europhysicsnews

THE MAGAZINE OF THE EUROPEAN PHYSICAL SOCIETY

Silicene: silicon conquers the 2D world

Soft Janus, wrinkles and all

Physics of rapid movements in plants

Project UPWARDS

European Science TV and New Media Festival

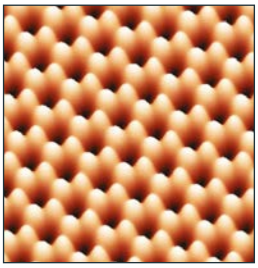
47/1
2016

Volume 47 • number 1
European Union countries price:
100€ per year (VAT not included)

Available at http://www.europhysicsnews.org

europhysicsnews

Cover picture: Close-up of Venus flytrap (*dionaea muscipula*) eating a fly. ©iStockPhoto. See: physics of rapid movements in plants, p. 27.



▲ PAGE 17

Silicene: silicon conquers the 2D world

▲ PAGE 22

Soft Janus, wrinkles and all

▲ PAGE 27

Physics of rapid movements in plants

EPS EDITORIAL

NEWS

HIGHLIGHTS

FEATURES

OPINION

[EDITORIAL]

A New Year in Focus

How pleasant would it be to read in a crystal ball the key breakthroughs in physics and the new developments in technology for 2016 and the following years? The IYL2015 and its related events worldwide have been an eye opener in how photonics could revolutionize our world. Indeed photonics is an innovation driver in many application areas such as communications, safety and security, lighting and displays.

According to the brochure produced by the Photonic group of Knowledge Transfer Network in the UK (www.photonicsuk.org), communication technology is moving into the terabit era with enormous data transfer capacity. Solid-state light sources will certainly outperform all other sources in efficiency and lifetime, offering enormous potential energy savings. New sensing technologies will also improve efficiency and safety of future vehicles and transport systems.

Big science will also bring its load of new results such as the LHC at CERN, where protons are already being smashed together at an energy of 13 TeV to observe new particles and develop original theories beyond the Standard Model. Space research is set for a busy year too when several missions by NASA, ESA or the Japanese Space Agency (JAXA) will enter their critical phase with spacecrafts reaching their destination. One example is the UPWARDS international project aimed in solving the global Martian puzzle by forging a link between past and new missions to Mars, in particular with the launch, next March, of ExoMars 2016, a surface module and orbiter (see article on p. 10). Scientific research is never short of interesting surprises. One of them is the recent announcement by astronomers at the Californian Institute of Technology (Caltech) of a possible ninth planet, 10 times the mass of Earth, orbiting far beyond Pluto at the solar system's edge. At a time when over 2000 exoplanets or extra-solar planets have been discovered, it is amazing to realize that our solar system can still unveil new mysteries.

Coming back down to Earth it is harder to predict what will happen in different fields of physics and it would be out of the scope of this editorial to list all of them. But, as described on p. 17 in the article by a group of Aix-Marseille University the two dimensional (2D) material science keeps expanding on the footstep of graphene. Novel layered materials are emerging such as silicene, its silicon analogue, and the other allotropes germanene and stanene, all of them having a 2D topological insulator nature thanks to their strong spin-orbit coupling. These systems hold great promises for future nanoelectronics, spintronics and quantum computing. Another paradigm shift will be triggered by neuromorphic computing or brain-inspired computing, that breaks away from Moore's law, followed for so many years by the semiconductor industry. It's no secret that today's computers are struggling to keep up with the enormous demands of data processing and bandwidth, and new solutions to this problem are looked for by the electronic industry. Neuromorphic chips are fast pattern-matching engines, consisting of multiple neurons and synapses, which process the data in the memory itself and are planned to perform several tasks such as machine learning, computer vision and data analytics. The ultimate goal is to achieve true artificial intelligence. Whereas neuromorphic technology, based on non-von Neuman architecture, should provide power and speed benefits in computing, replicating the function of human brain in silicon will remain a very strong challenge.

In the meantime our world will continue to be ruled by social networks dominated by the popular Facebook, Twitter or LinkedIn. Being reachable instantaneously everywhere, all the time, getting the latest updates from the news or from members of your community has become the reality. Impossible to think of tomorrow without a further expansion of the number of users and followers of such networks, with its load of positive and negative consequences.

Impossible to think of tomorrow without a further expansion of the number of users and followers of such networks, with its load of positive and negative consequences.

In this global and fast moving world, where the social dimension of science due to its strong impact on technology and our everyday life cannot be ignored (see opinion column by Carlos Hidalgo on p. 31), EPS will also be challenged on its structure and long-term strategy. Indeed 2016 will see the reassessment of its strategy plan 2010+, focusing on relevant issues related to its role as a learned society with its Divisions and Groups and as an umbrella organization for 42 Member Societies, forging its links to the EU institutions in Brussels.

With that I wish you all a successful and peaceful year 2016, and please keep 'following' EPS if you have a need for exciting news! ■

■ **Christophe Rossel**
EPS President

europhysicsnews
2016 • Volume 47 • number 1

Europhysics news is the magazine of the European physics community. It is owned by the European Physical Society and produced in cooperation with EDP Sciences. The staff of EDP Sciences are involved in the production of the magazine and are not responsible for editorial content. Most contributors to Europhysics news are volunteers and their work is greatly appreciated by the Editor and the Editorial Advisory Board.

Europhysics news is also available online at: **www.europhysicsnews.org**

General instructions to authors can be found at: www.eps.org/?page=publications

Editor: Victor R. Velasco (SP)
Email: vrvr@icmm.csic.es

Science Editor: Jo Hermans (NL)
Email: Hermans@Physics.LeidenUniv.nl

Executive Editor: David Lee
Email: d.lee@eps.org

Graphic designer: Xavier de Araujo
Email: x.dearaujo@eps.org

Director of Publication: Jean-Marc Quilbé

EPS Secretariat

Address: EPS • 6 rue des Frères Lumière
68200 Mulhouse • France
Tel: +33 389 32 94 40 • **fax:** +33 389 32 94 49
www.eps.org

Secretariat is open 09.00–12.00 / 13.30–17.30 CET except weekends and French public holidays.

EDP Sciences

Chief Executive Officer: Jean-Marc Quilbé

Publishing Director: Agnès Henri
Email: agnes.henri@edpsciences.org

Production: Thierry Coville

Advertising: Jessica Ekon
Email: jessica.ekon@edpsciences.org

Address: EDP Sciences
17 avenue du Hoggar • BP 112 • PA de Courtabœuf
F-91944 Les Ulis Cedex A • France
Tel: +33 169 18 75 75 • **fax:** +33 169 28 84 91

www.edpsciences.org

Subscriptions

Individual Members of the European Physical Society receive Europhysics news free of charge.

Members of EPS National Member Societies receive Europhysics news through their society, except members of the Institute of Physics in the United Kingdom and the German Physical Society who have access to an e-version at www.europhysicsnews.org. The following are 2015 print version subscription prices available through EDP Sciences (Prices include postal delivery cost).

Institutions - European Union countries: 100 € (VAT not included, 20 %). **Rest of the world:** 119 €

Student - European Union countries: 47.50 € (VAT not included, 20 %). **Rest of the world:** 57 €

Contact: EPN Europhysics News • BP 95 • 92244 Malakoff Cedex • **info@route66-agence.com** or visit **www.edpsciences.org**

ISSN 0531-7479 • ISSN 1432-1092 (electronic edition)

Printer: Fabrègue • Saint-Yrieix-la-Perche, France

Legal deposit: February 2016

EPS HISTORIC SITES

Hotel Metropole
Place de Brouckère 31, Brussels, Belgium

On 24 October 2015, the European Physical Society [EPS], the Belgian Physical Society [BPS, short for 'Belgische Natuurkundige Vereniging – Société Belge de Physique'] and the International Solvay Institutes [ISI] honored the Hotel Metropole in Brussels as *EPS Historic Site*.

At the initiative of Ernest Solvay, Hotel Metropole hosted in 1911 the first Solvay Council where the foundations of Quantum Physics where laid. A commemorating plaque was unveiled in the lobby of the Hotel by the president of EPS, Christophe Rossel, and the president of BPS, Jef Ongena, following an academic session attended by 80 participants.

Welcome addresses were presented by Mr. Freddy Thielemans, past-mayor and representative of the present-day mayor of Brussels, by Jef Ongena, president of BPS, Marc Henneaux, Director of ISI and by Jean-Marie Solvay as President of ISI and representing the Solvay family. They described briefly how the scientific and philanthropic legacy of Ernest Solvay has been taken up and continued over a time spanning five Solvay generations.

▾ Christophe Rossel and Jef Ongena, after unveiling of the EPS Historic Site plaque. It is now prominently located on top of the historic picture of the 1911 participants in the lobby of Hotel Metropole.

▲ Partial reenactment of the historic picture of the first Solvay Council 1911. **Seated** (L-R) Dieter Klingmüller [W. Nernst [4]], Ursula Klingmüller [W. Nernst [4]], Jean-Marie Solvay [E. Solvay [5]], Anna de Haas [H. Lorentz [4]], Yann Lapicque [J.-B. Perrin [4]], Françoise Chapuis [J.-B. Perrin [3]], Paul Siebertz [W. Wien [3]], Maria Rüchardt [W. Wien [3]], Pierre Joliot [M. Curie [3]]. **Standing** (L-R), Florian Baier [A. Sommerfeld [4]], Monika Baier [A. Sommerfeld [3]], Nathalie Ferrard [A. Einstein*], Mary Fowler [E. Rutherford [4]], Catherine Kamerlingh Onnes [4], Jeanne Kamerlingh Onnes [4]

[3] granddaughter or grandson – [4] great granddaughter or -grandson – [5] great great granddaughter or -grandson – *[5] of Caesar Koch, uncle of Albert Einstein.

Christophe Rossel then portrayed EPS and the EPS Historic Site program. The much appreciated keynote address was entitled 'The First Solvay Council on Physics: Legend and Facts', delivered by Franklin Lambert from ISI and the Free University of Brussels (Vrije Universiteit Brussel – VUB).

The attendance included members of Belgian and European academic and political institutions. Guests of honour were the many descendants of participants to the historic Solvay Council: fourteen family members of the Nobel Laureates that were present in 1911, three descendants of Ernest Solvay, and Mr. Wielemans, heir to the family that founded this famous hotel.

The celebration was complemented by the publication of a European Physical Journal Special Topic issue entitled "The Early Solvay Councils and the Advent of the Quantum Era" (EPJ ST, Vol. 224, Nr 10, September 2015), edited by Franklin Lambert, Frits Berends and Michael Eckert. The articles are available online at http://epjst.epj.org. As a unique memory of this unforgettable day, a HDTV recording is made from the event, and will be made available soon at the websites of BPS (www.belgianphysicalsociety.be), EPS and ISI.

The commemorative plaque reads:

European Physical Society – EPS Historic Site. The Hotel Metropole.

From 30 October to 3 November 1911, the Hotel Metropole was the venue of the Solvay Council, dedicated to what soon would be called "The Theory of Radiation and the Quanta".

This was the first of a series of meetings, called "Solvay Conferences", named after Ernest Solvay, a wealthy Belgian industrialist and scientific philanthropist, who issued the invitations to this first meeting.

This was a time when the foundations of physics were being shaken by the emergence of the quantum theory. The participants were 23 eminent scientists including Einstein, Kamerlingh Onnes, Lorentz, Nernst, Perrin, Planck, Poincaré, Rutherford, Skłodowska-Curie, Sommerfeld and Wien.

Their insights and exchange of ideas had a profound influence on the development of physics and chemistry in the twentieth century.

Brussels, 24 October 2015. ■

Jef Ongena,
President of BPS

European Science TV and New Media Festival and Awards 2015

The Physics Prize breaks new ground at the European Science TV and New Media Festival and Awards 2015 in Lisbon

▸ Lars Becker Larsen, the writer and director of the winner film TAMING THE QUANTUM WORLD, with Antigone Marino from the European Physical Society and the presenters of the ceremony

The European Science TV and New Media Festival and Awards started in 2001 as a way of recognizing and promoting the value of science in non-science TV productions, and notably TV drama which reaches large audiences. Following early success, it expanded its agenda and now encompasses science and technology in all genres of television and new media. The project is still innovating. In November 2015 a subject-based prize was introduced to reflect and enhance the interest created in specific events. As this was the International Year of Light, a creation of the European Physical Society, the decision was made that physics should be the first science subject to be feted.

Three criteria were being used to judge entries. Firstly the quality of the physics being presented. In other words the physics message. Secondly the production values of the films, such as the quality of the filming, pacing of the narrative and the script. And thirdly, whether it was innovative in some way, either through selection of the content or the method of presentation.

▾ Antigone Marino, from the European Physical Society which supported the prize for the best presentation of physics

It was perhaps not surprising that fundamental physics dominated the entries. The sense of awe it inspires amongst a wide audience carries across to programme-makers, and seems often to generate unexpectedly high viewing figures. I recall a BBC production on the discovery of the W particle (for which I led the production team) attracted a UK audience of 5 million (over two transmissions), something which bamboozled but delighted the channel controller!

Eight physics-based productions were selected for the Festival from entries from across Europe. They included a docu-drama on Niels Bohr from Denmark, a Danish documentary on understanding and applying quantum physics and two BBC documentaries – one on gravity waves and the other on the hot topic of dark matter. From France was a fresh drama on Marie Curie and her pioneering work on applying X-rays in the first world war. There was also an innovative series of short films called Avatars de Lumière from the channel la Huit, with an acting role for physicist Etienne Klein and supported by the EPS. From Germany a production from the acclaimed series Fascinating Universe was proposed, about the possibility of life elsewhere; and the list wouldn't be complete without an entry on the Rosetta space mission, this one a co-production between Sweden and France. The last two films went beyond physics alone, but the strength in depth of the productions and their variety underlined the quality of creative talent in presenting physics in Europe.

Three productions were short-listed by the international jury. They were all documentaries on fundamental physics. These were the two BBC films, on dark matter and gravity waves, and the Danish production which blended a teasing look at future applications of quantum physics with the challenge of explaining some fundamental concepts. The winner was the Danish production, Taming the Quantum

World, written and directed by Lars Becker-Larsen. It was felt to hold the viewers' interest well on a challenging journey, dealing with topics such as "entanglement" where quantum physics allows particles to be linked across large distances. An experiment linking signals between two of the Canary Islands was presented to illustrate the point. The film also recreated a celebrated discussion between Einstein and Bohr to remind us that Einstein was an early sceptic of such "action at a distance", much to the frustration of Niels Bohr.

One of the reasons that the audio-visual medium is so convincing as a way of communicating fundamental physics is that one can create a sense of understanding at different levels. For example, it is possible to appreciate the discussion between Einstein and Bohr in terms of the content, or on a different plane where great physicists can be seen to disagree on big concepts – without the viewer's need to understand the detailed argument. The visuals can provide a pathway to the next point without leaving a compelling need to probe deeper. Taming the Quantum World skillfully touched base with a wider audience in looking ahead to possible quantum computers and the enormous enhancement of computing power they might offer. If the gap between the quantum concepts and practical application here is still daunting, the film whetted the appetite to see how this on-going challenge will develop. What all three finalists showed was that in physics, the journey is often as thrilling as the final discovery or application; and that there is a large public ready to be entranced. As a footnote we should also add that BBC film on dark matter, "Dancing in the Dark: The End of Physics?" won the best TV Documentary Prize for its original and humorous style in presenting the riddle of the unknown dark matter which is believed to make up so much of the universe. ■

Andrew Millington
Festival and Awards Director

ECOSS 31 (BARCELONA 2015)

The 31st European Conference on Surface Science (www.ecoss2015.org) was held at the International Convention Center of Barcelona (www.ccib.es) from August 31st to September 4th, 2015, and chaired by Dr. Jordi Fraxedas, from the Catalan Institute of Nanoscience and Nanotechnology (ICN2), CSIC and The Barcelona Institute of Science and Technology.

▲ Best Poster Prize awarded to Jan Berger and handed by Dr. R. Felici, Chairman of ECOSS32.

ECOSS is a well-established meeting with a longstanding tradition that started back in 1978 in Amsterdam and is organized jointly by the Surface Science Division of International Union for Vacuum Science, Technique and Applications (IUVSTA) and the Surface and Interface Section of the European Physical Society (EPS). With almost 600 participants, among which 200 students, the Congress started with a plenary lecture imparted by Dr. M. Salmerón from the Lawrence Berkeley National Laboratory, CA (USA). The Congress was divided in five parallel sessions with 29 invited speakers, 298 contributed oral presentations and three poster sessions with a total of 266 posters. ECOSS31 was sponsored by several leading companies (22 exhibitors and 9 sponsors) and EPS sponsored the Best Poster prize, which was awarded to Jan Berger, as well as the travel expenses of Prof. Fernando Flores, who imparted the EPS Lecture in the closing ceremony. The Conference dinner was served at the Barcelona Royal Shipyard, a 13th century historical building, close to the world famous Columbus monument and had 500 attendees. ■

◄ Prof. P. Rudolf, Chair of Board of the ECOSS (right) introducing Prof. F. Flores before imparting his EPS Lecture.

Jordi Fraxedas
Chairman of ECOSS31

Summer School Alpbach 2015: A pilgrimage to Erwin Schrödinger's grave

Quantum physics and fundamental physics in space

Summer Schools on themes related to scientific space research have been held yearly in Alpbach, Austria, since 1975, organised by the Austrian Research Promotion Agency (FFG) with the support of the European Space Agency, the national space authorities of ESA's member and cooperating states and the International Space Science Institute, Bern, Switzerland.

Each year, the Summer School treats a different topic related to space research. It is open to 60 students from Europe, with diverse backgrounds in both space sciences and aerospace engineering. The Schools start with lectures by international experts in the selected scientific subjects and in space mission design. However, the bulk of the ten days (and nights) of the School is devoted by four teams of 15 students each to define, design and propose an original space mission that addresses aspects of the year's Summer School topic.

In the past, the topics led to missions with objectives in the solar system or in more distant astrophysical targets. Summer Schools have also been dedicated to observing the Earth from space. This year's Alpbach Summer School, however, addressed the difficult topic of how to exploit space missions as research tools for quantum- and fundamental physics. Space agencies, in particular ESA, have broad-ranging roadmaps in these fields, so the Summer School could call on many experts in Europe to come as lecturers or tutors. The four missions elaborated by student teams proposed to study effects of gravity on quantum systems including how quantum entangled photons are affected in a changing gravitational field, and the sensitive detection of gravitational waves in a new wavelength range.

It is an open issue whether quantum laws, originally established to describe nature at the microscopic level of atoms, are also valid in the macroscopic domain, for instance over long distances. Various proposals predict that quantum entanglement is limited to certain mass and length scales or is altered under specific gravitational circumstances. Testing quantum correlations over distances achievable with satellites placed in Earth orbit or even beyond would allow verifying both the validity of quantum physics and the preservation of entanglement over distances impossible to achieve on the ground.

▾The peaceful village of Alpbach, here photographed in the late afternoon, lets one forget that the students regularly work on their projects far into the night — 'closing shop' at 1 or 2 a.m. was not uncommon! (Courtesy Alpbachtal Seenland Tourismus)

One of the teams' proposed missions is entitled *Entanglement Propagation In Gravity* (EPIG). The mission will use two satellites, one (Erwin) in an elliptical orbit, the other (Albert) in a low circular orbit. The objective is to observe the interaction between gravity fields and entangled quantum states over a wide range of values for the gravitational potential. A source of polarisation-entangled photon pairs will be used, then the photons will be separated and travel over long distances, experiencing a changing gravitational potential before being detected. The data acquired by the two detectors on the satellites receiving the photons will be used to evaluate the normalised coincidence rate of the photon pairs. If the coincidence rate is 1, gravitational potential has no effect on the entangled photons. However, if the coincidence rate is dependent on the potential difference between the two satellites, it could prove a recently proposed nonlinear extension of quantum field theory that may be compatible with the closed time-like curves that appear in general relativity, thus proving a link between the two apparently contradictory theories.

A similar proposal by another team offers a different way of testing for any link between General Relativity and Quantum Entanglement (*General Relativistic Effects on Entanglement* or G.R.E.EN). In this proposal, entangled pairs of photons are generated on a single satellite and sent to the ground.

▲ The grave of Erwin Schrödinger (1887-1961) in the small cemetery next to the church in Alpbach. (Courtesy of André Balogh)

First, the distance over which entanglement has been observed can be extended to greater distances, and second, by measuring the frequency of the entangled photon on the ground, any departure from the classical value of the redshift would immediately lead to a revision of both Quantum Mechanics and General Relativity to take into account the unexpected departure from the more classical models.

The third team proposal (*JANOS*) was proposed as the first experimental study of quantum decoherence induced by space-time curvature. The two objectives of the missions were (a) to investigate the influence of gravitational time dilation on a single photon interference experiment, and (b) to compare single photon interference with interference of classical light. The experiment would involve preparing a superposition of two spatially separated parts, such that each of the parts experiences a different flight time due to the Shapiro delay. The Shapiro delay is a strictly general relativistic effect, and has no analogue in Newtonian gravity. Therefore one part of the single-photon wave function would "lag" behind the other due to general relativistic effects, which can be detected using conventional optics. The basis of the experiment is a single-photon interferometer, distributed between an Earth orbiter and a ground station.

By contrast, the fourth space mission proposal, the *Gravitational wave Laser Interferometry Triangle* (GLINT) will detect gravitational waves predicted by General Relativity. The proposed mission will use interferometry between three spacecraft; this is a concept similar to eLISA, the large project of ESA, but for GLINT, the three satellites will fly in a circular Earth orbit, forming an equilateral triangle of arm length of 100 000 km. The objective is to measure gravitational waves from the formation and evolution of the first black holes, with redshifts of $15 < z < 30$, from the very early stages of the Universe.

The Summer School, by its topic, celebrated two of the greatest physicists of the last century, Erwin Schrödinger and Albert Einstein. This intellectual pilgrimage to the two giants of modern physics was in fact also a literal pilgrimage: Erwin Schrödinger is buried in Alpbach and all the Summer School participants wandered, at least once, by his grave. ■

André Balogh
Imperial College London
Peter Falkner
European Space Agency

Project UPWARDS

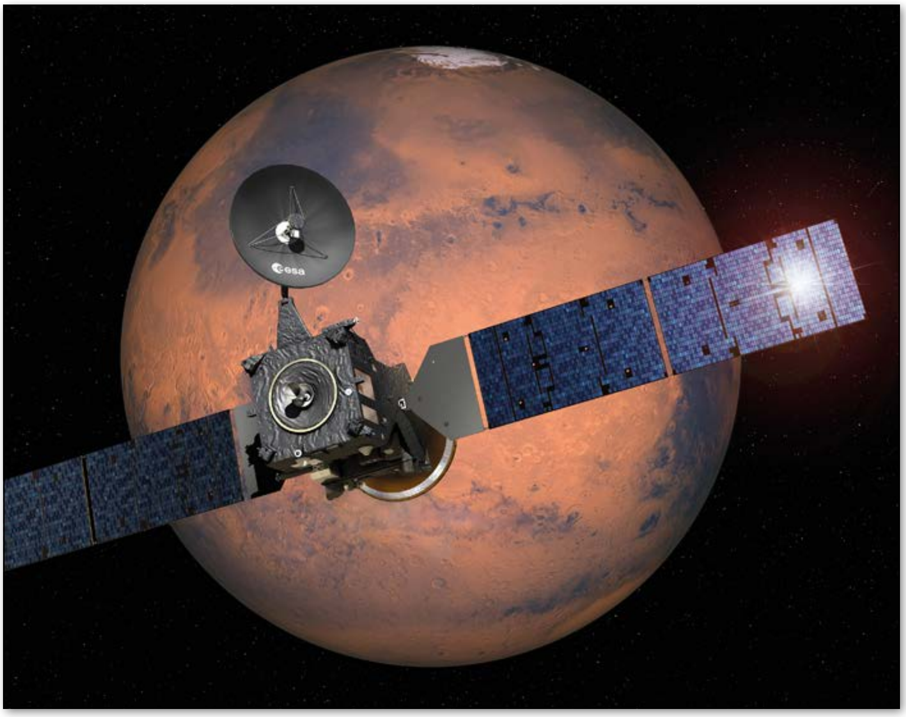
Rethinking Planet Mars in preparation for ExoMars

Most planetary scientists agree that Mars is a jewel waiting to be polished. A reddish diamond holding secrets about the history of the Solar System, including clues about the evolution of life on Earth.

Now, after more than a decade of continuously gathering data about the Red Planet from space missions including ESA's Mars Express, European experts studying Mars are questioning the usual isolated ways of analyzing Mars data. Each aspect, from dust storms, to the "water cycle", or from the subsurface ices and trace gases' reservoirs to the atmospheric escape at the top of the atmosphere, are thought to interact with each other in intricate ways. The current view of Mars is like a collection of results forming a puzzle waiting to be solved as a whole in order to really understand Mars.

Understanding Planet Mars With Advanced Remote-sensing Datasets and Synergistic Studies (UPWARDS) is an international scientific project with such an ambitious goal. Funded by the European Commission under the H2020 program, UPWARDS is a consortium formed by seven scientific institutions, located in five European countries, and coordinated from Spain by the Instituto de Astrofísica de Andalucía (IAA-CSIC). The approximately thirty scientists involved in this project, experts in different areas of planetary exploration, are engaged in solving the global Martian puzzle and in building a state-of-the-art vision of the numerous Mars couplings, from its interior to the surface, to the atmosphere, to outer space.

UPWARDS also aims at forging a link between past and new missions to Mars, in particular between the two milestones in the European space exploration of our neighbouring planet, Mars Express and ExoMars. ExoMars 2016, to be launched next March, consists of a surface module and an orbiter for remote observations. For the next three years, UPWARDS is developing innovative analytical tools for their application to review data from Mars Express and for immediate exploitation of the new data that *ExoMars 2016* will generate. Many of these, like synergistic retrievals and non-thermal inversion methods, are based on those used on terrestrial observations and meteorology, and will hopefully allow for a new and unprecedented exploitation of available measurements.



Moreover, these new techniques will be applied together with new geophysical and atmospheric models to the massive dataset from previous missions to Mars with the objective of addressing a wide selection of major challenges in current Martian research. Amongst the great challenges that will benefit from the new modelling and data analysis, those that stand out are the global water cycle, the exchange of methane and other gases between the atmosphere and the interior of Mars, the behaviour of dust storms and the characterization of the Martian surface and sub surface and the dynamical and chemical coupling between the lower and the upper atmosphere. In summary, in UPWARDS we are re-analyzing much of our knowledge about Mars in preparation of a revised scientific reference, hopefully useful for the immediate future but also for the *ExoMars* Rover operation, planned for 2018, and for missions to Mars in the more distant future.

■ **Miguel A. López-Valverde**
UPWARDS Coordinator
■ **Ana Tamayo**
Head of Communication of UPWARDS

OBITUARY
Wolfgang Sandner (1949-2015)

Professor Dr. Wolfgang Sandner passed away on 5 December 2015, completely unexpected at the age of only 66 years, out of a full life as talented physicist and science organizer – since 2013 he was as director general of the *"Extreme Light Infrastructure"* (ELI-DC) responsible for the coordination of this large European Laser Research Centre at three different locations in Eastern Europe.

Sandner, born March 2, 1949, studied physics at the University Freiburg/Br where he obtained his PhD in 1979 in atomic physics. As a postdoc at the Stanford Research Institute, USA he started working with lasers. After his habilitation in 1985 in Freiburg he became acting full professor in Würzburg and held then a professorship in Freiburg, performing pioneering experiments on the 3-body Coulomb-problem in atomic model systems. In 1991 he accepted a tenured full professor position at the University of Tennessee, USA.

In 1993 he was appointed as one of three directors of the newly founded *Max Born Institute for Nonlinear Optics and Short Pulse Spectroscopy* (MBI) in Berlin-Adlershof, a position which he filled with strategic vision and continuing scientific success until 2013 — since 1994 also as full professor at the Technical University Berlin.

His work at the MBI focussed on light-matter interaction at ultra-high intensities, with highlights on non-sequential multiphoton-double-ionisation, relativistic plasma dynamics and laser particle acceleration. A key issue was the development of ultra-high peak intensity and high average power laser systems and their applications, including laser-based UV- and X-ray sources and photocathode lasers for particle accelerators, specifically also for the Free Electron Laser XFEL at DESY. Sandner authored more than 200 publications in peer reviewed international journals which were quoted over 7000 times. He was a Fellow of the American Physical Society.

Wolfgang Sandner acted in many national and international science organisations, advisory and reviewing boards. Within the *German Physical Society* (DPG) he initiated important structural reforms and chaired the section *Atoms, Molecules, Quantum-Optics and Plasmas* until 2006. As president and vice president of the DPG (2010-2014) he emphasized the responsibility of physics for participating in the solution of the *Grand Challenges of society* and initiated several strategic studies.

European Science Policy was particularly important to Sandner. In the field of laser research he was intensely involved in shaping EU research structures – not least as coordinator and chair (2003-2013) of *"Laserlab Europe"*, an EU funded network of the 26 most important laser-research institutions in 16 European countries.

Wolfgang Sandner was an outstanding and guiding scientist in the field of atomic physics and laser research. He was a reliable and always highly engaged colleague of the first hour in Berlin-Adlershof. His profound scientific expertise and his distinct sense for promising developments combined with his leadership qualities, his judiciousness and commitment have contributed decisively to the development of the Max-Born-Institute as a place for internationally recognized cutting edge research in the field of laser based science. We mourn the loss of Wolfgang Sandner and shall sadly miss him. ■

Ingolf Hertel
Max Born Institute and Humboldt Universität zu Berlin

▼ The ELI-DC building project.

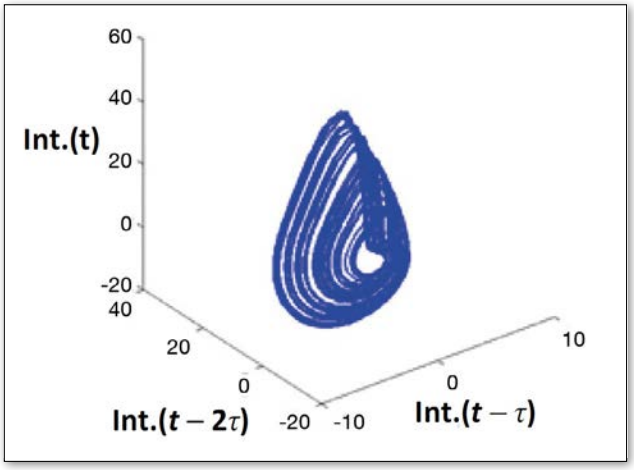
Highlights from European journals

OPTICS

Bringing the chaos in light sources **under control**

Study investigates how best to stabilise the output of quantum dot LEDs.

Noise is an issue in optical telecommunications. And findings means of controlling noise is key to physicists investigating light-emitting diodes or lasers. The authors have worked on a particular type of light source, called the quantum dot light-emitting diode (QDLED). They demonstrate that modulating bias current of the QDLED could lead to countering the noise. This, in turn, leads to stabilising such light sources, making them better suited for optical telecommunications.



▲ Experimental reconstruction of the phase portrait of the quantum dot light emitting diode using the embedding technique.

Most light sources exhibit fluctuations due to the quantum nature of the process underlying the emission of light. However, experiments show that these fluctuations—often described as quantum noise—are inherently chaotic and subject to oscillations, dubbed mixed mode oscillations. The authors have developed a theoretical model, which is able to reproduce the chaotic and oscillating phenomena observed experimentally. This can help them understand the nature of such phenomena.

They found that spiking competition of quantum dots in the part of the diode that emits lights enhances the way in which the diode receives its own self-feedback in terms of the light being emitted and it also has an effect on the impact of noise perturbation. They also show that the dynamics of these fluctuations are completely determined by the variation of the injecting bias current feeding into the QDLED.

As a result, those fluctuations can be brought under control by changing the bias current. The next step in their research will involve focusing on synchronisation phenomena in QDLED arrays for using this source in optical telecommunications. Other potential applications could include quantum dot-enhanced LED-backlighting of LCD televisions. ■

■ **K. Al Naimee**, **H. Al Husseini**, **S.F. Abdalah**, **A. Al Khursan**, **A. H. Khedir**, **R. Meucci** and **F.T. Arecchi**, 'Complex dynamics in Quantum Dot Light Emitting Diodes', *Eur. Phys. J. D* **69**, 257 (2015)

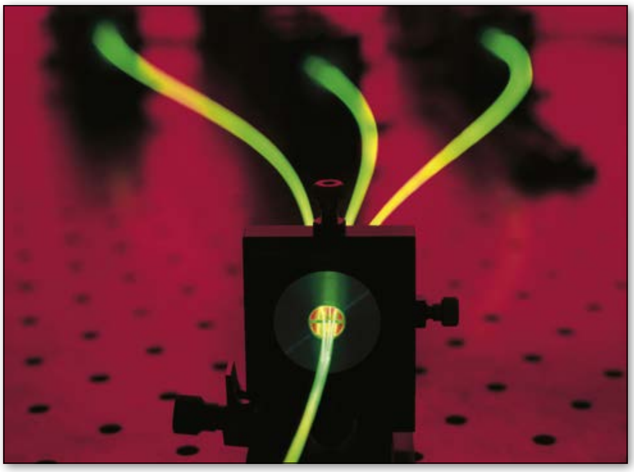
APPLIED PHYSICS

Laser-based accelerators: **yes, we CAN!**

Future ultra-fast high power lasers, dubbed Coherent Amplification Network (CAN) lasers, will deliver unprecedented accelerating power and efficiency.

Few technologies have the power that particle accelerator technology has to touch upon such a broad range of applications at the many frontiers of modern science. Today, thanks to improvements in laser technology, a new generation of accelerators could soon emerge to replace accelerators relying on radio frequencies. This special issue explores the requirements necessary to make such laser accelerators a reality, by presenting the work of the International Coherent Amplification Network (ICAN) research collaboration. The articles study: average/peak power and efficiency limits of coherently combined ultrafast laser systems; synchronization, spatial and temporal recombination of a large number of fibre amplifiers; temporal and

▼ Cover picture of the EPJ Special Topic issue on the Science and the applications of the coherent amplifying network (CAN) laser. © Fraunhofer IOF Jena, Germany, Bernd Müller



spatial beam quality; combining efficiency of coherent addition amplitude and phase stability as a function of the number of fibres and their individual performance; and reduction of pulse duration and manipulation of pulse shape. Potential applications include future colliders, solutions for vacuum physics, design of Higgs-particle factories, and creation of sources of high-flux protons and of neutrons, among others. Further, such accelerators open the door to solutions in nuclear pharmacology and proton therapy as well as orbital debris remediation. ■

▪ **Gérard Mourou**,
'Science and applications of the coherent amplifying network (CAN) laser', *Eur. Phys. J. Special Topics* **224**, Number 13 (2015)

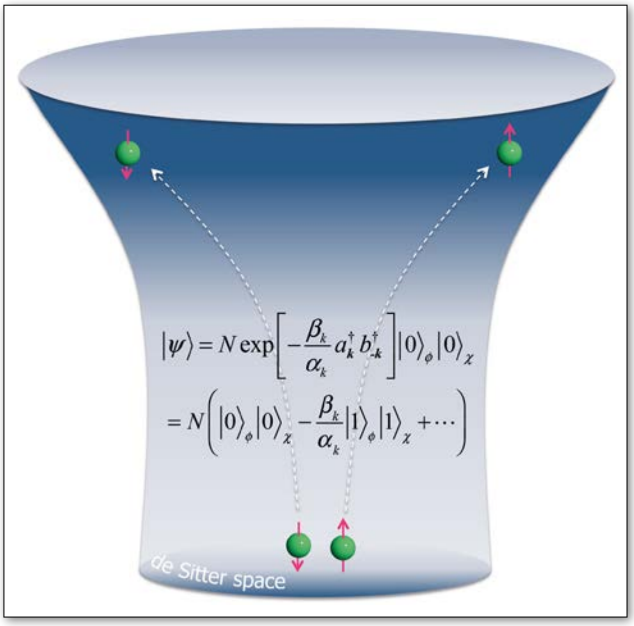
QUANTUM PHYSICS

Initial state entanglement **in inflationary cosmology**

Recent observational data indicate that inflationary cosmology gives an excellent description of the very early universe. Inflationary cosmology assumes that quantum fluctuations seed the observed large scale structure in the universe. So we may be able to test the initial quantum state of the universe observationally in the future. Especially, if primordial vacuum state is entangled, the effect of entanglement could then be observed.

We give a new interpretation of the effect of initial state entanglement on the spectrum of vacuum fluctuations. We consider an initially entangled state between two free massive scalar fields in de Sitter space. We construct the initial state by making use of a Bogoliubov transformation between the Bunch-Davies vacuum and a four-mode squeezed state, and then derive the exact power spectrum for one of the scalar fields. We demonstrate that an oscillatory spectrum hardly appears for the initially entangled state unless an ad hoc absolute value of the Bogoliubov coefficients is chosen. We stress that, on the contrary, an initially non-entangled state may naturally produce an oscillatory spectrum due to quantum interference if the initial state deviates from the Bunch-Davies vacuum. ■

▾ Entangled vacuum state of quantum fields in the inflationary universe.



▪ **S. Kanno**,
'A note on initial state entanglement in inflationary cosmology', *EPL* **111**, 60007 (2015)

HISTORY

May the 5th force be with you

The author revisits the wealth of research emerging from the quest for the fifth force, which he hypothesised in the 1980s as being a new fundamental force in nature.

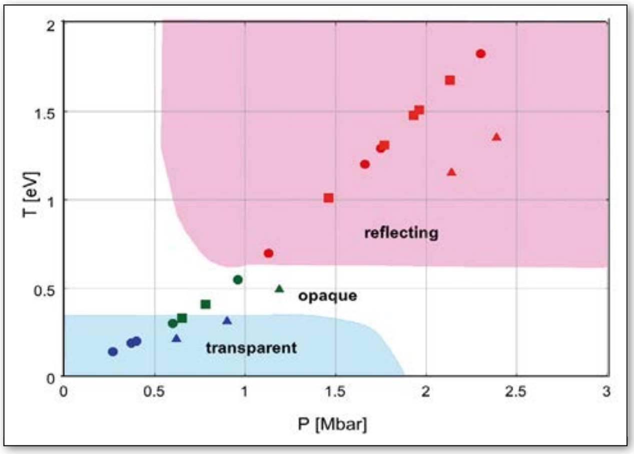
Discovering possible new forces in nature is no mean task. The discovery of gravity linked to Newton's arguably apocryphal apple experiment has remained anchored in popular culture. In January 1986, the author had his own chance to leave his mark on collective memory. His work made the front page of the New York Times after he and his co-authors published a study uncovering the tantalising possibility of the existence of a fifth force in the universe. In an article published recently, he gives a personal account of how the existence of the gravity-style fifth force has stimulated an unprecedented amount of research in gravitational physics - even though its existence, as initially formulated, has not been confirmed by experiment. ■

▪ **E. Fischbach**,
'The fifth force: A personal history', *Eur. Phys. J. H* **40**, 385 (2015)

OPTICS

Refraction index of compressed water at megabar pressure

Compressing water at megabar pressure through laser-driven shocks induces phase changes and may finally produce a metallic fluid. Such phase is particularly relevant for planetology since water is one of the main constituents of the mantles of giant planets like Uranus and Neptune, and its metallization has been recognized as a possible source of the magnetic field of such planets. In this work we study the transition of water by looking at its optical properties. Increasing pressure water changes from transparent to opaque (absorbing) and finally reflecting. We provide the first quantitative measurement of water refractive index in the megabar range, a measurement,



▲ Phase plane of water showing the experimental results for normal samples (circles: LULI; squares: RAL) and for samples precompressed at 10 kbar (triangles).

which can give information on how the material is approaching gap closure (metallization). We also performed measurements on water precompressed at 10 kbar, allowing getting off-Hugoniot states at high pressure but low temperature. Refraction index for transparent and opaque water was measured using a VISAR system. At high compression a sharp increase of the real and imaginary part of the refraction index was observed. Experiments were performed at the LULI and RAL laboratories. ■

■ **D. Batani**, **K. Jakubowska**, **A. Benuzzi-Mounaix**, **C. Cavazzoni**, **C. Danson**, **T. Hall**, **M. Kimpel**, **D. Neely**, **J. Pasley**, **M. Rabec Le Gloahec** and **B.Telaro**, 'Refraction index of shock compressed water in the megabar pressure range', *EPL* **112**, 36001 (2015)

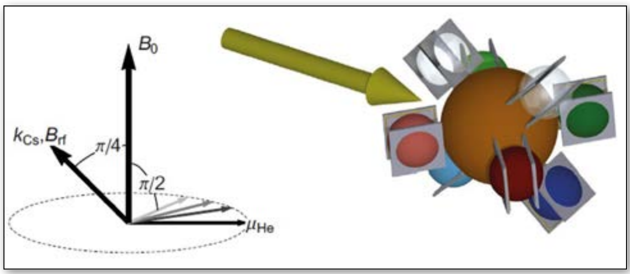
ATOMIC AND MOLECULAR PHYSICS

Minutest absolute magnetic field measurement

High-precision and high-accuracy magnetic field measurement to support quest for missing antimatter in the universe.

Every measurement is potentially prone to systematic error. The more sensitive the measurement method, the more important it is to make sure it is also accurate. This is key for example in measuring magnetic fields in state-of-the-art fundamental physics experiments. Now, an international team of physicists has developed an extremely high-precision method for the determination of magnetic fields. The resulting device, they found, has an intrinsic sensitivity that makes it ideal for fundamental physics and cosmology experiments attempting to explain the missing antimatter of the universe. The findings of the authors have been published recently. They calculated the sensitivity of the magnetometer in the envisioned application in an experiment searching for the electric dipole moment of neutrons (nEDM), which are basic constituents of ordinary matter. Observing an nEDM would imply a broken symmetry of the laws of physics, called CP-violation. Such a finding could help to account for the primordial matter-antimatter imbalance at Big Bang stage, leading to the current abundance of matter. ■

▼ Geometry of the experiment.



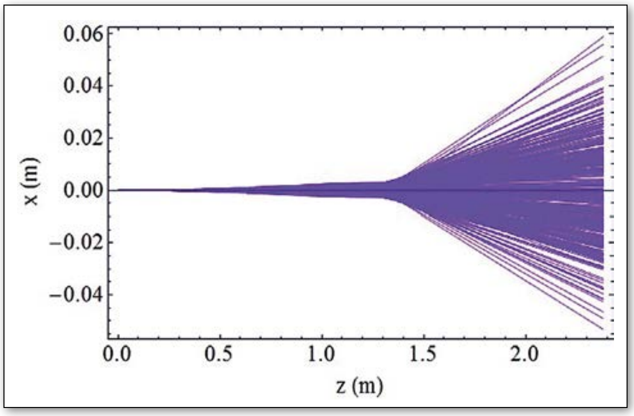
■ **H.-C. Koch**, **G. Bison**, **Z.D. Grujić**, **W. Heil**, **M. Kasprzak**, **P. Knowles**, **A. Kraft**, **A. Pazgalev**, **A. Schnabel**, **J. Voigt** and **A. Weis**, 'Design and performance of an absolute ^{3}He/Cs magnetometer', *Eur. Phys. J. D* **69**, 202 (2015)

APPLIED PHYSICS

Slowing dynamics of a supersonic beam

This investigation of the slowing dynamics of a supersonic atom beam by a counter-propagating resonant laser light is characterized by two special features: (i) a close coupling between simulations and experiments using a nozzle beam of metastable argon atoms, (ii) the use of a Monte-Carlo (MC) scheme aimed at analysing step by step the slowing process and describing in a realistic way atom random walks due to the spontaneous emission. It allows to calculate 2D images and radial profiles of the slowed beam, in good agreement with experiment. Other important characteristics as angular aperture, velocity spreads, coherence radius (not easy to be measured experimentally), *etc.* also result from the simulation. Since the 3D atomic motion within the laser field is considered, border effects, not directly accessible in a simple radiative force model, can be studied.

▼ 2D imaging of the slowed Ar* supersonic beam for a final velocity v_F = 61 m/s.



The calculations, assuming a point-like source, reproduce the experimental characteristics of the slowed beam. In general a laser beam is an efficient tool to manipulate the atomic motion. Its interaction with atoms can be accurately characterized by the present MC-code. Actually any configuration combining resonant light and atoms is relevant (if the semi-classical approximation is valid). A "pushing" laser to generate a slow atomic beam from a magneto-optical trap has been successfully tested with metastable argon atoms. The MC-code predicts accurately the characteristics of the generated beam. ■

■ **M. Hamamda**, **T. Taillandier-Loize**, **J. Baudon**, **G. Dutier**, **F. Perales** and **M. Ducloy**, 'Slowing dynamics of a supersonic beam, simulation and experiments', *Eur. Phys. J. Appl. Phys.* **71**, 30502 (2015)

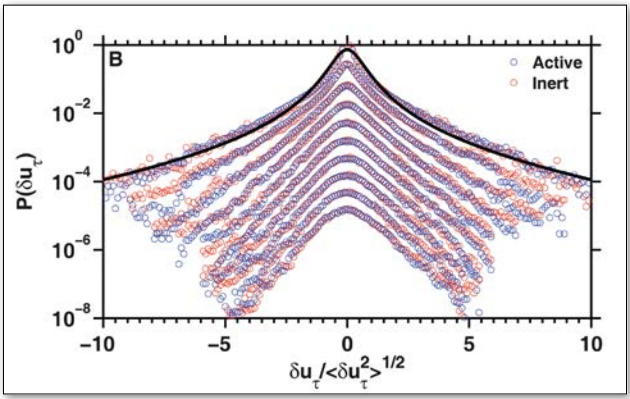
LIQUID PHYSICS

Zooplankton: not-so-passive motion in turbulence

Physicists show that despite their limited swimming abilities, zooplankton called calanoid copepods display active, energetic behaviour in turbulent flows.

Imagine a species that is only one millimetre long and has only a limited swimming ability. Yet, its mobility is sufficient for moving, feeding and reproducing in freshwater and seawater. That's exactly what a type of zooplankton of the crustaceans family—namely the calanoid copepods—does. In a study published recently, the authors shed new light on how these zooplankton steer large-scale collective motion under strong turbulence. To do so, they study the zooplankton's small-scale motion mechanisms when subjected to background flow motion. They found that at short time scales, due to the copepods' frequent relocation jumps, the intermittent nature of their self-induced motion amplifies the intermittent properties of the underlying flow. Ecological applications in the field of zooplankton behaviour ecology include, for example, modelling the feeding efficiency of their predator, fish larvae. ■

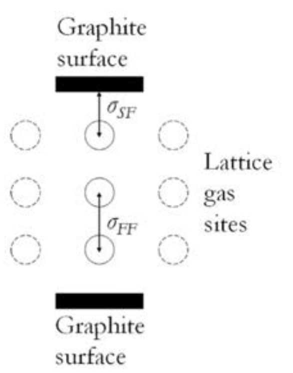
▼ Probability of speed increments for living copepods in still water (black) and for living (blue) and inert (red) copepods in turbulence, for different separation times.



■ **F.-G. Michalec**, **F.G. Schmitt**, **S. Souissi** and **M. Holzner**, 'Characterization of intermittency in zooplankton behaviour in turbulence', *Eur. Phys. J. E* **38**, 108 (2015)

COMPUTATIONAL PHYSICS

Trapping climate pollutant methane gas in porous carbon



▲ Schematic diagram of the confined lattice gas model used in some of the study's calculations.

New adsorption of gas into porous carbon simulations are of interest to energy research and climate change mitigation.

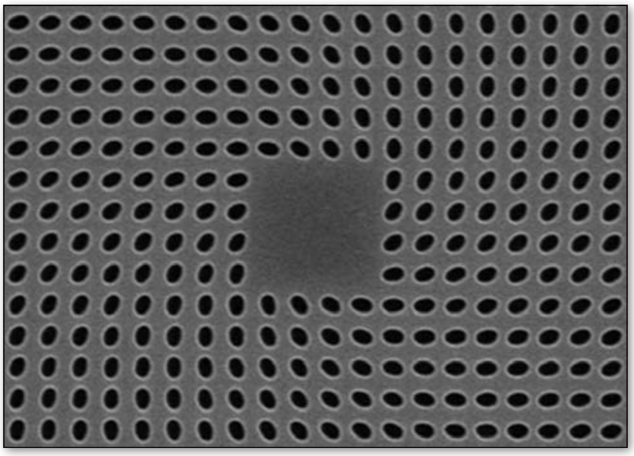
As talks of global warming are once again making headlines, scientists have renewed their efforts to understand how to best limit its effects. For example, sequestrating short-lived climate pollutants, such as methane and black carbon, yields much faster reductions in global warming compared to reductions in CO_2. To do so, it is essential to have a better grasp of the nature of physico-chemical properties of gases interacting with porous carbon. Now, a team of chemical engineering researchers has established ways of accurately simulating methane adsorption and desorption in carbon with nanopores. These findings have been published recently. Alternative applications for such findings are relevant for future energy research, such as energy storage and the development of natural gas extraction methods. ■

■ **M. Lasich** and **D. Ramjugernath**, 'Influence of unlike dispersive interactions on methane adsorption in graphite: a grand canonical Monte Carlo simulation and classical density functional theory study', *Eur. Phys. J. B* **88**, 313 (2015)

OPTICS

Lasing with **topological defects**

A new laser based on a swirling vortex of light has been created by the authors. The 'topological-defect laser' could be a useful addition to lab-on-a-chip devices, where it could manipulate fluids and tiny particles. The design could also be modified to create beams of light with orbital angular momentum.



▲ Scanning-electron microscope (SEM) images of the topological defect laser where a photonic crystal surrounds the optical cavity.

Conventional lasers confine light by bouncing it back and forth in an optical cavity made of two opposing mirrors. The authors have taken a new twist on this design by making an optical cavity that confines light by having it swirl around in a vortex. They made their optical cavity within a photonic crystal, which is a material containing a regular array of elements which are separated by distances on par with the wavelength of light. Light at certain wavelengths and travelling in certain directions will pass freely through a photonic crystal, whereas light not meeting these criteria will be diffracted into a new trajectory. ■

∎ **S. Knitter**, **S.F. Liew**, **W. Xiong**, **M.I. Guy**, **G.S. Solomon** and **H. Cao**,
'Topological defect lasers', *J. Opt.* **18**, 014005 (2016)

BIOPHYSICS

Cancer risk **myth debunked**

Cancer risk debate laid to rest by novel calculations distinguishing population-wide risks for each organ and individual risks linked to environmental and genetic factors.

▼ Cancer risk is not just bad luck. ©Tilialucida / Fotolia

A recent study suggests that variations in terms of cancer risk among tissues from various organs in the body merely amount to pure bad luck. In other words, cancer risk is linked to random mutations arising in the normal course of DNA replication of healthy cells. It is also claimed that environmental and genetic factors play a lesser role. The scientific community has primarily reacted negatively to this interpretation and promptly refuted it with qualitative arguments and empirical evidence. Joining these voices are the authors, who uncovered the statistical fallacy at the source of the recent study's conclusion. The key is to distinguish between individual organ risks and population risks, they wrote in this work. They also contend that the role of genetic and environmental factors must not be underplayed, even if these factors cannot explain differences in cancer rates between different organs. ■

∎ **D. Sornette** and **M. Favre**,
'Debunking mathematically the logical fallacy that cancer risk is just "bad luck"', *EPJ Nonlinear Biomedical Physics* **3**, 10 (2015)

COMPUTATIONAL PHYSICS

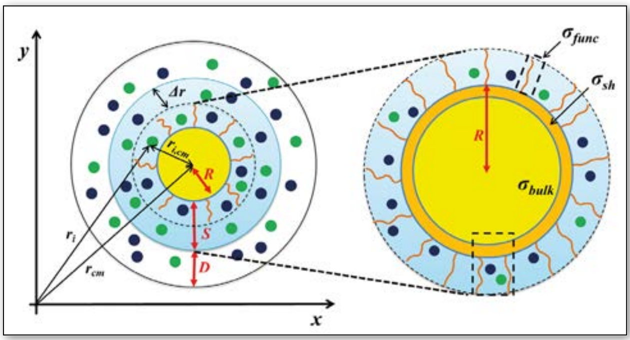
Anti-clumping strategy for nanoparticles

Scientists identify the factors involved in preventing nanoparticles used in industrial applications from aggregating.

Nanoparticles are ubiquitous in industrial applications ranging from drug delivery and biomedical diagnostics to developing hydrophobic surfaces, lubricant additives and enhanced oil recovery solutions in petroleum fields. For such nanoparticles to be effective, they need to remain well dispersed into the fluid surrounding them. In a study published recently, the authors identified the conditions that lead to instability of nanoparticles and producing aggregates. This happens when the electric force on their surface no longer balances by the sum of the attractive or repulsive forces between nanoparticles. ■

∎ **L. S. de Lara**, **V. A. Rigo** and **C. R. Miranda**,
'The stability and interfacial properties of functionalized silica nanoparticles dispersed in brine studied by molecular dynamics', *Eur. Phys. J. B* **88**, 261 (2015)

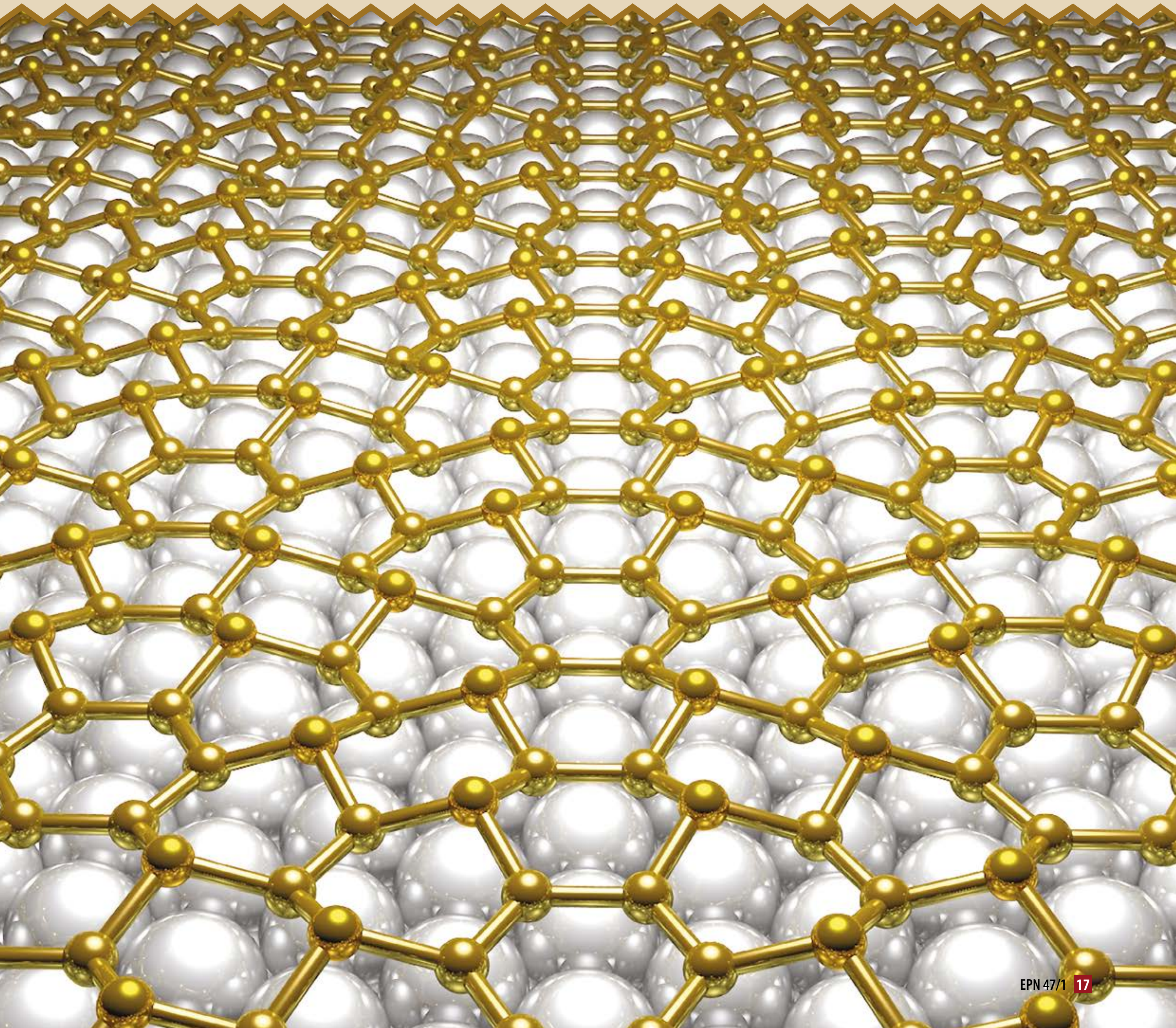
▼ Schematic representation for a functionalized nanoparticle (NP) in brine.



SILICENE:
SILICON CONQUERS THE 2D WORLD

Guy Le Lay*, Eric Salomon, Thierry Angot – DOI: 10.1051/epn/2016101
Aix-Marseille University – Physique des Interactions Ioniques et Moléculaires – UMR7345
Avenue Escadrille Normandie Niemen – 13013 Marseille, France – *guy.lelay@univ-amu.fr

We live in the digital age based on the silicon chip and driven by Moore's law. Last July, IBM created a surprise by announcing the fabrication of a 7 nm test chip with functional transistors using, instead of just silicon, a silicon-germanium alloy. Will silicon be dethroned?



Progress in electronics is governed by the motto "smaller, faster, cheaper" and still follows Moore's law, which predicted that the number of transistors in a semiconductor chip roughly doubles every 18 months. Indeed, the key electronic device, the field-effect transistor (FET), has been shrinking continuously. Yet, the characteristic length of the channel, presently 14 nm for Intel's most advanced commercial central processing units (CPUs), is approaching the limits where three-dimensional (3D) silicon would be problematic. The 7 nm Si-Ge transistors will enable at least 50% power/performance increase over most advanced 10 nm technology planned by Intel for 2016, especially by improving the mobilities of the carriers. Now the next step, the 5 nm node, appears at hand, which raises a fundamental question: at such a small nanoscale, what will be the next silicon?

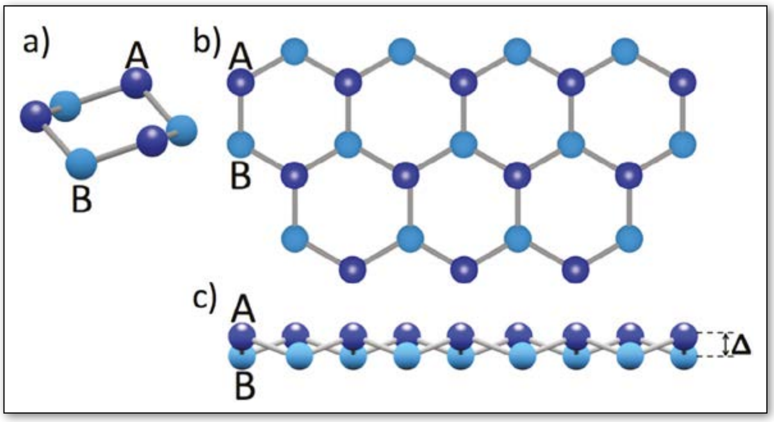
The end of the silicon age?

The advent in 2004 of graphene [1], the two-dimensional (2D) material by excellence, descendent from its parent crystal graphite, was celebrated by the Nobel Prize in physics in 2010, awarded to Andre Geim and Konstantin Novoselov. It has prompted enthusiasts of this "wonder material" to predict a new carbon-based electronics era.

However, it appeared that the difficulty in opening a sizeable band gap in graphene was an insurmountable handicap for digital applications. As a consequence, the question raised by Ross Kozarsky, senior analyst at Lux Research, at the Washington DC Nanotech Conference & Expo 2013: "Is Graphene the Next Silicon… Or Just the Next Carbon Nanotube?" was finally answered last July (2015): "Just don't expect graphene to live up to the untenable hype, or become the next silicon".

Hence, in the wake of graphene, researchers have initially looked for existing semiconductor lamellar crystals which – just as in the case of graphite - could be peeled to the ultimate limit by the famous scotch tape method. Success came in 2011 with molybdenum disulfide, which permitted the first fabrication of a transistor with a 2D single layer MoS_2 channel [2]. However, although potentially promising for flexible electronics and for optoelectronics, such transition metal dichalcogenides transistors cannot replace advanced Si ones.

▾ **FIG. 1: Illustration of the buckled structure (*corrugated* stage) of silicene: (a) perspective view, (b) top view, (c) side view. The A and B sites, composed of Si atoms, form two sublattices which are vertically separated by Δ ~ 0.04 nm.**



The birth of silicene

Concurrently, Patrick Vogt and Guy Le Lay (PV and GLL) in Marseille have been striving, in a creative endeavour, to synthesize silicene, the Si-based analogue of graphene. Already in an article published in 1994 [3], but essentially unnoticed for 17 years, Kyozaburo Takeda and Kenji Shiraishi had theoretically predicted its possible existence as a standalone novel 2D silicon allotrope with a *corrugated* stage, *i.e.*, with a ~ 0.4 nm out-of-plane buckling between the A and B sublattices, see Fig. 1. This is at variance with graphene, which is basically flat.

As underlined by Kehui Wu [4] and many experimentalists, the early claim in 2010 of "Epitaxial growth of a silicene sheet" with nearly planar *primitive* honeycomb structure and much too short Si-Si bond lengths was a false start. This illustrates the famous quote of Luigi Galvani: "for it is easy in experimentation to be deceived, and to think one has seen and discovered what one has desired to see and discover".

In fact, the first compelling experimental evidence for successful silicene synthesis on a silver (111) substrate appeared in April 2012 [5]. A significant consecutive marker has been the sudden jump in citations of Takeda and Shiraishi's paper, and of the number of articles on silicene, germanene and stanene, graphene's Si, Ge and Sn cousins, from year 2012 on.

Another milestone is the insertion of these novel elemental artificial 2D materials – which have to be created on a template since they have no parent crystal in nature – in the EU "Science and technology roadmap for graphene, related two-dimensional crystals, and hybrid systems" [6].

Here it is worth citing one of the small but strong lessons from chemistry for nanoscience by Nobel laureate Roald Hoffmann and his silicene interlude [7]: "We have graphene multilayers and the monolayer, and the intriguing physics of these. There is a growing literature out there of the Si analogue, silicene. And that literature talks about silicene as if it were graphene. In part this is an attempt to live off graphene's mystique, but part comes out of lack of knowledge of chemistry. I don't often say something categorical, but I will say that a pristine free-standing single layer sheet of silicene (or a Si nanotube) will not be made. Silicene exists and will be made only on a support of some sort, metal or semiconductor".

Compliant single layer silicene

Indeed, PV and GLL created, in situ, under ultra-high vacuum, single layer silicene on a silver plate, typically by exploring – like Alice – through the looking glass. Instead of depositing silver onto a piece of silicon wafer, to form an atomically abrupt prototypical noble-metal/semiconductor interface with a "magic" epitaxial relationship (as had been done by GLL during years of research on the formation of Schottky barriers, a very hot topic in the eighties [8]) the process was inverted: they deposited silicon onto a silver (111) single crystal surface kept at ~200°C. Then, sharp low-energy electron diffraction patterns and the splendid unique "flower pattern" discovered in STM imaging and displayed in Fig. 2a were observed, revealing a highly ordered 2D epitaxial system but *absolutely no direct graphene-like aspect*.

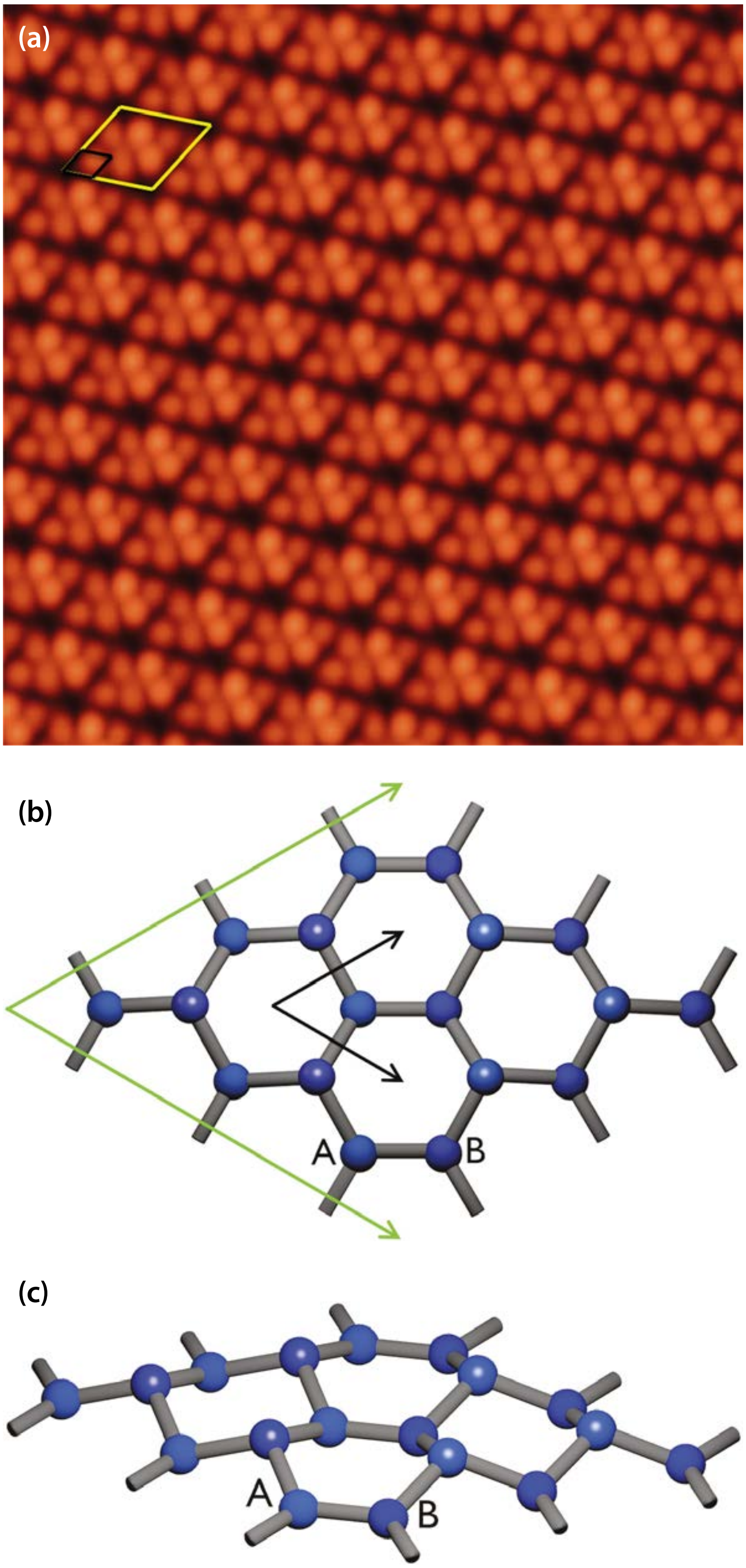
The hidden underlying honeycomb structure of silicene within the "flower pattern" was unraveled thanks to high-resolution synchrotron radiation angle-resolved photoelectron spectroscopy (SR-ARPES) measurements and thorough density functional theory calculations based on an initial geometrical model inferred from the knowledge of the "magic" relationship mentioned above. Typically, a *reconstructed* silicene monolayer on top (with basis vectors 3 times larger than the unit vectors of free standing silicene, corresponding to a so-called 3×3 reconstruction) matched nearly perfectly a facing 4×4 supercell of the (111) silver surface below –see Fig. 2b. Within the 3×3 silicene lattice the Si-Si bond lengths are close to those calculated for free-standing silicene (0.225 nm [9]) but the buckling is nearly doubled, increasing from 0.044 nm to 0.083 nm. This is nicely confirmed by dynamic LEED measurements and, strikingly, reflection high-energy positron diffraction experiments performed in Tsukuba (Japan) [10].

The high flexibility of silicene, inherent to its intrinsic buckling associated with its intermediate sp^2/sp^3 hybridization state, makes silicene a highly compliant 2D material: it conforms to its substrate instead of making loose Moiré patterns, as graphene grown on metals generally does.

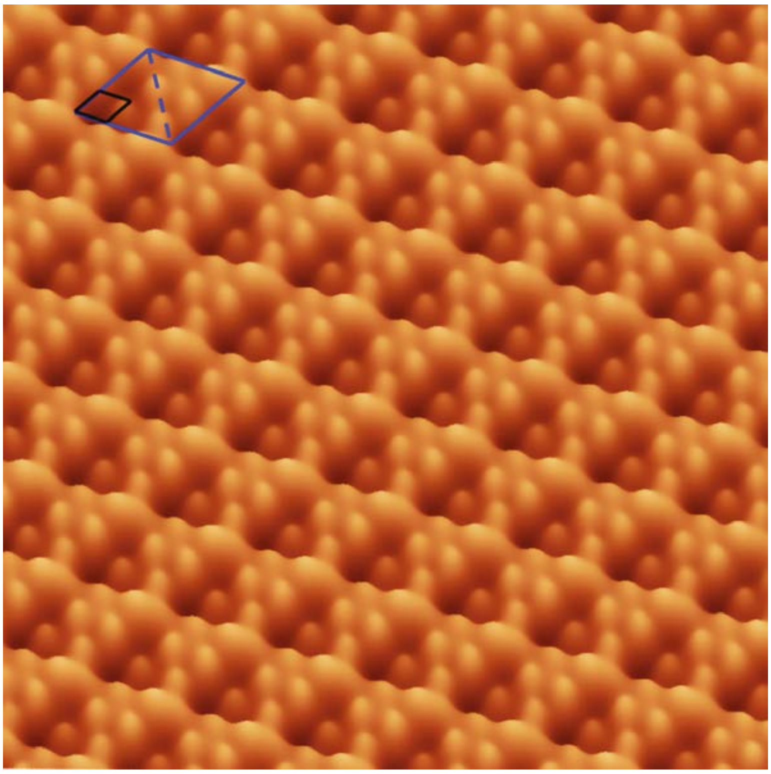
More Moore... and More than Graphene!

The intrinsic low buckling in standalone silicene preserves the key electronic features found in graphene, namely the massless Dirac fermion character of the charge carriers, their extremely high mobilities and the gapless semimetal nature. Yet, symmetry breaking of the A and B sublattices, in addition to reconstructions, as observed until now on *all* metallic substrates, can eventually open up a band gap [11].

Such an opening is further facilitated by the reactivity of silicene, at variance with the inertness of graphene. As a striking example, Fig. 3 displays the ordered adsorption of atomic hydrogen, first evidence by Qiu *et al.* [12], which will allow further band gap tuning.



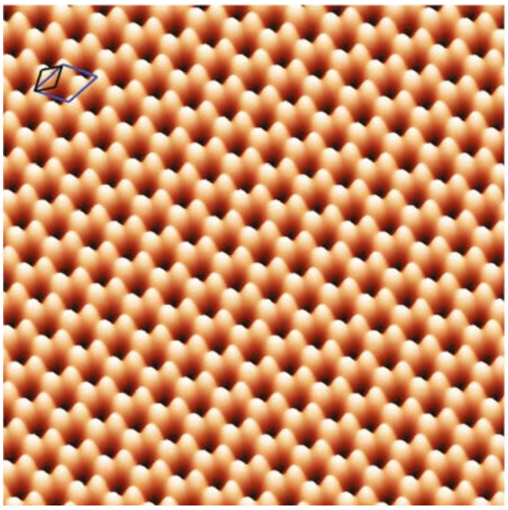
▲ **FIG. 2:** Top panel **(a)**: Scanning tunneling microscopy image (10 nm × 10 nm, tunnel current 0.55 nA, sample bias -520 mV = filled states) showing the observed "flower pattern" resulting from the protruding Si atoms within the 3×3 reconstructed silicene layer; the 3×3 supercell is indicated in yellow, while the primitive 1×1 cell is shown in black. Middle and bottom panels **(b)** and **(c)**: Top and Perspective views of the geometrical model of the 3×3 reconstructed silicene layer, as extracted from the Ag(111) surface where it lies in a 4×4 coincidence supercell. In the middle panel the 3×3 supercell vectors are indicated in green, while the basis vectors of the primitive unit cell are indicated in black.

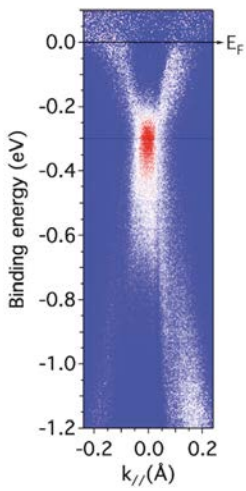


▲ **FIG. 3:** STM image (9 nm × 9 nm, 0.33 nA, -200 mV = filled states, 3D rendering) of an ordered, hydrogenated, single layer silicene on Ag(111). The observed protrusions correspond to adsorbed H atoms. Although a 3×3 supercell is preserved (shown in blue, while the primitive 1×1 is in black), the H atoms saturate the Si dangling bonds in a manner that favors one of the sublattices (6 H atoms on one sublattice the right half of the supercell) over the other (a single H atom on the other sublattice on the left half of the supercell).

> **A number of fascinating applications can be envisaged for this robust Dirac 2D material**

▼ **FIG. 4:** Left: 9 nm × 9 nm STM image (0.16 nA, -560 mV = filled states) of the √3×√3 reconstructed surface of multilayer silicene (the √3×√3 supercell is indicated in blue). Right: Evidence of Dirac fermions in multilayer silicene. A Dirac cone with π and π* states, below and above the Dirac point, respectively, is recorded in SR-ARPES at the center of the Brillouin zone due to the band folding associated with the reconstruction. The Dirac point is situated at ~0.3 eV below the Fermi level, (E_F = 0.0 eV).





This points to practical applications in electronics, which, as a matter of fact, were already demonstrated with the fabrication of the first silicene FETs operating at room temperature by the groups of Deji Akiwande in Austin (Texas) and Alessandro Molle in Milan (Italy) [13]. This fabrication was made possible by a very smart fabrication process. The tuning of a sizeable gap is, indeed, on the wish list to push Moore's law beyond the 5 nm node where 2D material channels will become indispensable [14].

Prospects

The strong spin-orbital coupling in silicene, germanene and stanene gives these novel allotropes a 2D topological insulator nature that could sustain a robust quantum spin Hall effect at accessible temperatures (in contrast to graphene) [15]. This would hold particularly exciting promises for spintronics and quantum computing.

Beyond the first layer in direct contact with the substrate, we can grow in a successive terrace fashion silicene multilayers, which all possess the same and unique reconstruction (a 30° rotated √3×√3 superstructure with respect to the primitive silicene cell) where protruding Si atoms form the nice honeycomb arrangement seen in Fig. 4 (left). Multilayer silicene hosts Dirac fermions, as evidenced by the measured ARPES cone shown in Fig. 4 (right); here the Dirac point is located at ~0.3 eV below the Fermi level because of charge transfer from the metallic silver substrate yielding partial filling of the π* upper cone [16].

While single layer silicene cannot stand air exposure for more than a few minutes (still long enough to measure the transistor characteristics, as indicated above), multilayer silicene is resistant for at least 24 hours: covered by an ultra-thin native oxidized skin, the rest of the body underneath is fully protected [17]. Clearly, a number of fascinating applications can be envisaged for this robust Dirac 2D material.

Conclusion

We have surveyed only few fascinating properties of single and multilayer silicene, created in 2012, just four years ago, during an 'adventure through the looking glass'. Two years later, single-layer germanene was synthesized on a gold plate [18], while multilayer germanene, which also hosts Dirac fermions, is just born [19]. Indeed, as both silicene and germanene are expected to be easily incorporated into the existing silicon-based industry, their recent synthesis excites a rapidly expanding community.

Furthermore, stanene has just made its debut [20]. All these emerging artificial elemental 2D materials, whose properties and potential applications are barely explored, are promised a bright future as they will offer exciting perspectives for future nanoelectronics, spintronics and for quantum computing. Will one of them be the next silicon? At this stage, we think that silicene, *i.e.*, the novel 2D silicon allotrope, can most probably win the race.

About the authors



Thierry Angot (left), **Guy Le Lay** (middle) and **Eric Salomon** (right) are professors in physics at Aix-Marseille University, in Marseille, France. They are surface/nano scientists, whose interests are in plasma surface interactions (in liaison with the ITER project in Cadarache), semiconductors, organics, and, especially 2D materials. They study both atomic and electronic structures of these novel materials, created in situ, with scanning probe microscopy/spectroscopy and synchrotron radiation based diffraction and spectroscopy advanced methods. ■

References

[1] N.M.R. Peres, *Europhysics News* **40-3**, 17 (2009).

[2] B. Radisavljevic, A. Radenovic, J. Brivio, V. Giacometti, and A. Kis, *Nature Nanotechnology* **6**, 147 (2011).

[3] K. Takeda and K. Shiraishi, *Phys. Rev. B* **50**, 14916 (1994).

[4] K.-H. Wu, *Chin. Phys. B* **24**, 086802 (2015)

[5] P. Vogt, P. De Padova, C. Quaresima, J. Avila, E. Frantzeskakis, M. C. Asensio, A. Resta, B. Ealet, and G. Le Lay, *Phys. Rev. Lett.* **108**, 155501 (2012).

[6] A. C. Ferrari *et al.*, *Nanoscale* **7**, 4598 (2015); Unfortunately, silicene on Ag(111) is naively represented in Fig. 53 by a primitive, nearly flat, honeycomb arrangement, an error to be corrected in the next editions.

[7] R. Hoffmann, *Angew. Chem. Int. Ed.* **52**, 93 (2013).

[8] G. Le Lay, *Surface Sci.* **132**, 169 (1983).

[9] S. Cahangirov, M. Topsakal, E. Aktürk, H. Sahin, and S. Ciraci, *Phys. Rev. Lett.* **102**, 236804 (2009).

[10] Y. Fukaya, I. Mochizuki, M. Maekawa, K. Wada, T. Hyodo, I. Matsuda, and A. Kawasuso, *Phys. Rev. B* **88**, 295413 (2013).

[11] A. Fleurence, R. Friedlein, T. Ozaki, H. Kawai, Y. Wang, and Y. Yamada-Takamura, *Phys. Rev. Lett.* **108**, 245501 (2012).

[12] J. Qiu, H. Fu, Y. Xu, A. I. Oreshkin, T. Shao, H. Li, S. Meng, L. Chen, and K. Wu, *Phys. Rev. Lett.* **114**, 126101 (2015).

[13] L. Tao, E. Cinquanta, D. Chiappe, C. Grazianetti, M. Fanciulli, M. Dubey, A. Molle and D. Akinwande, *Nature Nanotechnology* **10**, 227 (2015).

[14] F. Schwierz, J. Pezoldt and R. Granzer, *Nanoscale* **7**, 8261 (2015).

[15] M. Ezawa, *Phys. Rev. B* **87**, 155415 (2013).

[16] P. De Padova, J. Avila, A. Resta, I. Razado-Colambo, C. Quaresima, C. Ottaviani, B. Olivieri, T. Bruhn, P. Vogt, M. C. Asensio and G. Le Lay, *J. Phys.: Condens. Matter* **25**, 382202 (2013).

[17] P. De Padova, C. Ottaviani, C. Quaresima, B. Olivieri, P. Imperatori, E. Salomon, T. Angot, L. Quagliano, C. Romano, A. Vona, M. Muniz-Miranda, A. Generosi, B. Paci and G. Le Lay, *2D Materials* **1**, 021003 (2014).

[18] M. E. Dávila, L. Xian, S. Cahangirov, A. Rubio and G. Le Lay, *New Journal of Physics* **16**, 095002 (2014).

[19] M. E. Dávila and G. Le Lay, *Sci. Rep.* in press.

[20] F.-F. Zhu, W.-J. Chen, Y. Xu, C.-I. Gao, D.-D. Guan, C.-H. Liu, D. Qian, S.-C. Zhang and J.-F. Jia, *Nature Materials* **14**, 1020 (2015).

[Letter to the Editor]

by Jan Verhoeven
ARCNL, Amsterdam
DOI: 10.1051/epn/2016102

In defence of basic research

In *EPN* **46/5&6** the Opinion Column by Jo Hermans stresses the value of basic research. The message is that fundamental research may not always look useful, but that unexpected - and often extremely useful - applications emerge much later. Indeed, it is impossible to predict the pay-off of fundamental research.

I completely agree. However, this message is delivered to the wrong audience. We physicists must relentlessly deliver this message to politicians and other decision makers, and to the public at large. And we should put it in a language that is understood by laymen, however difficult that may be for scientists. We should write in popular newspapers and magazines, and we should not be afraid to overdo things or even sound alarming: 'Curtailment of fundamental research threatens future technological development'. Make it a Wake-up call. And use additional examples, especially cases where basic research has applications in medicine. For instance, the development of particle accelerators, combined with research into radiation damage performed decades ago, formed the basis for proton therapy, which saves healthy tissue while killing cancer cells. Other examples can be found in Angela Bracco's Feature NUCLEAR PHYSICS FOR MEDICINE (*EPN* **46/3**, p. 26-30).

So: come on, you European physicists: shake off your shyness and deliver this message in simple language to those who determine where the money goes. ■

SOFT JANUS, WRINKLES AND ALL

A.C. Trindade[1*], P. Patrício[2,3+], P.I.C. Teixeira[2,4#], P. Brogueira[5$] and M.H. Godinho[1€]
[1] CENIMAT- I3N, Departamento de Ciência dos Materiais – Faculdade de Ciências e Tecnologia, Universidade Nova de Lisboa, Portugal
[2] ISEL – Instituto Superior de Engenharia de Lisboa – Instituto Politécnico de Lisboa, Portugal
[3] CEDOC – Centro de Estudos de Doenças Crónicas – NOVA Medical School, Universidade Nova de Lisboa, Portugal
[4] Centro de Física Teórica e Computacional – Faculdade de Ciências da Universidade de Lisboa, Portugal
[5] CeFEMA – Centro de Física e Engenharia de Materiais Avançados Departamento de Física do Instituto Superior Técnico – Universidade de Lisboa, Portugal
[*]acrt@fct.unl.pt – [+]pedro.patricio@adf.isel.pt – [#]piteixeira@fc.ul.pt – [$]pedro.brogueira@tecnico.ulisboa.pt – [€]mhg@fct.unl.pt
DOI: 10.1051/epn/2016103

Right now you are probably sitting on a comfy cushion. This is most likely filled with polyurethane (PU) foam. PUs are very long molecules made up of many repeating units. If the repeating units are prepolymers – intermediate-mass building blocks – with more than two reactive end groups, a three-dimensional network will form – a rubber, or elastomer, which can behave elastically depending on the degree of network cross-linking.

What has all this to do with wrinkles? More than 15 years ago, one of our collaborators' postdocs had produced some polyurethane/polybutadiene diol (PU/PBDO) films – made up of "soft" PU prepolymer stars and "hard" polybutadiene diol linear segments - as part of his research project. These films had been stored in a box near a window. The films were very clear, with a faint yellowish tinge. Then one day, while on a visit to this collaborator's lab, one of us (MHG) casually took a film out of the box and stretched it with her fingers. Now if you do this with a piece of common clear plastic film, say polyethylene, it will turn whitish. If care is taken not to stretch it beyond the elastic regime, then this whitishness will disappear when the strain is removed.

But the PU/PBDO film would do nothing of the sort. Instead, it would remain fairly clear on stretching, but become translucent when released. A detailed examination of the film surface revealed a texture of bands, arranged *perpendicular* to the direction of stretching, whose origin was a mystery. Reproducing this effect in the lab took many months of effort and many false starts, until it was realised that the crucial ingredient was that the films had been stored *by a window*, hence it was essential to irradiate them with ultraviolet (UV) light in order to produce a higher density of crosslinks at the film surface.

Then again, if you were not involved in the above story, why should you care about wrinkles? It turns out that they are ubiquitous in nature, occurring not just in the skins of elderly humans and many animals, such as elephants, rhinoceroses and reptiles, but also in pumpkins, nuts and dehydrated fruits, as well as in single-cell organisms. These patterns evolved by natural selection over millions of years, have practical functions and can also confer a survival advantage. For example, wrinkles and folds play an important role in facilitating nutrient absorption in intestines. And they are invaluable when attempting to improve or correct nature, *e.g.*, by aiding cell adhesion at the interfaces of biomaterials and biological systems.

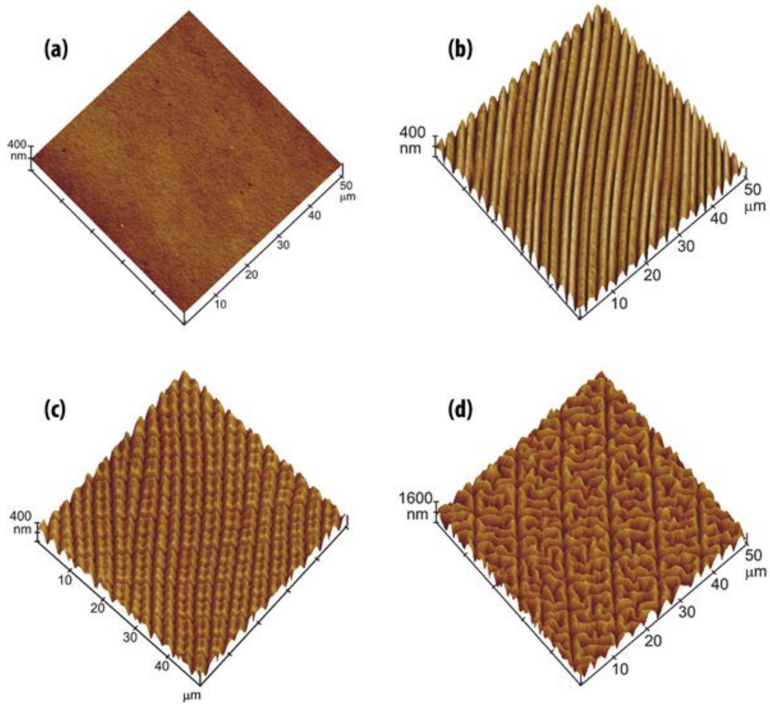
Before we proceed, a disclaimer is in order: this article is framed in the language of PU/PBDO elastomers because that is what we had on the bench at the time, and have expertise in. But qualitatively the same effects can be obtained with any other network-forming polymer.

◂ **Wrinkled dried berries of *Bryonia alba***

Films

So how does one make these peculiar films? PU prepolymer and PBDO react in the presence of a specific catalyst. Then the reacting mixture is poured on a treated glass plate and spread with a casting knife moving at a controlled speed, typically 5 mm/s. The resulting film, of thickness in the region of tens of microns, is then cured, first in an oven, then in air. Finally, the film is UV-irradiated for three days. Of course, things are more complicated than this, *e.g.*, the film composition has to be just right. For full details, see [1].

The film as made is unimpressive: even AFM cannot see anything unusual (see figure 1a). But stretch it by some 30% along some direction, then let go: now AFM will reveal a beautiful pattern of one-dimensional (1d) wrinkles, almost defect-free, with wavelengths in the micron range and amplitudes of tens of nanometres (see figure 1b). And this is not all: stretch the film again, by about the same amount, perpendicular to the original deformation, and you will see a beautiful checkerboard pattern appear that results from the superposition of two 1d wrinkle waves (see figure 1c). Even more intriguingly, either of these waves can be erased by again pulling along the direction perpendicular to it. Or, if you wait long enough – a few months should suffice - the whole texture just fades away and the films go back to their unwrinkled state. (If you are in a hurry to get rid of your wrinkles, just heat your films gently.) Thus the films behave elastically on short timescales, but as liquids over longer periods. In other words, they are *viscoelastic* – as, indeed, is much of soft matter. There is, however, a way to preserve the wrinkles for posterity: just swell the films in an appropriate solvent (toluene works best), and the resulting permanent



▲ **FIG. 1:** AFM images of a polyurethane/polybutadiene diol (PU/PBDO) film. **(a)** Immediately after UV irradiation and before any mechanical stress has been applied: the film is smooth, **(b)** Stretching the film along one direction induces a beautifully regular one-dimensional wrinkling. **(c)** Further stretching along a second direction perpendicular to the first induces a two-dimensional texture resulting from the superposition of two one-dimensional waves of wrinkling. **(d)** Swelling the film in toluene imprints the texture permanently. (Adapted from [2]. © EDP Sciences / Società Italiana di Fisica / Springer-Verlag 2007, reproduced with kind permission of The European Physical Journal (EPJ).)

deformation due to the large internal strains will imprint the texture permanently (see figure 1d).

Most importantly, it is only the UV-irradiated side of the films that wrinkles. We have thus created *Janus films* – named after the Roman god of gates, doors and passages, often depicted as having two faces: one looking into the past, one into the future (see figure 2). A Janus object likewise possesses two sides with distinct compositions or textures. Everything Janus is currently a hot research topic, on account of their many applications, as we shall see later. Methods for fabricating Janus objects typically involve depositing films (*e.g.*, metal) on soft substrates. In our case, however, no such complicated steps are necessary: both wrinkly (looking into the past, in our analogy) and smooth (looking into the future) faces are the same material, and adhere to each other no matter what.

But first: how do our films get their wrinkles? The mechanism was actually worked out by Bowden and co-workers many years ago [3]. Each film consists of a stiff skin and a soft(er) bulk. The skin results from the more extensive cross-linking of the PU due to UV irradiation. When the film is stretched, both skin and substrate deform; however, the skin will deform plastically more than the substrate. So when stress is removed, the substrate will want to go back to its original (pre-deformation) dimensions, whereas the skin is now bigger than it was before. The result is a net compressive stress acting on the skin (due to the bulk) and a net extensional stress acting on the bulk (due to the skin). In other words, the skin behaves as an elastic plate subjected to in-plane compression, hence it will buckle. The wrinkle wavelength λ will thus be determined by the competition between: the bending stiffness of thin stiff skin (which penalises short wavelengths); and the bulk elastic energy of the soft core (which penalises long wavelengths). This yields that the flat state becomes linearly unstable with respect to a wrinkled state of wavelength given by

$$\lambda \sim h(E_{SS}/E_{SC})^{1/3} \qquad (1)$$

where E_{ss} and E_{sc} are the Young's moduli of the stiff skin and the soft core, respectively, and h is the stiff skin thickness, assumed to be much smaller than that of the substrate. As might be expected, λ scales with h, the only relevant length scale in the problem.

Spheres

Now Janus films are interesting, but other geometries may be more convenient for applications. In particular, Janus *particles*, with two sides of distinct compositions or textures, have many potential uses: electronic paper, where one needs to switch between black and white states [4]; optical, chemical or biological biosensors, where the two hemispheres will respond differently to stimuli [5]; anisotropic building blocks for supra-assemblies, allowing a greater variety of novel structures to be built [6]; functional surfactants, where each hemisphere likes or dislikes some other component [7]; or self-motile colloidal particles (swimmers), propelled by the different ways in which either hemisphere interacts with the surrounding medium [8].

We have fabricated Janus spheres, where one hemisphere is wrinkled and the other smooth [9]. The chemistry is the same as for films, but now, rather than cast onto a glass plate, the elastomer solution is dripped into a stirred silicon oil bath, the stirring speed of which is adjusted to yield the desired range of sphere diameters, from millimetres to tenths of a micron. The spheres are then deposited on a cellulose film and UV-irradiated. Clearly we cannot deform a sphere as we do a film, *i.e.*, by direct application of a uniaxial stress. Instead, a high degree of deformation can be achieved by first swelling, and then de-swelling our spheres in toluene (figure 3a). On swelling, both the inner (softer) core and the outer (stiffer) skin deform by the same amount. The outer surface remains smooth. However, upon de-swelling the elastomer network will contract, owing to the loss of solvent and sol fraction (unreacted prepolymer blocks). The inner core has a lower cross-linking density and will recover its natural dimensions, whereas the stiff skin, being more densely cross-linked, will not. The consequent size mismatch leads to a buildup of internal stress, which, as in the case of films, triggers the buckling instability of the skin. The result is spheres with one smooth and one wrinkly hemisphere (see figure 3b).

Now in addition to the stiff skin thickness, there is one other length scale in the problem: the particle radius R. Put differently, the wavelength λ of linear instability will depend on the dimensionless ratio h/R. Figure 3c shows the wrinkle wavelength vs the co-latitude θ, where θ=0° corresponds to the "North Pole" (defined as the point where the incident UV light was perpendicular to the sphere) and θ=90° to the "equator". Clearly the thickness of the stiff skin (shown in the inset) decreases from the North Pole to the equator and this has a marked effect on λ, as does varying the sphere radius.

Our attempts at generalising equation (1) to a hemispherical shell on a spherical substrate were not successful, but we did manage to derive an analytical result for a cylindrical geometry:

$$\lambda/R \sim (h/R)^{3/4} \qquad (2)$$

valid for $R/h < 50$ (above this value one essentially recovers equation (1)), whereas a fit to our experimental data gave an exponent of 0.82 instead [9]. This is in reasonable agreement with numerical results by Cao *et al.* [10] for micron-sized particles consisting of a closed silica shell on a silver substrate, which suggest an exponent close to 0.8.

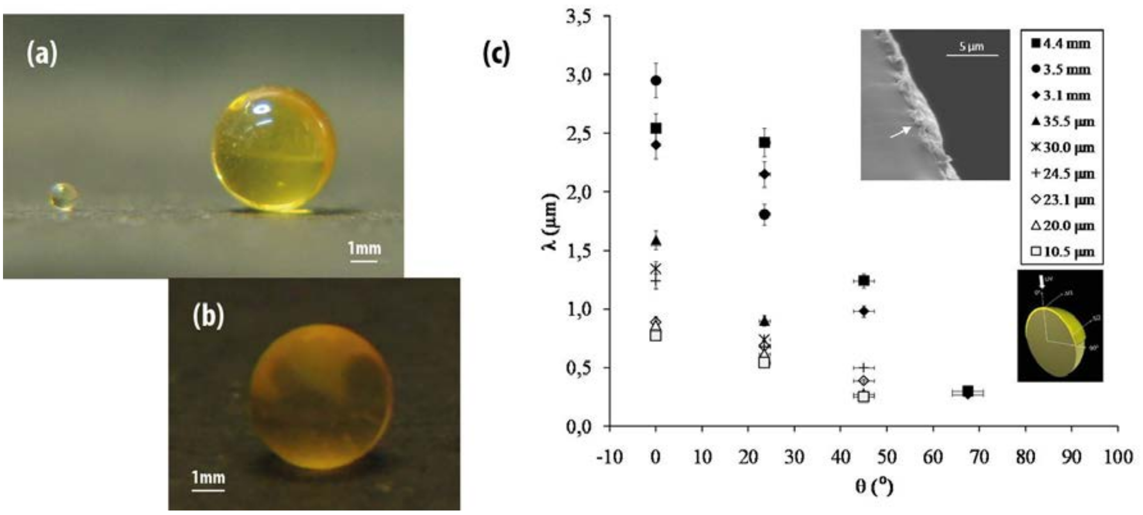
Fibres

If a theory for the spherical geometry seems difficult, what are self-respecting theorists to do? Ask your experimental co-workers to fabricate a system you *can* model – in our case a cylinder. And the experimentalists amongst us were kind enough to oblige: soon we had lots of data on long cylinders – PU/PBDO fibres [11]. These are made by a technique known as electrospinning: a syringe is filled with the reacting PU/PBDO mixture and a voltage is set up between the needle and a target – a rotating frame mounted some distance from the syringe. As the still-liquid elastomer exits the needle, it is accelerated by the voltage towards the target as a long thin fibre. The set of fibres on the target is known as a non-woven mat.

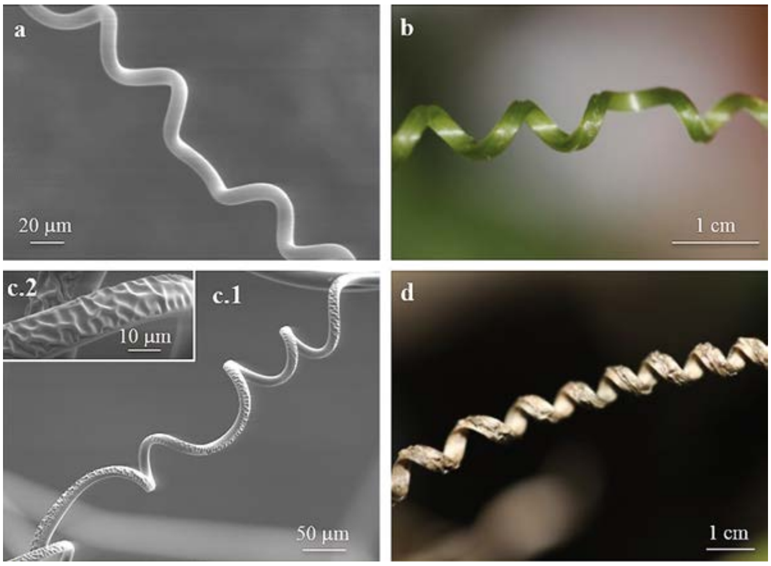
◂ **FIG. 2:** The Roman god Janus (Fubar Obfusco/ Public Domain.)

The fibres are then UV-irradiated on one side and swollen in toluene while still mounted on the target, *i.e.*, under tension. They are now anisotropic – the irradiated side has a stiff skin while the unirradiated side does not. This, together with solvent evaporation, again causes a size mismatch between skin and core. On removal from the target, the fibres immediately start curling into helices, like the ribbon on a Christmas present – but, surprisingly, the stiff skin remains smooth! Then at some critical radius the curling stops: the helix radius no longer changes and the stiff skin wrinkles instead.

Again, our simple model allows us to describe the crossover between the curling and wrinkling regimes. Both curling and wrinkling are governed by the interplay of bending the skin and dilating the core. The elastic energy of the curled, non-wrinkled state is proportional to ε^2, the square of the skin-core size mismatch, whereas the elastic energy of the wrinkled state grows linearly with ε. Thus, as the fibre dries, ε increases and the fibre curls, without wrinkling, with a radius that is proportional to ε^{-1}. Then at some critical mismatch, $\varepsilon_c \sim (E_{SC}/E_{SS})^{2/3}$, it becomes energetically favourable to stop curling and start wrinkling, with a wavelength given by equation (1).



◂ **FIG. 3: (a)** A PU/ PBDO sphere, before (left) and after (right) swelling in toluene. **(b)** Janus sphere with one smooth (shiny) and one wrinkly (cloudy) hemisphere. **(c)** Dependence of λ, the wrinkle wavelength of linear instability, on the skin thickness and sphere diameter. (Adapted from [9]. © 2011, American Chemical Society, reproduced with permission.)



▲ FIG. 4: Electrospun PU/PBDO fibres mimic plant tendrils. A smooth fibre (a) mimics a young tendril (b). An asymmetrically wrinkled fibre (c.1) mimics an old tendril (d). (c.2) shows the detail of the wrinkled fibre in (c.1). Notice the wrinkling is on the outside of the helix, consistent with the assumption that the stiff skin contracts less than the soft core on drying. (From [11]. © WILEY-VCH Verlag GmbH & Co. KGaA, Weinheim, reproduced with permission.)

Remarkably, the same qualitative behaviour is seen in the tendrils of climbing plants as they age and dry, albeit on a vastly different length scale: first they curl, then they wrinkle (see figure 4).

Outlook

Ours is a very simple method to fabricate Janus planar films, spherical particles and cylindrical fibres from a single elastomeric material. Janus particles and fibres with diameters ranging from tenths of a μm to a few mm can be produced using current chemicals and techniques. Remarkably, Janus fibres exhibit a crossover between curling and wrinkling regimes when they dry, which can be described by a simple elastic model. This latter result opens up new perspectives on biomimetic materials, as functionalities can be added by having "young" (smooth, small-surface area) and "old" (wrinkled, large-surface area) regions co-exist in the same material. For example, a fibre-based micromanipulator could conceivably be constructed, where a micro- or nano-sized object would be grabbed and carried by an array or wrinkled fibres, then released at a very precise location simply by adjusting the pattern [12].

About the authors

Ana Catarina Trindade is a postdoc working at CENIMAT-i3N, New University of Lisbon. Her current research focuses on polymeric liquid crystals, elastomers, ordered structures and Janus particles/membranes.

Pedro Patrício obtained a PhD in Physics at the "École Normale Supérieure" in Paris (France). His current research interests include geometrical instabilities in elasticity theory, the dynamics of complex fluids and the mechanics of cell tissues. He teaches at the Lisbon Polytechnic School of Engineering (ISEL).

Paulo Teixeira is a theoretical soft matter physicist. He gained a PhD from the University of Southampton (UK) and held postdoctoral positions in Amsterdam, Cambridge, Leeds and Lisbon. He is one of the first batch of *Outstanding Referees* of the American Physical Society. He teaches at the Lisbon Polytechnic School of Engineering (ISEL).

Pedro Brogueira is a Full Professor at IST – Lisbon University School of Engineering, where he obtained his PhD in Engineering Physics. His research interests are solid state physics, microelectronics, atomic force microscopy and cosmic rays. He has co-authored several physics textbooks and educational videos, organized science exhibitions, and co-written the skills framework blueprint for secondary education.

Maria Helena Godinho is head of the Soft and Biofunctional Materials Group at CENIMAT-i3N, New University of Lisbon. She is a chemical engineer and obtained a PhD in Materials Science. Her current interests are the molecular and mesoscopic properties of soft materials, such as polymers and liquid crystals. She teaches at the Faculty of Science and Technology, New University of Lisbon. Her extensive collaborations span Europe, North and South America.

References

[1] M.H. Godinho, J.L. Figueirinhas, P. Brogueira and P.I.C. Teixeira, Tuneable micro- and nano-periodic structures in urethane/urea networks. In Biomimetic and Supramolecular Systems Research, ed. by Arturo H. Lima (Nova Science Publishers, New York, 2008).

[2] M.H. Godinho, A.C. Trindade, J.L. Figueirinhas, L.V. Melo, P. Brogueira, A.M. Deus and P.I.C. Teixeira, *Eur. Phys. J.E.* **21**, 319 (2006).

[3] N. Bowden, S. Brittain, A.G. Evans, J.W. Hutchinson and G.M. Whitesides, *Nature* **393**, 146 (1998).

[4] M. Fialkowski, A. Bitner and B.A. Grzybowski, *Nature Mater.* **4**, 93 (2005).

[5] M. Himmelhaus and H. Takei, *Actuators B* **63**, 24 (2000).

[6] L. Hong, A. Cacciuto, E. Luijten and S. Granick, *Nano Lett.* **6**, 2510 (2006).

[7] B. P. Binks and P. D. I. Fletcher, *Langmuir* **17**, 4708 (2001).

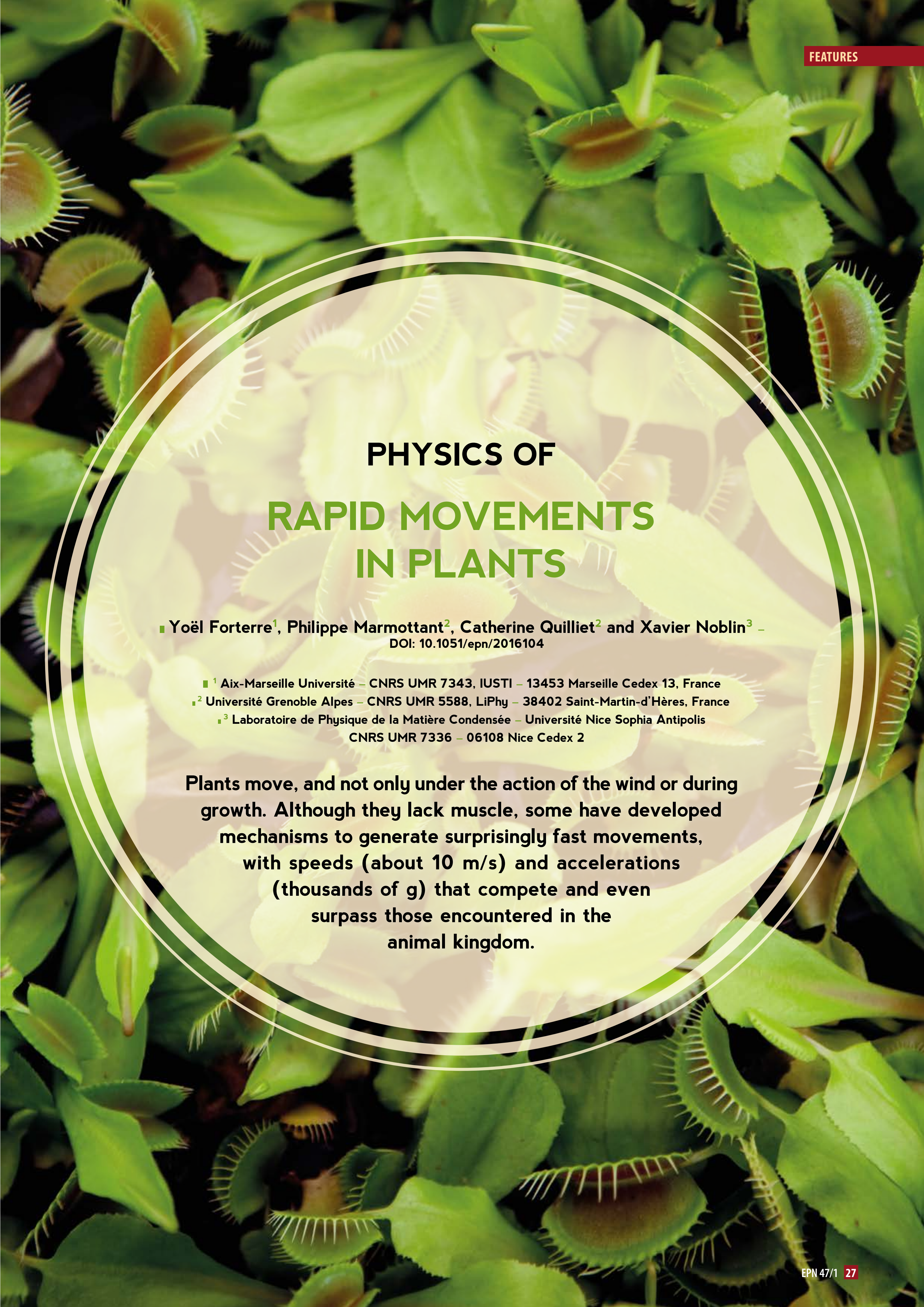
[8] R. Golestanian, T. B. Liverpool and A. Ajdari, *Phys. Rev. Lett.* **94**, 220801 (2005).

[9] A. C. Trindade, J. P. Canejo, L. F. V. Pinto, P. Patrício, P. Brogueira, P. I. C. Teixeira and M. H. Godinho, Wrinkling labyrinth patterns on elastomeric Janus particles, *Macromol.* **44**, 2220 (2011).

[10] G. Cao, X. Chen, C. Li, A. Ji and Z. Cao, *Phys. Rev. Lett.* **100**, 036102 (2008).

[11] A. C. Trindade, J. P. Canejo, P. I. C. Teixeira, P. Patrício and M. H. Godinho, *Macromol. Rapid Commun.* **34**, 1618 (2013).

[12] Y. Tokudome , K. Suzuki , T. Kitanaga , M. Takahashi, *Sci. Rep.* **2**, 683 (2012).



PHYSICS OF RAPID MOVEMENTS IN PLANTS

Yoël Forterre[1], Philippe Marmottant[2], Catherine Quilliet[2] and Xavier Noblin[3] –
DOI: 10.1051/epn/2016104

[1] Aix-Marseille Université – CNRS UMR 7343, IUSTI – 13453 Marseille Cedex 13, France
[2] Université Grenoble Alpes – CNRS UMR 5588, LiPhy – 38402 Saint-Martin-d'Hères, France
[3] Laboratoire de Physique de la Matière Condensée – Université Nice Sophia Antipolis
CNRS UMR 7336 – 06108 Nice Cedex 2

Plants move, and not only under the action of the wind or during growth. Although they lack muscle, some have developed mechanisms to generate surprisingly fast movements, with speeds (about 10 m/s) and accelerations (thousands of g) that compete and even surpass those encountered in the animal kingdom.

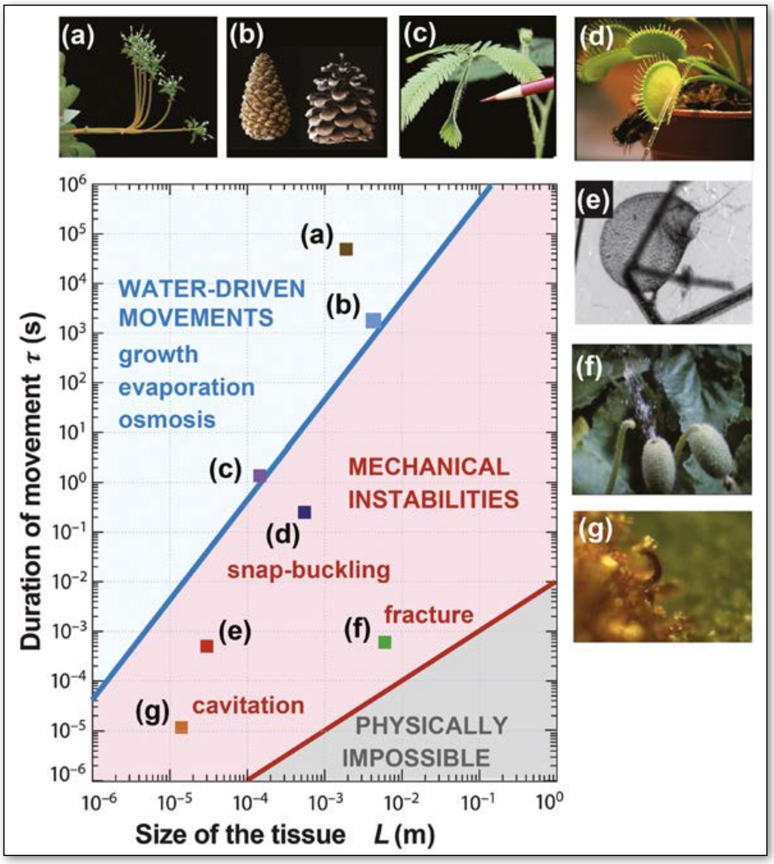
These fast movements are used to fulfill important functions such as reproduction (pollen catapult in some Orchids, explosive dispersal of seeds), defense against predators (the folding of the *Mimosa pudica* leaves) or nutrition (the traps of carnivorous plants). They have fascinated scientists since the first observations by Darwin and Linné and raise important questions in biology related to water transport across the cellular membrane, the mechanics of the cell wall or the perception of mechanical signals by plants. In this article, we discuss the physical mechanisms developed by plants to generate these rapid movements, in the light of recent studies carried at the frontiers of physics and biology.

Water-driven movements: turgor pressure, osmosis and evaporation

First of all, a crucial point in order to understand what a plant can do and cannot do is that, contrary to animal cells, plant cells are glued together and surrounded by a rigid cell wall mainly made of cellulose [1]. This prevents plant cells from using soft contractile proteins like those in animal muscles to deform and generate movement. However, the stiff wall allows plant cells to sustain a very high internal water pressure ("turgor pressure"), typically 4-8 bars and possibly up to 40 bars in special cells. Water in plants may also undergo negative pressures, thanks to the cohesive forces between water molecules, resulting in an inward pulling on walls; the mature cell wall of woody plants avoids damaging of structure even at the highest negative pressures (~ -100 bars).

Physically, such high absolute values of the hydrostatic pressure results from osmosis or evaporation phenomena [2,3]. The water fluxes between the plant and its surrounding induce a swelling or shrinking of the plant cells. This causes an internal turgor pressure, which in turn induces a mechanical movement at the macroscopic scale. Some of these movements correspond to an irreversible deformation of the cell walls, such as growth and the oriented movements against light or gravity (Fig. 1a). Some other are associated to a reversible motion, such as the osmotically induced folding of the sensitive leaves of *Mimosa Pudica* (Fig. 1c), or the opening/closing of pine cones depending on hygrometry (Fig. 1b).

▼ **FIG. 1:** Physical classification of plant movements according to the duration of the movement τ and the typical size L of the tissue over which motion occurs (adapted from[4]). Border $\tau = \tau_p$ (blue line) gives the poroelastic time (*i.e.*, the quickest movement based on water transport only), calculated using as diffusion coefficient of water in plant tissue the average value $D \sim 10^{-8}\,m^2/s$. Border $\tau = \tau_i$ (red line) gives the inertial time (*i.e.*, the quickest possible movement set by inertia and elasticity), obtained using as density $\rho = 1000\,kg/m^3$ and as Young modulus the typical value $E = 10$ MPa. **(a)** Growth response to gravity. **(b)** Hygroscopic motion of pine cone scales. **(c)** Folding back of *Mimosa Pudica* through osmosis. **(d)** Carnivorous plant Venus flytrap. **(e)** Carnivorous plant *Utricularia*. **(f)** Propulsion of seeds of *Ecballium elaterium* ("squirting cucumber"). **(g)** Catapult movement of a fern sporangium.



Physical limit on the speed of water-driven movements: the poroelastic timescale

For motions uniquely powered by water exchange, the speed is limited by the timescale for water transportation through the tissue [4]. In a porous and elastic medium like the plant tissue, this latter is a diffusive process that operates on a time $\tau_p = L/D$, where L is the transportation distance, and D an effective diffusion coefficient that takes into account the elastic and hydraulic properties of the medium. This time τ_p, called "poroelastic time", is compared in figure 1 to the duration τ of various motions observed in the vegetal kingdom, versus the typical size L of the moving tissue. Indeed, the duration of motions associated with growth (Fig. 1a) or due to modifications of ambient moisture (Fig. 1b) are to be found above the boundary $\tau = \tau_p$, which is consistent with their purely "hydraulic" nature. The rapid folding of Mimosa Pudica leaves also falls under this regime, even if, due to the small distances over which water has to be carried, the typical time of the motion is impressively short (typically 1 s).

Speeding up plant movements: elasticity and mechanical instabilities

If plants were relying only on water transport to move, they could not generate movements on a timescale shorter than the poroelastic time. However, figure 1 shows that many plants have managed to cross this hydrodynamic limit. Their common strategy is to take advantage of a mechanical instability, *i.e.*, a rapid release of previously stored energy when a threshold is crossed. Two types of instabilities are used by plants to generate fast movements:

(i) snap-buckling instabilities for the traps of carnivorous plants such as the Venus flytrap or the bladderworts, and (ii) ruptures, either solid or liquid (cavitation), for propulsion of seeds or spores. In the following, we discuss these two classes of mechanisms.

Snap-buckling instabilities: carnivorous plants Venus flytrap and Utricularia

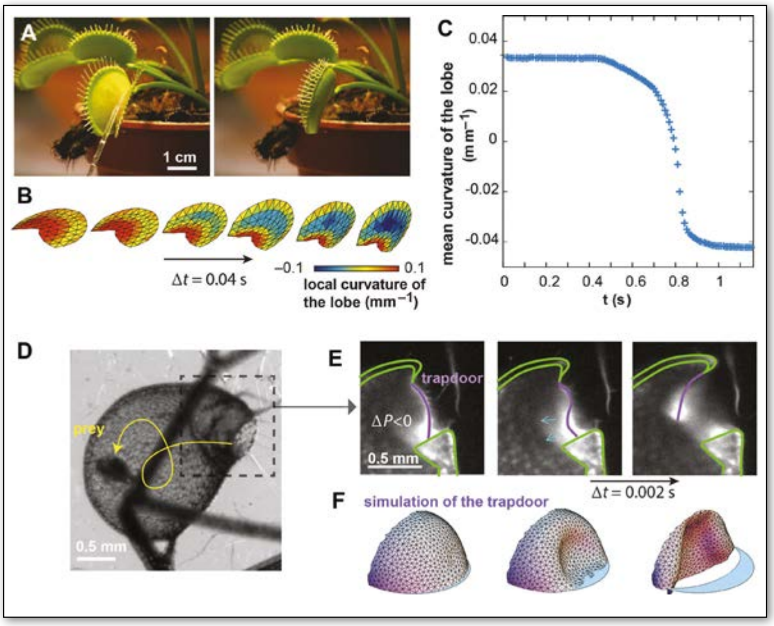
The trap of the carnivorous plant Venus flytrap (*Dionaea muscipula*) – called by Darwin the « Wonder of Nature » – is composed of two lobes attached by their base, that form a jaw (Fig. 2A). The internal side of each lobe contains mechano-sensitive hairs, which generate an electrical signal when touched. The trap closes in a few tenths of a second, which is too rapid to be due only to water transportation (Fig. 1). Recent studies have shown that the mechanism that amplifies the speed of closure relies on snap-buckling instability, analogous to the buckling of an elastic shell [5,6]. The two lobes of the trap are curved outward in the open state and inward in the closed state (Fig. 2B,C). Upon triggering, the lobes actively change their natural curvature, *i.e.*, the lobes 'try' to bend inward. However, because of the geometrical constraint of the shell-shape lobe, this active bending causes the trap to accumulate elastic energy, until the stored energy becomes so large that each lobe buckles inside out, rapidly snapping the trap shut.

A similar mechanism has been shown to operate in the suction trap of the less known but ubiquitous bladderworts (*Utricularia*) [7]. Each trap of this aquatic plant is remarkably sophisticated. It is made of an elastic closed leaf, bladder-shaped, in which water pressure slowly decreases under the action of pumping glands (Fig. 2d). The sealing of the trap is ensured by a flexible door that holds a few long sensitive hairs. Suction occurs within one millisecond – a record – thanks to an instability mechanism that, here too, results from a snap-buckling instability. In the initial configuration, the trapdoor is a shallow dome whose convex face is facing outward, thereby resisting the pressure difference across it much like a Gothic vault in architecture. Triggering lowers this resistance, either through an electrical signal or just as a weakness point, which induces a buckling of the door and its rapid opening (Fig. 2E,F). Surrounding water is then quickly sucked in, with an acceleration of up to 600g, and it drags small preys that cannot swim against such a flow (Fig. 2D).

Cavitation instability: propulsion of fern spores

Rapid movements may also be required for the dissemination of reproductive materials (seeds, pollens, spores). The squirting cucumber (Fig. 1f) is well known by the impressive way it launches its seeds, but the more discrete catapulting of spores ferns (Fig. 3A) is probably the most elegant mechanism. In most species of ferns, spores are gathered in quasi-spherical capsules (the "sporangia") holding a ring-like ridge that consists of a dozen of water-filled cells (the "annulus") (Fig. 3B). Evaporation of water from these cells induces a negative water pressure that pulls the cell walls in. Since the walls are thinner on the external side, they can bend inwards. This induces a slow and global outwards curvature at the ridge scale, up to the point (negative pressure around -100 bars) where cavitation bubbles catastrophically appear in the cells and grow, abruptly relaxing the stored elastic energy into a rapid closure of the sporangium, and ejection of its spores like in a catapult.

The ejection mechanism was roughly understood for more than one century, but many questions were not addressed until recently. In particular: how can the sporangium so efficiently propel its spores in the absence of any end-stop? In medieval or roman catapults, end-stops were used to arrest the catapult arm at half course, having it eject its projectile before it was tackled back on the floor. Recent experiments using ultrafast cameras have unveiled for the first time the ejection dynamics and explained how the sporangium functions without any structural end-stop [8]. The dynamics actually exhibits two phases occurring at very different timescale (Fig. 3C). The first one occurs just after cavitation and consists of the partial closure of the ring in a few tens of microseconds (probably the swiftest movement in the vegetal world), due to the transformation of the stored elastic energy in the sporangium annulus into kinetic energy. This inertial phase is so quick that the water trapped in the porous walls of the ridge has not yet been



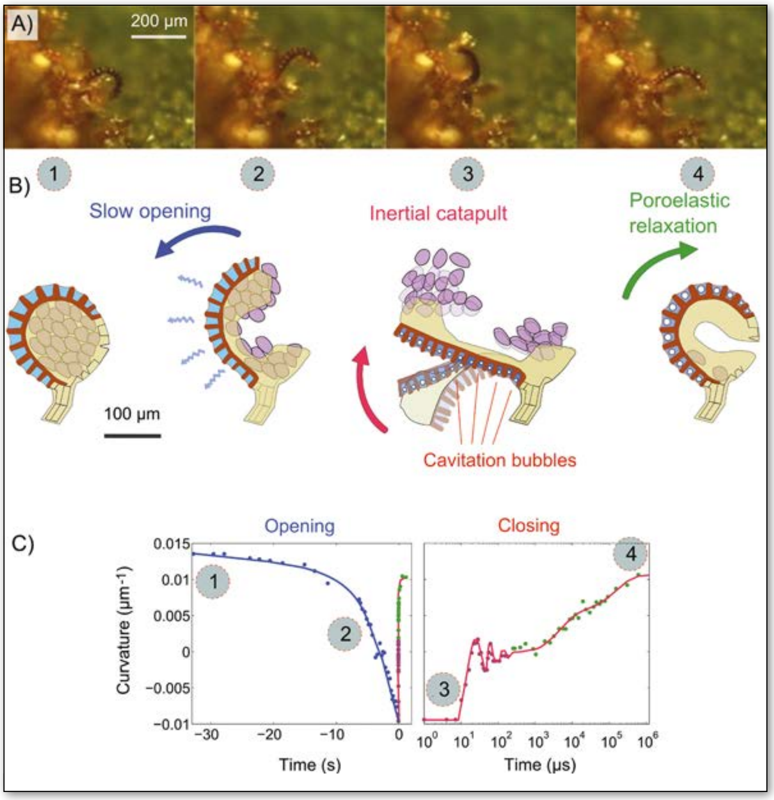
▲ **FIG. 2:** Snap-buckling instability in carnivorous plants *Venus flytrap* (a-c) and *Utricularia* (d-f). **(A)** Venus flytrap in the open **(left panel)** and closed **(right panel)** state. **(B)** Three-dimensional shape reconstruction of the lobe of one trap during closure (experiment, Δt is the time interval between two successive images). **(C)** Spatially averaged mean curvature of the lobe vs. time; the trap was triggered at $t = 0$. **(D)** *Utricularia* trap and trajectory of a small soft water crustacean, sucked in just after door opening. **(E)** Inversion of the trapdoor and buckling of the median door axis visualized by light sheet fluorescence microscopy. **(F)** Numerical simulation of the trapdoor opening. **(figures A-C according to [5] ; figures D-F according to [7])** redistributed. Hence, water pressure suddenly increases during the motion, which transiently stops the ridge at half course, and allows spores ejection at more than 10 m/s. In a second phase, after relaxation of the inertial oscillations of the annulus, water pressure slowly relaxes and the sporangium completely closes within a few hundreds of milliseconds. It is impressive to see how such a small system made of water and a few cells can perform all the key functions of a catapult, from the motive force for charging the catapult (water cohesion and evaporation) to triggering (cavitation), followed by end-stop due to the poroelastic behaviour of the cell walls.

Conclusion

Plants are hydraulic machines and most of their movements are simply the consequence of water flow driven by osmosis and evaporation phenomena. They are thus limited in speed by the poroelastic timescale of water diffusion through the soft plant tissue. In this article, we have seen how plants can use mechanical instabilities, such as elastic buckling, fracture or cavitation, to suddenly release some stored elastic energy and speed up their movements beyond the poroelastic limit. These elastic movements are nevertheless ultimately limited by the inertial time needed to accelerate masses [4]. This latter is set by the speed of the elastic waves in the body, and given by the inertial-elastic time $\tau_i = L/c$, where L is the object size and $c=(E/\rho)^{1/2}$ the speed of elastic waves, where E is the material Young modulus and ρ the material density. No plant movements are found below this limit (Fig. 1).

Fast plants are not only wonders for curiosity cabinets. Together with an increasing occurrence of biomimetic breakthroughs, they are a promising source of inspiration for realizing artificial micro-systems, such as micro-fluidic actuators [10], fast responsive surfaces [11] or jumping robots [12]. ■

▾ **FIG. 3:** **(A)** Opening and closing of a fern sporangium (which has already launched its spores). **(B)** Ejection mechanism in 4 steps, corresponding to the 4 pictures in (A) (on the third image in A), onlyposition before the triggering is displayed). **(C)** Mean curvature of the sporangium vs. time for the slow opening (blue curve) and the rapid closing (red curve). The logarithmic scale helps to separate the short time inertial oscillations of the first phase and the long time poroelastic relaxation of the second phase (according to [8]).



About the Authors

Yoël Forterre is CNRS researcher at IUSTI, Aix-Marseille University. He is working on granular materials, complex fluids, and plant biophysics (Venus flytrap mechanism of closure, plants response to gravity, hydraulic signals in relation with plants mechano-perception).

Philippe Marmottant is CNRS researcher at LIPhy Grenoble, and is interested in the physics of plants, including bladderworts suction traps, horsetail spores and sap flows in trees.

Catherine Quilliet is academic at Grenoble University. At LIPhy, she has opened for a few years her soft matter research themes to the deformations of elastic surfaces, in the aim to link the shape of soft objects to their small-scale properties.

Xavier Noblin is CNRS researcher at LPMC, Nice, working on soft matter (wetting, bubbles, microfluidics, granular media), biophysics (plant and fungi mechanics) and biomimetics.

References

[1] L. Taiz and E. Zeiger, *Plant Physiology*, Sunderland MA, Sinauer Assoc. 3rd ed. (2002).

[2] J. Dumais and Y. Forterre, *Annu. Rev. Fluid Mech.* **44**, 453 (2012).

[3] Y. Forterre, *J. Exp. Bot.* **64**, 4745 (2013).

[4] J. M. Skotheim and L. Mahadevan, *Science* **308**, 1308 (2005).

[5] Y. Forterre et al, *Nature* **433**, 421 (2005).

[6] S. Poppinga and M. Joyeux, *Phys. Rev. E* **84**, 041928 (2011).

[7] O. Vincent *et al. Proceedings of the Royal Society B* **278**, 2909 (2011).

[8] X. Noblin et al, *Science* **335**, 1322 (2012).

[9] Llorens C *et al., J. R. Soc. Interface* **13**: 20150930 (2016)

[10] D. Kim and D. J. Beebe, *Lab Chip* **7**, 193 (2007)

[11] D. P. Holmes and A. J. Crosby, *Adv. Mater.* **19**, 3589 (2007).

[12] H. Lee et al, *Soft Matter* **6**, 4342 (2010).

Opinion: Globalization, Development and Inequality

Carlos Hidalgo is Head of the Experimental Physics Division / Fusion National Laboratory at CIEMAT (Spain) and member of the EPS Executive Committee

From Aristotle to Einstein scientists have always sought to expand their views beyond national boundaries. Science inherently resists confinement, which reflects its global endeavour as a unique example of a global human enterprise. Historically scientific breakthroughs were steady but slow, occurring over a span of centuries. Today the pace of innovation has been accelerated drastically.

Although the scientific community has become more cohesive in our global world, there are risks and challenges. A real danger is that the gap in scientific capacity between developed and less developed nations will widen. At this point we should reflect on the social and economic price of inequality. As pointed out by the Nobel laureate Joseph Stiglitz, author of "The Price of Inequality", actions should be taken to control the forces driving inequality and what is at stake if it continues. Inequality contributes to the instability of our economic and social systems, which in turn contributes to the increase of inequality with concomitant failures that reinforce each other. A disturbing positive feed-back that we (physicists) know can be the prelude of bifurcations or – even worse – disruptive phenomena. Unemployment is a major cause of inequality and social stress, and for those hit by unemployment the future appears without any hope, which has devastating social consequences. Following Stiglitz's view, economic thinking deserves part of the blame, where economists just try to increase the size of the economic pie and let the politicians worry about distribution.

This is a key problem affecting social stability that scientists should also confront, providing our view about the causes and consequences of inequality and suggesting actions to be taken. The social dimension of science is fully visible via the increasing impact of technology on our quality of life. Scientific knowledge and technology have been at the root of unprecedented social and economic revolutions. It is difficult to think of any political, religious or economical doctrine that has been able to bring about such radical and robust changes on developed societies. But science should also target to raise the standard of living at the global scale in a fundamentally fair and marginally stable regime. This would require long-term perspectives on international cooperation with investment in research (in a growing knowledge-based economy), education (in a landscape of polarization of the labour force, *cf. "The Price of Inequality"*) and sustained development (in the global crossroad of energy sources).

Similarly, we need to watch against losing our ability to hear the voices of those at the margins who challenge accepted beliefs. Scientists should promote a better world based on the quest for truth and the ethics derived from it, confronting unethical behaviour that is at the root of inequality and social disruptive phenomena, being one of the most egregious actions which take advantage of uninformed groups with predatory and abusive practices. Science opened up a new mental option to cope with the world, the option of not just believing things, but rather critically analysing them (*e.g.*, has higher inequality led to more economic growth and social stability?). Here, the social dimension of science is visible via the role of critical citizens on our society. Because we need critical citizens to enable us to have an independent and well-founded view on difficult questions and threatening perspectives that lie ahead of us, critical citizens to promote a global world based on a fairer development. ■

Scientists should promote a better world based on the quest for truth and the ethics derived from it.

COMING EPS EVENTS

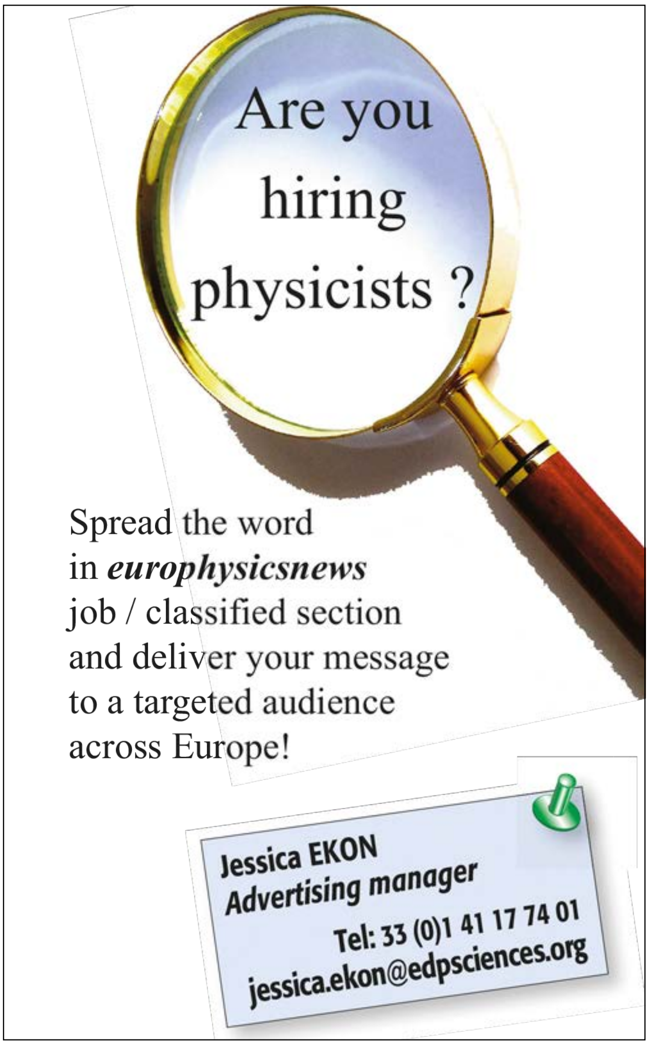
- **Magnetism 2016**
  04 » 05 april 2016
  Sheffield, UK
  http://magnetism2016.iopconfs.org/home

- **IPAC'16 - International Particle Accelerator Conference**
  08 » 13 may 2016
  Busan, KR - Korea, South
  www.ipac16.org

- **ARENA 2016**
  07 » 10 june 2016
  Groningen, Netherlands
  http://arena2016.org/

- **Inspiring Science Education Academy 2016**
  10 » 15 july 2016
  Attica, Greece
  http://ise.ea.gr/

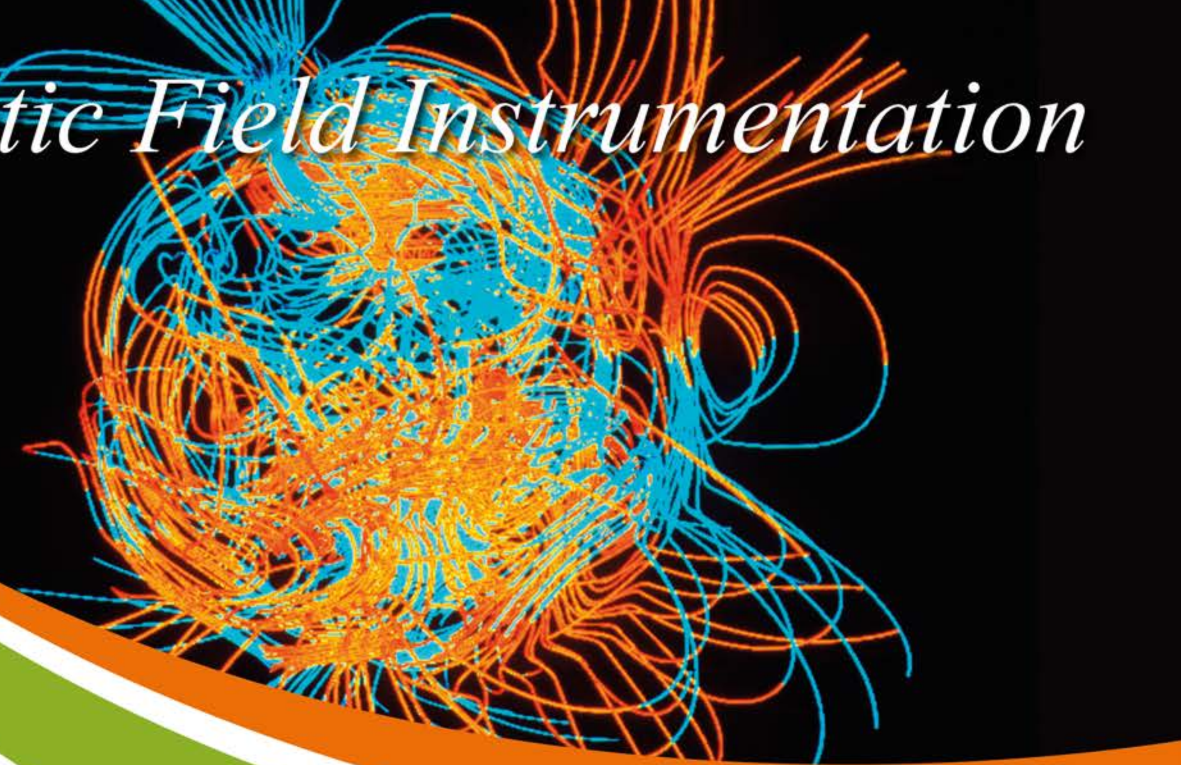
- **MORE ON:**
  www.eps.org



Are you hiring physicists ?
Spread the word in europhysicsnews job / classified section and deliver your message to a targeted audience across Europe!
Jessica EKON
Advertising manager
Tel: 33 (0)1 41 17 74 01
jessica.ekon@edpsciences.org

Astronomy & Astrophysics
A major international journal that publishes results of the worldwide astronomical and astrophysical research
www.aanda.org

Magnetic Field Instrumentation



Helmholtz Coil Systems

- 500mm and 1m diameter coils
- Field generated up to 500μT (at DC) and up to 5kHz (at 100μT) for 500mm coil system
- Power Amplifier and Control Unit available

Mag-01 & Mag-01H
Single Axis Fluxgate Magnetometers

- Measuring ranges up to ±2mT
- Resolution of 0.01μT
- Axial, transverse and cryogenic probes

Mag-13
Three-Axis Fluxgate Magnetometers

- Noise levels down to <4pTrms/√Hz at 1Hz
- Bandwidth to 3kHz
- Measuring ranges from ±60 to ±100μT

Innovation in Magnetic Measuring Instruments

T: +44 (0)1993 706565
F: +44 (0)1993 774813
E: sales@bartington.com

Bartington Instruments Limited
5,10 &11 Thorney Leys Business Park
Witney, Oxford, OX28 4GE, England.

Bartington® Instruments