Exploratory Workshops Scheme

Standing Committee for Physical and Engineering Sciences (PESC)

SCIENTIFIC REPORT

ESF Exploratory Workshop on

Extreme Laboratory Astrophysics: Advances and Opportunities in High-Energy Density Experiments

Observatoire de Paris (France), 22 - 24 September 2008

Convened by:

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EXECUTIVE SUMMARY

Advances in high-energy density plasma experiments have led in the last few years to the capability of recreating in the laboratory the extreme conditions of matter and the complex dynamical phenomena often found in space. Combined with advancement in numerical modelling and the use of high-performance computing (HPC) facilities, there is now a greater understanding of the possible connections between laboratory experiments and astrophysical observations and models.

Emerging areas of research in what we shall call *eXtreme Laboratory Astrophysics* (XLA) have been directly aimed not only at direct measurements of quantities such as opacities and the equation of state, but also at reproducing scaled complex dynamics, such as compressible hydrodynamic mixing, hypersonic jets and interaction with an ambient medium, magnetohydrodynamic jet formation, radiation dominated shocks, photo-ionised plasmas and magnetic reconnection. These phenomena encompass a wide range of astrophysical objects, including young stellar objects (YSO) and active galactic nuclei (AGN) jets, supernovae remnants, supernovae explosions, radiatively driven molecular clouds and accretion shocks to name a few.

The number and sophistication of XLA experiments in Europe is growing rapidly and a further boost is to be expected with the arrival of new and upgraded laser and pulsed-power European facilities, such as LIL/LMJ, PETAL, ELI and HiPER. Although these facilities will create even more extreme conditions of matter and considerably extend the astrophysical phenomena that may be studied in the laboratory, a collaborative effort which heavily involves the astrophysical community in the conception of existing and new experiments does not exist. It was agreed that the emergence of XLA as a novel interdisciplinary field may bring some very important new aspects to research in astrophysics. In particular, XLA work can provide fundamental insights into the physics of the astrophysical system under study, guide further developments and open new avenues of research. As new ideas emerge, they can be developed and directly tested in the controlled laboratory environment: such possibility would represent a totally new approach in astrophysics. Finally, astrophysical codes validation on laboratory data would also play a major role in the field.

The workshop brought together twenty scientists from the astrophysics and plasma physics communities with the aim of stimulating an interdisciplinary collaborative effort, and identifying common objectives in this emerging area of research. One of the key aims of the workshop was to expose astrophysicists to the recent advances and opportunities existing in XLA, and to provide a broad outlook of future developments. At the same time, the workshop was an occasion to present to the plasma physicists the current status of research in a number of key areas in astrophysics. The common objective was to identify fundamental issues that could benefit from current and future XLA research and to discuss the creation of a framework

for an integrated interdisciplinary approach comprising theory, numerical modeling, experiments and observations. The workshop also served as a platform to discuss funding issues at a European and International level.

The outcome of the workshop was very encouraging and positive. The following key points were highlighted in the discussions:

1. The need for increased visibility of XLA at the European level.
2. To define the boundaries of the research field.
3. The state-of-the-art of the field in Europe.
4. To provide an outlook for the next five years.
5. To discuss funding issues at the European level.

Finally it was agreed to create a task force to follow up on various issues raised during the workshop.

SCIENTIFIC CONTENT

Overview

Several facilities exist in Europe where state-of-the-art XLA experiments are currently being performed. These are both open-access or university-based facilities and include pulsed-power machines such as MAGPIE in the UK and high-power lasers such as LULI and LIL (FRANCE), PALS (Czech Republic), VULCAN (UK), and smaller table-top femto-second lasers.

Experiments of ***radiative shocks***, where radiation is reabsorbed upstream of the shock producing an ionization front, are opening the way to study complex radiation hydrodynamic regimes in the laboratory. Understanding the detailed dynamics and structure of these shocks can provide important information for example on accretion shock in classical TTauri stars and white dwarfs. The experiments have already shown that the topology of the shock, reaching velocities as high as 70 km/s, is very important on its structure and that multi-dimensional simulations are necessary to correctly describe its dynamics. In addition detailed opacities need to be used to correctly interpret the experiments, thus providing a validation tool for the atomic data. Looking at the future, there is also the possibility of extending those studies to include magnetic fields and thus produce experiments in the radiation magnetohydrodynamic regime.

In the radiatively cooled regime, where the plasma is optically thin, experiments can produce long-lived, steady-state shocks where both the level of radiative cooling and the presence of magnetic fields can be controlled. More recently experiments have also been able to produce supersonically rotating flows and shocks. The stability and structure of these shocks can be studied in detail, providing stringent tests to astrophysical shock models. In addition, the radiation sources available can also help to study the formation and propagation of ***ionization fronts*** and ***radiatively ablated fronts*** like those observed in and around HII regions.

Blast wave experiments are particularly interesting to study aspects of the structures seen in supernovae remnants. The experiments are now providing very detailed data on the shock front time-evolution and offer the possibility of studying comprehensively their stability. Moreover the possibility of using different gases (H, Ar, Xe, etc) which have different cooling rates extends the range of applicability of the results and provides excellent data for the validation of laboratory as well as astrophysical codes. In general, the flexibility of XLA studies means that the experiments can be extended to include more complex configurations, like blast wave collisions and/or more physics, like magnetic fields.

Another area of XLA which has received much attention is the study of ***jets***, which are in the context of YSO and AGN jets. Indeed both hypersonic hydrodynamic jets and super-fast-magnetosonic jets have been produced on several facilities. These are investigating the MHD jet formation as well as the jet propagation and interaction with an ambient medium. More recently supersonically rotating, radiatively cooled shocks and jets have also been produced, extending the range of astrophysically relevant flows that can be produced to tackle issues such as jet stability, entrainment of ambient gas, effects of heating and cooling on the jet kinematics, to name a few.

Scientific Presentations

The workshop program was dived into six broad sessions and ample time was put aside for discussions at the end of each day. The presentations and the book of abstracts can be found on the conference website: http://amrel.obspm.fr/ciardi/xla

The sessions were:

I. Overview of XLA, future experimental facilities, ground and space based telescopes.
II. Cosmic Rays, Supernovae, Gamma Ray Bursts…
III. Turbulence, Instabilities, Magnetic Reconnection…
IV. Jets and Outflows…
V. XLA experiments and modelling
VI. Radiative Flows, Massive Stars, Shocks…

The ***first session*** was dedicated to an overview of existing experimental facilities and new developments in the astronomical observations.

Mike Dunne presented an overview of the current and future high power laser facilities in Europe and worldwide. He then focused on examples of experiments which can create extreme states of matter, be well diagnosed and act as experimental test-beds which could be accessed by the laboratory astrophysics community. The examples included: transition to turbulence in the plasma regime, radiation transfer in clumpy media, nuclear reactions under high energy density conditions, production of electron-positron plasmas, particle acceleration. This was followed by general presentations discussing the studies that can be performed on facilities such as pulsed-power generators and high power laser.

Dimitri Ryutov described several possible new experiments of astrophysical relevance: (i) the in-situ measurements of thermal conduction in warm dense matter; (ii) Rayleigh-Taylor instability of a photo-ionization front for non-normal irradiation; (iii) the generation of differentially-rotating plasma discs; (iv) the effect of a large Reynolds number on the global dynamics of turbulent flows; (v) experimental comparison of electromagnetic filamentation instability and electrostatic beam-plasma instability.

Sergey Lebedev discussed a series of experiments to produce magnetically dominated jets on pulsed power facilities. These jets are driven and collimated by toroidal magnetic fields, have Reynolds and Magnetic Reynolds numbers much greater than unity, and are radiatively cooled. The data from these experiments, combined with 3-D resistive MHD modelling, allow direct contact with modelling of astrophysical outflows from young stars. The ongoing improvements of the diagnostic capabilities in these experiments will allow addressing issues such as the origin of variability of magnetically driven outflows and the efficiency of magnetic to kinetic energy conversion.

Finally the session was ended with an overview of the observational data and models of jets from young stars by Tom Ray. He also discussed in detail the advances expected with the development of new ground-based and space-based telescopes which will become available in the next few years. In particular it is expected that the launching zone of proto-star jets may become resolvable in the near future.

The ***second session*** was devoted to discussion of the physics of Cosmic Rays, supernova and gamma ray bursts.

Luke Drury discussed what can be learnt from XLA experiments about the acceleration of cosmic rays. He started with a general discussion of the scaling between the laboratory experiments and astrophysics, and then concentrated on the scaling of the diffusive shock acceleration model. The laboratory experiment can attempt to look at the injection and early time acceleration issues, which will require satisfying the following conditions: generation of strong plasma shock (compression ratio greater than 2.5 at least), acceleration rate greater than competing collisional losses (strong magnetic fields), a sufficiently large and long-lived shock.

Tony Bell discussed in detail mechanisms of particle acceleration by cosmic shocks, including the development of instabilities and turbulence. He then described relevant laser experiments and discussed in detail possible future experiments, directly aimed on the studies of particle acceleration by shocks. The experimental requirements include: super-alfvenic shocks, energetic electrons seeded with energy > mu^2 (u= shock velocity), energy gain greater than initial electron energy $euBR > mu^2$ (R= shock radius), rate of energy gain > rate of collisional loss $\omega\tau > v/u$ (v= electron velocity), energetic electron energy density ~ 0.1-0.5 ρu^2 to excite instability. He has also discussed another exciting possibility for the future laser experiments: pair production in multi-photon electron-laser interaction.

Jacob Frederiksen talked about computational plasma modelling in astrophysics. He discussed particle in cell (PIC) simulations of astrophysical plasmas, including GRB afterglow shocks, magnetic field generation and particle acceleration, electromagnetic turbulence in relativistic two-streams, radiation spectral synthesis from PIC plasmas, current sheets in driven PIC plasmas. He then described recent advances in the PIC simulation models and discussed future applications and tests.

Peter Biermann discussed observations and origins of ultra high energy particles, and their connection to the active galactic nuclei (AGN) and AGN jets. He has also discussed the physics of AGN jets, episodic activities driven by merges of AGNs and relevant oblique shock physics.

The ***third session*** was dedicated to turbulence, instabilities, and magnetic reconnection.

Steven Balbus discussed the physics of accretion disks and reviewed the stability of magnetized astrophysical plasmas. In particular he emphasized the extreme sensitivity to apparently very weak magnetic fields.

Gianluigi Bodo presented results of numerical simulations of instabilities in astrophysical jets and accretion disks. He has discussed the present state of direct numerical simulations and their limitations, emphasizing that Reynolds and magnetic Reynolds numbers in numerical simulations are significantly smaller than in the astrophysical systems. He also discussed the possible role of laboratory experiments, which can have the relevant dimensionless numbers comparable or better than can be achieved in simulations, for validation of computer codes and for development of physics intuition. Several numerical studies with astrophysics code "Pluto" were presented, including simulations of angular momentum transport in accretion discs, generation and propagation of astrophysical jets. Finally, he presented results of laboratory experiments with supersonic gas jets and their potential for verification of hydrodynamic simulations.

Gerard Belmont gave a talk on collisionless phenomena in space plasmas. He discussed the parameters and properties of the Earth magnetosphere, with emphasis on magnetosphere dynamics. Important phenomena here are the magnetic reconnection, collisionless shocks and interaction between the solar wind and the magnetosphere.

The ***fourth session*** was dedicated to discussion of jets and outflows.

Max Camenzind gave a talk on accretion and outflows in the vicinity of black holes and neutron stars. He discussed the observational data on the bipolar outflows in galaxies and in vicinities of black holes. Many systems show the presence of different states of outflow activity, with micro-quasars, black holes in binary systems, showing variability on a short time-scale so that a full accretion cycle takes only few years. He has also discussed global models of accretion on stars and black holes, emphasizing computational difficulties of these models.

Attilio Ferrari presented an overview of the present understanding of the launching mechanisms of astrophysical jets. He described the analytical steady state solutions of jet launching and then concentrated on numerical studies. He presented high-resolution time-dependent 3-D MHD simulations of jet launching from resistive accretion disks and discussed how the results depend on magnetization, magnetic diffusivity and diffusivity anisotropy. He has also presented preliminary results on the simulation of disk-star interaction.

The ***fifth session*** focused on examples of XLA experiments and modelling

Roland Smith described recent experiments on laser driven high Mach number, radiative and colliding blast waves in atomic cluster media. The use of cluster media allow achieve high efficiency for the absorption of laser energy in a relatively low density media, and the results of the interaction can be diagnosed with high accuracy. He presented results of investigations of radiative blast waves including attempts to observe thermal and dynamic instabilities of the blast wave. He has also presented investigations of colliding blast waves, which provide high resolution data for verification of numerical simulations.

Edouard Audit gave a talk on radiation-hydrodynamics simulations. There are many situations in astrophysics and in laboratory plasmas where radiation and matter are tightly and dynamically coupled. He presented the HERACLES code and the moment method used to describe the radiative transfer and discussed simulations of radiative shocks and young stellar jets where radiation plays a determinant role.

Michel Koenig gave overview of recent experiments in high energy density physics on laser facilities in Europe. He presented results of several experiments devoted to the studies of dynamic properties of matter (EOS) at high pressures (~1 MBar) and emphasized that progress in diagnostics is critical for providing high accuracy data. In the last part of the talk he concentrated on radiative shock experiments.

Andrea Ciardi presented computational studies of both astrophysical and laboratory jets. He concentrated on the investigation of the bending of astrophysical jets by cross-wind, which produces a C-shaped jets. The code was used to first simulate bending of radiatively cooled laboratory plasma jets, and comparison with the laboratory data was used for code benchmarking. After that the same code was used to simulate a scaled (in dimensionless sense) astrophysical jet bending. Simulations suggest that the presence of angular momentum in the jet (rotation) could lead to observable features which are not present in the interaction of non-rotating jets.

The ***sixth session*** was dedicated to the physics of radiative flows, massive stars and shocks.
Ernst Dorfi gave a talk on the radiation-driven winds from pulsating luminous stars. He discussed the physics of massive pulsating stars and highlighted that accurate knowledge of opacities and equation of state are critical for modelling. He then concentrated on the computational challenges in the modelling of massive pulsating stars.

Philippe Stee gave talk on physics of radiative winds, accretion disks and massive stars, concentrating on spectrally resolved high angular resolution observations with the VLTI and the CHARA interferometers. The observational data strongly suggest that non-LTE physics should be included in the interpretation of the observations.

Chantal Stehle discussed experimental studies of radiative shocks in astrophysical context. She presented several examples of radiative shocks and the properties of these shocks inferred from astronomical observations, and concluded that in many cases 1-D description of shocks appears to be insufficient. In the second half of the talk she described several laboratory experiments in which strong radiative shocks were studied. In some cases 2-D effects were observed (e.g. wall albedo) and included into simulations for the interpretation of the results.

ASSESSMENT OF THE RESULTS AND FUTURE DIRECTIONS

The workshop was very useful for establishing new interactions between the participants and strengthening existing ones. The laboratory plasma physicists were able to learn more about the physics of several classes of astrophysical objects and were able to present the existing experimental capabilities and those becoming available in the near future. The participants came to the conclusion that the best connection between the laboratory experiments and astrophysical observation in the context of Extreme Laboratory Astrophysics can be achieved via computational efforts already existing in both communities. Practical steps required to establish a coordinated effort in the XLA in Europe were discussed, and it was agreed to create a task force to follow up on various issues raised during the workshop. These are:

1. The need for increased visibility of XLA at the European level, with the possibility of setting up a conference in the area.
2. To define the boundaries of the research field and enlarging it experimental domains beyond high-energy density plasmas.
3. To outline the state-of-the-art of the field in Europe.
4. To provide an outlook for the next five years.
5. To discuss funding issues at the European level.

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PROGRAMME

Monday 22 September

08:30	*Registration and Coffee*
09:00	*Welcome - Aim of the Workshop*
09:10	**T. LERY** *Standing Committee for Physical and Engineering Sciences* ***Presentation of the European Science Foundation***
Session I	***Overview of XLA, future experimental facilities, ground and space based telescopes***
09:20	**M. DUNNE** - Rutherford Appleton Lab. - UK ***Overview of experimental opportunities to perform laboratory astrophysics***
10:00	**D. RYUTOV** - Lawrence Livermore Lab. - US ***Possible new astrophysics-relevant experiments with high-energy-density plasmas***
10:40	*Coffee*
11:10	**T. RAY** - DIAS - Ireland ***Simulating Jets from Young Stars: What Numbers to Use?***
11:50	**S. LEBEDEV** - Imperial College - UK ***Laboratory astrophysics: magnetically driven plasma jets on pulsed power facilities***
12:30	**T. LERY** - ESF Science Officer - & **T. RAY** - DIAS - Ireland ***Lessons learned from the Marie Curie JETSET Network***
12:50	*Lunch*
Session II	***Cosmic Rays, SN, GRB***
14:30	**L. DRURY** - DIAS - Ireland ***What can we learn from XLA about particle acceleration and supernova dynamics?***
15:10	**T. BELL** - University of Oxford & RAL - UK ***Energetic particles: acceleration and interactions***
15:50	*Coffee*
16:20	**J. FREDERIKSEN** - Niels Bohr Institute - Denmark ***Computational plasma modeling in astrophysics***
17:00	**P. BIERMANN** - Max-Planck-Institut für Radioastronomie- Germany ***Ultra high energy particles***
17:40	***Informal Discussions***

Tuesday 23 September

08:30	*Coffee*
Session III	***Turbulence, Instabilities, Magnetic Reconnection***
09:00	**S. BALBUS** - Ecole Normale Superieure - France ***MHD stability of accreting astrophysical plasmas***
09:40	**G. BODO** - INAF–Osservatorio Astronomico Torino - Italy ***Numerical simulations of instabilities in astrophysical jets and accretion disks***
10:20	**G. BELMONT** - CETP - France ***Collisionless phenomena in space plasma physics***
11:00	*Coffee*

Session IV *Jets and Outflows (AGN, YSO, ...)*

11:30 **M. CAMENZIND** - University of Heidelberg - Germany
Accretion and outflows in the vicinity of black holes and neutron stars

12:10 **A. FERRARI** - Universita di Torino - Italy
Launching mechanism of astrophysical jets

12:50 *Lunch*

Session V *XLA experiments and modelling*

14:30 **R. SMITH** - Imperial College - UK
Laser driven high Mach number, radiative and colliding blast wave experiments in atomic cluster media.

15:10 **E. AUDIT** - CEA - France
Radiation-hydrodynamics simulations using moment methods

15:50 *Coffee*

16:20 **M. KOENIG** - Ecole Polytechnique - France
High energy density physics and its connection to astrophysics in Europe

17:00 **A. CIARDI** - Observatoire de Paris - France
From laboratory to astrophysical jets

17:40 ***Informal Discussions***

20:30 **Conference Dinner**

Wednesday 24 September

08:30 *Coffee*

Session VI *Radiative Flows, Massive Stars, Shocks*

09:00 **E. DORFI** - University of Vienna - Austria
Radiation-driven winds from pulsating lunimous stars

09:40 **P. STEE** - Observatoire de la Côte d'Azur - France
Radiative winds, accretion disks and massive stars physics using spectrally resolved high angular resolution observations with the VLTI and the CHARA interferometers

10:20 *Coffee*

10:50 **C. STEHLE** - Observatoire de Paris - France
Experimental radiative shocks in astrophysical context

11:30 ***Discussion & Closing: Discussion on follow-up research activities, collaborative actions and funding issues.***

13:00 *Lunch*

Afternoon Departure

STATISTICAL INFORMATION ON PARTICIPANTS

Participants per Country:

France	7
UK	4
Germany	2
Italy	2
Ireland	2
Austria	1
Denmark	1
USA	1

Gender

Male	20
Female	1