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Virgo and the quest for gravitational waves
Loop quantum gravity
Physics in daily life: seeing under water
Vibrations in space as an artificial gravity?
The ins and outs of conical refraction

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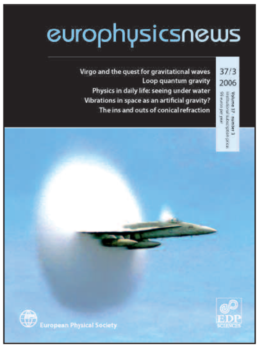

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Cover picture: Shock waves are more spectacular than gravity waves! A Hornet flying at a slightly smaller speed than the sound velocity breaks the sound barrier at some places. Water condensation occurs at these places of maximum pressure variations and takes a conical shape (© US Navy • Ensign John Gay). From "Ce que disent les fluides" p. 120, by E. Guyon, J-P. Hulin and L. Petit (Publisher: Editions Belin, Paris, 2005).

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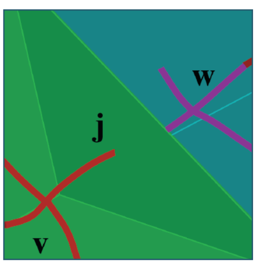
Virgo and the quest for gravitational waves



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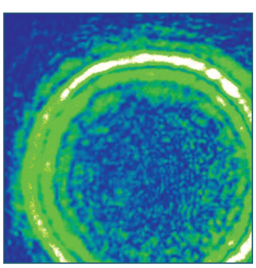
Loop quantum gravity



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editorial

Physics and society: a complex interface

Physics has traditionally enjoyed a strong interplay with society. It is an interaction with traffic both ways. In certain periods physics were given a free card to develop ultimate tools, in other periods society impressed on physics boundary conditions that were not considered constructive by professional physicists.

Today is a period of reflection in this continuing story of the role of science and of physics in modern societies. Research policy has come of age and plays a more and more decisive role both nationally, regionally and internationally. The European Union has set ambitious targets for creating a strong European research infrastructure with the aim of strengthening innovation and economic growth.

Those were topics discussed at a workshop Forum on Physics and Society, arranged by Max Lippitsch, at the University of Graz on 19-22 April, 2006. 50 physicists, representing 30 countries, of which 24 were European and 6 international, met to discuss outstanding issues of interest for the interplay between physics and society. The meeting was the first of its kind, sponsored by EPS and the WYP2005 steering committee as well as being part of the program of the Austrian Presidency of EU.

The last key-note talk of the Forum was given by Walter Kohn. He vividly gave the background and the history of parallel US activities which were started some 40 years ago. Walter Kohn's talk made it clear to all the participants, that the relations between physics and society are of such precious nature, that our first Forum in Graz should not be the last. EPS will further investigate the need for establishing a Forum on Physics and Society.

I had the opportunity to take part in the Forum, which summarised its deliberations in a final resolution with a set of recommendations. This resolution was handed over to the Austrian minister of education during the Forum. The main findings of the Forum were the following.

Forum Graz notes, that
- physics is one of the basic elements in our culture
- physics is a prerequisite for basic job skills
- science and physics are the foundation for the high-technology revolution
- new technologies influence other societal challenges such as the environment, energy supply, communication technologies and production technologies.

Forum Graz furthermore notes the major challenges facing physics
- globalization is putting pressure on the "physics enterprise"
- the linear innovation model has been abandoned
- complex systemic models have been introduced changing the way knowledge is produced, applied and commercialised in social settings.

The OECD shows a falling share of new tertiary graduates choosing physics. The Graz Forum recognizes this problem
- which gives physics a central role in the innovation process and points to
- the importance of strengthening physics as a field of study and the need for a strong scientific physics profession.

→

The Graz Forum notes that these challenges are of a global nature and expresses commitment to address the challenges in Africa and in other regions with similar problems.

The Graz Forum chose to address **five topics** of importance for understanding the role of physics in society
- **society and culture**
- **competitiveness and technology**
- **funding structures**
- **educational themes**
- **ethical issues**

On the role of **Physics in society, culture and the sciences** the Forum noted
- physics represents the rational analysis and accounting of our world
- electricity and electronics are now part of engineering
- medicine, transport, communications, information technology …and even the arts benefit from physics discoveries.

Physics is a proven vehicle for international cooperation:
- the www and the GRID soon to come
- large scale joint facilities as effective collaboration platforms.

Physics education at all levels, particularly for women, needs support:
- Asian countries as role models for a stronger science based culture
- urgent need for more teachers trained in physics
- WYP 2005 an effective benchmark to follow.

A sense of urgency is required due to
- the threats of climate change
- the anticipated global peaking of fossil energy production
- the upcoming shortage of oil and gas.

Graz Forum recommends actions on intensive research and development of clean energy sources, the most prominent candidates being biomass, nuclear, solar and wind power …while finally noting that Physics is an important provider of knowledge and methods of analysis concerning energy and environment.

Physics, competitiveness and technology
Studies show more than 40% of manufacturing employment in the UK is in industries based on physics
- physics (and engineering) based industries grow faster than other manufacturing sectors like the energy sector, medicine and pharmaceuticals, ICT technologies and photonics, supported by emerging technologies like nanotechnology
- physics underpins engineering and its role in wealth creation and plays a major role in present-day life sciences through the provision of techniques and equipment.

Physics possesses power to catalyze radical innovations: www, THz imaging and medical imaging technologies.
Forum Graz further notes, that radical innovations
- are based on unbiased and reliable research
- require international cooperation and open exchange of information.

Conflict of interest with later commercialization of results should be avoided as long as publicly funded research infrastructures themselves are not commercial competitors.

On the importance of **Research policies and funding,** the Graz Forum recommends that governments should accelerate the implementation of the Lisbon 2000 agenda and realize its objectives
- research infrastructure including large-scale facilities should be distributed across Europe in a balanced way and combined with strong "home bases" as an interface for cooperation
- structural funds should be better used for this purpose
- integration of the scientific potential of the new EU member and associate states should be accelerated.

The Graz Forum recommends that the bottom-up funding principle be kept for basic research and strengthened via the creation of the European Research Council [ERC].

The Graz Forum recommends a larger fraction of the EU budget as well as national funding to be spent on mathematical and physical sciences in accordance with tendencies in major regions of the world.

The Graz Forum notes with determination that harmonization of the whole European R&D effort is important however the presently proposed concepts of a European Institute of Technology are not the appropriate solution. The Forum therefore recommends that existing instruments be refined (e.g. technology platforms and ERC) and international cooperation be strengthened with countries outside the EU including also developing countries.

Educational issues played a major role during the discussion at the Forum.
- The Graz Forum endorses the **EPS position paper on Education**, noting that physics educational issues are truly international
- The Graz Forum recommends the support of platforms where pupils, teachers and scientists come together, such as in science centres, science festivals & teacher in-service training
- The Forum endorses boosting of networking of teachers, teacher trainers, physics education researchers and physicists, rethinking the goals of primary and secondary school physics education, which must include physics as a requirement for "scientific literacy".

Forum Graz underlines, that
- these goals are part of the Physics Teachers Education and
- in-service training should be provided to help teachers work
- interdisciplinarity must be boosted without losing the identity of physics as a tool to describe nature.

Ethical issues play a more and more important role, putting pressure on both the individual physicist as well as defining requirements for institutional frames.
Physicists need to
- improve self-regulatory practices
- accept personal responsibility
- transmit values to students
- enter into dialogue with fellow citizens.

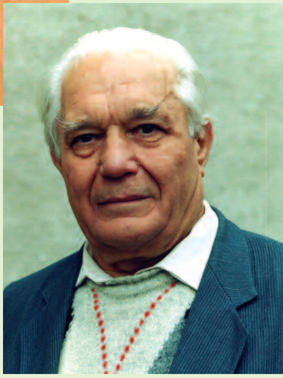
Authorities should refrain from any direct interference with the workings of science (and physics) and only regulate its practices to the extent deemed **absolutely necessary.**

Authorities shall ensure forms of funding to be agreed upon that minimize the risk of jeopardizing the integrity of physics research, professional standards, openness and good practice.

Forum Graz acknowledges ongoing efforts in developing appropriate codes of professional ethics *(a code of conduct).* ■

Ove Poulsen,
President of EPS

▲ Lutz Lilje



▲ Vladimir Teplyakov

Report: 10th workshop on MPTL[1]

[1] Multimedia in Physics Teaching and Learning

This workshop was organized at the FU Berlin from 5-7 Oct. 2005 by Dr. J. Kirstein and Prof. Dr. V. Nordmeier in cooperation with the authors (programme, internet communication). It belongs to a series of workshops (for details [1]), and it was attended by about 60 participants representing about 25 countries. In addition, members of the CoLoS group (Conceptual Learning of Science [2]) joined our meeting. The scientific program offered 9 invited talks (see below), 20 interactive posters (traditional posters in combination with PC and internet connection) and 10 oral presentations.

- **Richard Bacon** (Guildford, Surrey, UK): Use of Multimedia in Physics Teaching in the United Kingdom
- **Ruth Chabay** (Raleigh, NC, USA): VPython: 3D simulation and visualization in the introductory university physics course
- **Vitor Duarte-Teodoro** (Lisbon, PT): Mathematical Modelling with Modellus: linking mathematics and physics
- **Bodo Eckert** (Kaiserslautern, DE): New Initative: Status Report "Use of Multimedia in Europe"
- **Ton Ellermeijer** (Amsterdam, NL): Ten Years of MPTL-Workshops (Past and Future)
- **Hans-Jürgen Korsch** (Kaiserslautern, DE): Use of Multimedia in a Lecture about Nonlinear Dynamics
- **Leopold Mathelitsch** (Graz, AT): Report and Recommendations on Available Multimedia Material for Teaching Heat, Thermodynamics and Statistical Mechanics
- **Dieter Schumacher** (Düsseldorf, DE): E-Learning Tools in Student Labs
- **Frank Schweickert** (Amsterdam, NL): Introduction to MMPhys Wiki (Database for Status Report)

Further Conference highlights were:

- Interactive poster sessions (25% of the full-time)
- Status report about the use of multimedia in physics teaching and learning in Great Britain
- A planned report about MM projects and activities in Europe (MMPhys in website [1])
- Evaluation of multimedia material about Heat, Thermodynamics, Statistical Mechanics. Former reports about equivalent evaluations concerning Mechanics (Graz 2004), Optics (Prague 2003) and Quantum Mechanics (Parma 2002) can be found in the websites of the respective workshops [1]
- Lecturing with multimedia (introductory physics, nonlinear dynamics and quantum mechanics)
- E-learning tools in students labs

The message in all contributions to this workshop was to point out the importance of the use of MM in the teaching and learning of physics; to stress the fact that about several thousand multimedia products do exist worldwide but only very few (< %) are excellent; up to now, emphasis has been laid more on the physical and technical aspects of the material, less on the didactical implementation and evaluation; finally, due to modern communication techniques, interested groups worldwide are simultaneously working together now – not as in the past where we observed a time span of about 5-10 years in pedagogical initiatives between USA and Europe.

The e-proceedings from the 10th workshop in Berlin were available from the end of 2005 ([3]) as well as the e-proceedings of former workshops (Graz, MPTL9 – Prague, MPTL8 – Parma, MPTL7 etc.). Additional information about this series of workshops can be obtained from the web address [1] or by contacting jodl@physik.uni-kl.de, chairman of these workshops.

In 2006 the 11th workshop will be held at the end of September in Szeged, Hungary (contact: M. Benedict – Benedict@physx.u-szeged.hu). It is planned for 2007 to combine the 12th workshop with a summer-school for graduate students in Greece. ■

H.J. Jodl and B. Eckert,
University of Kaiserslautern • Germany

References

[1] http://pen.physik.uni-kl.de/w_jodl/mmeuro.htm

[2] http://www.colos.org

[3] http://pen.physik.uni-kl.de/w_jodl/MPTL/MPTL10

2006 accelerator prizes awarded by the EPS-AG[1]

[1] European Physical Society Accelerator Group

Two of the three EPS-AG prizes were decided at the meeting of the 2006 Prize Selection Committee chaired by Dr. Norbert Angert of GSI on 22 February 2006. These prizes are:

a) An Achievement Prize for outstanding work in the accelerator field with no age limit. The winner will receive an engraved medal and make an oral presentation during the Accelerator Prizes Special Session during EPAC'06.

b) A Prize for an individual in the early part of his or her career, having made a recent significant, original contribution to the accelerator field. The winner will receive a framed certificate, and a cash prize of 2000 Euros, and will also make an oral presentation during the Accelerator Prizes Special Session during EPAC'06.

Prize a) is awarded to **Vladimir Teplyakov** (IHEP, Protvino) "For the invention of Radio Frequency Quadrupole (RFQ) accelerator structure, in collaboration with I.M. Kapchinsky. RFQ revolutionized the technique for accelerating low energy ion beams."

Prize b) is awarded to **Lutz Lilje** (DESY, Hamburg) "In recognition of his major role in the development and testing of high gradient superconducting RF structures, including his original contributions in the development of fast tuning systems."

The third prize, for a student registered for a PhD or diploma in accelerator physics or engineering, or to a trainee accelerator physicist or engineer in the educational phase of their professional career, for the quality of work and promise for the future, will be decided at the beginning of the conference.

The prizes will be awarded and the award winners will make oral presentations of their work during the 10th European Particle Accelerator Conference, EPAC'06, on Thursday 29 June 2006 at the Edinburgh International Conference Centre (EICC), Edinburgh, Scotland. ■

Useful Links:

EPS-AG Home Page:
http://epac.web.cern.ch/EPAC/EPS-AG/
Past Winners EPS-IGA Prizes:
http://epac.web.cern.ch/EPAC/EPS-AG/Accelerator_Prizes/EPS-AG_Prize_Winners.htm
EPAC'06 Conference Home Page:
http://www.epac06.org
JACoW:
http://www.jacow.org

2006-general conference of CMD-EPS in Dresden

Jozef T. Devreese,
Universiteit Antwerpen • Belgium

It is the third time that the General Conference of CMD-EPS was organised in Germany: in 1985 it was held in Berlin, in 1993 in Regensburg.

The first General Conference of the EPS Condensed Matter Division took place in Antwerp in 1980. It was inspired by the desire to intensify the collaboration between the European scientists working in solid state physics. At that time (and also today) many of us met almost annually at the March Meeting of APS and it was felt we needed a similar platform in Europe.

The first conference in our series was a bit of "a shot in the dark". There was at that time no evidence that such a European conference could survive or even was desirable. It was clearly felt as an opportunity in the smaller countries but there was a concern, in the larger countries, that it would suppress some of the successful national meetings.

It came then as a surprise that, already in 1980, two new and outstanding candidates for a second such General Conference of EPS/CMD came forward: Manchester and Lausanne and, after intense consultation, Manchester it was in 1982, Lausanne in 1983. Den Haag followed in 1984. It was then with great satisfaction that the EPS, the CMD board and the Executive Committee, could receive an offer by the Deutsche Physikalische Gesellschaft to host the 1985 General Conference of CMD/EPS.

That offer was generous and far from obvious. Indeed, the Frühjahrstagung of the Deutsche Physikalische Gesellschaft – Arbeitskreis Festkörperphysik, already then, was a very successful meeting, with typically ~3000 or so German participants and already in its 25th year at that time. The General Conference of CMD/EPS had ~700 participants in its first years, 1980 –1984 and had just started.

The fact that physicists in large countries, as well as in smaller ones, continued to take initiatives to organise the General Conference of EPS-CMD has helped decisively to establish a regular series and to realise a dynamic and fruitful equilibrium between its European and its national character.

Today

Today the Condensed Matter General Conference of EPS indeed has become "*a strong conference with a clear international appeal*" a realisation justly stressed by the EPS president, Prof. Dr. Ove Poulsen, in his recent editorial "Physics in Europe" (*Europhysics News*, **37/2** – 2006). Dresden welcomed 4500 participants, 500 from outside Germany.

The General Conference of CMD-EPS has some *dual* characteristics. Next to the complementarities between its European and its national character, it is characterised by the tension between its aim to be *general* and the inherently *specialised* character of most contributions. The realisation of the "*general*" character can be boosted by the clever selection of invited talks, especially plenary and key-note talks, by the selection of attractive themes for symposia and sessions. However, given 14 plenary and prize talks, 248 invited talks, 2008 short talks and 1537 posters, much of the initiative to really make the conference "general" resides with each of the individual participants and how they compose their menu of talks. This makes our General Conference of CMD-EPS a multi-facetted, multi-valued observable and each participant sees a different facet.

▲ Plenary Session with Prize Ceremony, one of the highlights of the 21th General Conference of CMD/EPS in conjunction with the AKF/DPG-2006-Frühjahrstagung. (Courtesy Secretary of the AKF-DPG--CMD-EPS Conference Dr. Anke Kirchner)

Highlights

The Dresden General Conference of CMD-EPS offered a broad choice of themes, often very well presented and with quite a few "eye openers" to recent developments in Condensed Matter and even beyond.

Participants keen to perceive a broad scenery of recent key development in condensed matter physics could learn about the surprises of superfluidity in solid Helium and solid Hydrogen in the very first plenary lecture. This work recently was the subject of discussion in "Nature". On the same Monday they could hear about the *biophysics of cells and about the excitonic zoo in quantum dots*. That left ample time for excursions on "*The Scaling Law of Human Travel*" and "*Circuit QED; Quantum Optics with Superconducting Electrical Circuits*". Or, a participant could choose to join a very stimulating full session on superfluidity. On March 29, we were offered a splendid prize ceremony session with contributions about the development and application of dynamical mean field theory, about magneto-electric correlations in multi-ferroics and about the understanding of STM experiments on transition-metal structures. This ceremonial session was honoured with the presence of the Prime Minister of Saxony, Prof. Dr. Georg Milbradt, who addressed the audience about the development of Saxony today, stressing the pivotal role of science and technology. It was not only an academic session with fascinating and didactic presentations, but also it was a fine social occasion, attended i.a. by the President and the Secretary General of EPS, the Chairman of EPS-CMD and the program chairman, and the representatives of Agilent Technologies. The musical program offered by the "Dresdner Salon-Damen" was a swinging performance.

Input from the Sections

Twelve sections provided input to the program of the Dresden conference with invited talks, keynote talks, contributed papers and posters. Furthermore eight symposia were organised jointly by two or more sections. Large numbers of contributions were received by the "Chemical and Polymer Physics", "Semiconductor Physics", "Magnetism", "Surface Physic" and "Low Temperature Physics" Sections. Semiconductor Physics, the largest with more than 650 abstracts, contained enough material for a relatively large topical conference!

In semiconductor physics a central theme was nanostructures and in particular quantum dots and quantum wires (excitons, spin qubits, phase coherence, STM, entanglement, processing of information,…). "*QED in a Pencil Trace*" and the recent discovery that in grapheme, electron transport is essentially governed by the relativistic Dirac equation, was one of the highlights. Other themes attracting considerable attention were: single photon nanotechnology, quantum cascade lasers, InAlGaN optoelectronics, counting statistics of single electron transport in a quantum dot, photonic metamaterials, atomic scale analysis of magnetic doping atoms and self-assembled II/V semiconductor nanostructures. (By means of cross-sectional STM the authors have studied with atomic scale resolution the size, shape and compositions of self-assembled QDs and quantum rings. They are able to monitor the individual In atoms segregating from the wetting layer into the overgrown GaAs layers.)

In the sessions on magnetism, some of the work that could also attract non-specialists, included: multi-ferroics, magnetic characterisation of individual nanostructures in TEM, low noise magnetic sensors and their applications in biosciences: "Proteins and Patients", the Earths magnetic field during the new satellite era and the instability of the generating process of the geodynamo, the ultimate density limit of magnetic information storage, the spin-hall effect,…

Surface physics captivated our interest e.g. with papers such as "*towards molecular nano-machines*" and "*control of coherent electron motion*".

The Low Temperature Physics section presented four appealing symposia and jointly organised four more, with attractive titles such as: "Solid State meets Quantum Optics", "Molecular Electronics", "Quantum Fluids" and – almost a contradictio in terminis in a session on *low* temperature physics- " Twenty Years High-T_c Cuprates". We could learn about circuit QED, integrated atom optics on a Bose-Einstein-Chip, single-molecule transistors and vortices. In the corridors of the conference hall there were discussions-sometimes animated-a propos several of the topics mentioned above: about superfluidity in solid helium and solid hydrogen, on the status of our understanding of high-T_c superconductivity "after 20 years" or about the relative importance of the discovery of high-T_c versus the invention of STM, AFM. Together with von Klitzing's QHE, Abrikosov's vortices, the work of Ginzburg, Legett, Hänsch… those contributions are outstanding examples of pioneering physics research in Europe.

▲ Prof. Dr. Georg Milbradt, the Minister-president des Freistaates Sachsen, addresses the participants during the Prize Ceremony. (Courtesy Secretary of the AKF-DPG-CMD-EPS Conference Dr. Anke Kirchner)

List of cities where the General Conference of CMD-EPS has been held so far

01 > (1980) **Antwerp** (Belgium),
02 > (1982) **Manchester** (UK),
03 > (1983) **Lausanne** (Switzerland),
04 > (1984) **Den Haag** (The Netherlands),
05 > (1985) **Berlin** (Germany),
06 > (1986) **Stockholm** (Sweden),
07 > (1987) **Pisa** (Italy),
08 > (1988) **Budapest** (Hungary),
09 > (1989) **Nice** (France),
10 > (1990) **Lisbon** (Portugal),
11 > (1991) **Exeter** (UK),
12 > (1992) **Prague** (Czechoslovakia),
13 > (1993) **Regensburg** (Germany),
14 > (1994) **Madrid** (Spain),
15 > (1996) **Baveno-Stresa** (Italy),
16 > (1997) **Leuven** (Belgium),
17 > (1998) **Grenoble** (France),
18 > (2000) **Montreux** (Switzerland),
19 > (2002) **Brighton** (UK),
20 > (2004) **Prague** (Czech Republic),
21 > (2006) **Dresden** (Germany).

▲ The reconstructed Frauenkirche in Dresden, symbol of hope and reconciliation. (Courtesy: Rose-Marie Cuyvers).

The sections "Chemical and Polymer Physics", "Dielectric Materials", "Thin Films", "Dynamics and Statistical Physics", "Metal and Material Physics", "Vacuum Science and Technology", brought similarly exciting presentations. For lack of space I can only present a mini-selection of topics and titles here: "Optical tweezers – novel tools in nanophysics", "Microstructure design for food applications", "Integrated polymer circuits" that presumably will create a new electronics revolution, "Glassy Relaxation", "Quantum Computer-dream and realization", "The Materials Challenge for Hydrogen Storage", …

New Themes

A relatively recent and gratifying development is the entry of biological physics and the "physics of socio-economic systems", as very significant sessions in the General Conference. For many participants those two sections offered a special occasion to extend their horizon outside their own speciality. There were some very attractive lectures in biophysics: " Biophysics of Cells, Active Matter in Motion", on the fascinating, inherently dynamic, nature of living cells, on cell locomotion, on life in soft elastic shells and the importance of the hierarchical design. The session on physics of socio-economic systems offered us insight into novel research areas such as: competition between languages, traffic dynamics, phase transition models of catastrophe insurance claims etc. It is definitely satisfying to see how methods of condensed matter physics are increasingly used in fields such as biosciences and socio-economic problems.

The Dresden General Conference offered an extraordinary interesting program, diversified, up to date, challenging. I must confess that I did not attend a presentation that seemed to be truly earth-shaking, with a new Feynman or another von Klitzing (and maybe I overlooked one), but many contributions were truly outstanding and some were truly innovative.

Format

The format to start with plenary lectures and to begin the many separate sessions only after the plenary talks, remains a very successful trade mark of the CMD-EPS General Conference, much appreciated by the participants. Several said they do like the 15 minutes contributions: " it is exactly the time needed to say something without being boring". For the poster presentations there was maybe not enough space for smooth interaction.

The two years interval between successive CMD-EPS General Conferences is generally accepted as adequate. This partly also solves the timing problem for those who want to attend both the EPS-CMD and the March Meeting of APS.

About the combination of the EPS CMD Meetings with big national conferences, opinions are more divided. Almost all of our previous meetings in the series were organised as "Nth General Conference of the CMD of the EPS". This was even the case in Berlin, 1985. We read in the Foreword to the Proceedings of that conference: "*In 1985 the CMD of EPS had organised its* 5^{th} *General Conference in Berlin. Following the European idea the Deutsche Physikalische Gesellschaft this year, therefore, cancelled the traditional spring conference of the division Solid State Physics*". Regensburg and Dresden offered a format rather of the type "in conjunction" between EPS and DPG. A colleague noted about the Dresden meeting: "*Actually, it was almost not distinguishable from our big DPG Condensed Matter Spring Meetings in the previous years...*". For many EPS-members it remains desirable to organise the CMD-EPS General Conference as often as possible as such, with maximal European character and "EPS" - visibility, as a *sui generis* mirror image of the March Meeting of APS. A meeting "in conjunction" with DPG, given the strength of DPG, obviously has its own intrinsic plus points, both organisationally and scientifically.

The future of the General CMD meetings, no doubt, will also be influenced by the incorporation of new countries in the EU, leading to additional candidates for hosting the meeting.

Dresden

The city of Dresden celebrates its 800^{th} anniversary in 2006. The Frauenkirche was reconstructed and consecrated in November 2005. Its reopening represents "a symbol of hope and reconciliation".

Dresden constituted a revelation for participants on their first visit here. The city offers plenty of architectural and cultural treasures and a great fine art gallery. There is a remarkable science museum "Mathematisch- Physikalisher Salon" (in the Zwinger), with clocks and scientific instruments from the 16^{th} to the 19^{th} centuries. Next there is the lively musical agenda. On Wednesday evening, March 29, we could enjoy an organ concert in the *Kathedrale*, performed on the magnificent, historical *Silbermann-organ* (built around 1755) and restored, in an exemplary way, in 2002.

The atmosphere in Dresden tends to be friendly and hospitable. During the last days of the conference, unfortunately, we saw how the level of the Elbe river was gradually raising, threatening the city with a flood reminiscent of the drama of August 2002. Fortunately, this time it was less severe than in 2002.

Thanks

There was general enthusiasm among the participants for the highly stimulating and well-constructed scientific program and for the fluent and efficient organisation of the General Conference in Dresden. The excellent lecture Halls, the maps of the town, the prepaid tickets for public transportation, the serving of good meals in the conference area, the friendly and efficient practical assistance were highly appreciated, just as were the accompanying social events.

Profs. Rolf Haug and Eoin O'Reilly and their committee, Profs. Ludwig Schultz and Michael Loewenhaupt, Dr. Anke Kirchner and their co-workers and associates deserve our thanks and congratulations. We are very grateful for the hospitality, extended by our colleagues in Germany, to EPS-CMD.

And now we all look forward to Rome-2008, where Prof. Lucia Sorba has accepted to organise the 22^{nd} edition of our CMD-EPS General Conference! ■

Acknowledgement

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Physics in Ireland

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In the past physics in Ireland has been represented in EPS both by the Royal Irish Academy's National Committee for Physics and by the Institute of Physics, which has many members in Ireland. The Institute of Physics in Ireland (IOPI) has taken over the role of representing Irish physics and physicists in the EPS from the Royal Irish Academy with effect from the start of 2006. The IOPI is a branch of the Institute of Physics and has a wide ranging and multi-disciplinary membership of over 1700. It strongly promotes the role of physics in education, health, the environment, technology, and scientific literacy.

The Royal Irish Academy is a body comprising elected members, who have attained distinction in the arts and sciences. Following recent restructuring of the RIA's activities, including a rationalisation of the National Committee system, discussions arose between the Academy and the Institute of Physics and it was agreed that representation of Irish physics would be more naturally served by the Institute of Physics in Ireland as the professional body most representative of the bulk of Irish physicists.

The Institute of Physics in Ireland is managed by a voluntary committee of 16 members and also employs a branch representative, a policy officer and three teacher network co-ordinators. Since its formation in 1964 its activities have both broadened and deepened to include an extensive range of outreach work such as curriculum support, competitions, exhibitions, scientific meetings, cross industry support, careers promotion, public science awareness, preparation of reports and statistics on physics issues and government lobbying. It represents physics both in the Republic of Ireland and in Northern Ireland and has a strong network of support throughout all the third level institutes on the island of Ireland.

Outreach Activities

In common with developed economies world wide, Ireland is experiencing difficulty in attracting young people into science. At present around 14% of students sitting the final secondary school exam, the Leaving Certificate, take physics compared with a figure of 20% in 1990. To address these concerns, the Institute has been particularly active in promoting science at all levels and is working closely with government and other professional bodies to address this.

The IOPI has been to the fore in developing science awareness programmes most notably during the 2005 World Year of Physics (which was also celebrated both as Einstein Year and as the Hamilton bicentenary in Ireland) with dozens of events organised. Activities included competitions, plays, art exhibitions, debates, demonstrations, poetry, radio & television, cartoons, sports and radar, robots, comedy, museum exhibits, astronomy, medical physics, a human equation, computer games and more. In addition, Irish delegates, to the European Science Teaching Festival held at CERN in Geneva in November 2005, won a major award for their outstanding presentation of "Teaching Science as a Process".

Higher Education

Qualifications in physics are currently offered in 14 institutions in Ireland with over 200 students graduating each year with a Bachelors degree in the physical sciences and approximately 400 students engaged in postgraduate research.

Despite the concerns about attracting students into science, the research landscape for science in Ireland has improved dramatically in recent years with the establishment of dedicated funding bodies in the Republic such as Science Foundation Ireland and the Programme for Research in Third Level Institutions. These multi-million euro streams, coupled with European funding such as the Framework Programmes have led to a significant rise in research activity. In the past two years alone, research expenditure in the higher education sector has risen by 44% and the total number of researchers has increased by over 50% between 2002 and 2004. However, a significant challenge arises for research in fundamental physics as the emphasis of government funding has been in just two areas, biotechnology and ICT. Indeed the number of researchers in the physical sciences is less than half that in the biological sciences.

The position of research in physics is one of the key concerns of the Institute and on joining EPS the Irish branch hopes to draw on the experience and knowledge of the other European countries to address this. ■

Letters

Editor's note

We would like to develop this Section and call for your comments on the content of EPN. Here we publish a contribution about rainbows after an article in the 37/1 issue and a statement on publications after the editorial in the 37/2 issue. Comments on the Position Paper on Education (EPN 37/1) are presently too few to justify publication.

Medieval arab understanding of the rainbow formation

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Owen Davies, Jeff Wannell and John Inglesfield should be congratulated for their illuminating article on the Rainbow (*Europhysics News*, **37/1** 2006). The authors begin with the work of Descartes in 1637, as is customary. It would be relevant to go back further in time and add a complete section, *Medieval Islamic Achievement in Optics*, to the above article that is otherwise complete in detail. This section would describe the Arab achievements in optics including the detailed understanding of the phenomenon of *refraction of light and the formation of rainbows*; both the topics were well understood by the Arabs.

Between the middle of the eighth and the thirteenth century intellectual activity in the Arab world went through two stages in tandem: translations followed by original contributions. Both stages enjoyed an official patronage. Ancient science and philosophy preserved in the Sanskrit, Pahlavi, Syriac and Greek languages would have been lost for ever had the scholars centred around Baghdad during the 8-12th centuries not translated them into Arabic. These works were later translated from Arabic to European languages (see [2] for a comprehensive account of the translations into Arabic and then into the European languages). The contributions of the Arab world to science during the above centuries are to be understood against this background.

The phenomenon of reflection of light was understood by the Greeks prior to Archimedes who had tried to set fire to the Roman fleet approaching Alexandria using reflection of light. Among the vast literature translated into Arabic were Ptolemy's *Optics* and the *Conic Sections* of Apollonius. Applications of parabolic mirrors as burning instruments, first described by Anthemius of Tralles, were also known to the Arabs in Iraq. Abu Sad Al Alaa Ibn Sahl had translated Greek books on optics including Ptolemy's Optics. Ibn Sahl in 984 wrote his book, *On The Burning Instruments*. Ibn Sahl's book is both experimental (he provides the mechanical means to draw the conic sections) and theoretical. In this book he describes the law of refraction with a diagram [4-5].

In his book Ibn Sahl analyzed burning mirrors, both parabolic and ellipsoidal; he considered hyperbolic plano-convex lenses and hyperbolic biconvex lenses. He succeeded in stating the law of refraction of light (commonly known as the Snell's law after the Dutch scientist, Willebrord Snellius, 1580-1626) long before Snellius himself [3-5].

Ibn Sahl was well known among his colleagues and students. Abu Ali al-Hasan ibn al-Haytham, 965-1039, known as Alhacen/Alhazen (the Latin transliteration of his first name al-Hasan), wrote several books on optics acknowledging his mentor Ibn Sahl [4-6]. Ibn al-Haytham started his career in Basra, Iraq that then was the chief centre of translations and scientific activities. Later he emigrated to Egypt, made experimental contributions of the highest order in optics and *enunciated that a ray of light, in passing through a medium, takes the path which is the easier and* ***quicker***. In this he was anticipating the Fermat's Principle of Least Time by many centuries [7-8]. He authored fourteen books on optics alone. His magnum opus *Kitabl al-Manazir (Book of Optics)* earned him the title of Father of Optics. In this book he also examines the *double refraction* in a sphere and related problems. Three centuries after Ibn Haytham, the Persian physicist Kamal al-Din al-Farisi (1267-1319) wrote an important commentary on Ibn Haytham's Book of Optics, in which he set out to explain many natural phenomena. For example, by modeling a water drop using Ibn Haytham's study of double refraction in a sphere, he gave the first correct explanation of the rainbow. Al-Farisi also proposed the wave-nature of light [9]. By contrast, Ibn Haytham had modeled light using solid balls in his experiments on reflection and refraction. Thus the question was proposed: Is light wave-like or particle-like? Ibn Haytham's book was translated into Latin in 1270 as *Opticae Thesaurus Alhazen*, and many prominent European scientists including Roger Bacon (1214-1292), Leonardo da Vinci (1452-1519), Johannes Kepler (1571-1630), René Descartes (1596-1650), Isaac Newton (1643-1727), and many others benefitted from his theories in optics and other fields [6]. ■

References

[1] D.C. Lindleberg, Medieval Islamic Achievement in Optics, *Optics & Photonics News*, **14**(7) 30-35 (July 2003); A. Lakhtakia, Optics in Medieval Islam, *Letter in Optics & Photonics News*, **14**(9) 6 (September 2003)

[2] Z. Virk, Europe's Debt to the Islamic World, *Review of Religions*, **98**(07) 36-52 (July 2003).

[3] K.B Wolf and G. Krotzsch, Geometry and dynamics in refracting systems, *European Journal of Physics*, **16**(1) 14-20 (January 1995).

[4] K.B. Wolf, *Geometric Optics on Phase Space*, p. 8-9 and p. 57-58 (Springer 2004)

[5] R.Rashed, A. Pioneer in Anaclastics: Ibn Sahl on Burning Mirrors and Lenses, *ISIS*, **81** 464-491 (1990).

[6] R. Rashed, A Polymath in the 10th Century, *Science*, **297**, 773 (2 August 2002).

[7] A. Salam, *in Ideals and Realities*, third edition, p. 283 Editors: C.H. Lai and A. Kidwai, (World Scientific, Singapore, 1989).

[8] A.Salam, *In Renaissance of Sciences in Islamic Countries*, p. 31, Editors: H.R. Dalafi and M.H.A. Hassan (World Scientific, Singapore, 1994).

[9] M. Salih, M. Al-Amri and M. El-Gomati, The Miracle of Light, *A World of Science*, **Vol. 3** (4) 2-7 (October-December 2005). *Natural Science Quarterly Newsletter, UNESCO;* Publication No. **385** (February 2006), (Foundation for Science Technology and Civilization, www.fstc.co.uk/).

Overview on publications in physics

The Publication Committee of the French Physical Society
(X. Bouju, D. Jérome, J.F. Joanny, M. Leduc, J. Lequeux, J.M. Raimond and B. Van-Tigellen)

We are facing a situation where the European Union (25 countries) produces the largest number of scientific articles in physics (33.7% of the world production against 19.7% for the USA in 2003 [1]) whilst at the same time European publishers represent only a small fraction (27%) of the world market (this figure applies to the publications of letters, namely short articles presenting novel and important results).

A steadily increasing fraction of some of the 90.000 articles published every year appear in journals based in North America and more particularly those run by the APS [2] and AIP [3]. Such a situation enhances the attractiveness of American reviews to the detriment of all others and is likely to lead eventually to a practical monopoly. What a successful scientific activity needs is a variety of editorial approaches, a close interplay between journals and the scientific communities and finally an evaluation which takes into account the diversity of the evaluation committees.

What are the reasons for such a drift?

The first reason is that publications fulfil the legitimate need of authors for recognition and hence cannot be bypassed in the evaluation of researchers, research teams and institutions. This evaluation however is too often based on the prestige (characterized by the *impact factor* [4]) of the journal in which an article is published (a trademark policy) thus leading to a biased judgement. Let us take as an example the prestigious journal *Nature*: its impact factor of 32 in 2005 is based on papers which belong to all fields in Science but is largely dominated by the Life sciences [5]. This is attested by the fact that a physics paper published in this same review would not generally receive a larger number of citations than it would in any other good physics journal [6]. It is therefore clear that such an evaluation based on the impact factor is not reliable.

A second reason is that the world of European publications is made up of small units which each on its own cannot compete with a publication platform such as that the American Physical Society (APS) can offer. This platform is remarkable in several respects: its technical quality, its large thematic coverage and the on-line availability of all archives dating back to the early days of the jornals. All these reasons make the APS platform more and more attractive to European researchers and leads to an ever-increasing polarization.

What measures could be taken to reverse this tendency and guarantee a diversity which is a prerequisite for the quality of scientific production?

The first step is to persuade evaluation committees to modify their present criteria. Instead of the impact factor of a journal in which a given paper is published , the evaluation should rest on the real impact of the paper itself i.e. the number of citations it has received, properly weighted by the size of each scientific community, their particular practices and the trends of the moment [7]. Furthermore, one should go back to peer reviewing, with an evaluation to be conducted on the basis of only a limited number of articles chosen by the candidate. Furthermore, members of evaluation committees must be given free access to bibliographical data bases, as well as enough time to achieve an exhaustive examination. These improved criteria should also apply to committees dealing with the recruitment and the promotion of researchers as well as to national and international agencies which support research such as the National Science Foundation in the USA, the Agence Nationale pour la Recherche (ANR) in France and the Directorate for Research in the EU.

A second important step would be to make European publications much more visible, particularly outside Europe, resulting in an increased impact and attractiveness. A pivotal instrument would be the creation of a *Web portal providing access to all scientific information in physics*. Such a portal exists already in Astrophysics: the Astrophysics Data Sytem (ADS). The main objective of such a portal would be to create a worldwide data base including a powerful search engine able to gather all information on major publication centres, including the APS of course. This data base will not cover the entire content of these journals but will only point to this content. Publishing houses and learned societies will continue to manage the rights of access to the contents. The setting up of this new system will therefore be in no way detrimental to the publishers but will ensure an equal and increased visibility to the journals, thus eliminating the bias we have pointed to. The European Community could play an important moral and financial role in the creation of this portal.

The final and decisive step would be the creation of a unified publication platform in Europe, able to compete with that offered by the APS, both in size, technical quality and richness of the archives. This platform should include letters, topical archival journals, a journal for review papers and could include also a scientific magazine activity (inheriting, for instance, from Europhysics News). It should obviously bring together the contents of the major generalist European physics journals, as well as their archives.

Such a major platform should be under the scientific guidance of the scientific societies, and, in the first place, of the EPS. It should also be supported by professional or institutional publishers, whose expertise is essential for the success of the platform. This project does not imply, of course, a merger of these structures, but rather a tight cooperation between them for the sake of a common interest.

The creation of this unified publication platform is a major endeavour and will imply difficult negotiations. A strong political impetus from the learned societies is essential to start the process. We think that the time has come for a meeting of representatives of all learned societies participating in the European publication landscape, under the auspices of the EPS. This assembly could discuss and hopefully agree on the necessity of a unified publication system. A strong consensus along the lines developed here would be of considerable importance for the realization of this project. It is only the united European scientific community which could trigger such a major evolution of the European publication system. ■

References

[1] These statistics are provided by the Key Figures on Science and Technology, Observatoire des Sciences et des Techniques, Editions Economica, Paris 2006

[2] American Physical Society (www.aps.org)

[3] American Institute of Physics (www.aip.org)

[4] The impact factor is provided every year by the ISI-Thomson data base (http://scientific. thomson.com). It is given for the year N by the number of citations to a given journal over years N-1 and N-2 normalized by the total number of articles published in the journal over the same period.

[5] 10% of the articles in this review contribute to 90% of the impact factor.

[6] The impact factor of Physical Review Letters, the flagship journal of APS, and that of Europhysics Letters (European Physical Society) are respectively 7.2 and 2.12 for 2004.

[7] This number is obtainable from the ISI data base.

Highlights from european journals

A quantum dot triggers entangled photons

The generation of entangled photon pairs is a fundamental cornerstone of quantum optics, and an essential technology in the high profile field of quantum communication and computing. Currently the most widely used techniques for generating entangled photon pairs are nonlinear optical processes, such as parametric down conversion, which produce a probabilistic number of pairs per excitation cycle. Such a source is of limited use in quantum information/processing applications where a regular stream of single entangled photon pairs is usually required. We have produced such a triggered source from a semiconductor device for the first time [Stevenson *et al.*, *Nature*, **439** (2006) 179], using a two-photon cascade in single quantum dots, demonstrating efficiencies up to 70% [present article], tantalisingly close to the level required for useful applications. Single quantum dots could prove to be the first robust and compact triggered source of entangled photons.

Prior to this work experiments indicated that a splitting of the intermediate exciton energy caused the biexciton (states consisting of two bound electron–hole pairs) cascade in single quantum dots to produce only classically correlated emission. We control the splitting of exciton level either through a selective growth technique or by applying an in-plane magnetic field. By restoring the degeneracy of the exciton level we are able to engineer a source of entangled photons. The efficiency of entangled photon generation in this system is mainly limited by background light collection, due to layers other than the quantum dot emitting at the same energy. A sample redesign involving growth at a slight higher temperature was used to increase the efficiency found in conventional samples from 25% [1] on average to ~70% [present article]; optimisation should allow for further improvements. The proportion of entangled photons being produced by our device at present is approaching that required for useful applications. We believe this marks a major milestone in the development towards an entangled photon LED. ■

R.J. Young, R.M. Stevenson, P. Atkinson, K. Cooper, D.A. Ritchie and A.J. Shields,
"Improved fidelity of triggered entangled photons from single quantum dots",
New J. Phys. **8** (2006) 29.

Local polarisation in an ultra-thin ferroelectric

Because they exhibit a variety of interesting physical properties including piezoelectricity, pyroelectricity and a non-volatile switchable electric polarization, "nanoscale" ferroelectrics have recently attracted considerable attention. Up to the present, all the techniques that were used to study ferroelectrics of this kind have probed an average (across the depth of the films) response of the material. In order to obtain more detailed microscopic information on ferroelectricity and to be able to directly probe the ferroelectric polar distortion, an atomic-scale sensitive technique, such as X-ray photoelectron diffraction, needs to be employed.

For their investigation of epitaxial c-axis oriented PbTiO3 films, the authors of this paper combined atomic force microscopy and X-ray photo-electron diffraction. In order to analyze the data and to distinguish between up and down polarization, indicated by the local distortion of the crystallographic unit cells, the authors compare the experimental with calculated XPD patterns. It turns out that the calculations need to take into account multiple scattering in order accurately to simulate XPD diffraction patterns. In this way, a clear distinction between the up and the down state of the polarization of the film could be made and thus the goal, to establish the basic principles for a local probing of ultrathin ferroelectric films, was achieved. ■

L. Despont, C. Lichtensteiger, F. Clerc, M.G. Garnier, F.J. Garcia de Abajo, M.A. Van Hove, J.M. Triscone and P. Aebi,
"X-ray photoelectron diffraction study of ultrathin PbTiO3 films", *Eur. Phys. J. B* **49** (2006) 141.

"Classical tunnelling"

"Tunnelling" in physics is a term used to express some kind of unusual transport – in quantum mechanics (from where the name derives) it represents the penetration of e.g. electrons through a barrier, which energetically they cannot surmount. In crystals, normally, the lattice particles are unable to move, because they are located in potential wells much deeper than their thermal energy. However, it is possible to "dope" crystals by placing new and different atoms in interstitial sites. Here the energy well, which confines the new particles, is much shallower and therefore diffusion of such atoms throughout the crystal is feasible – thus allowing the production of materials of new electro-optical-mechanical properties. To observe this process at the individual (kinetic) particle level is not possible with current technology.

However, analogous measurements can be obtained from the investigation of such particle transport in (macroscopic) plasma crystals – where the crystal lattice is formed by charged microparticles embedded in a practically mass-less electron-ion plasma. Instead of the expected diffusive-like penetration of a given particle population through such a crystal, it was found that the system may choose at least two other paths: one appears to be a non-equilibrium phase transition, where one type of particle forms long chains (of 10's or 20's) which then pass through the other particle cloud like a "hot knife through butter"; the other involves single particles passing along lattice planes without any apparent scattering or momentum loss.

The first process has been predicted theoretically for colloidal solutions [Dzubielle et *al.*, *Phys. Rev. E*, **65** (2002) 021402], however, there the background (fluid) is not negligible in terms of mass, momentum etc. The second process is believed to be due to the non-Hamiltonian properties of "complex (or colloidal) plasmas" – the variability in the binary interaction potential with particle number density due to a process called "charge cannibalism". This is a physical process investigated in the context of complex plasma studies quite some time ago [Morfill, *Adv. Space Res.* **3** (1983) 87; Havnes et *al.*, *J.G.R.* **92** (1987) 2281, *et al.*] but the recently discovered manifestation of "classical tunnelling" had not been anticipated. In the broader context, it can be concluded that unusual transport effects (such as "classical tunnelling") could occur in many other non-Hamiltonian systems, in particular in strongly coupled systems. They may play a role in non-Newtonian liquids, visco-elastic fluids, radioactive and radiative clouds, rain clouds etc. – in short, wherever the interactions may depend on e.g. particle number densities. Hence the observations reported here for complex plasmas would appear to have a generic significance – and they are unique in the sense that controlled precision measurements are possible at the most elementary (kinetic) level. ■

G.E. Morfill, U. Konopka, M. Kretschmer, M. Rubin-Zuzic, H.M. Thomas, S.K. Zhdanov and V. Tsytovich,
"The 'classical tunnelling effect'—observations and theory", *New J. Phys.* **8** (2006) 7.

Complementary media of electrons

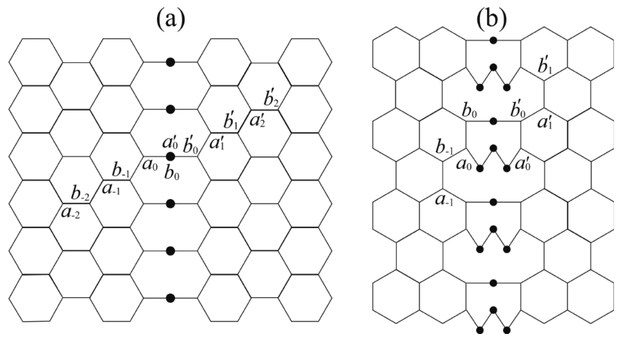
Pendry and Ramakrishna introduced the concept of a complementary medium - a material with permittivity $\varepsilon_c = -\varepsilon$ and permeability $\mu_c = -\mu$, where ε and μ are the permittivity and permeability of the original medium - which reproduces the information of amplitude and phase of electromagnetic waves in the original medium. This is the origin of negative refraction and perfect lenses.

Katsuyoshi Kobayashi of Ochanomizu University, Japan, has extended the formulation of complementary media to electron waves. He defines the complementary medium as having a transfer matrix which is the inverse of that of the original medium.

He describes an application to subsurface imaging in scanning tunneling microscopy. He simulates the impurity images for a simple subsurface impurity and an impurity hindered from imaging by an obstacle and shows that the resolution can be improved using complementary media.

He extends the formulation of complementary media to include interface scattering. Because the electron wavelength is of the order of atomic distances, the atomic structure of the interface is important. The extended formulation makes it possible to form effectively complementary systems only by tuning transmission properties at interfaces.

He designs interface structures forming complementary systems for the graphite lattice. They either interchange the A and B sublattices of the graphitic lattice while keeping the waves at points K and K0 in the Brillouin zone or vice versa. He proves the complementarity of these interfaces at the Fermi energy using a tight-binding model. The interface states have no dispersion at the Fermi energy over the entire Brillouin zone, a condition necessary for forming complementary systems. He simulates the images of an impurity in the graphitic lattice with and without a complementary region formed with double interfaces, and verifies that the interfaces work well as complementary structures even when the complementary conditions are not strictly satisfied.



▲ Interface structures forming complementary systems of the graphitic lattice. Closed circles show sites with only two π bonds.

Practical realization of complementary media for electrons is a difficult problem to be solved in future, but Kobayashi has shown that it is theoretically possible. ■

K. Kobayashi, "Complementary media of electrons", *J. Phys. Condensed Matter* **18** (2006) 3703

Compactivity in granular assemblies

Granular matter, like sand and other powders, is ubiquitous in everyday life and in industry, but it is only recently that the physics of this familiar state of matter has been put on a sound footing. One theoretical milestone occurred in 1989, when Edwards and Oakeshott proposed a way of defining a set of simply related, thermodynamic-like quantities for granular matter. At the time, this proposal seemed to many to be too simple to be true, but now a careful set of computer simulations has verified a central assumption of the theory.

At the heart of the Edwards theory was the assumption that as the dense packing of a granular material is very slowly driven, possibly by shear, it goes through a series of microscopic, mechanically stable states that are equally probable. This assumption leads to an analogy with the microcanonical ensemble of classical statistical mechanics, allowing one to define thermodynamic-like quantities for granular material. The most central of these quantities, the compactivity, plays a role similar to that of temperature in conventional thermodynamics.

This work studies the behaviour of the compactivity in the context of the fluctuation-dissipation relation (FDR) defined by the Stokes-Einstein relation. By looking at the relation of the FDR with shear rate and volume fraction, as well as the type of particle in the packing and the observable, it is possible to confirm that the compactivity is indeed an intrinsic property of the packing. Furthermore, it is found that the range of parameters that is important, i.e., where it is independent of shear rate, corresponds to the development of a yield stress in the packing. This is a step forward in developing a simple, universal framework for understanding the behaviour of this familiar, yet ill-understood, state of matter. ■

F.Q. Potiguar and H.A. Makse, "Effective temperature and jamming transition in dense, gently sheared granular assemblies", *Eur. Phys. J. E* **19** (2006) 171.

High electric fields probed in insulators

Electricity is a source of energy, which conditions our everyday lives. In the perfect situation, conducting materials allow the flow of electric charges whereas insulating materials prevent it. However in practice, charges can move and even build-up, in insulating materials under high electric fields. The consequence is local intensification of the electric field, which can irreversibly damage the material and then the system in which it is included. For this reason, measurement of the internal distribution of space charge is critical for the study and improvement of electrical insulators.

Three direct measurement methods are currently used, the thermal method, the pressure-wave propagation method, and the pulsed-electro-acoustic method. In the first two methods, a mechanical deformation of the material is induced either by the diffusion of heat or the propagation of an elastic wave. This generates an electrical current directly related to the distribution of charges. In the last method, a rapid electrical stress applied to the material makes any internal charges move, which generate elastic waves, subsequently measured by a transducer.

In many industrial situations, small filler particles are added to the host material to tune mechanical, thermal or electrical properties, or to reduce cost. This increases the difficulty of measurement interpretation because the filler particles may generate their own signals or modify those produced by the charges. In this work the authors investigate how such particles can perturb the measured signals, and show how important electrical information can be extracted from an apparently noisy signal. In the case of silica fillers in an epoxy matrix, the authors have been able to show that charges are trapped at the silica/epoxy interfaces, even though the signal is disturbed by the piezoelectric effect of the particles. ■

S. Holé, A. Sylvestre, O. Gallot Lavallée, C. Guillermin, P. Rain and S. Rowe, "Space charge distribution measurement methods and particle loaded insulating materials", *J. Phys. D: Appl. Phys.* **39** (2006) 950.

features

Virgo and the quest for gravitational waves

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In the past ten years, several giant interferometers have been built around the world with the goal of a first direct detection of gravitational waves. The most sensitive detectors, 2 interferometers for the US LIGO collaboration and the detector built by the Italo-French collaboration Virgo (fig. 1) are approaching their design sensitivity. Scientific exploitation of these instruments is now starting …

What is a Gravitational Wave?

Basically, Gravitational Waves (GW) are ripples of space-time, which propagate at the speed of light. They are predicted by general relativity and other, alternative, modern theories of gravitation, as an effect of accelerated motions of matter. This is somewhat similar to electromagnetic waves, produced by the motion of accelerated charges. A difference is that GW production requires non symmetrical distributions of matter. Thus a star collapsing with perfect spherical symmetry emits no GW. Another difference is that at the lowest order GW are quadrupolar waves while electromagnetic waves are dipolar.

An observable indication of the passage of these ripples of space-time is a modification of the measures of distance. More precisely, consider a circle of test masses at rest (Fig. 2). As a GW with normal incidence passes through the circle distances in one direction seem to expand while in a perpendicular one they seem to shrink, owing to the quadrupolar nature of GW. This *relative* distance modification is used in the definition of the GW *dimensionless* amplitude: $h(t) \approx \frac{1}{2}\frac{\delta L}{L}$ where L is the distance measured in the absence of GW (the ordinary flat space-time). The problem is that h is in general so weak that detecting a GW seems hopeless.

Astrophysical sources

In fact, only sources involving relativistic (compact) stars such as black holes or neutron stars may emit GW that can be detectable on Earth. The most promising sources are thought to be binary systems of inspiralling neutron stars or black holes. In such a system emitted GW carry away part of the orbital energy. This loss entails a decrease of the orbital radius: with time the two stars become closer and closer and as they get closer the GW emission becomes more and more intense. The resulting GW signal $h(t)$ is called a *chirp*, a sinusoid with increasing amplitude and frequency that ends when the two objects merge. Collapses of massive stars into neutron stars or black holes (gravitational supernovae) are also sources of GW that must be considered. Here typical GW signals (though very difficult to model) are bursts with estimated typical duration of the order of a few milliseconds. Finally let's mention other kinds of sources, such as isolated rotating neutron stars or pulsars that can emit weak continuous signals if the star is not perfectly symmetric or cosmological backgrounds.

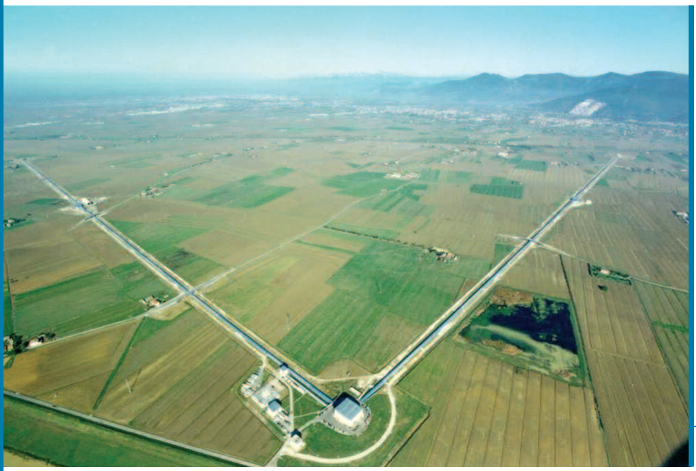
A survey of potential GW sources, orders of magnitude for amplitudes and rates, leads to a simple conclusion. A ground detector of GW must be designed to be sensitive to GW amplitudes of typically $h \sim 10^{-21}$ or less, in a bandwidth from 10 Hz up to a few thousands Hz to be able to observe these waves one day. This is the goal of the first generation GW interferometers that are in (or are entering into) operation today.

The interferometric detection of Gravitational Waves

The hunt for Gravitational Waves is not a recent story. It began at the end of the 50's under the impulse of the American physicist Joe Weber. The GW detector he invented was a cylindrical bar about 1.5 meters long equipped with piezo-electric transducers to record the vibrations of the bar, to be excited by the passing GW. This setup spawned several modern descendants: aluminium bars (and more recently spheres) cooled below 1 K. The main limitation of this kind of detector is its very narrow bandwidth (typically a few Hz). Detectors based on optical interferometry are not limited in this way.

Interferometric detection relies on the Michelson interferometer scheme (see fig. 3). The output port power is given by $P_{mich} = \frac{P_0}{2}\left[1+C\cos\left(2\frac{\omega_0}{c}\Delta l_{arms}\right)\right]$ with P_0 the input laser power, ω_0 the laser angular frequency, Δl_{arms} the optical path difference between the arms and C the interference contrast, as set by the parameters of the optical cavity. The interferometer must be tuned in order to optimize the sensitivity to a gravitational wave, that is to say to small variations in Δl_{arms}. The main fundamental noise limiting the sensitivity is shot noise. It imposes the dark fringe, where P_{mich} is minimized, as the best configuration. In order to improve sensitivity, we can lower the shot noise. Only two parameters are effective: the optical length of the interferometer arms and the power circulating in the interferometer. This is why interferometric detectors have kilometric arms (3 km in the case of Virgo). An optical path of about 100 km can then be obtained by placing a Fabry-Perot cavity in the arms. Concerning the light power, as continuous laser sources provide limited power, the trick consists in the addition of an extra mirror at the input of the interferometer. This mirror and the rest of the interferometer create a new cavity (*power-recycling cavity*) where the stored light power is enhanced at resonance (See fig. 3 for the final optical design of a Virgo-like detector).

A shot-noise limited spectral sensitivity of the order of $10^{-23}\,\mathrm{Hz}^{-1/2}$ can be achieved using the complete setup with Virgo dimensions: 3 km Fabry-Perot arm cavities with a finesse of 50, a 10 W input laser beam and a recycling power gain of the order of 50. Of course other noises are likely to limit the sensitivity in diverse spectral zones.



◀ **Fig. 1:** Aerial view of the virgo detector, near Pisa (Italy).

Fundamental, environmental and technological noises

The first obvious obstacle to low frequency measurements in a Michelson interferometer is seismic noise. Measurements of displacement spectral densities in quiet sites typically give $\tilde{x}(f) \approx 10^{-6} / f^2$ meters / $\sqrt{\text{Hz}}$.

The mirrors must therefore be isolated from ground motions. This can be achieved by suspending them. Basically the suspended mirrors then behave like harmonic pendulums with a natural angular frequency of oscillation $\omega_0 = \sqrt{g/l}$, where g is the gravitational acceleration and l the pendulum length. While ground motion is amplified at the natural frequency, it is by contrast damped by $\omega_0{}^2 / \omega^2$ at higher frequencies. In Virgo the mirrors are suspended in a multiple-stages pendulum (fig. 4) with a fundamental resonance below 1 Hz and a resulting seismic attenuation factor of the order of 10^{10} at 10 Hz.

Thermal noise is another annoying source of noise. Indeed mirrors and their suspensions all are mechanical resonators, whose degrees of freedom are excited at ambient temperature. The alternative to cooling the whole instrument is to select high quality-factor materials, in particular for the mirror substrates and suspension wires, in order to limit the spectral spread of the noise. Besides, sources of mechanical losses must be hunted.

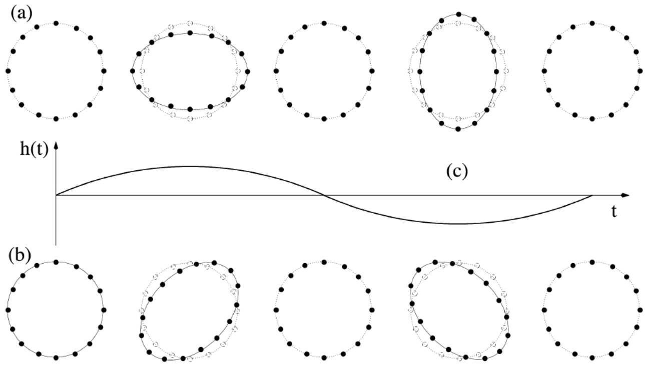
Laser noises must be also controlled. In particular fluctuations in laser frequency or power can couple to interferometer length asymmetries to give dangerous phase noises than can compete with the shot noise. The laser is therefore actively servoed on a length reference, provided by an Ultra Low Expansion (ULE) cavity, and therefore frequency-stabilised. Before entering the interferometer itself, the laser beam passes through another Fabry-Perot cavity, named the Mode-Cleaner. A cavity is indeed an optical resonator so it filters off-resonance beam fluctuations (more precisely it is a low-pass filter). This helps to attenuate the laser fluctuations, including beam jitters.

Ultra high vacuum is of course required in order to avoid spurious signals due to residual gas index fluctuations in the interferometer arms. The vacuum level specification corresponds to a residual pressure below10^{-7} mbar. The interferometer must be entirely under vacuum. Hence the mirrors and their suspensions are located in towers and the kilometric arms are in the material form of tubes (120 cm diameter in Virgo).
The inner parts of the tubes and towers are equipped with *baffles,* whose function is to remove the light scattered by mirrors in off-axis directions. Mirrors always have some residual rugosity, in spite of their very good quality. This rugosity causes a small part of the beam photons to travel off-axis and eventually reflect on the infrastructure (tubes, towers) which is not isolated from seismic noise. These photons then get random phases and the recombination of some of them with the main beam produces an extra phase noise which would be at the level of the shot noise if nothing were done!

The design sensitivity curve of Virgo is shown in figure 5. All technological noises are supposedly under control. The sensitivity is then limited at low frequency by the seismic wall (seismic noise below 4 Hz, not filtered by the *super attenuator*), at intermediary frequencies by the thermal noise (the high frequency tail of the pendulum thermal noise, the low-frequency tail of the mirrors' thermal noise plus the many resonances due to the suspension wires) and in the high frequency region by the shot noise.

Where are we?

The construction of Virgo was achieved in fall 2003. Since then the detector has been in the *commissioning phase.* Virgo is a very complex instrument and reaching the design sensitivity takes time. One of the main tasks is the control of the interferometer itself.



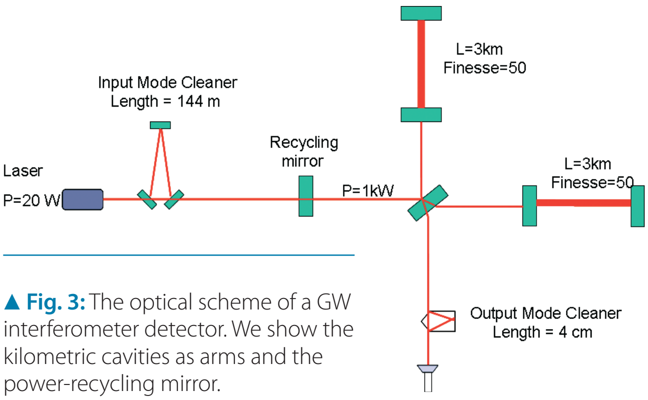
▲ **Fig. 2:** Effect of a GW passing through a circle of test masses. The wave incidence is normal to the mass plane. (a) the effect of a "+" polarised wave. (b) the effect of a "x" polarised wave. The amplitude of the GW *h(t)* is shown as a function of time *t*.

When free, suspended mirrors oscillate continuously at the pendulum resonance frequency. The working point of the detector is obtained when arm cavities are locked at resonance for the laser beam, the Michelson interferometer tuned at a dark fringe and the recycling cavity also resonant for the laser beam. This gives four optical lengths to be controlled, plus the mirror rotation degrees of freedom. We see that Virgo needs an active servo-system to control lengths and angular tilts of mirrors as far as 3 km apart, on a time scale of a fraction of second.

The commissioning has been carried out step by step, locking first the one-arm cavities, then the two arms plus the Michelson interferometer and finally the complete configuration. The automatic alignment (angular control) has been built and tested in parallel.

To date the Virgo sensitivity is roughly one order of magnitude above the design curve. Meanwhile the two 4 km detectors of the US LIGO collaboration have reached more or less their design sensitivity above 100 Hz (commissioning started earlier for LIGO).

Since the data produced by these instruments are mostly composed of noise, with hopefully someday an astrophysical signal, the first challenge for analysis is to distinguish signal from noise. Otherwise, we would be swamped by false GW detections, to be identified as such by eye. Most of the efforts so far have focussed on inspiral and burst scenarios, though all avenues are explored. Many types of algorithms have been tested, some looking for specific waveforms that general relativity may provide, others aiming at generic signal signatures. As short duration signals are easily mimicked by the instrument, successful analysis is strongly coupled to an understanding of the behaviour of the instrument.



▲ **Fig. 3:** The optical scheme of a GW interferometer detector. We show the kilometric cavities as arms and the power-recycling mirror.

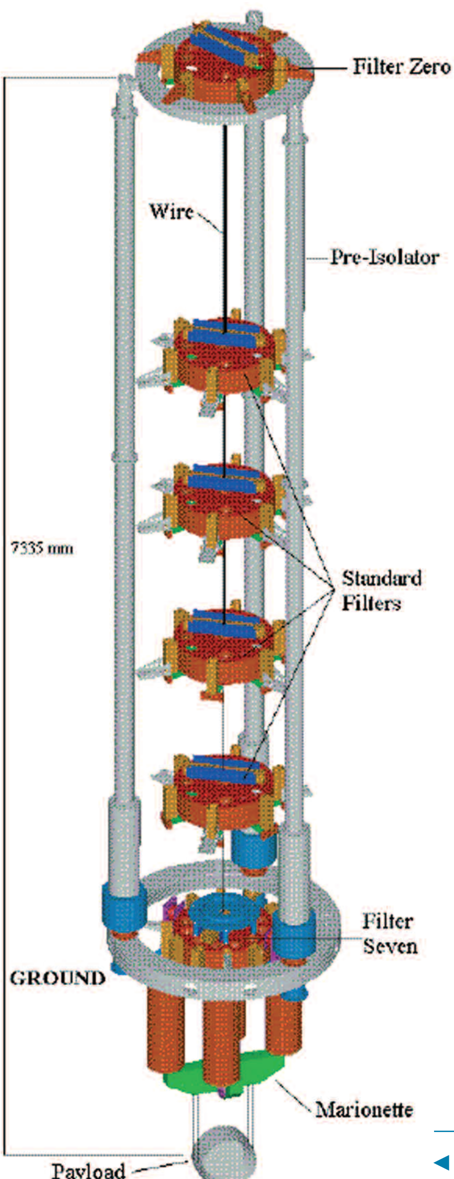
The future

The question is not if we will detect GW but rather when! Evidence for their existence is provided by the study of the binary pulsar PSR B1913+16 discovered by the Nobel laureates Hulse and Taylor in the seventies. This inspiralling system consists of two neutron stars, one being a pulsar detected by radio-telescopes. This is a perfect example of a GW emitter. Astrophysicists have been able to compare the behaviour of the binary pulsar to the predictions of general relativity. Concerning the orbital decay due to GW emission, measurements and theory agree within less than 1%. This is a beautiful proof that GW exist!

Of course physicists are now waiting for a direct detection. For the very near future it is likely that three (two for LIGO and one for Virgo) detectors with similar sensitivities will be on watch for a wave to come. With some luck, smaller instruments (the Anglo-German GEO 600 or the Japanese TAMA 300) may also contribute to the discovery.

To increase the chance of detection and to confirm detection, a network of detectors is necessary. Validation of detection can be achieved by studying coincident events with other types of detectors, such as neutrino detectors or Gamma-Ray satellites, since these signals are likely to be the counterparts of GW emitters, neutrinos in the case of a supernova event or Gamma Ray bursts in the case of the merger of neutron stars. However, to obtain a complete reconstruction of the passing waveform (amplitude, polarisation, location of the source …) at least three GW detectors are mandatory. Virgo-type instruments are indeed not directional as traditional telescopes. Their antenna pattern looks somewhat like a peanut, symmetrical with respect to the interferometer plane. With coincident events from three GW detectors at separate locations, source location can be reconstructed using triangulation. More details could be obtained through sophisticated coherent analysis methods.

Nevertheless even with three detectors (LIGO and Virgo) working at their design sensitivity a first direct detection in the near future is not guaranteed. Due to the uncertainties in rates of events (binary inspirals) or in waveform amplitudes (supernovae), it is believed today that to be sure to “see” several events per year the sensitivity of current interferometers has to be improved by about one order of magnitude. Work has already started on second generation detectors. An advanced LIGO has been funded by the NSF. R&D for the next generation is also going on in Europe and plans for future detectors are being discussed. Of course second-generation detectors are for the next decade. Today, the GW observation field is very active. We are really at the birth of GW astronomy and a new window is about to open on the Universe. ■



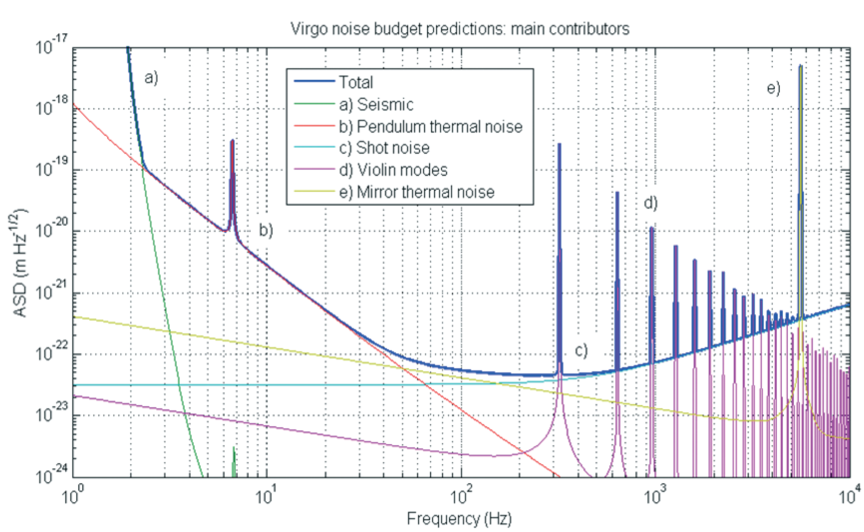
◄ **Fig. 4:** The Virgo super attenuator.

About the authors

André-Claude Clapson is currently finishing his PhD thesis and **Patrice Hello** is Maître de Conférences at the Orsay Campus near Paris. They are both hosted by the Laboratoire de l’Accélérateur Linéaire and members of the Italian-French Virgo collaboration. They are working together mainly on Gravitational Wave Data Analysis issues. Patrice Hello has also an interest in R&D for future Advanced Detectors of Gravitational Waves.

Usefull links :

Virgo collaboration:
www.cascina.virgo.infn.it
LIGO collaboration:
www.ligo.caltech.edu
GEO600 collaboration:
www.geo600.uni-hannover.de



▲ **Fig. 5:** The Virgo design sensitivity. The sensitivity is limited in the effective bandwidth by thermal noise and shot noise.

Loop quantum gravity

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The revolution brought by Einstein's theory of gravity lies more in the discovery of the principle of general covariance than in the form of the dynamical equations of general relativity. *General covariance* brings the relational character of nature into our description of physics as an essential ingredient for the understanding of the gravitational force. In general relativity the gravitational field is encoded in the dynamical geometry of space-time, implying a strong form of universality that precludes the existence of any non-dynamical reference system—or non-dynamical background—on top of which things occur. This leaves no room for the old view where fields evolve on a rigid preestablished space-time geometry (e.g. Minkowski space-time): to understand gravity one must describe the dynamics of fields with respect to one another, and independently of any background structure.

General relativity realizes the requirements of general covariance as a classical theory, i.e., for $\hbar = 0$. Einstein's theory is, in this sense, incomplete as a fundamental description of nature. A clear indication of such incompleteness is the generic prediction of space-time *singularities* in the context of gravitational collapse. Near space-time *singularities* the space-time curvature and energy density become so large that any classical description turns inconsistent. This is reminiscent of the foundational examples of quantum mechanics—such as the UV catastrophe of black body radiation or the instability of the classical model of the hydrogen atom—where similar singularities appear if quantum effects are not appropriately taken into account. General relativity must be replaced by a more fundamental description that appropriately includes the quantum degrees of freedom of gravity.

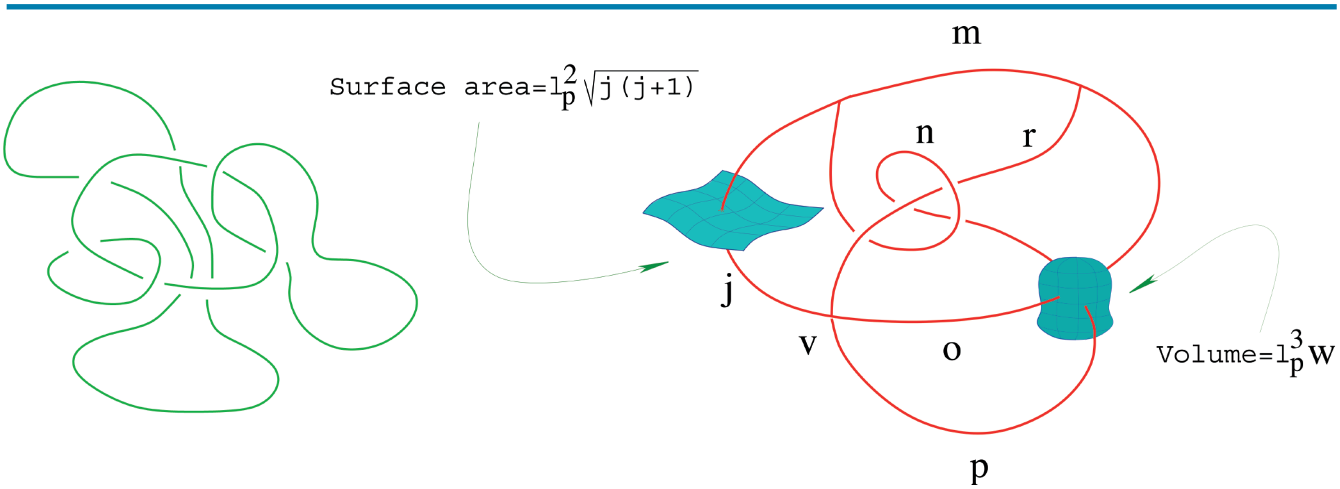
At first sight the candidate would be a suitable generalization of the formalism of quantum field theory (QFT). However, the standard QFT's used to describe other fundamental forces are not appropriate to tackle the problem of quantum gravity. Firstly, because standard QFT's are not generally covariant as they can only be defined if a non-dynamical space-time geometry is provided: the notion of particle, Fourier modes, vacuum, Poincaré invariance are essential tools that can only be constructed on a given space-time geometry. This is a strong limitation when it comes to quantum gravity since the very notion of space-time geometry is most likely not defined in the deep quantum regime. Secondly, quantum field theory is plagued by singularities too (UV divergences) coming from the contribution of arbitrary high energy quantum processes. This limitation of standard QFT's is expected to disappear once the quantum fluctuations of the gravitational field, involving the dynamical treatment of spacetime geometry, are appropriately taken into account. But because of its intrinsically background dependent definition, standard QFT cannot be used to shed light on this issue. A general covariant approach to the quantization of gravity is needed.

This is obviously not an easy challenge as in the construction of a general covariant QFT one must abandon from the starting point most of the concepts that are essential in the description of 'no-gravitational' physics. One has to learn to formulate a quantum theory in the absence of preferred reference systems or pre-existent notion of space and time. Loop quantum gravity (LQG) is a framework to address this task. In this article I will illustrate its main conceptual ideas, and established results. We will see that if the degrees of freedom of gravity are quantized in accordance to the principles of general covariance both the singularity problems of classical general relativity as well as the UV problem of standard QFT's appear to vanish providing a whole new perspective for the description of fundamental interactions.

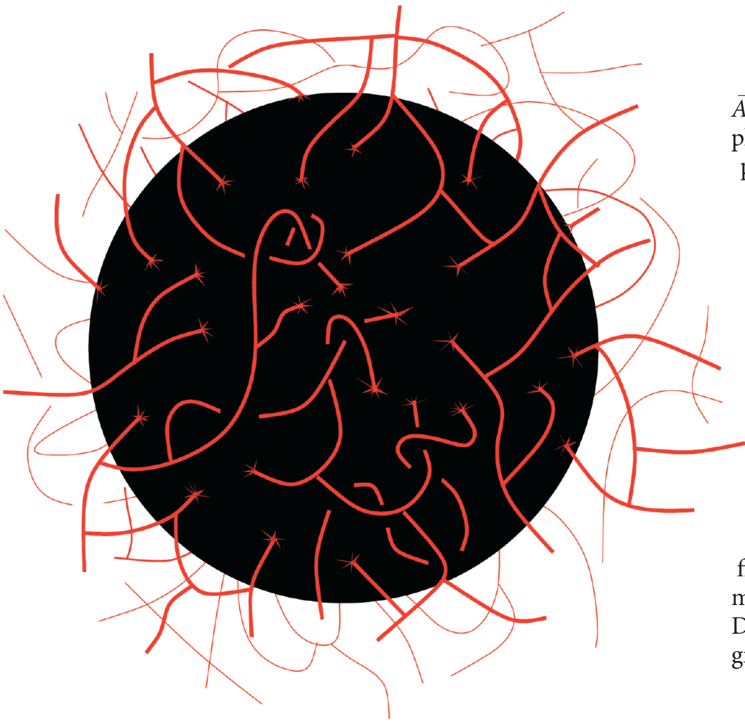
This is a brief overview of the theory aimed at non experts where nothing is explicitly proved. The interested reader can consult the book [1] and the references therein for more details.

Why background independence?

The remarkable experimental success of the standard model of particle physics is a great achievement of *standard* QFT. The standard model unifies the principles of *quantum mechanics* and *special*



▲ **Fig. 1:** The basic loop excitations of geometry are combined into states of an orthonormal basis of the Hilbert space called *spin network states*. These states are labelled by a graph in space and assignment of spin quantum numbers to edges and intersections ($j, n, m, r, o, p \in \mathbb{Z}/2$). The edges are quantized lines of *area*: a spin network link labelled with the spin j that punctures the given surface is an eigenstate of its area with eigenvalue $\sqrt{j(j+1)}$ times the fundamental Planck area. Intersections can be labelled by discrete quantum numbers of volume (v, and w here). In order for this page to have the observed area one would need about 10^{68} spin network punctures with $j = 1/2$!



▲ **Fig. 2:** In loop quantum gravity the Bekenstein-Hawking entropy formula for a black hole of area A, $S_{bh} = A/(4\ell_p^2)$, can berecovered from the quantum theory as $S_{bh} = \log(N)$, where N is the number of microstates (spin network states puncturing the 2-dimensional horizon with arbitrary spins) compatible with the macroscopic horizon area of the black hole.

relativity in the description of the strong, and electro-weak interactions. It is therefore valid as an approximation when the dynamics of the gravitational field is negligible. This limitation is implicit in the definition of standard QFT through the assumption of the existence of inertial coordinates in terms of which the field equations are defined.

In this regime it is easy to construct the idealized physical systems used to define inertial coordinates by starting from an array of test particles at rest with respect to one another, separated by some fixed distance, and carrying clocks which can be synchronized using light signals. By using neutral matter in the construction, the reference system will not be affected by the physical process being studied. Thus its dynamics is trivial, and its properties can be completely hidden in the definition of the inertial coordinates together with a notion of Minkowskian background geometry. In terms of these physical reference systems one writes (or discovers) the laws of physics (either classical or quantum) as long as gravity is neglected.

When the dynamics of the gravitational field cannot be neglected the situation changes dramatically. Due to the fact that everything is affected by gravity one can no longer construct a reference system whose dynamics is known beforehand: whatever physical system one chooses as reference it will be affected by the gravitational field involved in the processes of interest. It is no longer possible to identify any meaningful notion of non-dynamical background. One has no choice but to represent the dynamics of the system in a relational manner where the evolution of some degrees of freedom are expressed as functions of others. Processes do not happen in a god given space-time metric, they define the space-time geometry as they occur.

Except for very special situations, coordinates cannot be associated to physical entities so they are introduced as mere parameters labelling space-time events with no intrinsic physical meaning. As in electromagnetism where the choices of vector potential $\vec{A}$ and $\vec{A}+\vec{\nabla}\chi$ represent the same physical configuration, in gravitational physics a choice of coordinates is a choice of gauge. Any physical prediction in electromagnetism must be gauge-independent; similarly, in gravity they must be coordinate-independent or *diffeomorphism invariant*.

In classical gravity the importance of diffeomorphism invariance is somewhat attenuated by the fact that there are many interesting physical situations where some kind of preferred reference systems can be constructed (e.g., co-moving observers in cosmology, or observers at infinity for isolated systems). However, the necessity of manifest *diffeomorphism invariance* becomes unavoidable in the quantum theory where simple arguments show that at the Planck scale ($\ell_p \approx 10^{-33}$ cm) the quantum fluctuations of the gravitational field become so important that there is no way (not even in principle) to make observations without affecting the gravitational field. In this regime only a background independent and diffeomorphism invariant formulation can be consistent.

Despite all this one can try to define quantum gravity as a background dependent theory by splitting the space-time metric g_{ab} as

$$g_{ab} = \eta_{ab} + h_{ab} \qquad (1)$$

where η_{ab} is a flat Minkowski metric fixed once and for all and h_{ab} represents small fluctuations. Now if the field h_{ab} is quantized using standard techniques the resulting theory predicts UV divergent amplitudes that cannot be controlled using the standard renormalization techniques. The background dependent attempt to define quantum gravity fails. According to our previous discussion, the key of this problem is in the inconsistency of the splitting [1]. This statement is strongly supported by the results of the background independent quantization proposed by *loop quantum gravity*.

Loop quantum gravity

LQG is a background independent approach to the construction of a quantum field theory of matter fields and gravity. The theory was born from the convergence of two main set of ideas: the old ideas about background independence formulated by Dirac, Wheeler, DeWitt and Misner in the context of Hamiltonian general relativity, and the observation by Wilson, Migdal, among others, that Wilson loops are natural variables in the non-perturbative formulation of gauge theories. The relevance of these two ideas is manifest if one formulates classical gravity in terms of suitable variables that render the equations of general relativity similar to those of standard electromagnetism or Yang-Mills theory.

The starting point is the Hamiltonian formulation of gravity where one slices space-time arbitrarily in terms of *space* and *time* and studies the evolution of the space geometry along the slicing. In the standard treatment the metric of space and its conjugate momentum—simply related to its time derivative—are the phase space variables of general relativity. By a suitable canonical transformation one can obtain new variables consisting of: a triplet of electric fields $\vec{E}_i$ whose conjugate momenta are given by a triplet of vector potentials $\vec{A}_i$ with $i = 1, 2, 3$. The (unconstrained) phase space of general relativity is equivalent to that of an $SU(2)$ Yang-Mills theory (a non Abelian generalization of electromagnetism).

What is the physical meaning of the *new variables*? The triplet of vector potentials $\vec{A}_i$ have an interpretation that is similar to that of $\vec{A}$ in electromagnetism: they define the notion of parallel transport of spinors encoded in the 'Aharonov-Bohm phase' acquired by matter when parallel transported along a path γ in space—affecting all forms of matter due to the universality of gravity. Unlike in electromagnetism, here the 'phase' is replaced by an element of $SU(2)$ associated with the action of a real rotation in space on the displaced spinor.

This is mathematically encoded in the Wilson loop (related to the circulation of the magnetic fields $\vec{B}_i$) along the loop γ according to

$$W_\gamma[A] = P\exp\int_\gamma \tau^i \vec{A}_i \cdot d\vec{s} \in SU(2), \tag{2}$$

where P denotes the path-ordered-exponential, τ^i are the generators of $SU(2)$, and s is an arbitrary parameter along γ.

The electric fields $\vec{E}_i$ have a novel physical interpretation: they encode the (dynamical) geometry of 3-dimensional space. More precisely the triplet of electric fields $\vec{E}_i$ define at every point of space an (densitized) orthonormal local frame, which in turn can be used to reconstruct the space metric. Therefore, any geometric property of space can be written as a functional of $\vec{E}_i$.

There are two geometric quantities that one can construct in terms of simple functionals of $\vec{E}_i$ that will play an important role in the quantum theory. The first (and the simplest) one is the area $A(S)$ of a two dimensional surface S—corresponding to the 'absolute value of the flux' of the electric field across S—embedded in space, while the second is the volume $V(R)$ of a three dimensional region R in space. In equations,

$$\begin{aligned} &\textit{Area of } S \quad \rightarrow \quad A(S) = \int_S |\, E_i^\perp E_i^\perp \,|, \\ &\textit{Volume of } R \rightarrow V(R) = \int_R \sqrt{\vec{E}_i \cdot (\vec{E}_j \times \vec{E}_k)\, \epsilon^{ijk}} \end{aligned} \tag{3}$$

where $\perp$ denotes the component of E_i normal to S, ϵ^{ijk} is the Levi-Civita skew-symmetric tensor (repeated indices are summed). As anticipated, both the area of a surface S and the volume of a region R are written as functionals of the dynamical variable $\vec{E}_i$.

Einstein's equations are encoded in relations among the phase-space variables. They are given by to the so-called *kinematic constraints*, related to certain manifest gauge symmetries,

$$\begin{aligned} &\textit{Gauss law} \qquad\quad \rightarrow \mathrm{Div}\,(\vec{E}_i) = 0, \\ &\textit{Vector constraint} \rightarrow \vec{E}_i \times \vec{B}_i(A) = 0 \end{aligned} \tag{4}$$

and the *Hamiltonian constraint*, encoding the non trivial dynamics of general relativity,

$$\frac{(\vec{E}_i \times \vec{E}_j) \cdot \vec{B}_k(A)\, \epsilon^{ijk}}{\sqrt{\vec{E}_i \cdot (\vec{E}_j \times \vec{E}_k)\, \epsilon^{ijk}}} = 0 \tag{5}$$

where $\vec{B}_i(A) = \vec{\nabla}_A \times \vec{A}_i$ is the triplet of magnetic fields constructed from the $SU(2)$ connection $\vec{A}_i$.

Quantization

The quantization is performed following the canonical approach, i.e., promoting the phase space variables to self adjoint operators in a Hilbert space $\mathscr{H}$ satisfying the canonical commutation relations according to the rule $\{\ ,\ \} \rightarrow -i/\hbar\,[\ ,\ ]$. The classical constraints are imposed as operator-equations on the states of the theory. These are the *quantum Einstein's equations*. The kinematical conditions (4) are directly applied in the construction of $\mathscr{H}$. *Quantum dynamics* is governed by the quantum version of the Hamiltonian constraint, which formally reads

$$\widehat{\frac{(\vec{E}_i \times \vec{E}_j) \cdot \vec{B}_k(A)\, \epsilon^{ijk}}{\sqrt{\vec{E}_i \cdot (\vec{E}_j \times \vec{E}_k)\, \epsilon^{ijk}}}}\ \Psi[A] = 0 \quad \text{for} \quad \Psi[A] \in \mathscr{H} \tag{6}$$

and can be viewed as the the analog of the Schroedinger equation of standard quantum mechanics.

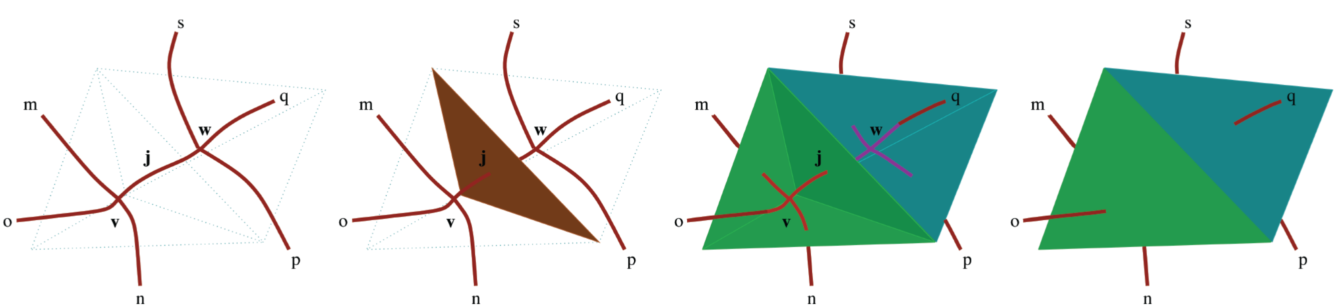
As there is no background structure the notion of *particle*, as basic excitations of a *vacuum* representing a state of minimal energy, does not exist. However, there is a natural *vacuum* associated with the state of no geometry $\widehat{\vec{E}_i}\,|0\rangle = 0$. This state represents a very degenerate quantum geometry where the distance between any pair of points is zero. The quantum version of (2), $\widehat{W_\gamma}[A]$ acts on the vacuum by creating a one-dimensional flux tube of electric field along γ. As $\vec{E}_i$ encodes the geometry of space, these fundamental *Faraday lines* represent the building blocks of a notion of *quantum geometry* as we shall see below.

These one-dimensional excitations are however not completely arbitrary as they must be subjected to the kinematical restrictions (4). For instance, $\mathrm{Div}(\vec{E}_i) = 0$ requires the flux of electric field through any arbitrary closed surface to vanish. This means that only those excitations given by closed lines of quantized electric field are allowed by quantum Einstein's equations, i.e., *loop states*. The construction of the Hilbert space of quantum gravity is thus started by considering the set of arbitrary multiple-loop states, which can be used to represent (as emphasized by Wilson in the context of standard gauge theories) the set of gauge invariant functionals of $\vec{A}_i$.

Spin network states

Multiple-loop states can be combined to form an orthonormal basis of the Hilbert space of gravity. The elements of this basis are labelled by: a closed graph in space, a collection of spins—unitary irreducible representation of $SU(2)$—assigned to its edges, and a collection of discrete quantum numbers assigned to intersections. As a consequence of $\mathrm{Div}(\vec{E}_i) = 0$ the rules of addition of angular momentum must be satisfied at intersections. They are called *spin-network states*, see Fig. 1.

Spin network states are eigenstates of geometry as it follows from the rigorous quantization of the notion of area and volume (given by equations (3)). For instance, given a 2-dimensional surface S one



▲ **Fig. 3:** Spin network intersections are quantum excitations of space volume. They are fundamental *atoms* of space related to one another through spin network links carrying quanta of the area associated to the extension shared by neighbouring *atoms*. The information about how the atoms are interconnected to form a quantum geometry is contained in the combinatorics of the underlying abstract graph. Here we show two 4-valent vertices connected by a link carrying spin j. We can interpret this portion of a spin network as being represented by two *tetrahedra* of volume $\ell_P^3 v$ and $\ell_P^3 w$ respectively sharing a face of their boundary (the brown triangle in the second diagram) with area $\ell_P^2\sqrt{j(j+1)}$.

▲ **Fig. 4:** The regulated Hamiltonian acts by attaching a Wilson loop to vertices and the loop size plays the role of an UV regulator. The regulator must be removed shrinking the loop. When the latter is small enough (last two diagrams on the r.h.s.) it can no longer entangle the gravitational field exitations around the vertex and the further reduction of the loop does not have any physical effect according to diffeomorphism invariance. The combinatorial structure of the quantum states in loop quantum gravity provides a *physical* cut-off regularizing all the interactions in LQG!

can define the quantum operator $\widehat{A(S)}$ associated to its area. It turns out that a spin network state that punctures S with an edge carrying spin j is an eigenstate of $\widehat{A(S)}$ with eigenvalue $\ell_P^2\sqrt{j(j+1)}$, see Fig. 1. In LQG the area of a surface can only take discrete values in units of Planck scale! Similarly, the spectrum of the volume operator $\widehat{V}(R)$ can be shown to be discrete and to be associated to the presence of spin network intersections inside the region R. Hence, the theory predicts a quantization of geometry.

The discovery of the discrete nature of geometry at the fundamental level has profound physical implications. In fact before completely solving the quantum dynamics of the theory one can already answer important physical questions. The most representative example (and early success of LQG) is the computation of black hole entropy from first principles in agreement with the semiclassical predictions of Hawking and Bekenstein (see Fig. 2).

Another profound implication of discreteness concerns the UV divergences that plague standard QFT's. It is well known that in standard QFT the UV problem finds its origin in the difficulties associated with the quantization of product of fields at the same point (representing interactions). A first hint of the regulating role of gravity is provided by the fact that, despite their non-linearity in $\vec{E}_i$, area and volume are quantized without the appearance of any UV divergences. This mechanism will become more transparent when we present the quantization of the Hamiltonian constraint.

The combinatorial nature of LQG

So far we have avoided UV divergences but perhaps at too high of a price, since the Hilbert space spanned by spin network states is so large—in fact two spin networks differing by a tiny modification of their graphs are orthogonal states!—that would seem to make the theory intractable. However, one must still impose the vector constraint given in (4). This is where the crucial role background independence starts becoming apparent as the vector constraint—although is not self-evident—implies that only the information in spin network states up to smooth deformations is physically relevant. Physical states are given by equivalence classes of spin networks under smooth deformations: these states are called *abstract spin networks*.

Abstract spin network states represent a quantum state of the geometry of space in a fully combinatorial manner. They can be viewed as a collection of 'atoms' of volume (given by the quanta carried by intersections) interconnected by edges carrying quanta of area of the interface between adjacent atoms. This is the essence of background independence: the spin network states do not live on any preestablished space, they define space themselves.

The details of the way we represent them on a three dimensional 'drawing board' do not carry physical information. The degrees of freedom of gravity are in the combinatorial information encoded in the collection of quantum numbers of the basic atoms and their connectivity (see Fig. 3).

Quantization of the Hamiltonian constraint

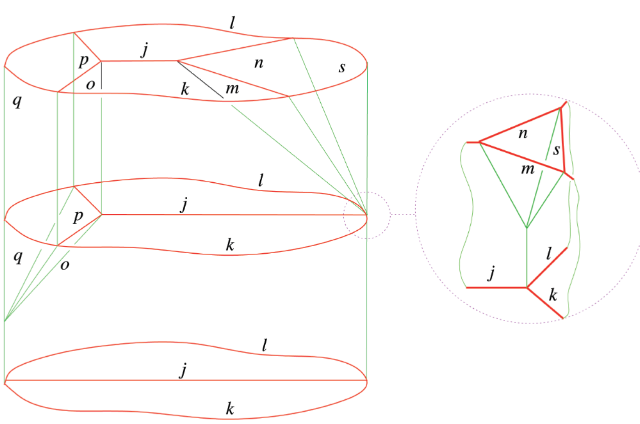
Up to this point we have constructed the kinematic setting of LQG by defining the Hilbert space satisfying the conditions (4). In order to impose the dynamical equation (6) one must quantize the Hamiltonian constraint (5). However, the non linearity of the latter brings in again the question of UV divergences in the quantum theory. From (3) and (6) one can write the Hamiltonian constraint as

$$\widehat{H} = -\frac{i}{\hbar}[\widehat{V}, \vec{A}_i]\vec{B}_i(A) \qquad (7)$$

which allows all the non linearities in $\vec{E}_i$ to be hidden in the commutator of the (free of UV singularities) volume operator and $\vec{A}_i$. As the magnetic field $\vec{B}_i(A)$ is given by the circulation of $\vec{A}_i$, one can express the non linear A-dependence by a non-local Wilson loop $W_{\gamma\epsilon}[A]$ around an infinitesimal loop γ_ϵ of size ϵ. In the quantum theory $W_{\gamma\epsilon}[A]$ creates a loop excitation and ϵ is an *UV-regulator*.

As the volume operator, the regulated Hamiltonian acts only on spin network intersections, and it does so by creating a new flux excitation $W_{\gamma\epsilon}[A]$. Due to background independence the regulated Hamiltonian depends on ϵ only through the position of the newly created loop γ_ϵ. Its action for different values of the regulator ϵ is shown in Fig. 4.

The physical Hamiltonian constraint is obtained by taking the limit $\epsilon \to 0$. In standard QFT's this process brings in all the well



▲ **Fig. 5:** A systematic control of the space of solutions is necessary to fully understand the dynamics implied by LQG. Feynman's path integral formulation can be adapted to the formalism in order to investigate this issue. Transition amplitudes that encode the dynamics of quantum gravity can be computed as sums of amplitudes of combinatorial objects representing histories of spin network states. These histories can be interpreted as quantum space-time processes and are called *spin foams*. In the figure we show a simple spin foam obtained interpolating between an 'initial' and 'final' spin network. An intermediate spin network state is emphasized as well as a vertex where new links are created as a result of the action of the quantum Hamiltonian constraint.

known UV problems that require renormalization. However, in LQG, background independence in fact assures that this limit exits without any UV divergences. For finite value of the ϵ the extra loop created by the quantum constraint can entangle the weave of links and nodes in the given *spin network* around the intersection (first three diagrams on the *l.h.s.* of Fig. 4). As ϵ becomes smaller the added loop shrinks and there is a critical value ϵ_c after which it can no longer wind around any of the neighboring links. At this point changing the value of ϵ amounts to a trivial deformation of the extra loop that, according to the combinatorial nature of the quantum states of gravity, has no physical effect. Therefore, for sufficiently small ϵ the action of the regulated constraint becomes regulator independent and the limit is defined without need of renormalization (see Fig. 4). This result also holds when coupling gravity with the matter of the standard model; the combinatorial nature of the states of quantum gravity provides a physical regulator for all interactions.

Perspectives and Conclusions

We have discussed how the dynamical equation of quantum gravity can be promoted to a quantum operator, and how the dynamics of the theory is in the solutions of the quantum Hamiltonian constraint. Although many solutions to the equation are known, there is no complete control of the space of solutions at present. A systematic approach to investigate the solution space is the path integral representation which in the case of LQG is known as the *spin foam* approach. In it, physical transition amplitudes are computed as sums of amplitudes associated with histories of spin network states (Fig. 5). These histories can be interpreted as the quantum counterpart of space-time: they represent the quantum evolution of the quantum states of space geometry.

Despite the fact that a full understanding of the dynamics of LQG has not yet been achieved, there are interesting physical situations where one can bypass these limitations. One of these is the computation of black hole entropy briefly mentioned above and the other is the application of the framework to systems with additional symmetry. Important examples are the study of quantum cosmology and the near-singularity regime in black hole physics, where due to symmetry assumptions most of the technical problems of the full theory can be overcome. Even though these symmetry-reduced models must be regarded as toy models, as an infinite number of degrees of freedom are ignored in the treatment, there are interesting results that indicate that the singularity problem of classical general relativity would be resolved due to the fundamental discreteness predicted by LQG.

Another important open issue in LQG is the semiclassical limit: how to recover from the fundamental polymer-like excitations of LQG the smooth physics of general relativity and the standard model at low energies.

LQG realizes a unification between the principles of general covariance and those of quantum mechanics. The approach suggests that the outstanding problem of divergences in QFT's and singularities in classical general relativity are resolved when the quantum dynamical degrees of freedom of gravity are included in a background independent manner. The results obtained so far are encouraging; future research will tell whether all this is consistent with the so far elusive nature of quantum gravity. ■

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Reference

[1] C. Rovelli, *Quantum Gravity*, Cambridge Univ. Press, (2005).

Physics in daily life: seeing under water

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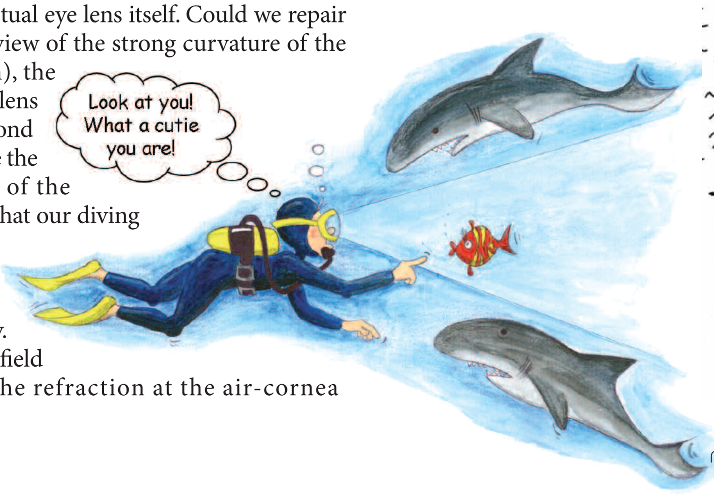
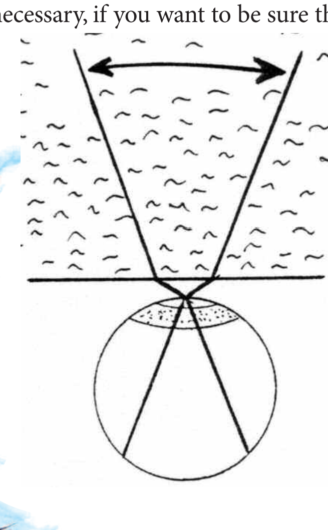
Most physicists realize that the human eye is not made for seeing under water. For one thing, if we open our eyes under water to see what's going on, our vision is blurred. The reason is obvious: since the index of refraction of the inner eye is practically that of water, we miss the refractive power of the strongly curved cornea surface. With its $1/f$ of about 40 diopters it forms an even stronger lens than the actual eye lens itself. Could we repair that with positive lenses? In view of the strong curvature of the cornea surface (radius 8 mm), the idea of replacing it by a glass lens in a water environment is beyond hope. We really need to restore the air-water interface in front of the cornea, and that is precisely what our diving mask does.

But there is more to it: under water, our field of vision is reduced dramatically. Whereas we normally have a field of more than 180° due to the refraction at the air-cornea interface, we loose that benefit once we're under water. The diving mask does not repair that, as schematically indicated in the figure.

So, scuba divers, beware! You have to turn your head much further than you may think necessary, if you want to be sure that you are not followed by a shark. ■





Vibrations in space as an artificial gravity?

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The environment for satellites and spacecraft in space is markedly different from the terrestrial situation. Apart from the high vacuum, low temperature and intense external radiation environment, gravitational effects are absent. A wide variety of fundamental processes involving fluids and living systems are drastically affected; one of the major reasons being the absence of buoyancy flows (Fig. 1)

One way to improve the management of fluids and that of life support systems would be to create an "artificial" gravity. Classically, an artificial gravity can be produced in space in two ways. A centrifugal force, created by spinning the spacecraft or space station, can be used. However, large Coriolis forces are also present and everything would fall in curves instead of straight lines. One can also linearly accelerate the spaceships, but this cannot be continued over long periods because of the enormous energy costs. Less known would be the possibility to produce a uniform force field as coming from a magnetic field gradient, but here also the cost in energy is very high. (However, this solution can be advantageously used to compensate gravity on Earth as described below, see Box above fig. 4).

Fluids and vibrations

If we narrow our focus to fluid systems and to some extent to living organisms, vibrations provide another possible means of reproducing some of the effects of gravity. First of all, large amplitude (with respect to the system size), low frequency (with respect to the system time response) vibration gives a periodic acceleration – and then a periodic artificial gravity – to any entity. In order to illustrate this fact by an example, Fig. 2a shows a sample of supercritical fluid CO_2 heated on Earth by a point source (a thermistor). It results in the convection of the less dense hot fluid parallel to gravity and an accumulation of hot fluid at the top, with a hot-cold interface perpendicular to gravity. The same phenomenon in space conditions and under vibration gives a similar convection pattern that is symmetrical with respect to the direction of vibration (Fig. 2b).

At small amplitude and high frequency, the situation is more complex and, at the same time, more interesting. In addition to local vibrations of the fluid, average flows are created. These flows are of inertial origin; they are connected to the nonlinear response of the fluid to the vibration and are initiated because of the existence of density inhomogeneities $\Delta\rho$. Average flows can also originate in the viscous hydrodynamic boundary layers at the cell walls or inclusions from where they propagate to the whole sample.

When submitted to a simple harmonic linear vibration $X = a\cos\omega t$, a density inhomogeneity $\Delta\rho$ in a fluid of mean density ρ can thus acquire a velocity difference $\Delta V = (\Delta\rho/\rho)a\omega$. Contrary to the effect of vibrations of large amplitude and low frequency that direct inhomogeneities parallel to the direction of vibration, the low amplitude and high frequency vibration induces, in general, mean flows *perpendicular* to the vibration direction, as discussed below.

As a matter of fact, it is well known since the work of G.H. Wolf [1] that a gas-liquid interface subject to a horizontal vibration progressively orientates itself parallel to gravity. Simple reasoning, based on the presence of a Bernoulli pressure difference, gives a qualitative picture of the onset of motion at the beginning of the process. The difference in density of gas and liquid results in a difference in velocity ΔV and a steady Bernoulli pressure difference $\Delta P \approx \rho(\Delta\rho/\rho)^2 a^2\omega^2$ that moves the interface perpendicularly to the vibration direction. Indeed the final interface arrangement, almost perpendicular to the vibration direction, corresponds to a minimum of energy when we consider both potential and kinetic energy.

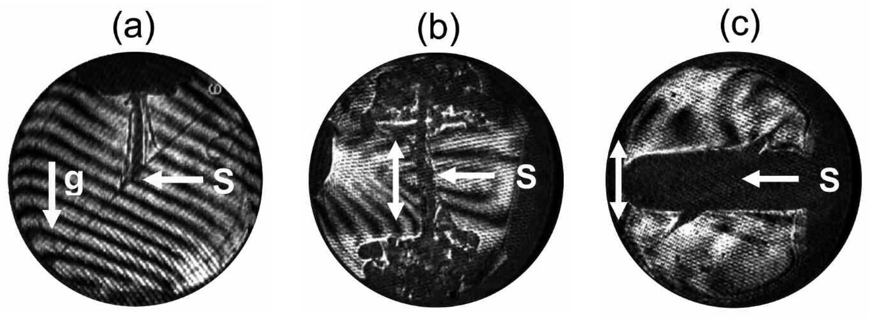
In the configuration of a hot point source, natural convection (1g) is revealed in Fig 2.a. Under weightlessness and high amplitude, low frequency vibration (Fig. 2b), the situation is similar to 1g, except that buoyancy flows are now symmetrical along the vibration direction. When (Fig. 2c) the amplitude of the vibration is reduced and the frequency increased from case (b), a hot layer moves under convection *perpendicularly* to the vibration direction (Fig. 1c) - in contrast to the previous case (b).

It is also quite interesting to analyse the case of the well-know Rayleigh-Bénard cell configuration where a fluid is maintained between two horizontal plates separated by the thickness L. The lower plate is maintained at a hotter temperature than the top plate, with a constant temperature difference ΔT. A fluid element of size r starts to rise when the typical convective time across the fluid element is shorter than the diffusion time to the surface, that is $r/V < r^2/D_T$. Here D_T is the thermal diffusivity and V is the convective velocity. V is given by the well-known Stokes formula $V \approx r^2 g\Delta\rho/\eta$. η is the shear viscosity. The Rayleigh number gives a measure of the ratio of these two diffusive and convective times:

$Ra = g\dfrac{\alpha\Delta TL^3}{\nu D_T}$ where α $(= (1/\rho)(\partial\rho/\partial T)_P$ is the thermal expansion coefficient. Here one has used the relation $\Delta\rho = \alpha\Delta T$. Convection starts for $Ra > 1700$.

Let us now consider the same configuration without gravity but under vibration. The criterion for buoyancy-driven convection can be replaced by the presence of a Bernoulli – like pressure difference $\Delta P \sim \rho(\Delta\rho/\rho)^2 a^2\omega^2$. It results in a driving force $r^2\Delta P$. Applying the same procedure used to define the Rayleigh number, another number is obtained, the vibrational Rayleigh number $Rav = \dfrac{(\alpha a\omega\Delta TL)^2}{2\nu D_T}$. The most unstable situation is when the vibration is *parallel* to the plates (Rav is of the order of 2000) and vibration perpendicular to the plates corresponds to a stable situation (no convection).

◄ **Fig. 1:** The conditions of weightlessness in space complicate and make hazardous the management of fluids in satellites and spacecraft as well as the survival of human beings and, more generally, of living systems (J.P. Heigneré in the MIR station, 1999).



◄ **Fig. 2:** Interferometer images of a sample of supercritical CO_2 (12 mm diameter, 7 mm thickness) when heated by the point source thermistor S. **(a)**: convection under Earth's gravitational field g. **(b)** Convection under 64 mm and 0.2 Hz large amplitude and low frequency vibration (double arrow) under weightlessness (MIR station, 2000). **(c)** Convection under lower amplitude (0.8 mm) and higher frequency (1.6 Hz) vibration (double arrow) (MIR station, 2000).

Phase transition without vibration

In all the examples given above, the inhomogeneity in density is eventually directed perpendicularly to the vibration direction. Therefore, in some sense, high frequency vibrations can recreate some features of the effects of gravity. However, it is clear that the vibration - and buoyancy - induced flows have different origins. The question that can be now asked is: can this simple and rather naive view be extrapolated to condensation and evaporation? These are quite essential and basic processes since they involve significant heat and mass exchanges and are very non-linear and non-equilibrium phenomena.

The phase transition is concerned at the fundamental level with (i) the nucleation of individual drops or bubbles, not influenced by gravity or vibration flows and (ii) subsequent growth, where drop-drop or bubble-bubble interactions have to be taken into account. Here convective flows really matter. The interactions between drops or bubbles are generally due to the collision and subsequent fusion – i.e. coalescence - of individual bubbles and droplets. Under the Earth's gravitational field, buoyancy that directs bubbles upwards and droplets downwards makes them fuse very quickly, within a kinetics determined by gravity-induced flows. Eventually, after a furious burst of coalescence, the gas-liquid phase separation ends with the gas phase upwards and the liquid phase downwards, separated by a flat meniscus (Fig. 3a).

In space, the effects of gravity are suppressed and the phase transition kinetics is only driven by the haphazard and slower process of collision between droplets or bubbles. Depending on the mean distance between drops or bubbles (which depends on the volume fraction of the minority gas (subscript g) or liquid (subscript l) phase $\phi = v_{g,l} / (v_g+v_l)$ as $\phi^{1/3}$), the collision can be due to only two processes. For drops or bubbles sufficiently far apart from each other (volume fraction < 30 %), the collisions are due to Brownian motion (Fig. 3b), with the diameter D of bubbles or drops growing as $D \sim (k_BT/6\pi\eta)^{1/3}\, t^{1/3}$. Here T is the temperature and t is the time. The Brownian diffusion ($t^{1/3}$) growth law corresponds to a very slow evolution.

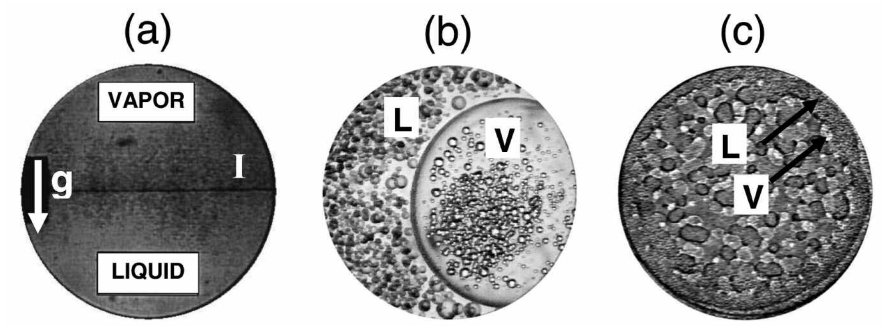
For a phase transition corresponding to a volume fraction larger than 30 %, the drops or bubbles are close together and a new phenomenon becomes important. The hydrodynamic attraction caused by the flow during coalescence is now able to push neighbouring drops close enough to provoke coalescence, thus inducing a kind of chain reaction of drop or bubble fusions. The coalescence of two drops or bubbles leads to fusion with a neighbouring one, and so on. The pattern then looks interconnected (Fig. 3c), with a typical wavelength Lm. The dynamics is at present limited by the flow resulting from coalescence and, for low flow velocity (low Reynolds numbers), growth is linear with time, $Lm \approx (\sigma/\eta)t$, where σ is the gas-liquid surface tension.

In any case, the kinetics of phase separation, whether limited by Brownian collisions or hydrodynamic interactions, is much slower than when gravity flows stimulate coalescence.

Phase transition under vibration

In order to investigate under space-like conditions the effect of vibration on evaporation or condensation, experiments have been carried out in a magnetic set-up that creates "artificial" weightlessness on Earth (see Box above fig. 4)). Then "artificial" gravity is added back in, this time in the form of high-frequency (<50Hz), low-amplitude (<0.5 mm) vibrations.

Hydrogen was the fluid under study because of its large diamagnetic susceptibility with respect to other fluids, allowing the magnetic compensation to be achieved with relatively low magnetic field gradients (500 T/m^2). In addition, the phase transition was studied near its critical point (33 K). The critical point is the end point of the saturation curve and does indeed exhibit very interesting properties. Near the critical point, critical slowing down makes the growth of drops and bubbles very slow. (The gas-liquid surface tension σ goes to zero whereas viscosity η does not vary very much). Also the latent heat goes to zero. In addition, the phase transition can be induced by simply lowering the temperature -thus ensuring no external flows- and within minutes thermal quenches occur (of order on mK). A rapid return to



▲ **Fig. 3:** Phase separation in a CO_2 sample (10 mm diameter, 5 mm thickness) from above the critical point (supercritical state) to below (gas-liquid equilibrium). **(a)** Under a gravitational field. I is the gas-liquid interface. Turbulent coalescence of droplets (in the vapour-rich phase V above) and bubbles (in the liquid-rich phase L below) are observed that are induced by buoyancy flows. **(b)** Under weightlessness, with low (<30%) vapour volume fraction. The gas-liquid interface is round. Brownian collisions now drive the process. **(c)** The same as (b), but with high (>30%) vapour volume fraction. The pattern is interconnected and the evolution is driven by coalescence-induced capillary flows.

thermal equilibrium is thus ensured and drop and bubble evolution occurs at strictly constant temperature and pressure (and mean density). In the vicinity of the critical point the results can be expressed in universal, scaled form - but this point will not developed here – see [3]).

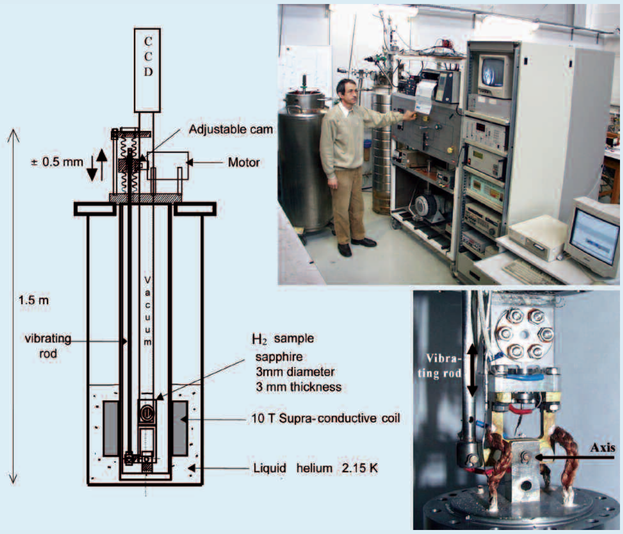
What, then, is the effect of vibration? Concerning the interconnected pattern of drops and bubbles (volume fraction larger than 30%), the results are striking, as shown in Fig. 5. At very early times, the drop and bubble size is so minute that evolution is the same as if there were no vibrations (a). Indeed, for very small domains, the viscous interaction maintains a uniform velocity field, despite the density difference. In other words, the viscous boundary layer $\delta = (\eta/\rho\omega)^{1/2}$ [4] is still larger than the typical drop-bubble size Lm. As drops/bubbles grow, Lm exceeds δ. At this moment, a faster evolution is observed (b). This acceleration is followed by the deformation of the gas-liquid interfaces (c) that grow faster in the direction perpendicular to vibration, eventually forming alternate bands of gas and liquid (d). From the simple argument that interfacial energy – and thus interfacial area - has to be a minimum at the end of the process, the steady state should correspond to a single band (bubble) of gas separated by two symmetric liquid bands (drops), as liquid must wet the cell walls. This stage is rarely observed, because the coalescence of alternate bands is impossible without fluctuations; it corresponds to an energy barrier that cannot be overcome with thermal fluctuations. Instead, the sample is pinned in a metastable state that depends on the details of its evolution.

When the volume fraction of the minority phase is lower than 30%, the pattern of evolution is markedly different although retaining some general features of the former evolution. Here too, the effect of vibration remains invisible as long as the size of the growing bubbles does not exceed the viscous boundary layer. The evolution obeys $D \sim t^{1/3}$. Then, for $D > \delta$, the bubbles start to "feel" the vibration. It is known [5] that the hydrodynamics of two vibrated inclusions result in repulsion between inclusions in the vibration direction and attraction in the direction perpendicular to vibration. The effect of these repulsive and attractive interactions naturally results in a pattern similar to that shown in Fig. 6, where bubbles organise themselves in periodic, parallel layers. Attraction in the layers increases the bubble coalescence rate and then growth becomes limited by the flow during coalescence (the same as for the interconnected pattern), thus resulting in a linear growth law. For the bubbles that continue to stay between the layers, the growth law remains driven by Brownian coalescence, with the classical $t^{1/3}$ law.

Recreating the zero-gravity environment of space on Earth

Gradients of magnetic fields, as provided near the end of a coil, can provide a force proportional to the density of diamagnetic and paramagnetic materials. At exact compensation, an artificial gravititational micro-environment is provided for the materials. Most of the studies that are described here were carried out in hydrogen (H_2) near its critical point (33 K, 1.3 MPa) using such a method. Indeed, an advantage is that H_2 exhibits a relatively large magnetic susceptibility that enables gravitational forces to be compensated with a realistic superconductor coil (500 T/m^2 near the end of a 10 Tesla coil). Compensation is at the molecular level. It was uniform within 1.5% of the Earth's acceleration constant in a sample cell of 3 mm diameter and 3 mm thickness. Note that it can be shown that a perfect uniform compensation cannot be strictly achieved according to Maxwell's laws [2]).

Vibrating a sample in such high magnetic fields is difficult since the vibrational motion induces eddy currents in metals. For this reason the experimental cell was made with sapphire with the exception of the screws and seals (Fig. 4). The cell was vibrated thanks to a stepping motor and a cam, providing vibration with amplitude < 0.5 mm and frequency < 50 Hz.



▲ **Fig. 4:** Set-up to compensate gravity by magnetic forces (left and top right) and a special vibrating sapphire cell (bottom right).

Conclusion

Returning to the initial question: can high frequency, low amplitude vibrations be used in space as an artificial gravity? The answer is "yes… but" since it depends on the very phenomenon involved. When one deals with thermal convection, interface localisation and even – as mostly reported here – phase separation, vibration can indeed induce mean flows that closely resemble buoyancy. In this sense vibration can really serve as an artificial gravity.

As a matter of fact, small amplitude and high frequency vibration was recently used as an artificial gravity for astronauts. Past studies have shown that vibrating an astronaut's legs and feet helped to prevent muscle decay or bone decalcification, due to the stress induced by vibrations [6]. ■

About the Author

After receiving an engineering diploma at the Institut d'Optique (Paris), **D. Beysens** obtained his Ph.D. at Université Paris-6. Director of Research at the CEA he has taken positions at CEA-Saclay and CEA-Grenoble. He is now working at ESPCI (Paris). He is interested in phase transitions in fluids, experimenting in space. He loves practicing mountain skiing and hiking – and avoids experiencing free-fall!

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Further reading

General on phase transition in fluids:

A. Onuki, *Phase transition dynamics* (Cambridge University Press, Cambridge, 2002)

Phase separation under vibration:
D. Beysens, D. Chatain, P. Evesque, Y. Garrabos, High-frequency driven capillary flows speed up the gas-liquid phase transition in zero-gravity conditions, *Phys. Rev. Lett.* **95**,
General on thermo-vibrational phenomena:
G. Z. Gershuni and D. V. Lyubimov, *Thermal vibrational convection* (John Wiley & Sons, Chichester, 1998)
Magnetic compensation of gravity in fluids:
R. Wunenburger, D. Chatain, Y. Garrabos and D. Beysens, *Phys. Rev.E* **62**, 469 (2000)

References

[1] G. H. Wolf, *Z. Physik B*, **227**(3), 291 (1961);

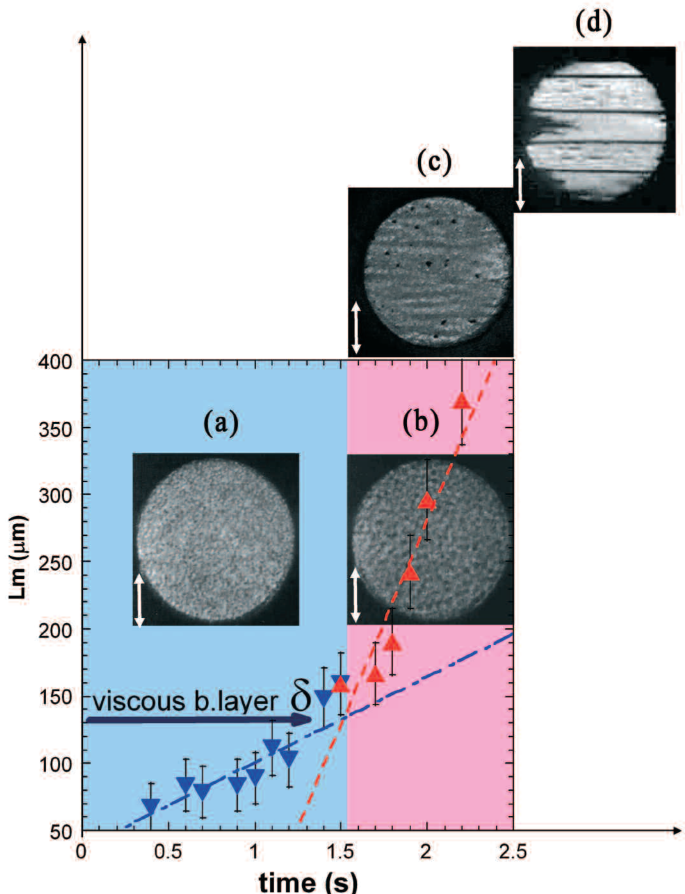
[2] L. Quettier, H. Felice, A. Mailfert, D. Chatain, D. Beysens., *Europhys. Journal of Applied Physics* **32**, 167 (2005)

[3] D. Beysens, Y. Garrabos, *Physica A* **281**, 361 (2000)

[4] L.D. Landau and E.M. Lifshitz, *Fluid Mechanics* (Pergamon Press, Elmsford, New York, 1975)

[5] D.V. Lyubimov, T.P. Lyubimova, S.V. Shklyaev, *1st International Symposium on Microgravity Research & Applications in Physical Sciences and Biotechnology, Sorrento* (Italy), Sept. 10-15, 2000, ESA-SP 454, 879 (2001)

[6] The absence of gravity, by the absence of exercise of muscles and stress on bones, cause muscular and bone losses. Slight vibrations (10µm amplitude, 90 Hz frequency) transmitted by the life fluids inside the muscles and bones reproduce stresses and, perhaps, could be a solution - at least for bones: astronauts might prevent bone loss by standing on a lightly vibrating plate for 10 to 20 minutes each day. Held down with the aid of elastic straps, the astronauts could keep working on other tasks while they vibrate. The same therapy might eventually be used to treat some of the millions of people who suffer from bone loss, called osteoporosis, here on Earth. (C.T. Rubin, G. Xu, S. Judex, The anabolic activity of bone tissue, suppressed by disuse, is normalised by brief exposure to extremely low magnitude mechanical stimuli. *The FASEB Journal* **15**, 2225-2229 (2001).



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▶ **Fig. 5:** Evolution of an interconnected pattern of drops and bubbles (volume fraction larger than 30%). The double arrow represents the vibration. **(a)**: Lm < δ, no vibration influence. **(b)**: Lm ≈ δ, vibration speeds up the evolution and orientates the drop-bubble interfaces perpendicular to vibration **(c)** till a steady state is obtained in **(d)**. **From (a) to (c):** 3 mm diameter, 3 mm thickness H_2 sample under magnetic compensation of gravity and vibration 20.3 Hz frequency and 0.3 mm amplitude, 0.6 mK below the critical point. **(d)**: 10 mm diameter, 10 mm thickness CO_2 sample in a sounding rocket free fall environment (vibration 42 Hz, 0.31 mm, 2 mK below the critical point, ESA Maxus-5 rocket, 2003).

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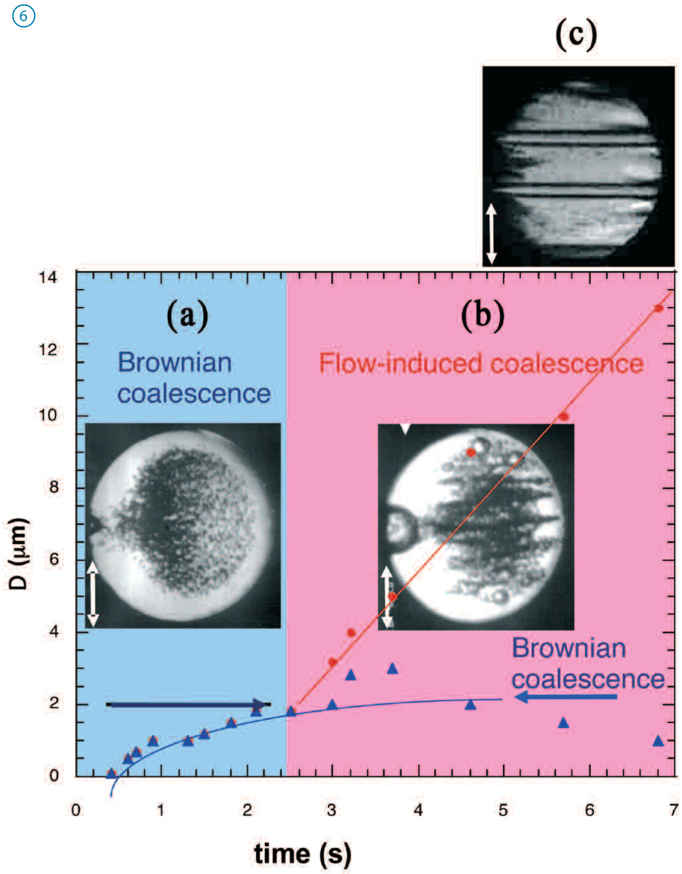

▶ **Fig. 6:** Evolution of a pattern of bubbles (volume fraction smaller than 30%). The double arrow represents the vibration. **(a)**: Lm < δ, no vibration influence, $t^{1/3}$ growth law . **(b)**: Lm > δ, vibration induces repulsion (parallel to vibration) and attraction (perpendicular to vibration) that creates a regular pattern of bubbles. In the layer, coalescence is reinforced by the attraction between bubbles, growth speeds up as a linear law. Between the bands, growth is still given by $t^{1/3}$. **(c)** Steady state. **From (a) to (c):** 3 mm diameter, 3 mm thickness H_2 sample under magnetic compensation of gravity and vibration 20.3 Hz frequency and 0.3 mm amplitude. **(d)**: 10 mm diameter, 10 mm thickness CO_2 sample in a sounding rocket free fall environment (vibration 42 Hz, 0.31 mm, 14 mK below the critical point, ESA Maxus-5 rocket, 2003).

The ins and outs of conical refraction

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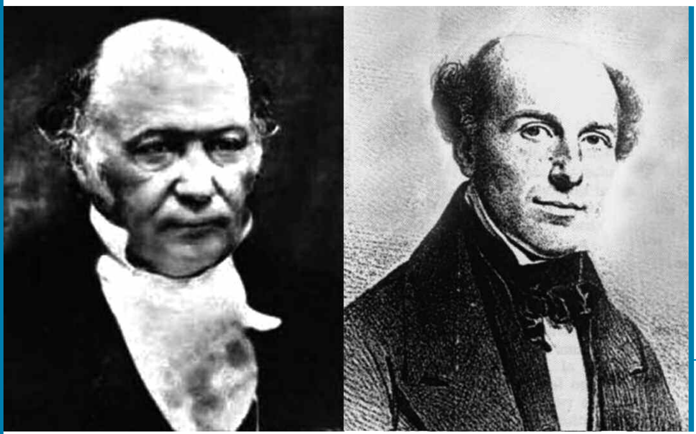
It was the Irish poet Aubrey de Vere (1814-1902), flushed with patriotic pride, who called conical refraction **"the radiant stranger"** in a florid passage in his memoirs. The two physicists responsible for the theoretical prediction and experimental confirmation of conical refraction were William Rowan Hamilton (1805-1865) and Humphrey Lloyd (1800-1881), both professors of Trinity College Dublin (fig. 1). Ireland's recent *Year of Hamilton* (2005) provided an opportunity for re-examining and celebrating their achievement.

Stripped to their essentials, two versions of conical refraction are shown in figure 2, adapted from Thomas Preston's *Theory of Light* (1890) [1]. In both cases a crystal causes a narrow beam of light to develop into a hollow cone, where a pair of rays might be expected from the theory of double refraction.

Unusually in science, other researchers do not seem to have had any vague premonition of the curious effect before Hamilton's insight and formal theory exposed it. By 1832 Fresnel's wave theory of light had become one of the most worked-over topics in physics, yet an important detail had escaped attention in both theory and experiment. Perhaps it is more excusable to overlook the effect in experiment since it requires a crystal that is both *biaxial* and of good optical quality. Moreover the effect is a small one in practice: the cones in figure 2 normally have angles of only a few degrees.

As for theory, many of Hamilton's contemporaries must have felt disappointed that they had failed to notice the anomaly. A Trinity colleague, James MacCullagh (1809-1847), was distraught to the point of launching a pointless retrospective campaign for credit. That failure, and his general eclipse by Hamilton, may have contributed to the eventual suicide of MacCullagh in 1847. Fresnel (1788-1827) did not live quite long enough to suffer any pangs of remorse at his oversight.

For Hamilton it was a crowning achievement, a realisation of his precocious promise [2]. For mathematical physics in general it was a significant milestone: arguably the first mathematical prediction of a novel physical property that was subsequently confirmed by experiment. It has been said that Hamilton claimed that his theory was so secure that it had no need of experimental validation. If he did say this, it must have been a rare jest from this serious man, for he did not regard the theory as a closed book. He did everything he could to encourage and assist Lloyd in his difficult task.



(a) (b)

◄ **Fig. 1:** **(a)** Sir William Rowan Hamilton 1862, **(b)** Humphrey Lloyd 1840.

Isaac Todhunter (1820-1884) once made a jocular remark that, having taught this subject all his life he did not want to have his ideas upset by a demonstration. Those ideas might well have been upset by some of what follows below.

Whether the conical refraction story was a triumph for the wave theory of light (as distinct from those theories based on particles) was debated at the time, but Hamilton's success certainly added momentum to its growing acceptance. The discovery was no paradigm shift, despite being totally unexpected. It was a confirmation of a growing orthodoxy.

James O'Hara, in his 1982 telling of the story, wrote that "it was little more than a curious optical phenomenon which had no conceivable application" [3]. After being highlighted in some of the optical textbooks of the 19th century, conical refraction had indeed been consigned to the lumber-room of miscellaneous minor curiosities. Preston's compendious work included it, but with no great drama. At about the same time Fletcher seems to have completely ignored it in his otherwise exhaustive treatment of double refraction, *The Optical Indicatrix and the Transmission of Light in Crystals* (1892).

However the topic did catch the attention of Raman in the 1940s when he investigated conical refraction in crystalline naphthalene and made an important contribution to its understanding [4].

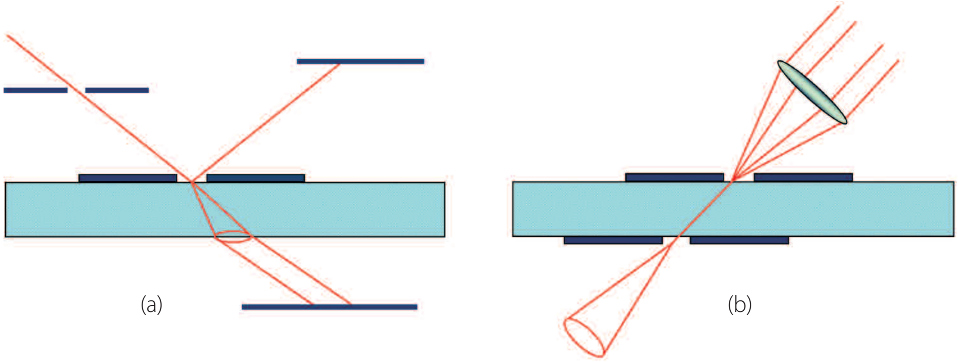
But lately conical refraction has been taken out and dusted off. Like most antique curiosities in physics, it contains further layers of intriguing detail if closely examined. Berry has pointed out that conical refraction is the first example of a wave singularity to be discussed in the scientific literature [5]. And in the age of lasers and optical communication the search is on for novel applications. A manufacturer of crystal optics, Vision Crystal Technology AG, is marketing a laser beam shaping device based on internal conical refraction. It seems likely that new applications will emerge to exploit the unique spatial distribution of intensity and polarisation which can be produced by conical refraction.

Essential Theory

Whether pursued with algebra (as Hamilton did) or with geometry (as many physicists would prefer), an understanding of conical refraction requires an extensive background of optical theory. Its literature, old and new, is obscured by an extraordinary variety and ambiguity of basic nomenclature that is not easily assimilated. So we will try to offer at least a friendly introduction.

From today's perspective, the heart of the matter is Maxwell's theory, applied to the propagation of light in a transparent (non-magnetic) medium, in our case a crystal. In general it allows a light wave to take the familiar plane-wave form, with wave-vector **k**, and field amplitudes **E**, **D**, **B**, **H**, just like a light wave in a vacuum, except for one significant difference. While **D**, **B**, and **H** are always to be oriented as in the vacuum, **E** can be canted at an angle, while remaining in the plane of **D** and **k**, as shown in figure 3. Maxwell allows this freedom, and no more.

For a given crystal, **E** is a function of **D** that is dictated by its dielectric polarisation properties. It is usually a very good approximation to assume that this is a linear function, but this does not



◀ **Fig. 2:** The optical configurations used by Lloyd for the observation of **(a)** internal and **(b)** external conical refraction (adapted from Ref. 1).

imply that the vectors **D** and **E** must point in the same direction. Except for cubic crystals and other isotropic materials, they do not.

So to find acceptable light waves for any direction of **k**, we must find directions of **D** (at right angles to **k**) such that **E** lies in the required plane. In a crystal of low symmetry we find *two* distinct directions for **D** and can proceed to construct two waves of different polarisation. Maxwell's theory then specifies the velocities for these waves.

Much of optics is described in terms of rays rather than plane waves. A ray is the path taken by a narrow beam of light: it travels in the direction of the vector **S** that Poynting introduced into Maxwell's theory. Just as we cannot assume that **E** is parallel to **D** in a crystal, neither can we assume that **S** is parallel to **k**. Rather, it is perpendicular to **E** and **H**, whereas **k** is perpendicular to **D** and **H**.

So a correspondence exists between the directions of rays and waves, but not a simple one in the case of a crystal of low symmetry. In general, two rays are associated with a wave of given direction, and vice-versa. Whenever rays are refracted, we may revert to consideration of the corresponding waves, for refraction is a wave property: incident and refracted waves must match at an interface.

The traditional geometrical representation of crystal optics proceeds from the *optical indicatrix*, expressing the **E**(**D**) relationship for the crystal, to two related and quite similar double-sheeted surfaces: the *wave-normal surface*, relating the magnitude of wave velocity to direction, and the *ray surface*, playing the same role for rays. As an example of the pitfalls of the nomenclature, "Fresnel's wave surface" is in fact the ray surface.

Figure 4(a) shows a beautiful and rare (perhaps unique) wire model of the double-sheeted wave-normal surface (or alternatively the ray surface) for a biaxial crystal: this is the lowest possible optical symmetry. Figure 4(b) shows a plaster model of part of the outer sheet of the same surface. A radial line drawn in most directions will encounter two parts of the wave surface, the inverse radii giving the velocities of two possible waves, of different polarisation.

But two directions (together with their opposites) are very special: only a single velocity is found. In this direction the inner and outer surfaces intersect as in a diablo – two shallow cones touching point to point (figure 5). These special lines are called the *optic axes of wave normals,* or *binormals* (or several other names), in the case of the wave-normal surface.

At first sight these binormals might seem less interesting than the general directions that yield two distinct wave velocities and hence are associated with double refraction, but Hamilton saw that even more exotic refractive properties are associated with the optic axes.

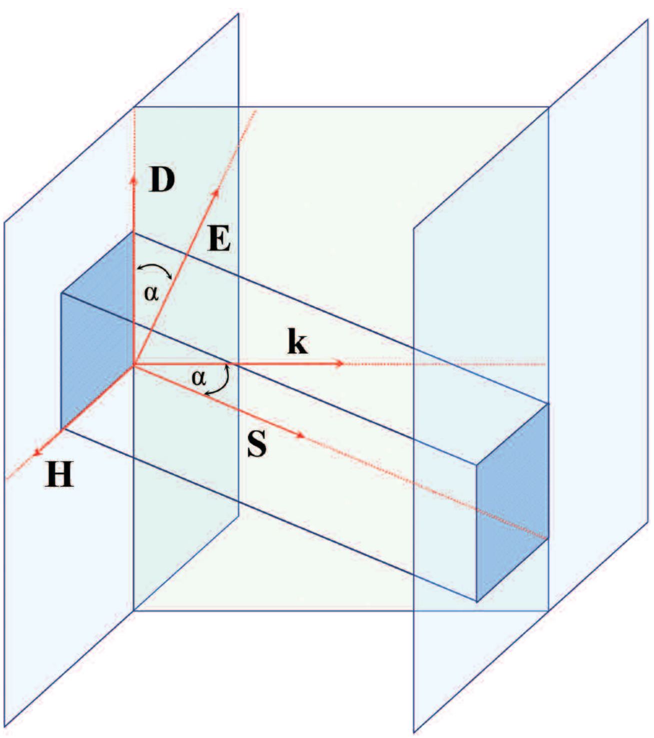
So what kind of waves can be constructed having this very special choice of wave vector? It turns out that *any* perpendicular direction of **D** is acceptable and that as we rotate it around **k**, the corresponding **E** vector describes a cone, as does **S** also. Recall that the Poynting vector **S** determines the direction of the corresponding rays. The rays associated with this special choice of wave vector are infinite in number and travel in all of the directions of a cone.

The ray surface has *biradial* lines like the binormals of the wave-normal surface. The biradial ray corresponds to waves whose directions are again disposed in a cone. The similarity of the two surfaces and close proximity of the directions of binormal and biradial lines is a further source of confusion that permeates the subject.

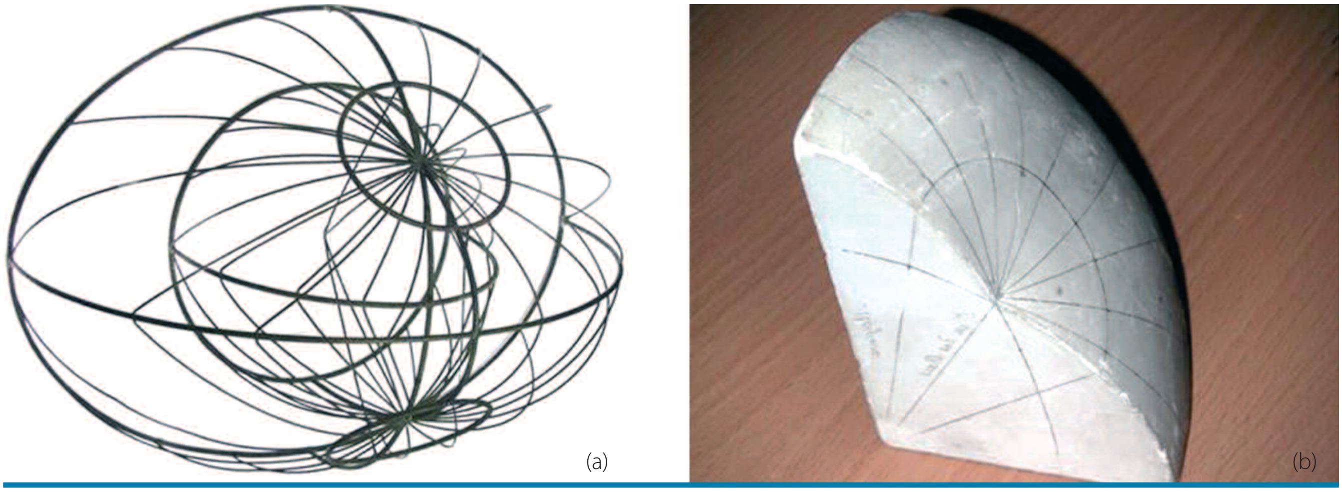
Conical refraction arises from the properties of these two kinds of special directions in the crystal. They require different experimental arrangements, as follows.

Internal conical refraction

Internal conical refraction is the case shown in figure 2(a). Its name is appropriate: the cone lies within the crystal. To set up an experimental demonstration, we must direct an incident beam so that a refracted wave would travel within the crystal in the direction of the binormal. So instead of one or two discrete rays, a diverging cone of rays fans out within the crystal. On leaving the back face they refract into a hollow cylindrical beam. That this final beam is perfectly circular is one of the strangest aspects of the effect; it is not related to any trivial symmetry. We have to resort to crystals of the lowest symmetry to produce this strikingly symmetric consequence! It goes against the grain of intuition.



▲ **Fig. 3:** Relative orientations of the vectors **E**, **D**, **H**, **k** and **S** associated with a plane electromagnetic wave (adapted from *Light* by Ditchburn [6]).



▲ **Fig. 4:** (a) Wire model of the double-sheeted wave-normal (or ray) surface of a biaxial crystal (courtesy of Ian Sanders, Trinity College Dublin). (b) Plaster model of the outer sheet of the same surface (courtesy of Colin Latimer, Queen's University Belfast).

External conical refraction

Lloyd first looked for external conical refraction, which produces a diverging hollow cone of light. For this, a beam must travel through the crystal along a biradial line, rather than a binormal.

In the arrangement shown in figure 2(b), pinholes allow only propagation along the required direction, and a lens focuses light on the front pinhole, so that some of its light is refracted in the necessary direction. This ray can be considered as a mixture of waves, whose directions form a cone. They refract at the back face and a cone of rays emerges, each ray associated with a refracted wave. Thrown up on a screen to form a circular image, this is the radiant stranger of 1832.

These experimental arrangements may today be simplified, if a crystal is cut so that its faces are normal to either the binormal or biradial directions. And lasers provide convenient bright beams, making demonstrations possible even on a large scale. Yuriy Mikhaylichenko of Tomsk University has made a speciality of this in recent years [7]. He has used crystals of sulphur in which the semiangle of conical refraction is quite large at about 3.5°.

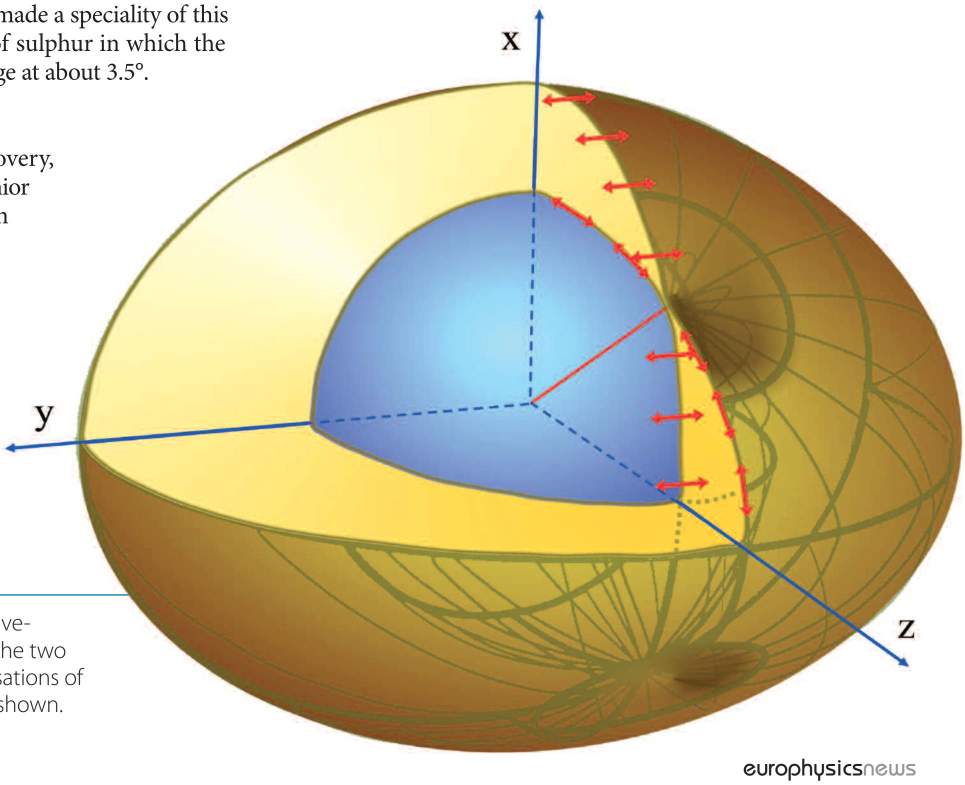
Hamilton's prediction

Although only 27 at the time of this discovery, William Rowan Hamilton was already a senior and celebrated academic. He had been diverted into the position of professor of astronomy, directing Dunsink observatory some 5 miles from Trinity College and rejoicing in the title of Royal Astronomer of Ireland, while still an undergraduate. The college politics of that extraordinary appointment remain obscure, but it did give the young man an opportunity to fully immerse himself in his mathematics. Provided, that is, that he was not obliged to take observational astronomy too seriously.

His first intensive research programme was in optics, which he explored with characteristic rigour and originality. Out of that programme, in the fourth of a series of papers, came conical refraction in 1832. It was to become a favourite topic of correspondence between Hamilton and Peter Guthrie Tait (1831-1901) of Edinburgh, now available in a collection of their letters edited by David Wilkins [8].

Lloyd's experiments

In 1832 Hamilton's colleague Humphrey Lloyd had recently taken up the chair of natural and experimental philosophy at Trinity, following his father Bartholomew Lloyd in a distinguished career as an academic scientist and eventually as provost. His early career was devoted to optics, which he saw as a wonderful probe of the physics of materials, not just a set of rules for the propagation of light. So he eagerly grasped the opportunity to provide experimental confirmation for Hamilton.



► **Fig. 5:** Diagram of the double-sheeted wave-normal surface showing the intersection of the two sheets and one of the binormals. The polarisations of waves propagating in the x-y plane are also shown.

He had no success until he obtained a particularly good crystal of aragonite from a commercial supplier. With this he demonstrated external conical refraction, measuring a cone angle of about 3 degrees, as predicted. Lloyd was a thorough experimentalist, a fitting counterpart to Hamilton the systematic theorist. Not content with seeing the phenomenon as predicted, he examined the polarisation of the emergent light, and was surprised to find that "every ray of the cone was polarised in a different plane", as is shown in figure 6(b). Hamilton had passed over this obvious consequence of his theory.

Lloyd encountered much more difficulty when he tackled internal conical refraction, which is the favourite today, but he soon enjoyed the same success. He gave a full account of both experiments in the Proceedings of the Royal Irish Academy (1833), and a more public airing at the meeting of the British Association for the Advancement of Science (1834), on the same occasion that he presented his authoritative report on "the progress and present state of physical optics". It was a triumph for the tiny community of Dublin physicists, and may have influenced the decision to bring that Association's meeting to the city in the following year, in spite of some opposition. It must have been reckoned worth a rough sea crossing to an unruly country, to visit the home of Hamilton. It was at the meeting that, as reported by Robert Perceval Graves, "Lord Normanby, then Lord Lieutenant, seized, with a happy tact, the opportunity of paying a most handsome compliment both to Professor Hamilton and to Ireland, by conferring the foremost representative of our nation's science, and in the face of the assembled Association, with the honour of knighthood" [9].

The finer details

As early as 1839, the bright ring exhibited by internal conical refraction was resolved by the experiments of Poggendorf into two concentric rings (Everything seems to come in twos in this subject). Figure 6(a) shows the distribution of intensity produced by internal conical refraction in a 2 cm long crystal of $KGd(WO_4)_2$. The same is true of the external case, though Lloyd did not observe this double ring structure, since the size of the optical apertures in his experiment caused the two circles to be blurred. With modern equipment, additional fainter rings are discernible and Lloyd's simple manifestation of the effect has become a complex pattern, offering a fresh challenge to theoreticians.

The extra structure appears because the light beams that are used are of finite extent, rather than those idealised rays, mere lines, upon which the elementary theory is based. The modern methodology of Gaussian (and related) laser beams can provide an adequate representation of the finite beam, and its propagation can be computed in full and compared with experiment [10 - 12].

Conclusion

Often in constructing (or deconstructing) the history of science, the story is edited for the sake of clarity. J. J. Thomson did not discover the electron on a certain day in Cambridge, but we tell it so. The case of conical refraction is an exception, in which the revelatory process is unambiguous, and priority is sharply defined - in spite of the anguished protestations of MacCullagh. It is a tale of two virtuous and dedicated scientists who richly deserved the accolades that they received. It is a tale worth recounting, for generations to come. The emergence of the radiant stranger can still startle, entertain and educate us. ■

About the authors

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Acknowledgements

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References

[1] T. Preston, *Theory of Light* (Macmillian & Co.) (1890).

[2] D.R.Wilkins, *Physics World*, August (2005).

[3] J O'Hara, *Proceedings of Royal Irish Academy*, **82A**, 231, (1982).

[4] C.V. Raman, V.S. Rajagopalan and T.M.K. Nedungadi, *Proc. Ind. Acad. Sci.* **A14**, 221, (1941).

[5] M.V. Berry, *Nature*, **403**, 21, (2000).

[6] R.W. Ditchburn, *Light*, (Academic Press) (1976).

[7] Y.P. Mikhaylichenko, *Izv. Vuzov. Physika*, **No. 6**, 96, (2000) [in Russian].

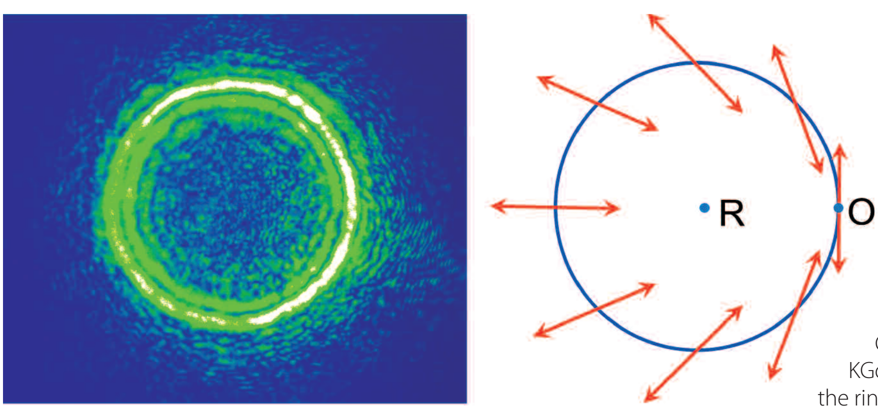
[8] D.R Wilkins, *Perplexingly easy: selected correspondence between William Rowan Hamilton and Peter Guthrie Tait*, (Trinity College Dublin Press and School of Physics, Trinity College Dublin) (2005).

[9] R.P. Graves, *Dublin University Magazine*, **19**, 94, (1842).

[10] A.J. Schell and N. Bloembergen, *J. Opt. Soc. Amer.* **68**, 1093, (1978).

[11] M.V. Berry, *J. Optics A*, **6**, 289, (2004).

[12] M.V. Berry, M.R. Jeffery and J.G. Lunney, *Proc. Roy. Soc.* (to be published).



◀ **Fig. 6:** (a) Beam profile produced by internal conical refraction of a 532 nm Gaussian laser beam in a 2 cm long crystal of $KGd(WO_4)_2$. (b) Variation of the polarisation around the ring-shaped light beam.

NEMO in Amsterdam, outreach on the waterfront

Marieke Hohnen (science center NEMO) and **Jo Hermans** (Leiden University)

For the unsuspecting tourist visiting Amsterdam's harbour, it may look like a huge green ship emerging from the water. For locals, NEMO is well known as the leading National Science Centre. But for the crowds of children pouring daily into NEMO, it means an exciting trip to the many wonders of a discovery paradise, on the interface between reality and fantasy.

Designed by Italian architect Renzo Piano - well known, *e.g.*, for the Pompidou Centre in Paris and Berlin's Potsdamer Platz – it opened in 1997, and was originally baptized New Metropolis. It is conveniently located at a 10-minute walk from Amsterdam's railway station. Once inside, the visitor is immersed in a lively ocean of exhibits. They are designed to surprise, to puzzle, and to amuse. And, yes: to teach something in the process. But, being meant primarily for children, the first goal is to tease them, to raise their curiosity, to make them think and wonder why.

NEMO is no traditional Science Museum: it has no historic collection that has to be shielded from curious hands. On the contrary, visitors are encouraged to touch everything. All exhibits are interactive: *hands-on, minds-on* is the key. Some are standard experiments that every physicist knows, ranging from optical illusions to angular momentum conservation tricks. But there are also permanent exhibitions featuring specific themes. Examples include, *e.g.*, '*You, me, electricity*', about electricity and magnetism and their tremendous impact on communication technology. Another exhibition explains the role of hydrogen as an energy storage medium, showing the complete cycle from electrolysis to fuel cells, and allowing children to make their own hydrogen.

NEMO also looks beyond Physics: one exhibition focuses on DNA, for example, and another one ('Teen facts') on adolescence. All accompanying texts are in both English and Dutch. Additional educational material and lessons connected with the exhibits can be downloaded from the web site.

An important outreach activity is a lecture series for primary school children, so-called 'Wake-up lectures' on questions like *Why do we have tides?* and *Why is snow white?* Experiments are an important part of these lectures, which are more like a discussion between the children and lecturer than a conventional lecture. The lecturers are scientists and professors from the University of Amsterdam. Interestingly enough, the age of the scientist seems irrelevant. For children that age, 8-12 years, *everybody* is old, whether Ph.D. student or emeritus professor. Enthusiasm is more important than age.

During school holidays, NEMO uses its theatre for Science shows, such as *Spooky Sparks* on static electricity. In addition, it organizes a *Take-it-apart Lab*, where children are invited to disassemble domestic appliances and find out how they work, and a *Test Lab*, where children can build small boats and cars and modify them to improve their performance.

NEMO has about 315 000 visitors a year (which amounts to 2% of the population of Holland). Approximately 35% consists of organized school visits. NEMO also hosted the main event of the World Year of Physics in The Netherlands: *Science Unlimited*, a large discovery festival featuring some 70 exhibits from universities and industry.

But, as may be clear from the above: vibrant outreach continues. Especially for children: they are having a great time.

NEMO is open Tuesday through Sunday 10:00 to 17:00 (daily during vacations). ■

Address: Oosterdok 2; www.e-NEMO.nl

▲ The NEMO building
◀ Electrostatics in action!

Fusion – the energy of the universe

Jo Lister, Lausanne, Switzerland

This book outlines the quest for fusion energy. It is presented in a form which is accessible to the interested layman, but which is precise and detailed for the specialist as well.

The book contains 12 detailed chapters which cover the whole of the intended subject matter with copious illustrations and a balance between science and the scientific and political context. In addition, the book presents a useful glossary and a brief set of references for further non-specialist reading.

Chapters 1 to 3 treat the underlying physics of nuclear energy and of the reactions in the sun and in the stars in considerable detail, including the creation of the matter in the universe. Chapter 4 presents the fusion reactions which can be harnessed on earth, and poses the fundamental problems of realising fusion energy as a source for our use, explaining the background to the Lawson criterion on the required quality of energy confinement, which 50 years later remains our fundamental milestone.

Chapter 5 presents the basis for magnetic confinement, introducing some early attempts as well as some straightforward difficulties, treating both linear and circular devices. The origins of the stellarator and of the tokamak are described. Chapter 6 is not essential to the mission of usefully harnessing fusion energy, but nonetheless explains to the layman the difference between fusion and fission in weapons, which should help the readers understand the differences as sources of peaceful energy as well, since this popular confusion remains a problem when proposing fusion with the "nuclear" label. Chapter 7 returns to energy sources with laser fusion, or inertial confinement fusion, which constitutes both military and civil research, depending on the country. The chapter provides a broad overview of the progress right up to today's hopes for fast ignition.

The difficulty of harnessing fusion energy by magnetic or inertial confinement has created a breeding ground for what the authors call "false trails", since it is so tempting to produce a "backroom" solution to mankind's hunger for energy. Unfortunately, Chapter 8 can only regret that none of them has passed closer peer review.

Chapters 9 and 10 concentrate on the "tokamak" concept for magnetic confinement, the basis for the JET and ITER projects, as well as for a wealth of smaller, national projects. The hopes and the disappointments are well and very frankly illustrated. The motivation for building a project of the size of ITER is made very clear. Present fusion research cannot forget that its mission is to develop an industrial reactor, not just a powerful research tool. Chapter 11 presents the major challenges in getting from ITER to a reactor.

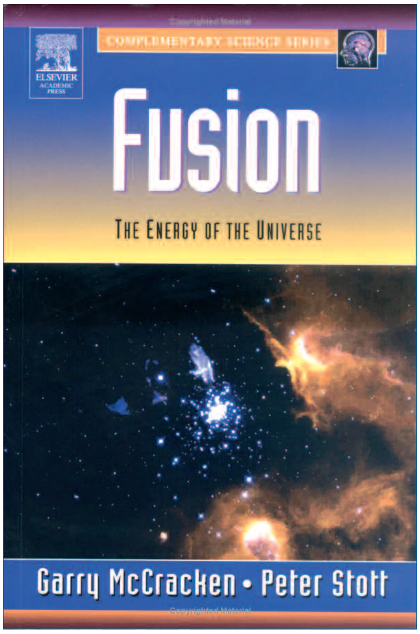
Finally, Chapter 12 reminds us of why we need energy, why we do not have a credible solution at the mid-term (20 years) and why we have no solution in the longer term. The public awareness of this is growing, at last, even though the arguments were all on the table in the 1970's. This chapter therefore closes the book by bringing the reader back to earth rather suitably with the hard reality of energy needs and the absence of credible policies.

This book has already received impressive approval among a wide range of people, since it so evidently succeeds in its goal to explain Fusion to many levels of reader. Gary McCracken and Peter Stott both dedicated their careers to magnetic confinement fusion, mostly at Culham working on UKAEA projects and later on the JET project. They were both deeply involved with international collaborations and both were working abroad when they retired. The mixture between ideas, developments and people is most successfully developed. They clearly underline the importance of strong international collaboration on which this field depends. This open background is tangible in their recently published work, in which they have tried to communicate their love and understanding of this exciting field to the non-specialist. Their attempt has resulted in a remarkable success, filling a hole in the available literature.

The format of this book, with boxed technical details, allows the casual reader to browse without being trapped by excessive detail, whereas the information is still there for the more assiduous reader. The only technical fault is the marring of the presentation by some unresolved production details in chapter 10.

With the long-awaited decision to site ITER in Europe, there will inevitably be a strong demand for more information on fusion research for non-specialists, simply to understand what is behind this large project. This book fits the bill. It is written with technical accuracy but without resort to mathematics – a notably tricky target. The non-specialist wishing to find out about the field of fusion research, whether working as a journalist, administrator, secretary, politician, engineer or technician, will find a wealth of detail expressed in an accessible language. The specialist will be surprised by the precision of the text, and by the depth of the historical basis to this research. He will learn much, even if he is already familiar with the current state of art of fusion research. The younger researchers will find a clear history of their chosen field.

The reviewer knows of no other book which has met this difficult goal with such ease, and strongly recommends it to the educated layman as well as to the ITER generation of younger physicists who did not live through the evolutionary period of fusion research, with its doubts, disappointments and successes. ■



Gary McCracken and Peter Stott, Elsevier Complementary Science Series, 2005. 224 pages.