ASTROPHYSICS IN THE LABORATORY WITH EXTREME LIGHT

G. RAVINDRA KUMAR*

This paper offers a few glimpses of recent experimental efforts to create temperatures and pressures similar to those in the stellar environment, in a laboratory on the earth. Creation and study of such 'extreme' states is throwing up possibilities for mimicking astrophysical conditions in a small laboratory that houses femtosecond, high power (yet compact) lasers. A few examples are offered to illustrate this research.

Introduction

Astrophysics, always a fascinating subject, is presently even more attractive as it is undergoing several revolutions, the detection of gravitational waves being the latest and most striking. We are able to see further than ever before and scan wider across the energy spectrum, discover more and more objects, launch probes far and wide and plan more and more adventures in space. And computer simulations of astrophysical systems are getting ever more sophisticated, throwing new light on the physics and giving us fresh insights into the fascinating processes that are happening out there.

An equally significant revolution is also happening right here on the earth in several laboratories. And this revolution could change the very character of astrophysics. But before I spell that out, let me give my perspective as an experimental physicist working in a small laboratory. Typically, my daily life involves measurements where I build in options to (a) change one parameter at a time, (b) make many measurements to ensure repeatability and improve accuracy (and this automatically implies creating the same situation again and again for observation) and (c) change over to another parameter and repeat the above process.

You can immediately see that little of this is applicable to astronomy. Events in the universe occur at their own will, completely outside human control. They occur as and when conditions stimulate them. And many of them are not repeatable. Even if they are in their natural course repetitive, the time scale of repetition could be so large that making comparisons is not feasible or is extremely time consuming. One can of course observe many similar astrophysical objects for making comparisons and drawing general conclusions but we really have no option but to take things as they come! Lastly, it might be worth noting that astronomers are always living in the past (!), given that signals from events that occur far away from us take millions and billions of years to travel to the human observatory, on the earth or in space.

Can astrophysics get some help from an earth bound laboratory? This is the revolution that I hinted at in the above paragraph. All over the world, laboratories that are big and small are beginning to join the race to simulate astrophysical conditions using high energy drivers like accelerators, lasers and special plasma devices like the Z-pinch[1]. Lab experiments that can simulate astrophysical phenomena can be very useful in testing and refining astrophysical models. Laboratory astrophysics is emerging as an important branch of laser driven plasma physics. The most recent, biennial High Energy Density Laboratory Astrophysics international conference, the 12th in the series, was held in Japan at the end of May 2018 and show cases some of this excitement (http://www.ile.osaka-u.ac.jp/hedla2018/). It can give you a feel of the major questions being addressed from plasma jets to magnetic turbulence

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* Tata Institute of Fundamental Research, 1 Homi Bhabha Road, Colaba, Mumbai 400 005, grk@tifr.res.in; www.tifr.res.in/~uphill

and magnetic reconnection and from plasma instabilities to the equation-of-state of dense, hot matter.

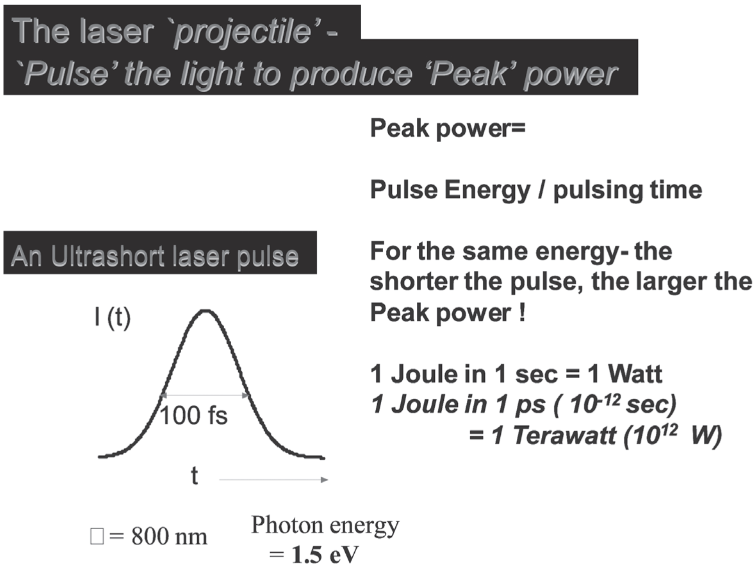
Much of the impetus for the lab experiments comes from the fact that the fluid flows in astrophysical objects can be scaled down to the lab levels with appropriately rescaled parameters in the equation for fluid flow[2]. Needless to add, the famous Saha ionization equation conceptualized and derived for stellar atmospheres is equally applicable for the plasmas created in the laboratory. Using high peak power, femtosecond (10^{-15} s) laser pulses we can also simulate on a small scale in the lab, planetary interiors and new phases of matter inaccessible by conventional methods of increasing temperature and pressure. These pulses can accelerate charged particles to high energies (millions and billions of electron volt level) for applications in science, technology and medicine and can drive novel types of radiation sources ranging from terahertz to gamma rays[1,3]. All these and more on a table top, at much more modest budgets than those operative a couple of decades ago.

We must of course acknowledge the longer pulse (nanosecond) lasers that occupy a very important place in this research area and have traditionally been the drivers for much of the exploration. These facilities have been built for achieving laser fusion, studying properties of shocked materials for other applications etc. Currently the most energetic laser of this type is the mammoth National Ignition facility in the USA, which has 192 laser beams and launches megajoules of energy in a nanosecond burst at a millimeter sized target. These are large facilities operated on a scale similar to accelerators. I will not venture into discussing these experiments due to lack of direct experience with this regime, but point you to some of the excellent review articles that exist in the literature[2,4]. The NIF also has very lucid, appealing descriptions (including videos) of this science (https://lasers.llnl.gov/)

In this article, we quickly review a few basics of 'extreme' light and appreciate how such light excites extreme states in matter. We touch upon the vast canvas of lab astrophysics with a brief mention of some notable experiments (my personal taste!). I will then present, a short overview of some of the work that TIFR has done over the last few years . I would like to caution that this is by no means an attempt to overlook the enormous contributions of many other groups. For a more elaborate tutorial on the subject, you may refer to G R Kumar, Pramana-Journal of Physics (2009)[5] and other papers, particularly the reviews, cited at the end of this article.

Extreme Light

In short, this is light produced over extremely small time duration, resulting in high 'peak' power (see below). Such pulses can be focused to achieve gigantic fluxes of photons. (number of photons/cm^2/sec). How is this achieved? The intuitive way to achieve high intensities is to focus light beams to a small spatial area. There is however a limit to the focusing of light due to diffraction. The best one can do is to focus down to the order of the wavelength, but that calls for aberration free optical components of a very short focal length and a good spatial profile of the beam being focused. In practice, this can give a best focused intensity of 10^7- 10^8 W cm^{-2} for a 1 W of input beam for visible light (500 nm). The key to further enhancement lies in *'focusing in time*', that is producing pulses of light as shown in Figure 1 below.



The laser `*projectile*' -
`*Pulse' the light to produce 'Peak' power*

Peak power=

Pulse Energy / pulsing time

An Ultrashort laser pulse

For the same energy- the shorter the pulse, the larger the Peak power !

1 Joule in 1 sec = 1 Watt
1 Joule in 1 ps (10^{-12} sec)
= 1 Terawatt (10^{12} W)

Figure 1. The picture above shows the leaps in peak power (and intensity) that can be achieved by short light pulses. Today we can produce intensities as large as 10^{22} W cm^{-2} pulses[6] using technology that was realized first in the mid-1980s, discussed below. The time frontier has shrunk further to the attosecond (10^{-18} s) level[7].

Towards Extreme Light

In 1985, Mourou and Strickland[8] adapted an old idea from radar technology to increase the peak power by many orders of magnitude. An ultrashort, low energy pulse, with small energy per pulse (and hence low peak power) is stretched in time to further decrease the peak power. This is then amplified in energy. Thus the energy of the pulse can be increased substantially without reaching peak power levels that can damage optical components in the laser system. It is finally compressed back to its original ultrashort duration. This final pulse can now have orders of magnitude larger energy than what it had initially and hence its peak power is boosted by the same order of magnitude[9].

The technique of stretching the pulse in time, subsequent amplification and compression is called chirped pulse amplification (CPA) [Fig.2]. Stretching in time causes the pulse to ‘chirp’, i.e. its frequency evolves as a function of time within the pulse itself. Fig. 3 shows a part of a 100 terawatt, 25 femtosecond laser at TIFR,that uses this methodology.

What is the electric field that is produced when such high peak power, ultrashort laser pulses are focused? For example at the highest peak intensity of 10^{22} W/cm^2 [6] achieved so far, the electric field is a gigantic ~ 10^{13} V/cm! To get a true feeling for this number, let us again look at an electric field ‘scale’ provided by nature. The binding between the nucleus and electron in an atom provides a good scale. This field is ~10^{10} V/cm corresponding to an intensity of ~10^{16} W/cm^2. This implies that the highest intensity laser pulses can apply on the same electron an electric field that is 1000 times larger. Such excitation is extremely strong and was unheard of till these lasers came along.

That sets the basic scale for intense light (>10^{16} W/cm^2) interaction with matter. Light is the major driver for the electrons and electrons can be treated essentially like ‘free’ particles.

Matter in Intense Light Fields

Matter inevitably gets ionized in the focal volume of a high intensity laser. The ionization process can take two independent routes or a mixture of both, depending on light intensity. For infrared light (~1 eV photon energy), below 10^{13} W/cm^2, the electron is ionized by a multiphoton process, where many photons act collectively to couple the required energy (multiphoton ionization, MPI). Above 10^{15} W/cm^2, the bound electrons find a way to leak out of a coulomb barrier, now distorted by light, a process referred to as tunneling (or ‘field’) ionization. In the intermediate regime, both processes can occur[10].

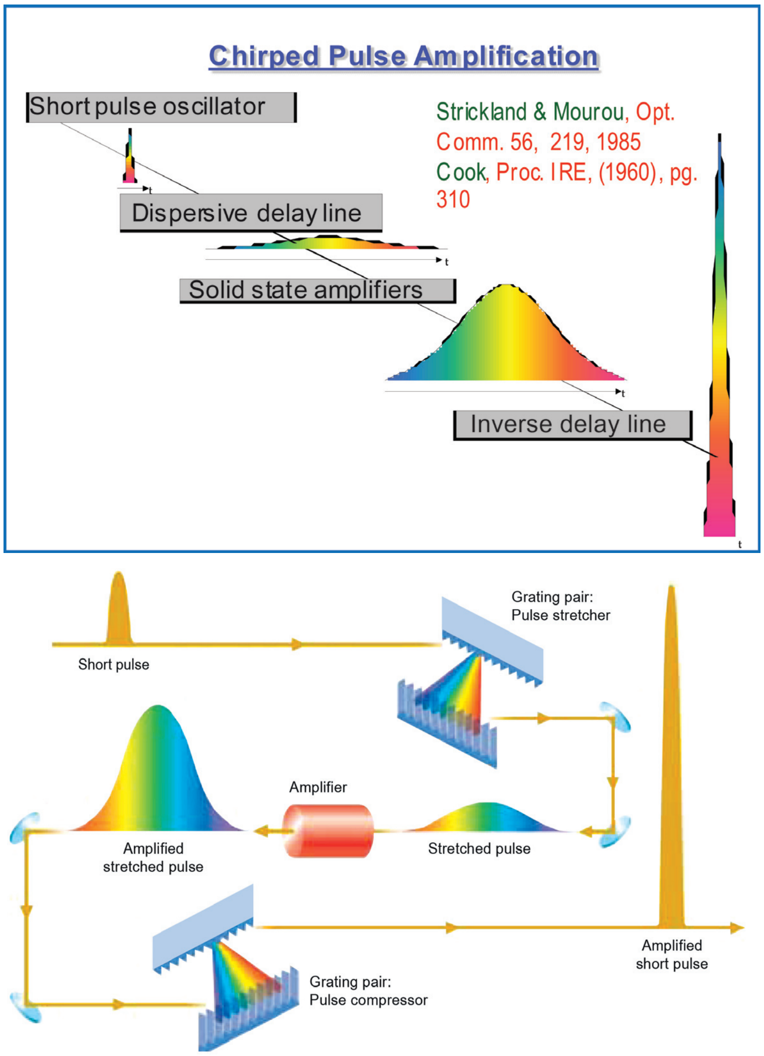


Figure 2. The principle of chirped pulse amplification (CPA) that has made table top terawatt and petawatt lasers possible (Picture at the bottom taken from Mourou and ‘Umstadter’ Scientific American, May 2002).

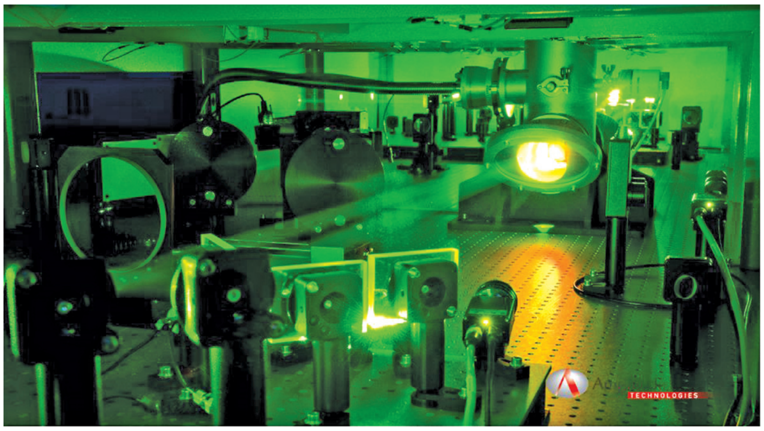


Figure 3. The reddish glow of the final amplifier of the 100 terawatt laser system at UPHILL, TIFR, Mumbai. In our country, the Raja Ramanna Centre for Advanced Technology (RRCAT), Indore has a 150 terawatt laser system of a similar architecture. They are currently in the process of installing a petawatt (1000 terawatt) laser based on the CPA principle.

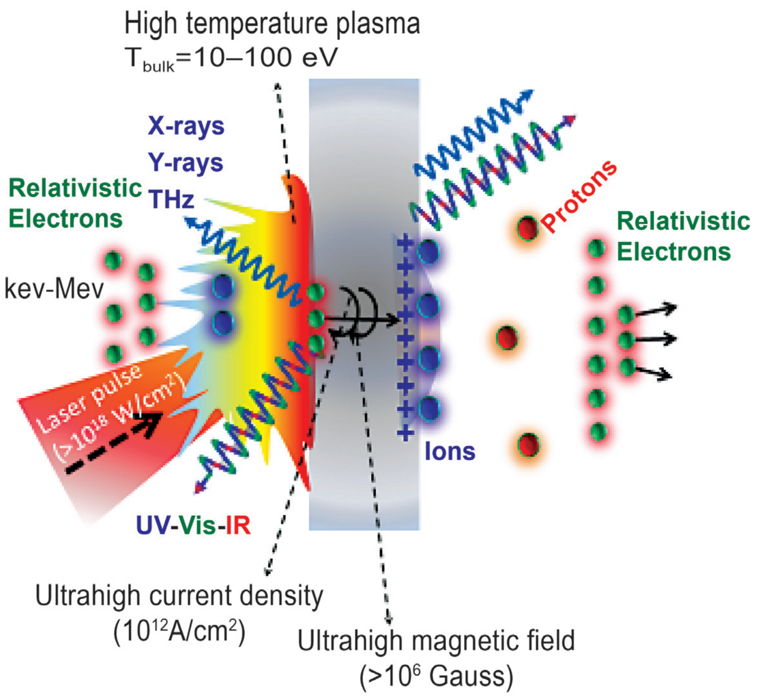


Figure 4. Interaction of a high intensity, femtosecond laser pulse with a solid, creating a highly excited plasma (see the paragraph below).

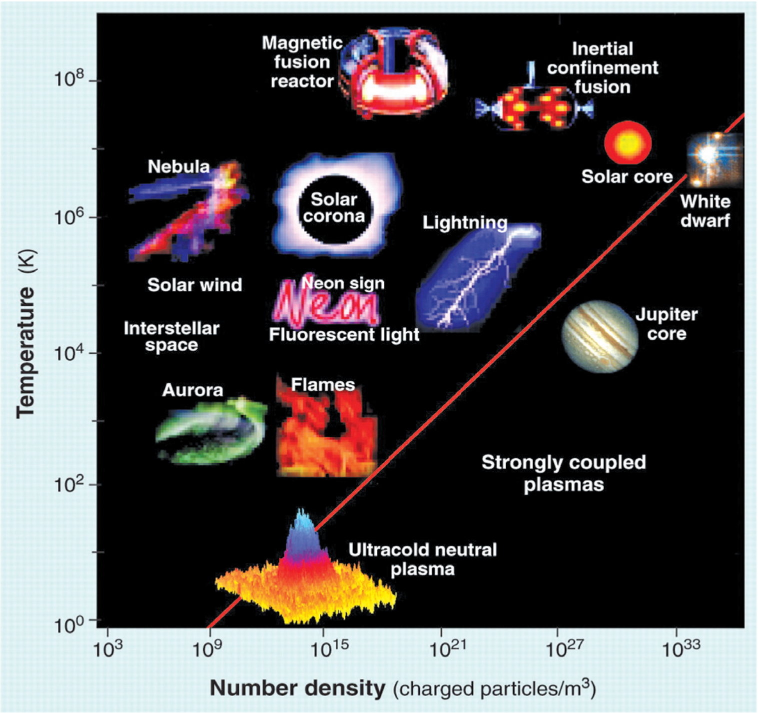


Figure 5: Plasmas, plasmas everywhere…. of all hues and shades. See the position occupied by laser plasmas (marked 'Inertial confinement fusion').

Interaction of intense light with dense matter (solid, liquid, dense gases and gaseous clusters) has thrown up the most amazing possibilities in terms of science and technology. High density ensures stronger interaction because light can now drive electrons not only on its own, but can also use the driven electrons to efficiently cause other excitations in the medium. These 'other' excitations can be at the individual particle level or at the collective level. This implies much larger transfer of energy leading to higher ionization and excitation levels. And since the excitation happens on femtosecond timescales, the ions in the target are basically frozen in their places, no motion occurs and density remains the same. This leads to high energy density in the matter in a 'macroscopic' volume of matter as we will discuss a little later. The laser excited plasma [Fig. 4] can emit all sorts of signals, depending on excitation and type of target conditions – electromagnetic radiation ranging from terahertz to gamma rays and material particles like electrons, ions, neutrons and positrons with energies up to billions of electron volts. See Fig. 5 for a variety of plasmas both natural and those created in the laboratory.

High Energy Density Physics (HEDP):

It is now a matter of common knowledge that our universe houses not just enormous, incredible amount of energy but stores it at remarkably high density [Fig.6]. Beginning science students learn about the birth, growth and death of a star. Astrophysicists have theorized about the violent, high energy density environment for a long time and built many models for explaining various phenomena. These have been motivated by astronomical measurements which have also leap-frogged in sophistication over the past few decades. As observed at the beginning of this article, the biggest challenge in astronomy, unlike in many other branches of science however, is the total dependence on phenomena as they occur in nature rather than measuring the response to a chosen, controlled stimulus in a laboratory.

Laboratory Astrophysics

All this seems set to change now. Short and ultrashort, ultrahigh intensity lasers can now access pressure, temperature and density conditions similar to those encountered in intra-stellar matter and the laser experiments can do it at the physicist's will, repeatedly and reproducibly. This 'astrophysics on a tabletop' is very different from the 'take it as it comes' feature of astrophysics prevalent till now.

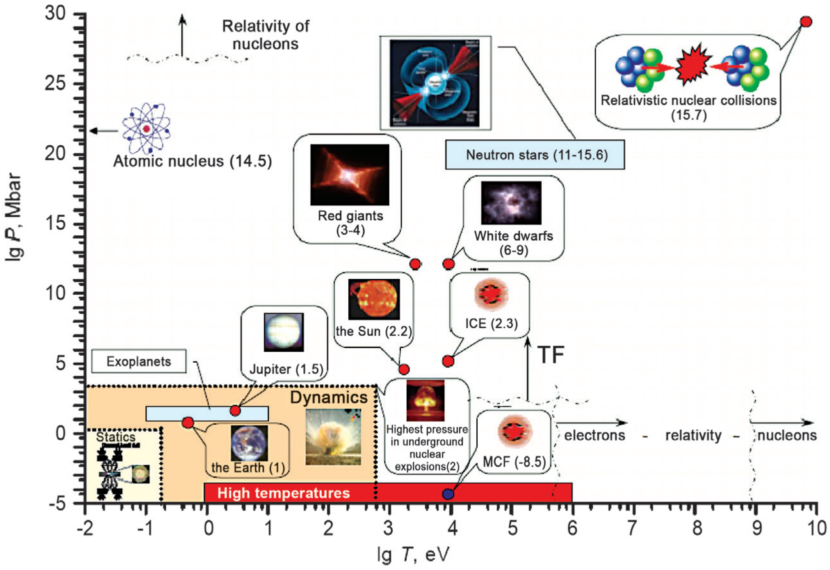


Figure 6. High temperatures and pressures across the universe. 'Statics' at the left bottom corner indicates the conditions achieved in a diamond anvil pressure cell, a popular way of studying the properties of condensed matter under steady high pressures in the lab. The other methods in the picture are all dynamic. ICF stands for inertial confinement fusion or laser fusion while MCF stands for magnetic confinement fusion, also called tokamak fusion. Relativistic nuclear collisions (topmost and right) are studied at the particle accelerators [Picture taken from V.E. Fortov, *Extreme States*[1]. This book has many other details of the physics and experimental facilities.]

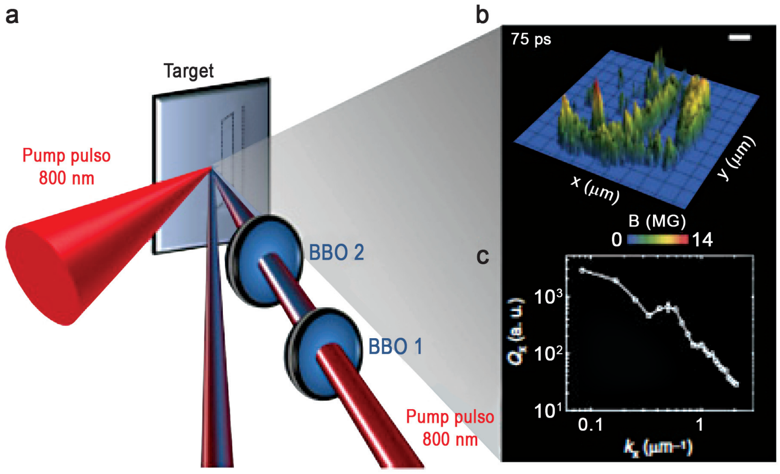


Figure 7. Magnetic turbulence similar to astrophysical scenarios: Experiment at TIFR- A powerful femtosecond 'pump' pulse at 800 nm (red) creates dense, hot plasma while a second, much weaker pulse at 400 nm (probe) measures the magnetic field as a function of pump-probe delay period. The top picture on the right is the transverse spatial profile of the magnetic field at one instant, which looks totally random. Several such pictures are taken at different delay periods. The bottom picture on the right shows the power spectrum, i.e. magnetic field energy density as a function of the inverse spatial scale. This curve shows a power law behavior, clearly indicating that the magnetic field is turbulent. (Chatterjee et al., Nature Communications 2017, Ref. 20)

The levels of ionization and temperature created by ultrahigh intensity laser pulses are being studied include the opacity of stellar matter[11], routes to phase transitions, synthesis of forms of matter possible only at high temperature that is simultaneous with high pressure, elemental synthesis, obtaining the equation of state (EOS) and the response of matter to extreme shocks[1-3]. These exemplify perhaps the 'classical' problems of astrophysics. But laser experiments have gone much further to simulate even exotic astrophysical phenomena. One example is that of the gamma ray burst (GRB)[12]. A GRB can be an intense millisecond-hundreds of second flash of gamma radiation, containing 10^{50}-10^{51} ergs of energy, a million to trillion times brighter than the sun and hundreds of times brighter than a supernova. GRBs have fascinated astronomers for decades now, are found to occur at an average of one per day and their origin is a hotly debated topic.

We also note that some interesting experiments on analogue gravity and analogue Hawking radiation have also been performed in recent years[13], indicating the vast potential of ultrafast, high peak power lasers for triggering absolutely novel and fundamental studies that can further our understanding of the universe.

I now turn to an aspect that is particularly interesting to our group, namely the study of magnetic fields in laser driven plasmas, which has interesting implications for understanding magnetic fields in the universe. The article by Arnab Rai Choudhuri in this issue describes the very interesting behavior of the magnetic fields in the sun and their role in solar plasma dynamics. It is well known that magnetic fields are ubiquitous in the universe and control many astrophysical processes but their origin continues to be a topic of huge debate (see the article by Kandaswamy Subramanian in this volume). Recent lab scale laser experiments have simulated conditions that can generate the seed 'protogalactic' magnetic fields[14]. Another fascinating process that occurs in the sun is the magnetic reconnection[15] which is understood to power the solar flares and cause the ejection of high energy particles from the sun. This occurs due to the sudden changes in the topology of the magnetic field lines of opposite polarity in neighbouring regions of the plasma. Lab experiments have simulated this process[16] using two laser beams each creating a plasma spot of its own with its own internal magnetic field. If the spots are close to each other the magnetic field lines in each spot (of opposite polarity) can change their topology, opposite field lines connect in the intermediate region, releasing energy to the particles and heating up the intermediate region to high temperatures, and this region then emits x-rays. The measurement of this x-ray brilliance is then a measure of the energy released in the magnetic reconnection process.

Yet another important aspect of the laser experiments is the creation of gigantic magnetic fields[17]. In fact, the largest magnetic fields created on the earth are found in laser driven plasmas and these can measure hundreds of megagauss (the earth's magnetic field is barely a gauss) over regions extending tens of micrometers. High intensity, femtosecond laser excitation of a solid creates relativistic electrons that stream into the target behind the excited spot. Such electrons can form femtosecond current pulses with peak currents as large as mega-amperes (peak current densities can reach trillions of ampere per square centimeter!). The transport of currents through dense, hot plasma is fraught with the well-known filamentary (Weibel) instability[3,10]. This instability, arising from the electromagnetic interaction of the relativistic forward current with the nullifying return current drawn from the background plasma, retards and breaks up the forward current into microscopic filaments, destroying beam integrity and limiting beam transport to a few tens of microns[3,10]. Such filamentation is obviously detrimental to the transport and serious efforts are being made to understand and improve the collimation of these mega-ampere electron currents[18]. One nice way to capture the transport process is to measure the magnetic fields in the plasma.

TIFR experiments over the past two decades have studied the time and space evolution of these magnetic fields (Fig. 7) and derived information on the fast electron transport. In addition, these experiments show that the magnetic fields become turbulent[19] and the features of such turbulence are very similar to those in solar wind, solar corona as well as earth's magnetosheath[20].

TIFR experiments have also discovered acoustic oscillations at terahertz frequencies with analogous to oscillations postulated in in core collapse supernova[21].

As the world moves on to build lasers at 10 petawatt and 100 petawatt peak power levels (Extreme Light Infrastructure (ELI) in Europe and Shanghai Institute of Optics and Fine Mechanics in China), laboratory astrophysics is set to emerge as a major frontier in science throwing up new perspectives and tests on astrophysical models.

Shall we say, "Welcome to Taare zameen par!"

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Some websites on intense laser field science:

Here are addresses of some websites where you can get more details of the kind of research being performed in intense laser physics and perhaps can even access some of the research papers published. These have been chosen to give a flavor of the field.

India

Ultrashort Pulse High Intensity Laser Lab (UPHILL), TIFR. Mumbai: http://www.tifr.res.in/~uphill/

(Many papers and theses summarising UPHILL research can be downloaded from here)

Raja Ramanna Centre for Advanced Technology, Indore: www.cat.ernet.in

Bhabha Atomic Research Centre (BARC): http://www.barc.ernet.in/

Institute for Plasma Research, Gujarat, India: http://www.ipr.res.in/

Around the world

Institute of Laser Engineering, OSAKA, Japan : http://www.ile.osaka-u.ac.jp/index_e.html

Rutherford Appleton Lab: http://www.stfc.ac.uk/About/Find/RAL/Introduction.aspx

Forschungszentrum Dresden-Rossendorf, Dresden: http://www.fzd.de/db/Cms?pNid=0

Laboratoire d'Optique Appliquée LOA Palaiseau: http://loa.ensta.fr/index_gb.html

Ecole Polytechnique - Applied Optics Laboratory, Paris: http://www.polytechnique.edu/page.php?MID=84

Advanced Laser Light Source,Canada:http://steacie.nrc-cnrc.gc.ca/programs/as/as_alls_e.html

The York Plasma Physics and Fusion Group, York university: http://www.york.ac.uk/

Advanced Photonics Research Institute (APRI) Korea: http://apri.gist.ac.kr/eng/main.php

Chinese Academy of Sciences, Beijing: http://english.cas.ac.cn/

Plasma Physics Group, Imperial College London: http://www3.imperial.ac.uk/plasmaphysics

The High Intensity Laser Group - University of Texas at Austin: http://www.ph.utexas.edu/~utlasers/

National Ignition Facility & Photon Science - The Power of Light https://lasers.llnl.gov/

ELI : the *Extreme Light* Infrastructure european project www.**extreme-light**-infrastructure.eu/

CEA LASER MEGAJOULE

www-lmj.cea.fr

References

1. R.P. Drake, "High energy density physics- Fundamentals, inertial fusion and experimental astrophysics" (Springer-Verlag, Heidelberg 2006); V.E. Fortov, "Extreme States of matter on the earth and in the cosmos" (Springer-Verlag, Berlin Heidelberg, 2011); J. Colvin and J. Larsen, 'Extreme physics- Properties and behavior of matter at extreme conditions' (Cambridge University Press, Cambridge, 2014)
2. D. D. Ryutov and B. A. Remington**,** Scaling astrophysical phenomena to high-energy-density laboratory experiments, *Plasma Phys. Control. Fusion* **44,** B407–B423 (2002)
3. S. V. Bulanov, T. Zh. Esirkepov, M. Kando, J. Koga, K. Kondo, and G. Korn, On the Problems of Relativistic Laboratory Astrophysics and Fundamental Physics with Super Powerful Lasers, *Plasma Physics Reports* **41**, 1(2015)
4. B. A. Remington, R. P. Drake, D. D. Ryutov, Experimental astrophysics with high power lasers and *Z* pinches, *Rev. Mod. Phys.* **78**, 755 (2006)
5. G. Ravindra Kumar, Ultrashort, intense light and dense, hot matter, *Pramana- Journal of Physics* **73**, 113 (2009)
6. S.-W. Bahk, P. Rousseau, T. A. Planchon, V. Chvykov, G. Kalintchenko, A. Maksimchuk, G.A. Mourou, and V. Yanovsky, Generation and characterization of the highest laser Intensities (10^{22} W/cm^2), *Opt. Lett.* **29**, 2837 (2004)
7. F. Krausz and M. Ivanov, Attosecond physics, Rev. Mod. Phys. **81**, 163 (2009); 'Attosecond Photonics', Nature Photonics Focus Issue, **8** (March 2014)
8. D. Strickland, and G. Mourou, Compression of amplified chirped optical pulses, *Opt. Commun.* **56**, 219 (1985)
9. P. Maine, D. Strickland, P. Bado, M. Pessot, and G. Mourou, Generation of Ultrahigh Peak Power Pulses by Chirped Pulse Amplification, *IEEE J. Quantum Electron.* **24,** 398 (1988).
10. P. Gibbon, "Short pulse laser interactions with matter: an introduction", Imperial College Press London (2005)
11. S.J. Rose, Controls for the heart of the sun, *Contemp. Phys.* **45**, 109 (2004)
12. J. Warwick, T. Dzelzainis, M. E. Dieckmann, W. Schumaker, D. Doria, L. Romagnani, K. Poder, J. M. Cole, A. Alejo, M. Yeung, K. Krushelnick, S. P. D. Mangles, Z. Najmudin, Experimental Observation of a Current-Driven Instability in a Neutral Electron-Positron Beam, *Phys. Rev. Lett.* **119**, 185002 (2017)
13. D. Faccio, Laser pulse analogues for gravity and analogue Hawking radiation *Contemporary Physics*, **53**, 97 (2011)
14. G. Gregori, B. Reville, F. Miniati, The generation and amplification of intergalactic magnetic fields in analogue laboratory experiments with high power lasers, *Phys. Rep.* **601**, 1 (2015)
15. J. L. Burch and J. F. Drake, Reconnecting magnetic Fields, *Amer. Scientist*, **97**, 392 (2009)
16. J. Zhong, Y. Li, X. Wang, J. Wang, Q. Dong, C. Xiao, S. Wang, X. Liu, L. Zhang, L. An, F. Wang, J. Zhu, Y. Gu, X. He, G. Zhao and J. Zhang, Modelling loop-top X-ray source and reconnection outflows in solar flares with intense lasers, *Nat. Phys.* **6**, 984 (2010)
17. A.S. Sandhu, A. K. Dharmadhikari, P. P. Rajeev, G. R. Kumar, S. Sengupta, A. Das, and P. K. Kaw, Laser-Generated Ultrashort Multimegagauss Magnetic Pulses in Plasmas Phys. Rev.Lett. **89,** 225002 (2002); 'Physics News Update No.614' (American Institute of Physics, Nov 20, 2002).
18. S. Mondal, V. Narayanana, W.J. Ding, A. D. Lad, B. Hao, S.A. Ahmada, W.M Wangb, Z.M. Sheng, Sudip Sengupta, P.K. Kaw, A. Das and G. Ravindra Kumar, Direct observation of turbulent magnetic fields in hot, dense laser produced plasmas *Proc. Natl.Acad. Sci.* USA **109**, 8011(2012)
19. G. Chatterjee, P.K. Singh, S.A.Ahmed, A. P. L. Robinson, A. D. Lad, S. Mondal,V. Narayanan, I. Srivastava, N. Koratkar, J. Pasley, A. K. Sood and G. Ravindra Kumar Macroscopic Transport of Mega-ampere Electron Currents in Aligned Carbon-Nanotube Arrays, *Phys. Rev. Lett.* **108**, 235005 (2012)
20. Gourab Chatterjee, K. M. Schoeffler, Prashant Kumar Singh, Amitava Adak, Amit D. Lad, Sudip Sengupta, Predhiman Kaw, L. O. Silva, Amita Das, and G**.** Ravindra Kumar, Magnetic Turbulence in a Table-Top Plasma Relevant to Astrophysical Scenarios *Nature Communications* DOI 10:1038 ncomms15970 (2017)
21. A. Adak, A.P.L. Robinson, P. K.Singh, G. Chatterjee, A. D. Lad, J. Pasley and G. Ravindra Kumar, Terahertz acoustics in dense, hot laser plasmas *Phys. Rev. Lett.* **115,** 115001 (2015)

Author's Note : *This article is my personal tribute to late Prof. Predhiman Krishan Kaw, a brilliant plasma physicist, inspiring leader, generous mentor, great teacher and an invaluable collaborator.*