Ride the soliton ‘wave’

Drs Ioannis Kourakis and **Vikrant Saxena** are committed to elucidating the behaviour of solitons. Here, they talk in detail about their work and how their passion for these unusual waves began

How were you introduced to the field of nonlinear phenomena in plasma physics?

IK: My attraction to this fascinating field has been long and multifaceted. I fell in love with nonlinear dynamics at an early stage, dealing with charge transport across hydrogen-bonded macromolecules during my Master's in France. My PhD was dedicated to non-equilibrium statistical dynamics of plasmas as many-body systems. From there, it was only a small step to solitons in plasmas, which are an excellent testbed for nonlinear theories.

VS: I was introduced to various aspects of plasma science and technology by some eminent plasma physicists at the esteemed Institute for Plasma Research in Gandhinagar, India, where I was selected for the PhD programme. Professor Abhijit Sen – later my PhD supervisor – taught a course on nonlinear dynamics, and it was he and my co-supervisor Professor Amita Das who encouraged me to appreciate the connection between nonlinear dynamics and plasma physics. My PhD was on the dynamics of electromagnetic solitary waves in plasmas. Since then, I have been working in the fascinating and rich field of laser-plasma interactions (LPI).

In lay terms, what is the theory underpinning solitons?

VS: Solitons are remarkably robust due to a balance between two mechanisms: dispersion and nonlinearity. We all know about the chromatic dispersion of a light beam when it propagates through a prism; this mechanism is active when a rainbow is formed. Light is composed of different wavelengths, each of which moves at different phase velocity inside a raindrop or prism causing white light to spread into different colour components. Dispersion therefore has a tendency to spread a wavepacket as time progresses.

Another inherent characteristic of soliton dynamics is nonlinearity, manifested in the fact that wave components which have higher amplitude move faster than their lower-amplitude counterparts. A localised wavepacket subject to nonlinearity tends to steepen and even break.

Therefore, dispersion tends to spread a wave, whereas nonlinearity steepens and breaks it. In some situations these two effects may perfectly balance each other, resulting in waveforms which preserve their shape at all times and propagate coherently. Thus described, solitons occur in various media, and despite the inherent differences between their various manifestations, they share similar characteristics.

Are there specific properties of solitons that make them significant entities to support information and signal transmission in various media?

IK: Coherent waveforms of the solitonic type remain unperturbed through mutual collisions. Furthermore, being remarkably robust against external disturbances such as turbulence and noise, solitons cast a good paradigm in physical contexts where energy transport over long distances needs to be modelled. As they are coherent, robust entities, they can potentially carry information without any loss; in optical fibre communications, signal transmission efficiency has gone up by several orders of magnitude in the last couple of decades thanks to soliton-based techniques.

Your recent paper was a numerical investigation of standing electromagnetic solitons in plasmas. What were the main findings?

VS: We recently investigated the interaction of standing solitary waves using fluid Maxwell simulations. We observed that the interaction of two standing solitary waves essentially depends on their initial separation, amplitude and phase difference. In the special case of equal small amplitudes and matched initial phases, the two structures form an oscillating bound state, their distance varying periodically at a frequency that depends on the initial separation.

Introducing a finite difference in their amplitudes tends to reduce the interaction, whereas a finite phase difference results in breaking of the oscillating bound state. In the large amplitude case, we did not observe the formation of an oscillating bound state.

Is there overlap with other soliton media such as in fibre optics?

We have studied the behaviour of soliton-like excitations in large ensembles of charged particles (plasmas). Strictly speaking, our findings describe propagating localised electromagnetic field excitations along with associated disturbances in plasma fluid properties. However, our results bear generic characteristics and share common properties with solitons in other physical systems. For instance, our work on coupled electromagnetic pulses is in qualitative agreement with earlier findings on optical solitons in fibres. A non-negligible component is also the mathematical side of our modelling, which relies on a generic toolbox that is of relevance in many fields: materials, optics, photonic crystals, etc., including most facets of materials science. Finally, we have recently investigated the occurrence of extreme events (freak waves, rogue waves) in laser-beam excitations with a plasma, thus mimicking the behaviour of the ocean in the laboratory. We thus find our work on plasma dynamics to be part of a growing trend in complexity theory, promoting unifying paradigms across disciplines. A vision to pursue in the future…

Shedding light on laser-plasma interactions

Ongoing studies at the Centre for Plasma Physics, **Queen's University Belfast** are developing innovations in nonlinear laser-plasma interaction research, a field which could hold benefits for multitudinous applications

LASER-PLASMA INTERACTION (LPI) is one of the most rapidly evolving fields of modern plasma science. In addition to its relevance for inertial confinement fusion (ICF) – a laser-assisted method of energy production offering the hope of sustainable energy for future generations – developments in LPI could lead to significant advances in a number of industrial and technological specialities, not least through improved laser design for microelectronic devices. As a result, a great deal of fundamental and experimental research into LPI is being conducted around the world, much of it fuelled by the exciting new avenues opened up by next-generation lasers capable of producing ultrashort pulses at ultrahigh intensities.

Within the expanding field of plasma physics, solitons are emerging as a fascinating area of research. Bell-shaped (pulses) or kink-shaped (shocks) structures possessing a stationary profile which does not disperse over time, solitons are ubiquitous across all levels of plasma physics. Although the theory underpinning solitons was presented decades ago, it is now gaining impetus thanks to recent advancements in laser technology, and also in computational power available for numerical modelling of plasma dynamics.

Leading the growing body of research into these waves, Dr Ioannis Kourakis is conducting ongoing studies into solitons at the Centre for Plasma Physics (CPP) within the Department of Physics and Astronomy at Queen's University Belfast (QUB) in Northern Ireland, UK. As a lecturer in the Department and expert in nonlinear dynamics and soliton theory, including their applications in plasma physics, Kourakis is confident that his group's findings will be of high relevance and use to researchers and industry bodies around the world.

NONLINEAR PHENOMENA IN LPI

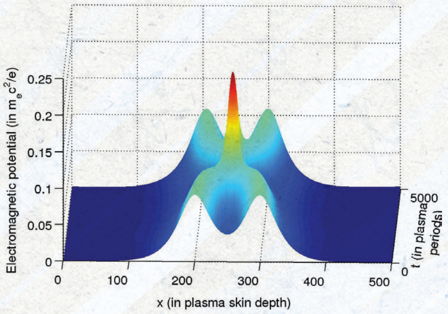
Investigations in plasma physics have shifted increasingly towards nonlinear phenomena. "Plasmas are highly complex forms of matter, and as dynamical systems they exhibit a plethora of nonlinear phenomena, ranging from soliton formation to various types of instabilities, collective modes, harmonic generation, turbulence and chaos," Kourakis highlights. This has been fuelled by the dramatic and continuing advances in laser technologies, which have opened up the possibility of studying exotic regimes of LPI. For instance, as ultrahigh intensity ultrashort laser pulses become ever more available, the previously inaccessible field of quantum electrodynamics in LPI has emerged as a potential route for researching phenomena such as pair production and vacuum polarisation.

THE BENEFITS OF ICF

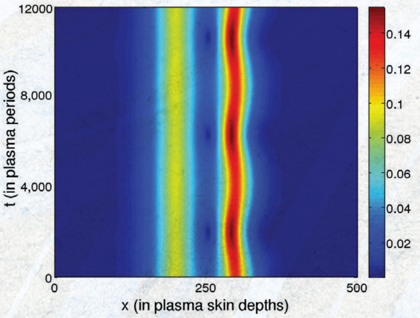
Such LPI studies are central to the progress being made in developing ICF, a laser-driven technique for nuclear fusion which is currently being honed by teams of researchers from across Europe and beyond. Given that ICF is a theoretically challenging method of generating sustainable energy, substantial efforts to prepare it for widespread use are ongoing. "From first principles, both in fusion schemes – where a fuel pellet is ignited by an incident high-power beam – and in industrial applications, the target is to harness energy transport mechanisms," explains Kourakis. As a consequence, a detailed and accurate understanding of nonlinear structures is of enormous benefit, and it is exactly this which Kourakis and his team are seeking through their research.

SOPHISTICATED THEORETICAL MODELLING OF ELECTROMAGNETIC ENVELOPE PULSES WITH MULTIDISCIPLINARY IMPACT

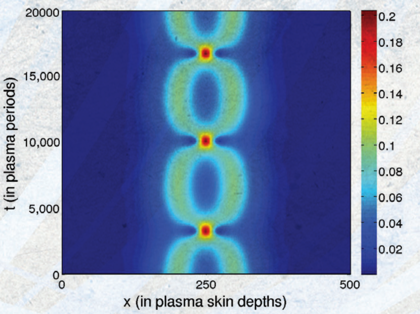
Solitary structures such as pulses and shocks are an essential component of plasma dynamics and, as a result, a better grasp of their behaviour could have implications for laboratory studies, in space and in a plethora of industrial and commercial settings. Kourakis and his colleagues have chiefly focused on exploring the dynamics of electromagnetic pulses in plasmas. "To do this we used a sophisticated theoretical model which was based on a combined fluid-plasma/Maxwell system of equations and computer simulations," he clarifies. This methodology allows them



Interaction between standing pulses might lead to rogue wave formation.



A difference in the amplitude of two solitary waves reduces the interaction between them while still resulting in a bound state. This effect is very useful in optical fibre communication where tuning the interaction among solitary waves may improve the quality of transmitted data.



Interaction between two identical standing solitary waves results in the formation of an oscillating bound state.

The groundbreaking investigations carried out by Kourakis and his fellow researchers have only been made possible through the combined knowledge, skills and resources of a number of the UK's leading experimental laser-plasma interaction groups

to examine both the stability and interaction properties of pulses as they interact with a plasma in the presence of a magnetic field. As a result, CPP researchers have produced a set of findings which, beyond an obvious fundamental interest from a nonlinear dynamical point of view, are relevant to numerous fields, including: the wider study of LPI; near-Earth space plasmas; radar detection; and interpreting observations detected by instruments onboard satellite missions.

ELECTROSTATIC STRUCTURES

Alongside this work, the Belfast team has also been modelling the electrostatic structures – such as solitary wave trains, holes or collisionless shocks – which can be observed during interactions between a laser beam and plasma. As part of this effort, they have been examining electrostatic structures produced through experiments both within the sophisticated in-house (TARANIS) laser facility at CPP and at other sites around the UK, such as the Rutherford Appleton Laboratory at the Harwell Science and Innovation Campus in Oxfordshire. The experiments saw the CPP researchers modelling shock creation, plasma expansion and Weibel-type instabilities. "Following the creation of these phenomena by experimental colleagues in the lab, we succeeded in contributing to the interpretation of those structures, and to their identification," Kourakis enthuses. "Belfast provides a unique environment for this kind of synergetic research, combining cutting-edge experimental facilities and modern theoretical and computational modelling tools, alongside inspiring interactions among world-reknowned colleagues."

COLLABORATION IS THE KEY

The groundbreaking investigations carried out by Kourakis and his fellow researchers have only been made possible through the combined knowledge, skills and resources of a number of the UK's leading experimental LPI groups.Amongst the most notable of these is Professor Marco Borghesi's group, also based in CPP, which uses proton imaging diagnostic tools to probe plasma dynamics in order to garner a more thorough understanding of laser-driven ion acceleration, a field which could potentially lead to advances in medical physics such as the treatment of cancer.

In addition to collaborations with research leaders in Belfast, Kourakis has also relied on close international collaborations with a wide network of experts: "This illustrious group of researchers combines massive theoretical expertise with extensive computational knowhow, and has allowed us to make great leaps in our attempts to understand and master the nonlinear aspects of beam-plasma interactions, among other facets of plasma dynamics," Kourakis summarises.

THE FUTURE OF LPI STUDIES

As laser pulses continue to shrink and their intensity becomes higher with advances in understanding and technology, the interaction time between laser beam and plasma is concurrently reducing. Not only will this fundamentally change the dynamics of LPI, but researchers exploring LPI will also have to take into account the effect of ultrahigh intensity beams, which will mean working in extremely relativistic regimes, with pair production also becoming a factor. "As intensities get higher, exotic states of matter will be attained and classical approaches invalidated, to be replaced with quantum or ultra-relativistic models", Kourakis predicts. "In this context, the necessity for novel nonlinear models for beam-plasma interactions will be greater than ever."

In order to model these effects, either a hydrodynamic description or statistical-dynamical model is required. Fuelled by their desire to innovate, Kourakis and his team are already searching for methods of developing a hybrid approach to modelling these highly complex systems, combining mathematical modelling with an advanced computational approach. In this way, the studies at CPP are expected to remain at the forefront of plasma studies, giving the group every chance of facilitating significant benefits for a wide variety of research, industrial and commercial applications.

INTELLIGENCE

FLUID THEORY AND SIMULATION FOR LASER-PLASMA INTERACTIONS

OBJECTIVES

Within the framework of laser-plasma interactions, the aim is to elaborate an improved fluid-theoretical description for coherent structures, incorporating elements (building blocks of the theory) which were neglected in previous studies. In particular, the focus centres on one- and two-dimensional aspects of electromagnetic soliton propagation.

KEY COLLABORATORS

Dr Vikrant Saxena; **Professor Marco Borghesi**; **Dr Gianluca Sarri**, Centre for Plasma Physics (CPP), Queen's University Belfast (QUB), Northern Ireland, UK • **Dr Mark Dieckmann**, Linköping University, Sweden • **Professor Dimitri J Frantzeskakis**; **Giorgo Veldes**, National and Kapodistrian University of Athens, Greece • **Professor Manfred Hellberg**, University of Kwazulu-Natal, South Africa • **Professor Frank Verheest**, Ghent University, Belgium • **Dr Evangelos Siminos**, Max-Planck Institute Dresden, Germany • **Dr Gonzalo Sánchez-Arriaga**, Universidad Politecnica Madrid, Spain

FUNDING

Engineering and Physical Sciences Research Council (EPSRC)

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DR IOANNIS KOURAKIS is Lecturer of Physics at CPP, QUB. Prior to taking up this post in October 2007, he was a postdoctoral research associate at the Ruhr University Bochum, Germany. His main research interests are nonlinear phenomena in plasma physics, including electromagnetic pulse propagation in laser plasmas, localised nonlinear wavepackets and solitary waves in laboratory and space plasmas. His research has also focused on soliton dynamics and instabilities in various physical contexts, including nonlinear metamaterials, nonlinear optics and condensed matter.

DR VIKRANT SAXENA earned his PhD from the Institute for Plasma Research, Gandhinagar, India in the field of theoretical laser-plasma physics before he moved to CPP at QUB in November 2011. His research is mainly focused on the hydrodynamic modelling of electromagnetic solitary waves in plasmas.

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