy? The diagnosis of the sate of matter in such research is not easy, as the time evolution is fast. We need to develop a series of diagnostic techniques in optical and X-ray regimes.

Another simple example of irradiation of short pulse lasers on matter is that of clusters (solid, liquid or even gas clusters). In the cosmos it is believed that there are countless (invisible) particles (clusters). For example, the famous fullerene (soccer ball) of carbon was first found in space. [It is now so famous that even organic carbon compounds are often found in space] As the well-known theory of Kawahata-Kubo[14] tells us, nanoclusters show anomalous plasma resonance absorption of electromagnetic radiation. In addition typically clusters are cold but weakly ionized so that they behave as a strongly coupled plasma.[15] Furthermore, it has become clear[16] that an intense laser irradiation on such clusters induces anomalous absorption of light and very strong emission of bright X-rays. These observations indicate that matter in the form of clusters and laser can particularly strongly interact. This may be due to a possibility that collective behavior of electrons becomes specifically intense at an appropriate size of clusters, but we do not know detailed elementary processes.

Finally, let us talk about a hot plasma around a blackhole with a lot of imagination. It is believed[17] that between the blackhole horizon (R_s) and $3R_s$ (R_s is the Schwarzschild radius) matter does not exist stably due to the orbital instability. We have found,[18] however, that a plasma as a (collisional) fluid can sustain a series of (magneto)hydrodynamical equilibrium solutions and thus matter even between $1R_s$ and $3R_s$. For example, a hot tenuous plasma can be spread in space sandwiched by the horizon and the accretion disk (that ends at $3R_s$) as indicated in Fig. 3. Such a plasma may be extremely hot and may reach (or exceed) 1 MeV near the horizon. The plasma should form a boundary layer that is so hot that it forms a quantum electrodynamic (QED) sea from which photons continually emit electrons and positrons and vise-versa. The energy to sustain this matter creation should be supplied by the gradual accretion of the plasma toward the horizon and associated anomalously large magnetic viscosity.[19] Here a sample magnetic field bounded by the horizon and the accretion disk may be given[20] as a solution of the general relativistic Grad-Shafranov equation for the magnetic flux function ψ as

$$\Delta^* \psi = \frac{\partial}{\partial r}\left(\alpha^2 \frac{\partial \psi}{\partial r}\right) + \frac{\sin\theta}{r^2}\frac{\partial}{\partial \theta}\left(\frac{1}{\sin\theta}\frac{\partial \psi}{\partial \theta}\right) = F(\psi), \tag{1}$$

where the lapse function $\alpha = \sqrt{1 - R_s/r}$ and F is the functional characterizing the plasma equilibrium quantities. We have obtained several solutions of equilibrium to Eq. (1).[21] The plasma in such an equilibrium may undergo an instability, if, for example, the viscosity enhances and subsequent clump plasma suffers the orbital instability. This could give rise to a sudden cataclysmic infall of plasma and to a sudden energy release which we may observe as γ-ray bursts.[20,21] Such physics of relativistic plasmas has been considered to be strictly in the realm of theory, but now the extremely hot plasma generated by a T^3 laser irradiation might show some experimental aspect of the physics to us.

3 T^3 Laser as an Integrator of Science

It appears that at the end of the 20th Century the experimental method and equipment to carry out the cutting edge research in astronomy, physics, and even biology are getting ever larger and more highly specialized: Telescopes with a wider aperture, accelerators with higher energies, and so forth. Taking an example of accelerators, just till a generation ago each country had one, or several if they were lucky, accelerator(s), carrying out various experiments. Now, however, there is only one, or at best two, accelerator(s) for a given type in the world. Is it coming to the point where the entire world can afford to produce but one and eventually zero?[22] In addition, these instruments not only are becoming scarcer, but also so complicated and huge that a layman who has an interest in science cannot grasp its entirety, nor can a graduate student or a starting young scientist. Thus we witness the tendency that although science is getting ever deeper, each scientist is ever more unable to see the next neighboring discipline of science. It is our wishful expectation that perhaps the development of T^3 laser science briefly sketched above may help fight against such a recent general tendency of ever finer and narrower specialization of science and may tend to help integrate various subdisciplines. This is in part due to the inexpensive compactness of a T^3 laser and in part due to its ability to induce a variety of extreme conditions so that there will be a forum (or saloon) where many scientists of different disciplines come and go freely and exchange their findings with their fellow colleagues of equally disparate fields through the T^3 laser as a sparkplug of discussion of a common interest; a biologist or material scientist using a compact X-ray source based on such a laser, a nuclear scientist or high energy physicist building and using a compact laser accelerator, an astrophysicist studying extreme astronomical conditions created by a T^3 laser. For example, the wake excited behind a short intense laser pulse is so strong that it may be utilized for high energy particle acceleration, but simultaneously it might present an interesting astronomical possibility of strong "gravity." This is because according to Einstein's equivalence principle particles on the frame of that strong accelerating field experience equivalent gravity. The wakefield accelerating field due to a 10^{18} W/cm^2 laser pulse corresponds to a "gravitating field" of a blackhole (about one Schwarzschild radius away) with about a million solar mass. Isn't it intriguing whether we can detect redshift of photons in such a field[23,24] etc. to carry out astrophysical experiments of a table-top blackhole? It is fun to imagine that via a T^3 laser many a conversation sprouts out among astronomers, physicists, chemists, material scientists, biologists,... . We may call this potential of a T^3 laser an *integrator* of science. We wish that scientists of various different disciplines knock the door of the physics under extreme conditions = "experimental astrophysics" that a T^3 laser plays a key overcoming the traditional compartmental barriers.

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FIGURE CAPTIONS

FIG. 1. Phase diagram of hydrogen (mass density vs. temperature) [after H. van Horn, Science **252**, 384 (1991) and some additions are made]. The broad arrow starts from the solid ice condition at the left center and moves to the right with a wide possible passage of the phase diagram, depending on the irradiation scenario.

FIG. 2. Phase diagram of iron. [again after *ibid.* with additions].

FIG. 3. Superhigh temperature plasma near a blackhole and the QED sea near the horizon.