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Special issue on exoplanets
Vitrimers
30 years of moving atoms
Anniversary of PAO
Emmy Noether Distinction

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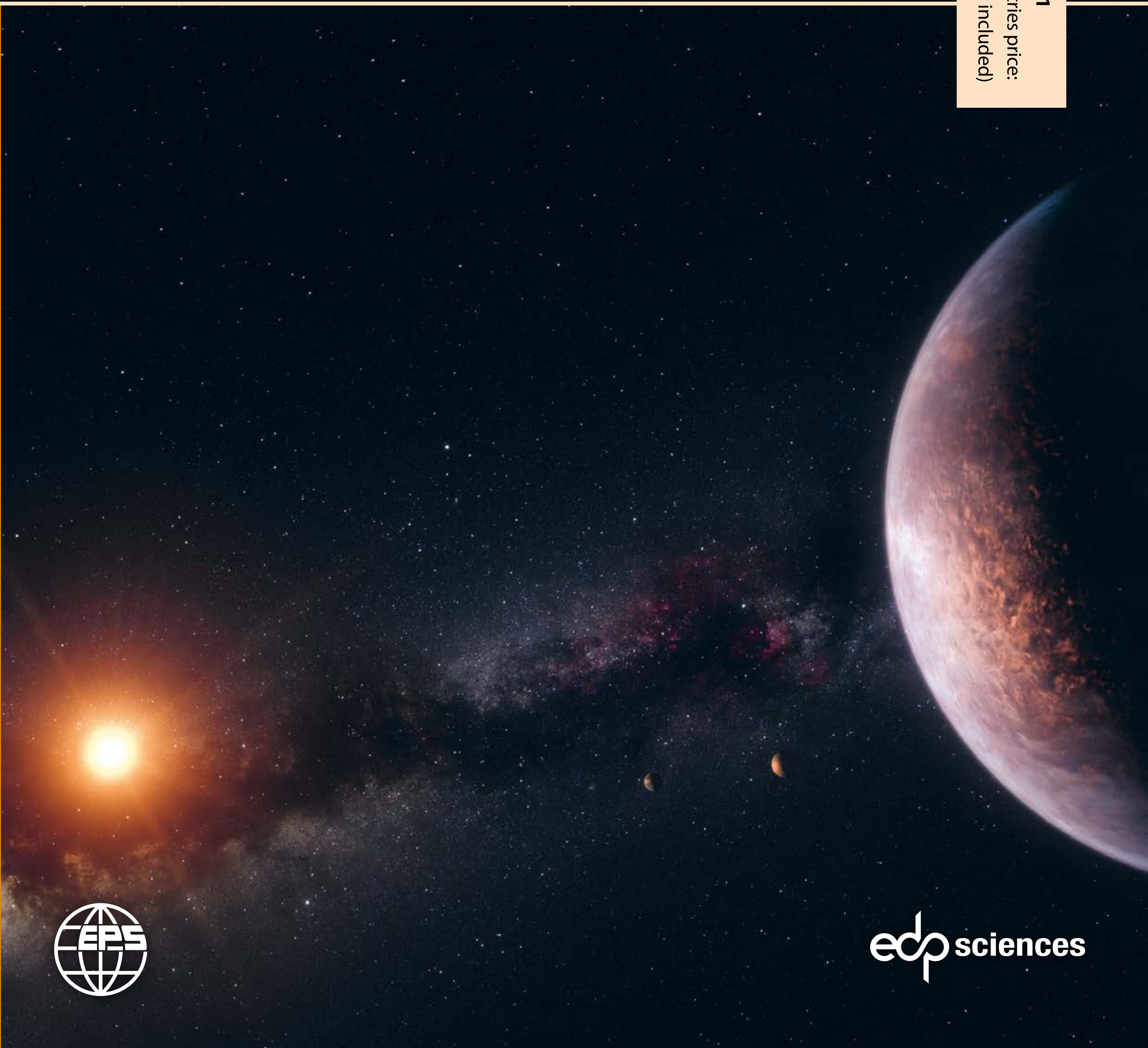

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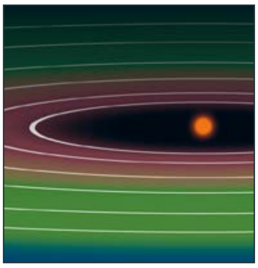
Cover picture: This artist's impression shows several of the planets orbiting the ultra-cool red dwarf star TRAPPIST-1. New observations, when combined with very sophisticated analysis, have now yielded good estimates of the densities of all seven of the Earth-sized planets and suggest that they are rich in volatile materials, probably water. © ESO/M. Kornmesser



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Extrasolar planets: from dust to new worlds

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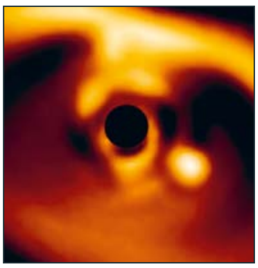
The search for extraterrestrial life



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The cradles of planet formation

[EDITORIAL]

Careers with a Physics Degree

In 1990, the World Wide Web (WWW) was invented at CERN by the physicist Tim Berners-Lee. The objective at the time was to create a network for sharing information between physicists around the world. But that network changed the life of everybody. It impacted our lives, and improved our access to information.

We all have now at our fingertips a "macroscope" where we can search for input to make decisions and conduct our social life and work. The internet is the most compelling example of how careers in physics can lead to unexpected turns and be truly transformative at a global level. The internet took the place of the *Encyclopédie* of the Enlightenment. For Diderot, the *Encyclopédie* aimed at changing how people thought. The online information is much broader than information in print and its diffusion is almost instantaneous. This is indeed changing very quickly how people think, and it is also changing their professions.

Throughout human history, professions were established to cope with unequal distribution of knowledge, of both *know-what* and *know-how*. A single human being cannot know or do everything, and many professions became increasingly specialised. Nowadays, the internet, as well as the use of nano-devices and new materials, are changing many professions again.

Medicine is a showcase. For instance, telemedicine is growing, gene editing promises to prevent and cure diseases, 3D printing is making the fabrication of implants simpler and more precise, and, as predicted by Richard Feynman, in the future nano-robots will be surgeons that we will literally eat. Once these resources will be largely available and automatised, general practitioners will be more needed than specialists.

Also the profession of the physicist is being re-shaped. Increasingly, more value is given to large-scale simulations of complex systems than analyses based on simplified models. Humans have intrinsic limitations in interpreting large volumes of data. But with machine learning and artificial intelligence algorithms, physicists can work with big data sets in a great variety of problems, making them more like general practitioners than specialists. Available information on large groups can be used to model social behaviour and hopefully lead to the early detection of potentially critical situations, such as the spread of epidemics. In the natural world, new systems of monitoring the earth's oceans and atmosphere produce massive amounts of data that contain the clues to predict catastrophic events. In these processes, ethics and law will become closely intertwined with physics. Max Planck, Enrico Fermi and Lise Meitner, among others, belonged to the last generation of physicists that tackled both experimental and theoretical problems. Nowadays, the normal path in the training of a physicist, from generalist to specialist, is inverting. The general tools of physics tend to bring back the "general" physicist. The alliance of physics to computation and data analytics accentuates this trend.

This 4th Industrial Revolution brought new technologies that blend the physical, digital and biological worlds, impacting all fields, industry and the economy, and may even change our views on what it means to be human. On the brink of this revolution, universities started offering degrees in Engineering Physics, or a track in Engineering Physics within Engineering Sciences degrees. Stanford and Harvard in the US and KTH in Sweden are examples. In Portugal, all Science and Engineering Schools, including *Instituto Superior Técnico* (IST) at the University of Lisbon, created such a degree in the mid 1980's. Engineering Physics is a form of crafting physics into innovative applications and industrial research. Computational, analytic and experimental tools are the basis of Physics and Engineering Physics training. Majors in Engineering Physics are featured as delivering professionals to work on forefront ideas in technology and science, in either industry or academia. The presented areas of work include aerospace, biophysics, medical physics, renewable energy, quantum information, and materials development. IST graduates in Portugal, where industry provides only very few scientific jobs, very often find career opportunities in science policy and government, science writing, software engineering, banking and risk analysis, consulting in health care, telecommunications, and financing sectors. Many of them created start-up companies in bioengineering technologies and renewable energy production, and others hold academic positions, frequently abroad.

If interdisciplinarity is essential in engineering physics, it is no less so in physics. For instance, links between astroparticle, nuclear and particle physics are needed for questions on dark matter as well as on the physics of gravitational waves. On the technological front, investigating the invisible "extremely small" provides instruments useful for medical applications and radiation safety. In physics, as in other professions, the 4th Industrial Revolution is challenging the paradigm of specialisation. It embraces Richard Feynman's vision: "A poet once said, 'The whole universe is in a glass of wine.' (…). But it is true that if we look at a glass of wine closely enough we see the entire universe. If our small minds, for convenience, divide this glass of wine, this universe, into parts — physics, biology, geology, astronomy, psychology, and so on — remember that nature does not know it! So let us put it all back together, not forgetting ultimately what it is for." ■

■ **Teresa Peña,**
IST, Universidade de Lisboa, Department of Physics and Department of Nuclear Sciences and Engineering, and LIP

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Vitrimers: combining the best of both polymeric worlds

Vitrimers are a promising new type of polymer glasses that combine the recyclability of thermoplastics with the high mechanical performance of thermosets. At the heart of their exceptional material properties lies highly unusual glass-forming behaviour.

Polymers are conventionally classified as either thermosetting or thermoplastic, depending on whether the polymer chains are covalently cross-linked or not. Each class has its own advantages: thermoplastics are generally easily malleable and recyclable, whereas cross-linked thermosets are insoluble and mechanically robust. With the recent advent of vitrimers—a polymer glass invented by Ludwik Leibler and co-workers [1]—it is now possible to combine the best of both polymeric worlds. Vitrimers are covalently cross-linked polymer networks, but the cross-linking bonds can swap reversibly by thermally activated reactions. This enables vitrimers to behave as viscoelastic liquids at high temperatures and as rigid thermosets as low temperatures, culminating in a recyclable yet high-performance plastic with vast application potential.

Fragility

The exceptional processability and recyclability of vitrimers is manifested in the so-called fragility—an empirical property that quantifies how rapidly a glass-forming material changes from liquid to amorphous solid upon cooling. Materials in the 'fragile' category solidify rather abruptly, whereas 'strong' glass formers vitrify in a more gradual manner. Curiously, while many glassy polymers are fragile, vitrimers turn out to be 'superstrong', solidifying even more gradually than the prototypical strong glass-former silica. This behaviour not only constitutes a striking departure from conventional glassy phenomenology, but it also explains in part why vitrimers are so easy to process: a superstrong fragility implies a very broad glass-transition-temperature range, creating a large temperature window in which the material can be molded and (re)shaped.

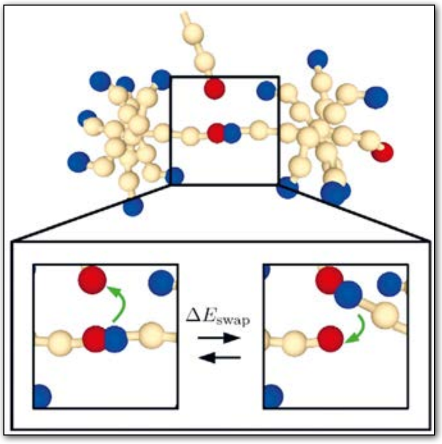
▲ Vitrimer samples. © CNRS Photothèque / ESPCI / Cyril FRÉSILLON

In-silico vitrimers

How can we better understand the remarkable glass-forming properties of vitrimers from a molecular perspective? A recent study addresses this question using computer simulations and theory [2]. First, to mimic vitrimers *in silico*, a coarse-grained simulation model was developed that represents vitrimers as cross-linked star-polymer networks; the vitrimeric bond-swapping functionality was implemented through a three-body potential that preserves the total number of bonds. Interestingly, the simulations could reproduce the anomalous superstrong fragility of experimental vitrimeric materials, thus capturing the main phenomenology of vitrimers in a minimal computational model. But the simulations also predicted another effect: by increasing the bulk density by a factor of 2-3, the simulated vitrimers were found to solidify as a strong or even fragile glass former upon cooling. This suggests that the bulk density may provide a suitable control parameter to tune the vitrimer fragility and even induce a superstrong-to-fragile crossover—a prediction that will hopefully also be tested in experiment.

Linking structure to glassy dynamics

Next, to elucidate the microstructural origins of the vitrimeric fragility, the simulation results were subjected to a theoretical analysis. To this end, an approximate but purely first-principles-based theory of the glass transition was employed—so-called Mode-Coupling Theory (MCT). Briefly, this theory seeks to predict the glassy relaxation dynamics of a material (as a function of time, temperature, density, and wavevector k) using only simple microstructural information—such as the static structure factor $S(k)$—as input. Hence, MCT provides a fit-parameter-free framework to rationally relate structural properties to dynamical ones. By taking the simulated static structure factors of the vitrimers as input, MCT could predict the same fragilities as observed in simulation: fragile vitrimer behaviour at high densities, strong behaviour at intermediate densities, and superstrong behaviour at low densities. This result is *a priori* surprising, as MCT is conventionally assumed to



▲ Vitrimer simulation model [2].

only account for fragile behaviour. Furthermore, the striking agreement between theory and simulation made it possible to establish a direct link between the vitrimer microstructure and the fragility—a link that still remains elusive for most glass-forming materials.

Suppressed cage effect

A detailed analysis of the MCT results revealed the physical origin of the anomalous fragility of vitrimers, as well as of the superstrong-to-fragile crossover induced by increasing the bulk density. The key underlying structural property was found to be the main peak of the static structure factor, $S(k_0)$, where k_0 corresponds to the average (inverse) nearest-neighbour distance. Briefly, within conventional MCT, a growing $S(k_0)$ peak gives rise to the so-called cage effect: particles become trapped in local cages formed by their nearest-neighbours, causing a non-linear dynamical slowdown and eventual kinetic arrest across all length scales. It was found that a significant growth of $S(k_0)$ upon cooling indeed led to a rapid slowdown of the vitrimer dynamics, most notably in the high-density (fragile) regime. Interestingly, however, at *low* vitrimer densities, the temperature-dependent growth of $S(k_0)$ became anomalously weak—almost logarithmic with inverse temperature—, thus causing a *suppression* of the cage effect. This in turn resulted in a far more gradual dynamical slowdown and an extremely low fragility. The same MCT analysis also provided an explanation for the observed fragile-to-superstrong crossover in simulation: as the bulk density decreased, nearest-neighbor correlations encoded in $S(k_0)$ became less sensitive to temperature variations, leading to a weakening of the cage effect and a manifestly lower fragility.

The results of this study [2] reveal some unusual aspects of glass formation in a model system of vitrimers. It is hoped that future experiments will test some of these predictions, in particular the role of the density as a tunable fragility parameter, and the anomalously weak growth behaviour of the static structure factor in superstrong materials. Such a combined experimental and theoretical approach holds exciting potential for the ultimate rational design of the next generation of recyclable high-performance polymer materials. ■

Liesbeth M. C. Janssen
Eindhoven University of Technology, The Netherlands

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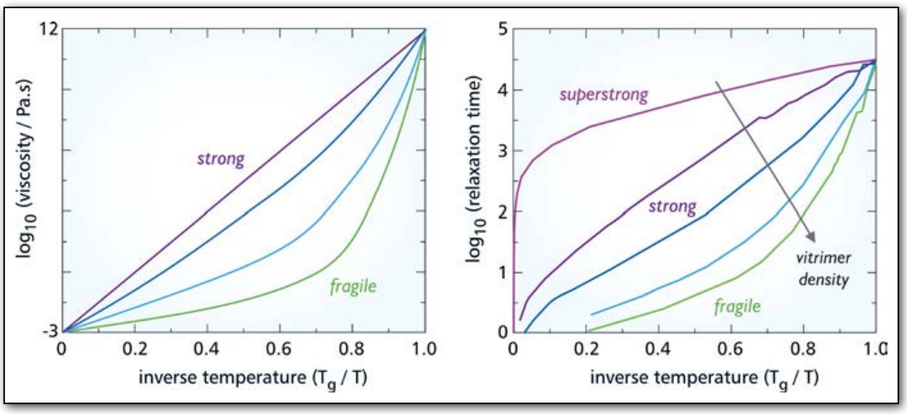
[1] D. Montarnal, M. Capelot, F. Tournilhac, and L. Leibler, *Science* **334**, 965 (2011).

[2] S. Ciarella, R.A. Biezemans, and L.M.C. Janssen, *Proc. Natl. Acad. Sci. USA* **116**, 25013 (2019).

▼ Conventional fragility classification (left) and vitrimer fragilities obtained from simulation (right) [2].



Doubt cast on 'dark energy'

The observed acceleration of the Hubble expansion rate has been attributed to a mysterious 'dark energy' which supposedly makes up about 70% of the universe. A new analysis of 740 supernovae shows that this acceleration is a local effect – it is directed along the same direction we appear to be moving with respect to the cosmic microwave background, which exhibits a similar dipole anisotropy. Thus a Cosmological Constant or dark energy cannot be invoked as explanation for cosmic acceleration.

This article is an edited version of a news item at the website of the Mathematical, Physical and Life Science Division of the University of Oxford. Permission for publication in EPN was given by S. Sarkar.

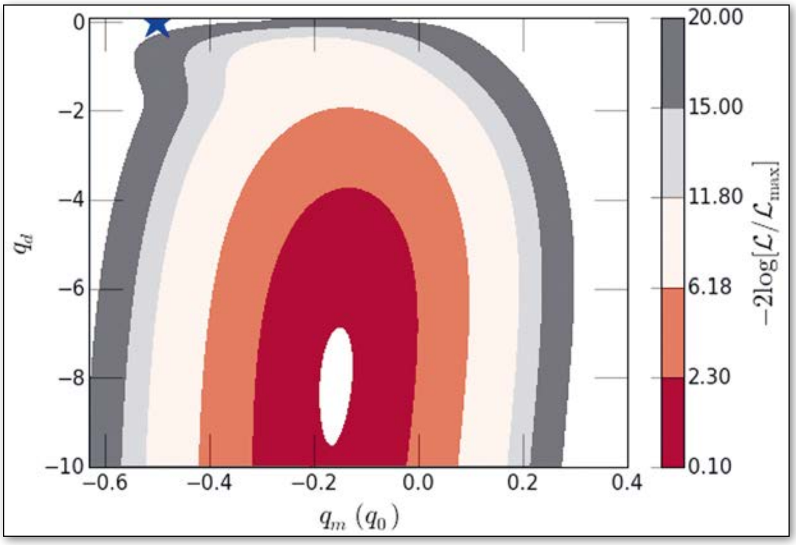
The Cosmological Constant problem

The cosmological standard model rests on the assumption that the Universe is isotropic around all observers. This 'Cosmological Principle' is an extension of the 'Copernican Principle' – namely that we are not privileged observers. It affords a vast simplification in the mathematical construction of the cosmological model using Einstein's theory of General Relativity. However, when observational data are interpreted within this framework we are led to the astonishing conclusion that about 70% of the universe is constituted of Einstein's Cosmological Constant or more generally 'dark energy'. This has been interpreted as due to quantum zero-point fluctuations of the vacuum but the associated energy scale is set by H_0, the present rate of expansion of the universe, which is a factor of 10^{44} below the energy scale of the Standard Model of particle physics – the well-established quantum field theory that precisely describes all subatomic phenomena. Its zero-point fluctuations have therefore a huge energy density which would have prevented the universe from reaching its present age and size if they were to indeed influence the expansion rate via gravity.

The "Why now?" problem

To this well-known 'Cosmological Constant problem' must be added the 'Why now?' problem, namely why has dark energy come to dominate the universe only recently? It was negligible at early times, for example at an age of ~400,000 years when the primordial plasma cooled enough for atoms to form and the cosmic microwave background (CMB) radiation was released. Hence, the CMB is not directly sensitive to dark energy.

> **A Cosmological Constant or dark energy cannot be invoked as explanation for cosmic acceleration**



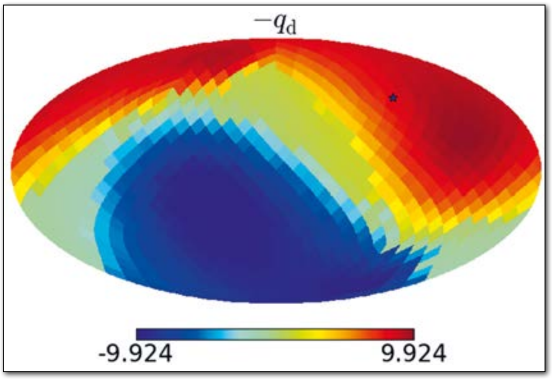
◂ **FIG 1.** The cosmic 'deceleration parameter' inferred from the JLA catalogue of Type Ia supernovae is negative (*i.e.* the expansion rate is accelerating), but as seen in the left panel it is mainly a dipole (q_d) *i.e.* in a specific direction, while its monopole (q_m) component is close to zero. The current 'standard cosmological model' (indicated by a blue star) which has q_m = -0.55, q_d = 0, is excluded at over 4σ.

Using a data sample of 740 supernovae

It is against this background that Jacques Colin & Roya Mohayaee (Institut d'Astrophysique, Paris), Mohamed Rameez (Niels Bohr Institute, Copenhagen) and Subir Sarkar (University of Oxford), set out to examine whether dark energy really exists. The primary evidence – rewarded with the 2011 Nobel prize in Physics – concerns the *"discovery of the accelerated expansion of the universe through observations of distant supernovae"* in 1998 by two teams of astronomers. This was based on observations of only about 60 Type Ia supernovae but meanwhile the sample has grown to 740 objects scattered over the sky for which the data is public ('Joint Lightcurve Analysis' catalogue). The researchers looked to see if the inferred acceleration of the Hubble expansion rate is in fact uniform over the sky. First they worked out the supernova redshifts and apparent magnitudes as measured (in the heliocentric system), undoing the corrections that had been made in the JLA catalogue for local 'peculiar' (non-Hubble) velocities. This had been done in an attempt to determine their values in the 'CMB frame' in which the universe should look isotropic – however previous work by the team had shown already that such corrections are suspect because these peculiar velocities do not fall off with increasing distance as they should, so there is no convergence to the CMB frame even as far out as a billion light years. Whether the CMB dipole is of kinematic origin is itself in doubt, as *e.g.* high redshift radio sources exhibit one that is 4 times bigger.

Dark energy

When the researchers analysed the reconstructed data employing the standard 'Maximum Likelihood Estimator' to quantify the most probably values of the parameters they made an astonishing finding. The supernova data indicate, with a statistical significance of 3.9σ a clear dipole anisotropy in the inferred acceleration (see figure 1) in the same direction as we are moving locally, which is indicated by a similar, well-known, dipole in the CMB. By contrast any isotropic acceleration (which can be ascribed to dark energy) is about 50 times smaller and consistent with being zero at only 1.4σ.



▲ **FIG 2.** Within uncertainties the acceleration vector is aligned with the dipole (q_d) in the cosmic microwave background radiation (indicated as a black star).

Unexpected local flow

This data-driven analysis supports the theoretical idea propounded by Christos Tsagas (University of Thessaloniki) that we infer acceleration because we are not Copernican observers but are embedded in a local 'bulk flow' (shared by nearby galaxies). This is unexpected in the standard cosmological model and the reason for such a flow remains unexplained. But independently of that it appears that the acceleration is an artefact of our local flow and cannot be attributed to a Cosmological Constant or dark energy.

More data expected

Forthcoming observations will be able to confirm or rule out this finding. The forthcoming *Large Synoptic Survey Telescope* will measure many more supernovae and be able to check at even higher significance if the dipole in fact exists. The *Dark Energy Spectroscopic Instrument* and *Euclid* satellite will measure the subtle imprint of 'Baryon Acoustic Oscillations' in the distribution of galaxies precisely and test the standard cosmological model further. The *European Extremely Large Telescope* will measure the 'redshift drift' of distant sources over time and thus make a direct measurement of the expansion history of the universe. ■

Reference:

[1] J. Colin, R. Mohayaee, M. Rameez & S. Sarkar, *Astronomy & Astrophysics Letters* **631**(2019) L13 (https://doi.org/10.1051/0004-6361/201936373)

THE VERA C. RUBIN OBSERVATORY - FORMERLY LSST

On 6 January 2020 it was announced that the Large Synoptic Survey Telescope (LSST) was named the Vera C. Rubin Observatory in honor of the famous astronomer who provided important evidence of the existence of dark matter. It is the first US National Observatory named after a women. The Vera C. Rubin Observatory, currently under construction in Chile, will allow for studying dark energy and dark matter by measuring gravitational lensing, baryon acoustic oscillations and photometry of type Ia supernovae as function of redshift. With the telescope, astronomers will conduct a deep survey over a large area of the sky by making repeated images of the visible sky every night during ten years. It will build astronomical catalogs thousands of times larger than ever previously been compiled. The data will become available for everyone interested. The telescope is scheduled for science operation early 2022. Scientific motivation and design details can be found in https://arxiv.org/pdf/0805.2366.pdf. ■

Website: https://www.lsst.org
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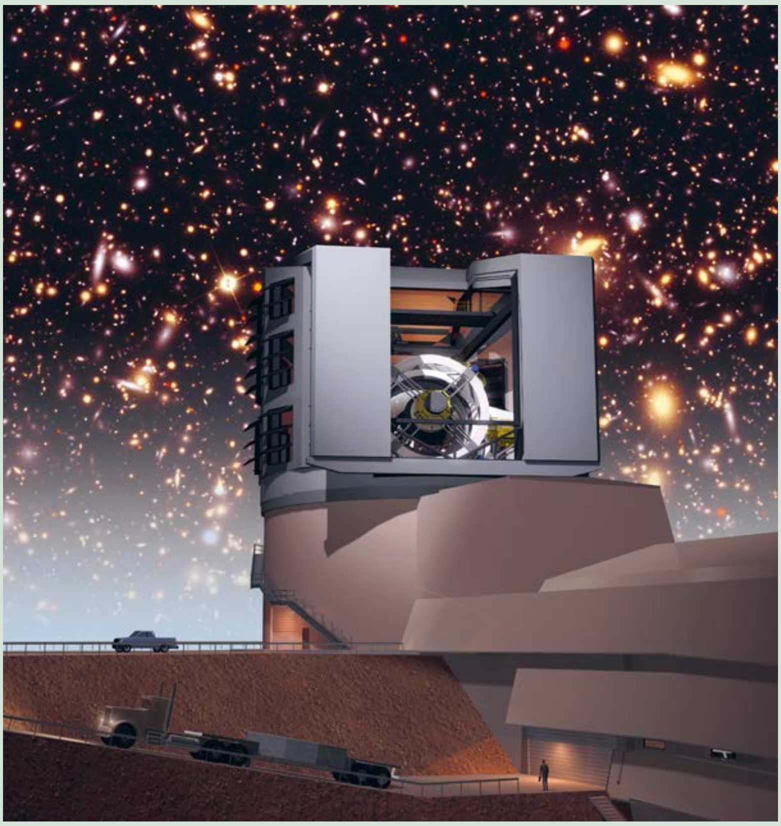


Heinz Billing Prize
for the advancement of scientific computation awarded for Binary Neutron Star Simulations

A new era in astronomy
The first direct detection of gravitational waves from the collision of two black holes in 2015 and the combined gravitational wave and electromagnetic wave observation of a binary neutron star merger in 2017 inaugurated a new era in astronomy and astrophysics. The Nobel Prize in Physics, the Special Breakthrough Prize in Fundamental Physics, and numerous other awards recognized the importance of these scientific achievements. Similarly, the fact that I received the Heinz Billing Prize for the advancement of scientific computation for my work in numerical relativity is yet another proof for the rising importance of gravitational wave astronomy.

How do we simulate binary neutron stars?
Modeling matter at densities higher than inside an atomic nucleus is among the most challenging problems in theoretical physics. In fact, cold matter at supranuclear densities cannot be produced and tested by any experiment on Earth, but such conditions are created inside neutron stars – ultracompact objects formed at the end of their stellar evolution. This makes neutron stars, in particular neutron star collisions, a perfect laboratory to study matter at its extreme limit. To study these mergers, one needs to solve the equations of general relativity combined with the equations of general relativistic hydrodynamics. No analytical solution exists for this problem, thus, numerical relativity simulations are inevitable to model and to understand the ongoing physical processes and the emitted radiation in the form of gravitational and electromagnetic waves. Even a single simulation is challenging and runs for weeks or up to months on a supercomputer. We collected and released results of several hundred simulations and created the first publicly available database for binary neutron star simulations. In total, about 200 million CPUhours were used for our work in the last few years. Although we can simulate generic binary neutron star systems, numerical relativity simulations are computationally too expensive to be directly used for the interpretation of gravitational wave signals. Typically, one needs to compute hundreds of millions of templates spanning thousands of gravitational wave cycles to extract the parameters from possible detections. Even with the best supercomputers in the world, this is not affordable. Therefore, based on our most accurate simulations, colleagues and I developed an analytical framework that produces an approximation of the gravitational

wave signal ten billion times faster than numerical relativity simulations. The approximation is accurate enough to be directly employed to analyze gravitational-wave signals, which makes the new framework a key ingredient in the analysis of gravitational waves. In addition to the development of efficient gravitational-wave models, our large set of numerical simulations allowed us to connect the observed electromagnetic signals in the optical, infrared, and ultraviolet bands to the properties of the neutron stars, which led to a better understanding of the internal structure of the stars. Finally, it is of crucial importance as a numerical relativist to visualize complicated physical processes to allow an easier understanding. Therefore, I produced several animations that have not only been of scientific interest but have also been used by hundreds of newspapers and various television shows. Thus, our simulations turned out to be a perfect tool to attract the interest of the public community.

How to obtain an award as a junior scientist and what is it worth?
As with most prizes and awards, you cannot apply directly for the Heinz Billing prize. You need to get nominated by a senior scientist, which is already well known and established in the community. In most cases, this is your former Ph.D. supervisor, your employer, or sometimes a scientist who knows your work through common projects. In my case, I was nominated by my former employer Prof. Dr. Alessandra Buonanno, who is a director of the Max Planck Institute for Gravitational Physics. Although the Heinz Billing prize is endowed with 5000 Euros, the biggest benefit is the recognition of the own work. This is crucial at an early career stage, when one does not have a long track record and is undecided whether one should continue in academia. Clearly, every kind of award improves your chances on the job market and increases the success rate for future applications. Therefore, it helps to keep you motivated and to give your best. ■

> “An award helps to keep you motivated and to give your best”

Tim Dietrich,
Marie Sklodowska-Curie Fellow at Nikhef, Amsterdam

Cristiane de Morais Smith
awarded the Emmy Noether Distinction

Cristiane de Morais Smith, a Full Professor at the University of Utrecht, has been awarded the prestigious Emmy Noether Distinction of the European Physical Society for her outstanding scientific contributions to the theory of condensed matter physics, in particular to the understanding of topological phases in two-dimensional atomic and electronic systems.

During the last years, she made very important contributions to several topics, but one could summarise them by mentioning *"her seminal contributions to the understanding and design of quantum simulators in ultracold atoms and electronic systems, aiming at unveiling novel quantum states of matter."*

Born in Brazil, her scientific career is strongly connected to Europe, where she studied and worked during the last 27 years. She started her physics studies in Brazil, but performed a large part of her PhD at ETH Zurich, Switzerland, was a visiting scientist at ICTP Trieste, Italy, did a postdoc in Hamburg, Germany and in Fribourg, Switzerland, where she received the Professor Award of the Swiss National Science Foundation and became an Associate Professor in 2001. Since 2004 she holds a full Professor Chair in Condensed Matter Physics at Utrecht University, the Netherlands, where she established a well-known research group in the field of strongly correlated systems. Morais Smith advances the field by using analytical techniques to deepen our theoretical understanding and by closely collaborating with experimentalists such as Andreas Hemmerich (Hamburg), in the area of cold atoms or with the group of Daniel Vanmaekelbergh and Ingmar Swart (Utrecht), on the design of novel nano-lattices. In 2008, she was awarded the prestigious VICI Prize by the Netherlands Research Organization (NWO). Moreover, three years ago she was a recipient of the Dresselhaus Prize "for her outstanding contribution to the understanding of topological phases in two-dimensional atomic and electronic systems" by Hamburg University, Germany. Prof. Morais Smith speaks seven European languages and collaborates actively with top researchers in France, Spain, Italy, Germany, the Netherlands and Sweden.

Prof. De Morais Smith is also actively establishing research bridges between Europe and other countries oversea. She was awarded a Special Visiting Professor Fellowship by the Brazilian Agency CNPq from 2013-2016, and two years in a row she was awarded the High-End Foreigner Expert (HEFE) visiting Professorship from the Chinese Government. She is currently an Associate Faculty of the Wilczek Quantum Center, a member of the Advisory Board and a Fellow of the Tsung-Dao Lee Institute in Shanghai. Her recognition in the international scientific community can be judged from the many (~300) invited and plenary talks she has been giving.

Apart from her excellent contributions to science, Cristiane de Morais Smith is also a passionate teacher who attracts many students to her group by her enthusiasm and passion for science, which has already led to 22 Bachelor, 42 Master and 23 PhD theses. Many of her students have received prices for their work and have found excellent positions in academia and industry all over the world. In addition, she is very engaged in outreach activities, combining Science and Art and participating in movies in which she is capable of conveying her enthusiasm and passion for science in a contagious manner. She is a role model for all her colleagues, and especially, for the few young female researchers, who represent less than 15% in our field in Europe. The 2019 Emmy Noether Distinction is therefore a well deserved highlight in her brilliant carreer. ■

■ **Gloria Platero,** *Instituto de Ciencia de Materiales de Madrid, CSIC*
■ **Theo Rasing,** *Radboud University Instute for Molecules and Materials*

The 20th anniversary of the Pierre Auger Observatory
A Success Story for International Science

In mid-November 2019 over 200 scientists and their guests made their way to Malargüe, a small, remote city snuggled between the Andes and a vast expanse of the Argentine pampa. The occasion was the celebration of the 20th anniversary of the ground-breaking for the Pierre Auger Observatory that featured a scientific symposium and celebration ceremony. Also celebrated was the start of a major upgrade, AugerPrime, that will extend the productive life of the world's largest and most sensitive ultra-high energy cosmic ray observatory by another decade.

The Pierre Auger Observatory was conceived at the 1991 International Cosmic Ray Conference in Dublin by particle physicist Jim Cronin from the University of Chicago and cosmic ray physicist Alan Watson from the University of Leeds. The objective was to uncover the mystery of the origin and nature of the rare, but enormously energetic cosmic rays. It was clear to them that only a detector of unprecedented size would provide enough exposure to answer questions raised by nearly a century of earlier study.

Hybrid detector
The Pierre Auger Observatory design, developed in 1995 at a six-month Design Workshop, consists of a "hybrid" detector system consisting of a 3000 km^2 array of 1600 particle detectors overlooked by 27 optical telescopes. These complementary detector techniques record particle cascades initiated in the upper atmosphere by ultra-high energy cosmic ray particles. The surface array records the footprint of the shower particles on the surface while, on dark nights, the telescopes record the faint fluorescence light produced as the shower cascades through the atmosphere.

> **AugerPrime upgrade promises new insight**

Leadership
The leadership of Cronin, Watson and others soon attracted a collaboration of skilled and committed researchers from 17 countries. A unique organisational structure, also a product of the Design Workshop, was formed and in which no region, country, or institution dominates and where decisions are made by consensus. Strong leadership, a cohesive collaboration of scientists, strong international and local support, and an effective organisation have ensured the last 20 years of success for the Observatory.

Scientific results
The Auger Observatory has carried out studies of the energy spectrum, mass composition, and arrival directions of the highest energy cosmic rays. The data have produced a detailed energy

▲ Night sky at the Pierre Auger site

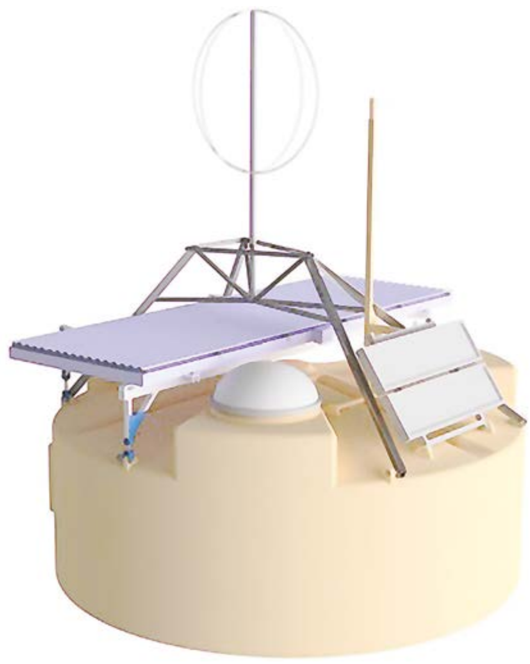
▸ Celebrating the 20th Anniversary of the Pierre Auger Observatory spectrum from 10^{17} eV to above 4×10^{19} eV where a clear suppression has been established. A large-scale ~7% dipole anisotropy is found at energies above 8×10^{18} eV with the transition from galactic to extragalactic sources appearing at 1-2×10^{18} eV. There are indications of an anisotropic distribution of the arrival directions of particles with energies above 5.5×10^{19} eV, though no discrete sources can yet be identified. A deficit in the simulations of approximately 40% in the shower muon content in the energy range 3×10^{17} eV to 2×10^{18} eV has been measured relative to the current shower models indicating an incomplete understanding of particle production early in the cascade development at these ultra-high energies. Competitive limits have also been placed on neutrino and gamma ray fluxes.

Unexpected

One of the most unexpected results was the evolution of the mass composition of cosmic rays in the energy range from $10^{17.2}$ to $10^{19.5}$ eV. Interpreting the observed longitudinal shower profiles with LHC-tuned interaction models, the composition appears consistent with a large fraction of protons at 10^{18} eV but then becomes heavier with increasing energy. Data indicate that, in addition to the GZK–like propagation effect, this flux suppression at the highest energies may also result from the astrophysical sources reaching a limit in their ability to accelerate the highest-energy primary particles. Auger lacks statistics for composition analysis at energies above 5×10^{19} eV, in the spectral region of the flux suppression where the arrival directions of cosmic rays appear to correlate with nearby matter. Knowing the composition at this energy scale is crucial and is a key objective of planned upgrade.

AugerPrime

The AugerPrime upgrade includes 3.8 m^2 scintillation detectors above the existing water Cerenkov detectors, upgraded electronics, extended dynamic range for the water Cerenkov detectors, a radio antenna to measure radio emission of showers, and a limited (61 detector position) area of underground muon detectors. The objective of AugerPrime is to untangle the constituents of high-energy air showers to investigate the composition of the primary cosmic rays as well as hadronic interactions at the highest energies. Isolation of light primaries will enable charged particle astronomy. The upgrade will also extend the flux limits on gamma ray and neutrino-initiated showers at these energies. At high zenith angles the radio detector together with the water Cerenkov detector will allow increased sensitivity to neutrinos. Triple hybrid events that include the fluorescence detector will also be possible. With this sensitivity to gamma rays and neutrinos, and the ability to isolate light primaries, Auger will be able to play a strong role in the era of multimessenger astronomy.



▲ Upgraded surface detector for AugerPrime

Ready for the future

While celebrating 20 years of success, the Auger collaboration looks forward to the future where the AugerPrime upgrade promises new insights into the mysteries of the highest energy cosmic rays. ■

■ **Paul Mantsch,** *Fermilab*

▼ Surface detector and fluorescence detector

▼ Celebrating the 20th Anniversary of the Pierre Auger Observatory

For all those *not* reading this column

On 22 October 2019 a report[1] commissioned by the EPS was released on the contribution of physics to the European[2] economy. I find it quite shocking that this report has remained largely unnoticed. It was not in the news on TV, nor on the radio, nor could I find it in the newspapers. And that despite my effort to retweet it to my 439 followers! For those who did not read it, here the ultra-short version: the report states that 16% of the European economy is physics industry based. While the figure is not unfamiliar to me, it nevertheless struck me as very relevant to underline the need for adequate 'public' support for physics research and education. However, if only a few people, like you and I, just take note of this number and all others don't really care, the report will have zero impact. It deserves better.

The message, the importance of physics-based industry, may appear straightforward, but the underpinning of it is far from simple. The definition of "physics industries", which in this case is very transparently given as a list of NACE[3] codes in an appendix, may provoke questions as to when an industry is physics based. Changes in assignment of codes with respect to the previous version of this report[4], which appeared in 2013, testify to the intrinsic uncertainty in assigning "physics based" to certain types of industry, but also shows how little the outcome depends on the details of this assignment.

“Friend raising before fund raising for physics”

Then, there may be an issue with the status of the document itself. Very transparently again, the report starts with saying that the study was commissioned by the EPS from the Centre for Economics and Business Research (Cebr), a consultancy organisation that supplies independent economic forecasting and analysis to private firms and public organisations. The fact that the EPS commissioned the study possibly creates an impression of self-interest. It would be very helpful if the study were to be advocated publicly by parties other than the EPS, such as by the physics-based industry itself and other economists than those of Cebr. The physics-based industry, large and small alike, could add weight to the study by subscribing to it and publicly drawing attention to its findings.

In the previous issue, EPS president, Petra Rudolf, stressed the need for funding of physics education and research, with the Cebr report as an important argument. I would advocate the idea of friend raising before fund raising. With the report being accepted by as many (possibly new) friends as possible, it will be much easier to make the funding argument at a later stage. Public funding is the domain of politicians. The surest way to win the hearts and minds of the politicians is public attention (and pressure). However, despite the presentation of the report to the press in October last year, we did not do very well on that account.

Contemporary standard tools to attract public attention are yellow vests, tractors, going viral on the social media and strikes. Striking scientists, however, are an ineffective curiosity. The social media have the potential of generating wide attention, but in all my disconnectedness (wrong bubble) I myself failed. You may have a try, but when was the last time a physicist reporting on economic impact went viral? Large public demonstrations have proven effective if accompanied by major disruptive public action. Surely, physicists possess the means for such action. Fortunately, for all of mankind, violent actions are rather alien to our professional group.

A civilised alternative uniting some of the above characteristics is to massively address the traditional media, newspapers and periodicals. For maximum effect this should be done at, or around, the same date. We are all pressed for time, but this year we have the extra day, 29th February 2020. *To all readers:* Please send a letter to at least one newspaper and one periodical on this leap day to draw attention to the Cebr report and the importance of physics for the European economy. Just refrain from asking money this time around. For the sake of all new friends not reading this column. ■

Sijbrand de Jong,
Radboud University, Nijmegen

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[1] The Importance of Physics to the Economics of Europa, *A study by Cebr for the period 2011*-2016, Cebr – Centre for Economics and Business Research for the European Physical Society, *22 October* 2019, https://www.eps.org/resource/resmgr/policy/eps_pp_physics_ecov5_full.pdf, with an executive summary in https://www.eps.org/resource/resmgr/policy/eps_pp_physics_ecov5_abs.pdf.

[2] Europe is defined here as the EU28 plus Iceland, Norway and Switzerland.

[3] Nomenclature statistique des activités économiques dans la Communauté européenne.

[4] For the previous version of the report, see https://cebr.com/reports/economic-importance-of-physics

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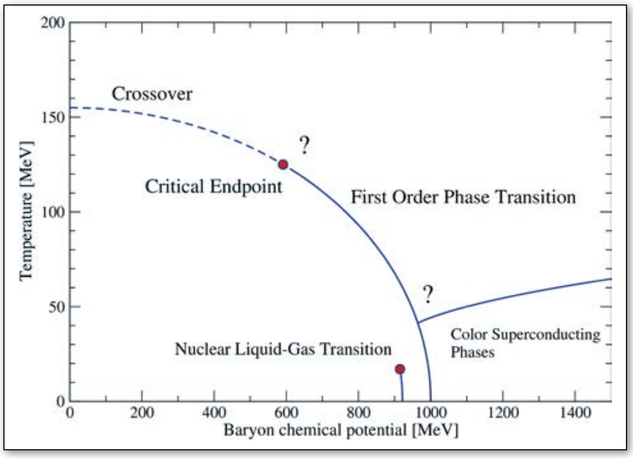
The EPS is not responsible for the content of this section.

Highlights from European journals

NUCLEAR PHYSICS

Validity of the Silver-Blaze property for QCD at finite chemical potential

The properties of the theory of strong interactions, QCD, at finite chemical potential are of great interest for at least two reasons:
(i) Model studies suggest a potentially rich landscape of different phases with highly interesting analogies to those found in solid state physics;
(ii) the resulting thermodynamic properties have far reaching consequences for the physics of neutron stars and neutron star mergers.



▲ Sketch of the QCD phase diagram in the temperature and baryon chemical potential plane.

Investigating the properties of light scalar and pseudo-scalar quark-antiquark bound states at finite chemical potential by solving coupled sets of Dyson-Schwinger equations , the meson masses, wave functions, and decay constants are computed, as well as changes in the quark dressing functions for chemical potentials below the first-order chiral phase transition while tracing charge-conjugation parity breaking. Eventually, we confirm the validity of the Silver-Blaze property: in observables all dependencies of coloured quantities (propagators, wave-functions, *etc.*) on chemical potential cancel out and we observe constant masses and decay constants up to and into the coexistence region of the first-order chiral phase transition. ■

▪ **P. J. Gunkela**, **C.S. Fischerb** and **P. Isserstedtc**, 'Quarks and light (pseudo-)scalar mesons at finite chemical potential', *Eur. Phys. J. A* **55**, 169 (2019), DOI 10.1140/epja/i2019-12868-1

MATERIAL SCIENCE

Determining the shapes of atomic clusters

By considering the crystal structures of atomic clusters in new ways, researchers may be able to better assess whether the groups have distinctive shapes, or whether they are amorphous.

Too large to be classed as molecules, but too small to be bulk solids, atomic clusters can range in size from a few dozen to several hundred atoms. The structures can be used for a diverse range of applications, which requires a detailed knowledge of their shapes. These are easy to describe using mathematics in some cases; while in others, their morphologies are far more irregular. However, current models typically ignore this level of detail; often defining clusters as simple ball-shaped structures. In research published in *EPJ B*, José M. Cabrera-Trujillo and colleagues at the Autonomous University of San Luis Potosí in Mexico propose a new method of identifying the morphologies of atomic clusters. They have now confirmed that the distinctive geometric shapes of some clusters, as well as the irregularity of amorphous structures, can be fully identified mathematically. ■

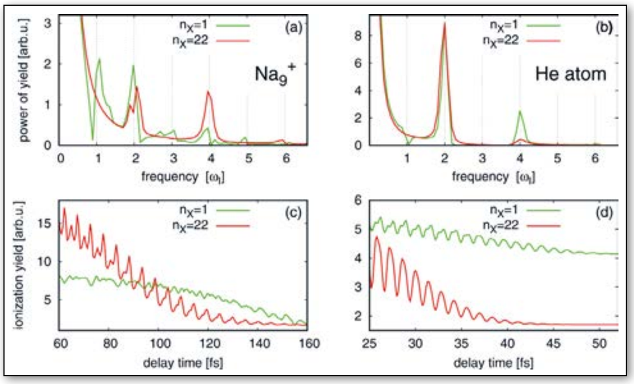
▪ **J.M. Cabrera-Trujillo**, **J.M. Montejano-Carrizales** and **C.G Galván**, 'Amorphicity and Structural Changes in Binary Clusters', *Eur. Phys. J. B* **92**, 237 (2019), https://doi.org/10.1140/epjb/e2019-100312-4

LASER PHYSICS

Inhibitory neurons retrieving physical properties from two-colour laser experiments

Useful information about ultrafast light-matter interactions is buried deep in the signals produced by two-colour pump-probe experiments, and requires sophisticated techniques to disentangle it.

When photons of light interact with particles of matter, a diverse variety of physical processes can unfold in ultrafast timescales. To explore them, physicists currently use 'two-colour pump-probe' experiments, in which an ultrashort, infrared laser pulse is first fired at a material, causing its constituent electrons to move.



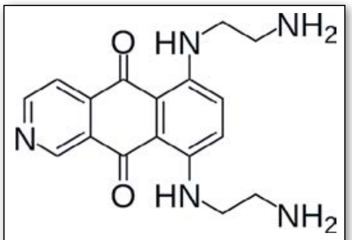
▲ Extracting ionisation yields following ultrafast interactions.

After a controllable delay, this pulse is followed by a train of similarly short, extreme-ultraviolet pulses, ionising the material. By measuring the total ionisation following the pulses along with the resulting electron energy spectra, physicists can theoretically learn more about ultrafast, light-matter interactions. In new research published in *EPJ D*, an international team of physicists, led by Eric Suraud at the University of Toulouse, discovered that these signals are in fact dominated by the less interesting interplay between electrons and the initial infrared laser. They show that more useful information is buried deeper within these signals. ■

■ **T. Brabec**, **P. M. Dinh**, **C. Z. Gao**, **C. R. McDonald**, **P-G. Reinhard** and **E. Suraud**,
'Physical mechanisms encoded in photoionization yield from IR+XUV setups', *European Physical Journal D* **73**, 212 (2019), DOI: 10.1140/epjd/e2019-90507-4

APPLIED PHYSICS

Advanced cancer drug **shrinks and intercalates DNA**



▲ Pixantrone thoroughly damages cancer cell DNA.

Experiments and statistical models reveal that the recently developed cancer drug Pixantrone forces itself inside the double helix structure of DNA molecules, then shrinks their backbones.

Because of the harmful side-effects of chemotherapy, and the increasing resistance to drugs found in many cancer cells, it is critical for researchers to continually search for new ways to update current cancer treatments. Recently, a drug named Pixantrone (PIX) was developed, which is far less damaging to the heart than previous, less advanced compounds. PIX is now used to treat cancers including non-Hodgkin's lymphoma and leukaemia, but a detailed knowledge of the molecular processes it uses to destroy cancer cells has been lacking so far. In a new study published in *EPJ E*, Marcio Rocha and colleagues at the Federal University of Viçosa in Brazil uncovered the molecular mechanisms involved in PIX's interactions with cancer DNA in precise detail. They found that the drug first forces itself between the strands of the DNA molecule's double helix, prising them apart; then compacts the structures by partially neutralising their phosphate backbones. ■

■ **C.H.M. Lima**, **J.M. Caquito jr**, **R.M. de Oliveira** and **M.S. Rocha**
'Pixantrone anticancer drug as a DNA ligand: Depicting the mechanism of action at single molecule level', *Eur. Phys. J. E* **42**, 130 (2019), DOI 10.1140/epje/i2019-11895-6

HISTORY

Unpacking the mystery of Feynman's reference amplifier

A review of lectures given by Feynman between 1946 and 1971 showcase the strong influence that his involvement in the Manhattan Project held on his research, while revealing an intriguing mystery surrounding one particular amplifier device.

▲ Feynman's research strongly influenced modern physics. Credit/copyright: The Nobel Foundation, public domain.

Richard Feynman was one of the 20th century's most celebrated physicists. In 1943, he began his career in the Manhattan Project, where one of his tasks was to develop a device which could count the neutrons produced by nuclear reactions. Neutron signals emerging from counters must be strongly amplified to achieve this, but in the 1940s, practical amplification devices were hindered by their distorted signals. To overcome the issue, Feynman proposed a theoretical 'reference amplifier', which could provide amplifiers with a standard signal to be compared with. Through analysis published in EPJ H, researchers at the University of Naples, Italy, propose that this line of research exemplifies the influence which Feynman's involvement in the Manhattan Project held over his later teaching and research. ■

■ **V. d'Alessandro, S. Daliento, M. Di Mauro, S. Esposito** and **A. Naddeo**
'Searching for a response: the intriguing mystery of Feynman's theoretical reference amplifier', *European Physical Journal H* **44**, 331 (2019), DOI 10.1140/epjh/e2019-90071-6

BIOPHYSICS

Cell motility in a compressible gel

Cell motility is crucial to biological functions ranging from wound healing to immune response. Spontaneous movement and deformation are physically driven by the cell cytoskeleton.

The cytoskeleton consists of protein filaments and motors which constantly consume chemical energy (ATP) and convert it to work. In particular, actin filaments interact with myosin motors to generate contraction forces in the cell, which drive cell motion and division. Most of the research has focused, both experimentally and theoretically, on cell migration on a two-dimensional substrate (crawling), providing a detailed outline of some basic migration mechanisms. However, some cells, such as breast tumor cells, can also "swim" in a straight line inside a 3D tissue or a polymeric fluid, in the absence of substrates. The authors present a minimal model for pattern formation within a compressible actomyosin gel, which is numerically solved both in 2D and 3D. Contractility leads to the emergence of an actomyosin droplet within a low-density background. This droplet then becomes self-motile for sufficiently large motor contractility. Simulations also show that compressibility has the effect to facilitate motility, as it decreases the value of the isotropic contractile stress beyond which the droplet starts to move. ■

■ **G. Negro *et al.***,
'Hydrodynamics of contraction-based motility in a compressible active fluid', *EPL* **127**, 58001 (2019).

APPLIED PHYSICS

Science reveals improvements in Roman building techniques

A variety of scientific techniques have been combined to highlight improvements in the technologies employed by the Romans in successive modifications to the *Atrium Vestae* in Rome.

The Romans were some of the most sophisticated builders of the ancient world. Over the centuries, they adopted an increasingly advanced set of materials and technologies to create their famous structures. To distinguish the time periods over which these improvements took place, historians and archaeologists typically measure the colours, shapes and consistencies of the bricks and mortar used by the Romans, along with historical sources. In new research published in EPJ Plus, Francesca Rosi and colleagues at the Italian National Research Council improved on these techniques through scientific analysis of the materials used to build the Roman Forum's *Atrium Vestae*. They found that successive phases of modification to the building saw improvements including higher quality raw materials, higher brick firing temperatures, and better ratios between carbonate and silicate building materials. ■

▲ The Atrium Vestae in Rome. © Carole Raddato from Frankfurt, Germany [CC BY-SA 2.0 (https://creativecommons.org/ licenses/by-sa/2.0)]

■ **E. Boccalon, F. Rosi, M. Vagnini** and **A. Romani**
'Multitechnique approach for unveiling the technological evolution in building materials during the Roman Imperial age: the Atrium Vestae in Rome', *Eur. Phys. J. Plus* **134**, 528 (2019), DOI 10.1140/epjp/i2019-12936-y.

CONDENSED MATTER

Multiple magnon modes in a magnetic Weyl semimetal

An area of interest in condensed matter physics is topological Weyl semimetals (WSMs). There are only a few candidates of magnetically ordered materials for the realisation of WSMs, like the kagome-lattice ferromagnet $Co_3Sn_2S_2$.

Novel magnon branches are predicted in magnetic Weyl semimetals, which can be understood as a result of the coupling between two magnetic moments mediated by Weyl fermions. Here, we experimentally investigate electron transport in the kagome-lattice ferromagnet $Co_3Sn_2S_2$, which is regarded as a time-reversal symmetry broken Weyl semimetal candidate. We demonstrate dV/I(I) curves with pronounced asymmetric dV/dI spikes, similar to those attributed to current-induced spin-wave excitations in ferromagnetic multilayers. In contrast to multilayers, we observe several dV /dI spikes' sequences at low, $\approx 10^4$ A/cm^2, current densities for a thick single-crystal $Co_3Sn_2S_2$ flake in the regime of fully spin-polarised bulk. The spikes at low current densities can be attributed to novel magnon branches in magnetic Weyl semimetals, which are predicted due to the coupling between two magnetic moments mediated by Weyl fermions. The presence of spin-transfer effects at low current densities in $Co_3Sn_2S_2$ makes the material attractive for applications in spintronics. ■

■ **O. O. Shvetsov *et al.***,
'Multiple magnon modes in the $Co_3Sn_2S_2$Weyl semimetal candidate', *EPL* **127**, 57002 (2019).

PHOTONICS

Focusing surface acoustic waves into an **optomechanical nanobeam**

Cavity optomechanics (OM) is a topical issue of growing interest due to the potential applications ranging from sensing and communications to quantum information technology. However, the number of phonons created in a cavity by an external optical fibre remains relatively low. An alternative way to induce large phonon population is the use of a phonon pump by transforming an RF signal into surface acoustic waves (SAW). In a simulation work, we demonstrated an efficient focusing and conversion of SAW generated by focusing interdigital transducers (IDT) on piezoelectric aluminum nitride film deposited on silicon on insulator (SOI) into the guided modes of a silicon nanobeam. For a straight nanobeam, we achieve an efficiency of -22dB and displacements about 50pm when applying a voltage of 1V to the IDT. When the nanobeam is structured to form a phononic crystal with a cavity, the guided modes excite some localized modes around 2 GHz inside the cavity with a magnitude of the vibrational motions around 1nm. The preliminary experiments confirm the simulations.
Work is supported by the European Commission through project PHENOMEN, Grant Agreement No. 713450. ■

▪ **A. V. Korovin *et al.***,
'Conversion between surface acoustic waves and guided modes of a quasi-periodic structured nanobeam', *J. Phys. D: Appl. Phys.* **52**, 32LT01 (2019).

NUCLEAR PHYSICS

NSD2019 Conference Proceedings

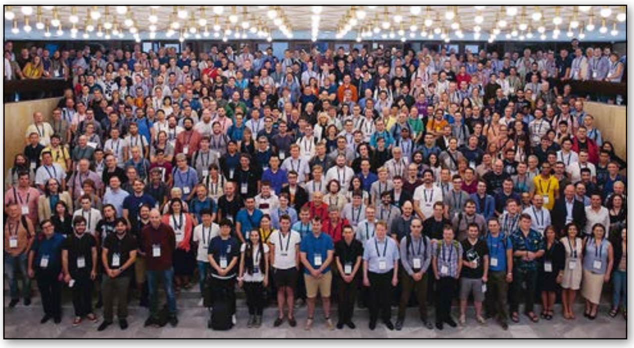
▲ NSD2019 group photo

The fourth International Conference on Nuclear Structure and Dynamics NSD2019 was held in Venice on May 13-17, 2019. The conference belongs to a series of conferences devoted to the most recent experimental and theoretical advances in the field of nuclear structure and reactions. The focus was on topics covering most of the research areas in low energy nuclear physics: Nuclear structure and reactions far from stability, Collective phenomena and symmetries, Dynamics and thermodynamics of light and heavy nuclei, Sub and near barrier reactions, Fusion and fission dynamics, Ab-initio calculations, cluster models and shell model, Nuclear energy density functionals, Nuclear astrophysics, Fundamental interactions. Important new results were outlined in the various subfields, spanning the whole range from neutron-deficient to neutron-rich nuclei and from light to heavy ions. ■

▪ **G. de Angelis** and **L. Corradi (Eds.)**,
'IV International Conference on Nuclear Structure and Dynamics (NSD2019), Venice, Italy, May 13-17, 2019', *EPJ Web of Conferences* **223** (2019), ISBN: 978-2-7598-9084-2.

COMPUTING

CHEP2018 Conference Proceedings



The 23rd International Conference on Computing in High Energy and Nuclear Physics was held in the National Palace of Culture, Sofia, Bulgaria from 9th to 13th of July 2018. The program consisted of 27 plenary, 323 parallel presentations and 188 posters. The plenary talks covered topics such as HPC and cloud computing, machine learning in High Energy Physics (HEP), overviews of experiment software for data acquisition, high level triggering, reconstruction and analysis, experience from astro-particle and neutrino physics, as well as broader subjects like multithreading and vectorization in HEP, use of blockchains, quantum computing, software citation mechanisms. Progress on common and widely used tools and packages in HEP such as ROOT, EOS and CVMFS was also presented. A dedicated talk and a panel discussion were devoted to the implementation of a successful diversity program in the field of HEP and nuclear physics computing. ■

▪ **A. Forti**, **L. Betev**, **M. Litmaath**, **O. Smirnova** and **P. Hristov (Eds.)**,
'23rd International Conference on Computing in High Energy and Nuclear Physics (CHEP 2018), Sofia, Bulgaria, July 9-13, 2018', *EPJ Web of Conferences* **214** (2019).

Interview with Cristiane Morais Smith

On the occasion of receiving the EPS Emmy Noether Distinction, we asked Cristiane Morais Smith about her current work, her view on diversity in the physics community and the impact of the distinction.

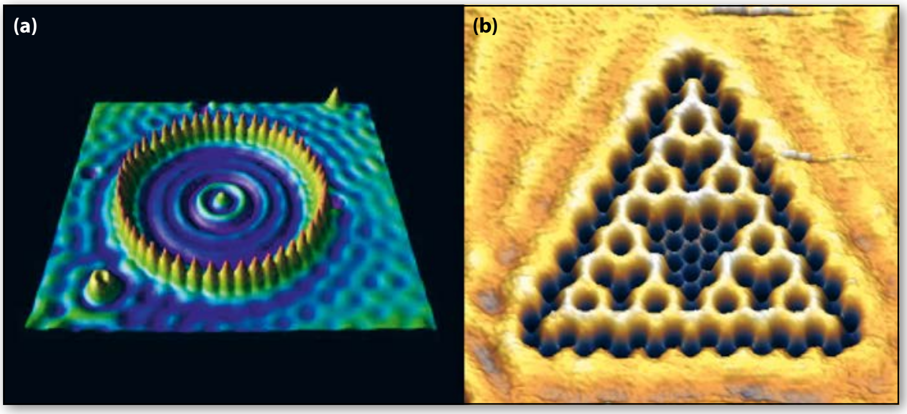
In 2004, Cristiane de Morais Smith came to Utrecht University in the Netherlands to build a group working on the theory of strongly-correlated systems. On our question why she chose to work in the Netherlands she answered: "Actually, it happened more or less by chance. I wanted to get a job in a place where I did not know anyone because I did not want to be helped. I wanted to get a position all by myself. I saw an announcement of a position in the Netherlands, and given the high status of the country in the scientific scenario, I thought that it would be an ideal place to work."

Current research

Recently, in collaboration with experimentalists at Utrecht University, her group has been working on the development of a platform for quantum simulations in electronic systems. "Sixty years ago, Feynman proposed that we could build matter in a bottom-up approach to simulate model Hamiltonians that are supposed to describe complex materials, or even to build metamaterials. Although the field of quantum simulators has been flourishing in ultracold atoms for about 20 years, and in photonics for about 15 years, almost nothing was done involving electrons. We are actively contributing to the field." With this collaboration in Utrecht, the group aims at establishing a new kind of quantum simulator platform, involving electrons. The endeavour is based on the pioneering experiment performed by the group of Don Eigler (Almaden), in which iron (Fe) atoms were manipulated using the tip of a scanning tunneling microscope on the surface state of Cu(111) to build a quantum corral [1] (see Fig. 1a). Later on, the same technique was used by the group of Hari Manoharan (Stanford) to build *molecular graphene* [2]. The manipulation of the atoms on top of Cu are performed on the nanometer scale and there is a large flexibility with respect to the structure that could be built. "Indeed, we have shown that despite the fact that the underlying lattice is triangular and the COs can only be put on top of a copper atom, one can control the geometry of the lattice and build square or Lieb lattices [3]. In addition, one can control the *dimensionality* of the object formed, going even into fractal dimensions [4] (see Fig. 1b). One can also manipulate the *orbital degrees of freedom*, which can be selected in real space and separated in energy [5]. We have shown that this setup can be used to generate and control topological states, and have realised a *higher-order topological insulator* [6]. My group has been performing the theoretical calculations (muffin tin and tight binding) and most of the conceptual development of the projects, and we are recognised by the community as being among the pioneers of this emerging field. A next step is to *realise interactions* in this single-particle system. Although the CO on copper platform consists of free electrons, one can simulate two-body interactions in 1D by appropriately designing a non-interacting 2D system. This is being currently investigated, theoretically and experimentally. Preliminary results seem to confirm the theoretical predictions."

Proud

Morais Smith is proud of the collaborative work of her group on several subjects and with several experimental and theoretical groups in Utrecht, Sweden, Brazil, and Germany. "But a work that I consider really original is our formulation of a thermodynamic description of topological phase transitions. This work was done completely in my group, by some very bright PhD students, and I am very proud of it because nobody thought that this could be possible. Topological systems have metallic states at the boundary, and this seems to be in contradiction with the thermodynamic limit, in which one studies infinite systems. Nevertheless, we found a way to circumvent that…" As a theoretical physicist she enjoys working with experimentalists. "I have a deep respect for experimental work, since it brings the connection to the real world. I collaborate extensively with experimentalists, and learn a lot from them, as probably became clear from the answers above. Experiments are for me a motivation to do a new theory, but I also want to go beyond and predict something else, that could stimulate my colleagues to perform further experiments. One of the highlights in



▲ FIG. 1: (a) A quantum corral is realized by depositing Fe adatoms (yellow-red dots) in a ring on the surface of Cu(111) [1]. The corresponding electronic waves (blue) are then visible in the confined geometry. (b) Local density of electronic states in a Sierpinski triangle, generated by patterning CO molecules (black dots) on the surface of Cu(111) [4].

connection with theoretical predictions is a work we did in 2004. It is a mean-field calculation of the electron-solid phases in a quantum Hall system, and I did not expect it to work very precisely in experiments. However, 6 months after we published the theoretical results, the group of Dan Tsui measured exactly what we had predicted, and even the numbers worked out well. I was enchanted."

Role model

Morais Smith makes an effort of being a good role model and accepts many invitations for conferences. At many occasions she is the only woman giving an invited talk. "Every time when I think that it is too much, and I could stay calm at home, I think: but if I do not go, maybe there are no female speakers….And I feel an urge to accept the invitation. Fortunately, things are improving during the last years, and now there are more female colleagues who are invited. But the numbers are still low." Participating in committees or boards she keeps a keen eye on the participation of women in physics. "As a member of the International Advisory Council of the T. D. Lee Institute in Shanghai Jiao Tong University, I recently suggested that they could create a prestigious Fellowship with the name of Madame Wu, to honour this brilliant physicist who deserved a Nobel Prize but unfortunately did not get it, and stimulate further Chinese women to follow her example. I was delighted when I learned that the Director, Prof. Frank Wilczek decided to accept the suggestion and implement it." She stresses the importance of being a role model not only for physicists but for women in general and in particular for women in minority groups. "One day I had a wonderful experience in my office at the University of Utrecht. We had a very intelligent cleaning lady who came originally from Morocco. She entered my office and told me that she had decided to pursue her studies at the University, and that she wanted to let me know that I was her source of inspiration. Her husband was not very happy about it, since she also had a child, but she was determined to do so. I was enchanted! I think that when someone like me sits in a professor chair, it implicitly tells everyone that they can also. And this is very positive."

▲ **FIG. 2:** Cristiane Morais Smith (with red scarf) amidst (part of) her research group.

Diversity and Inclusion

Currently, her group comprises many Dutch students, but still a student from Russia and some from Brazil. She had more than 100 students in total, including Bachelor theses, Master theses, PhD students and postdocs, and from very different countries, like Malaysia, Italy, Germany, Spain, France, Switzerland, Norway, Ukraine, Serbia, Brazil, and Argentina. "But the majority is from the Netherlands, since I work there. I also have several female students, at all levels (Salma Ismaili for the Bachelor theses, Silke Schonecker for the Master, and Jette van den Broeke and Mariya Lizunova for the PhD). Unfortunately, many of them were not there the day when the professional photographer could take the group photo [see the picture] …. It is really a pity!" As a Brazilian, she makes an effort to attract PhD students and Postdocs from Brazil. She hopes to be a hub in Europe for Brazilian physicists or scientists from South America in general. "I kept a strong scientific link with Brazil and have already formed 3 Brazilian professors, and I hope to form more. At the moment, there is a professor and 2 PhD students visiting my group with Brazilian fellowships. Two more are going to arrive in 2020. I was awarded a Special Visiting Professor position in the framework of the Science Without Borders Program between 2013-2016 for a collaboration with the group of Eduardo Marino in Rio de Janeiro. Recently, we were awarded a NUFFIC/CAPES proposal for a collaboration between Brazil and the Netherlands, from 2018-2021. I am very glad to get support for this very prolific collaboration and I am glad to establish these links."

Emmy Noether Distinction

Cristiane Morais Smith has received prestigious grants and prices, but even so considers the Emmy Noether Distinction very important as recognition of her work "….and it really warms the heart!!! Especially because Emmy Noether has always impressed me so much…every time when I lectured about her life, I had tears in my eyes. She was an incredible woman."

We asked whether she knew that she was nominated for the Emmy Noether Distinction. Her answer is encouraging for others who consider nominating their outstanding female colleagues: "Yes, I knew it. My colleagues had informed me and I was delighted to learn that they were making time in their busy lives to do that."

■ **Els de Wolf,** *EPN Editor*

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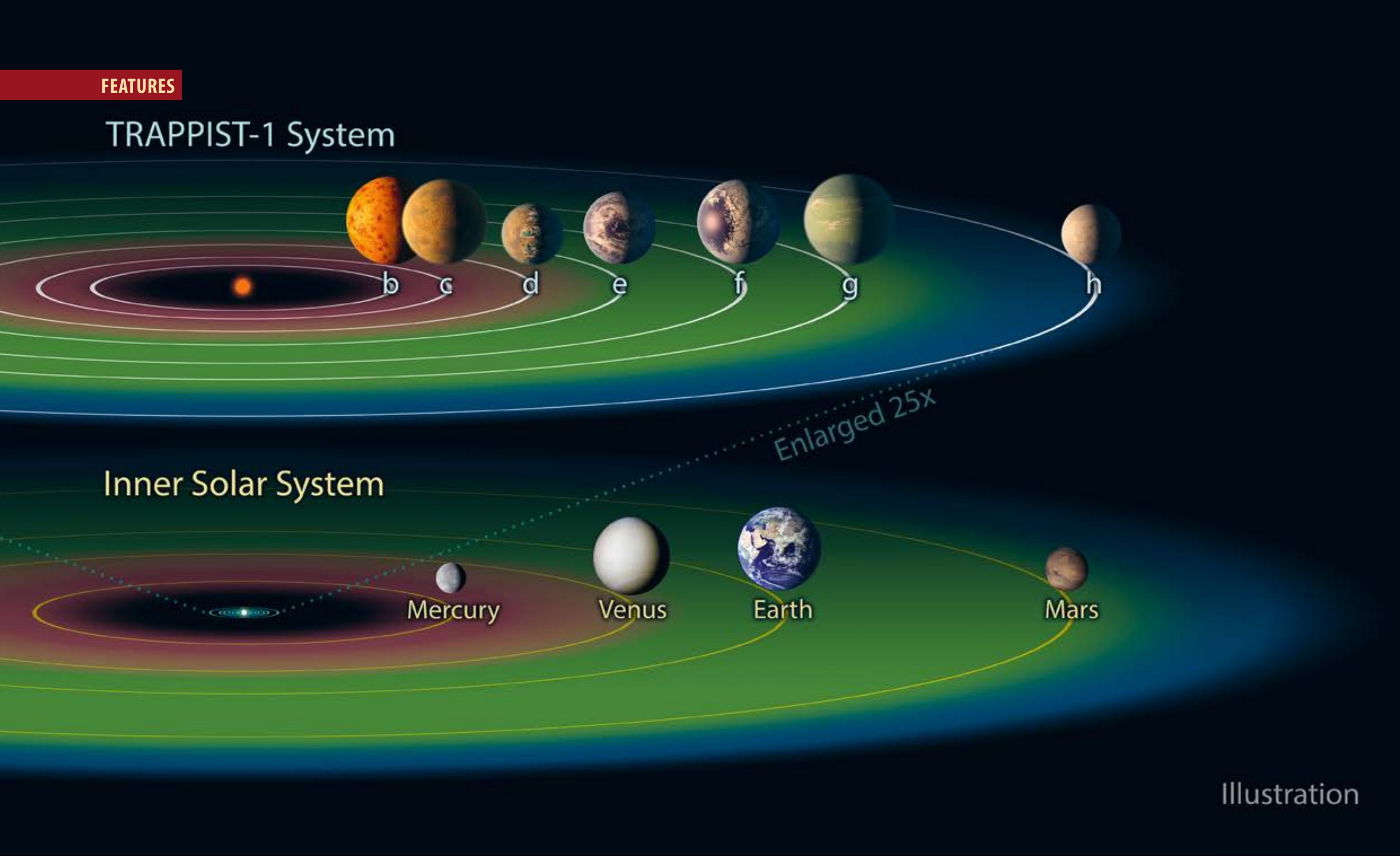

EXTRASOLAR PLANETS: FROM DUST TO NEW WORLDS

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Thousands of exoplanets have been discovered and the search for for life outside Earth is at the forefront of astrophysical research. The planets we observe show a mind-blowing diversity that current theories strive to explain as part of the quest to assess the chances of finding life outside the Earth.

▲ The Trappist 1 system, discovered by the Kepler mission, which comprises 7 terrestrial in the habitable zone of their host star. © NASA/JPL-Caltech

This year's Nobel prize in Physics went to Michel Mayor and Didier Queloz, who discovered the first extrasolar planet orbiting a Sun-line star. 51 Pegasi b, is a gas-giant with a mass approximately half of that of Jupiter. Unlike Jupiter in our Solar System, however, this planet orbits very close to its host star, 100 times closer than Jupiter to our Sun, earning it the classification of "hot Jupiter". One year on 51 Pegasi b lasts only just over 4 days compared to nearly 12 years on Jupiter.

The combination of large masses and small semi-major axes of hot Jupiters makes them easier to discover through their gravitational interaction with their host stars. The stellar "wobble" induced by the fact that planet and host star orbit around their common centre of mass is detectable via the observation of bright stellar spectral lines which appear periodically blue- or red-shifted as the planet pulls the star towards and away from us. This observation however requires extremely stable instruments, spectrographs able to resolve the tiny radial velocity component of the star. In the case of 51 Pegasi this velocity is 55 m/s, however a planet like Jupiter orbiting the Sun at 5 au is expected to provide a signal of 12.5 m/s, while **the Earth orbiting at 1 astronomical unit (au) from the Sun only produces a signal of 9 cm/s, which is slower than the average walking speed of humans on Earth of roughly 1.5 m/s.**

For the detection of the first planet we have to thank the ability of Michel Mayor and his then student Didier Queloz, who were able to build for the first time a spectrograph capable of producing the extremely precise measurements required to detect planets and measure their approximate mass. Since 1995, the discovery year of the first planet, this field has been growing exponentially with new planets being discovered at an ever increasing rate via a variety of methods (Figure 1). Today we know of more than 4000 extra-solar planets and it is expected that current missions like the Transiting Exoplanet Survey Satellite (TESS) will discover thousands more via the "transit" method.

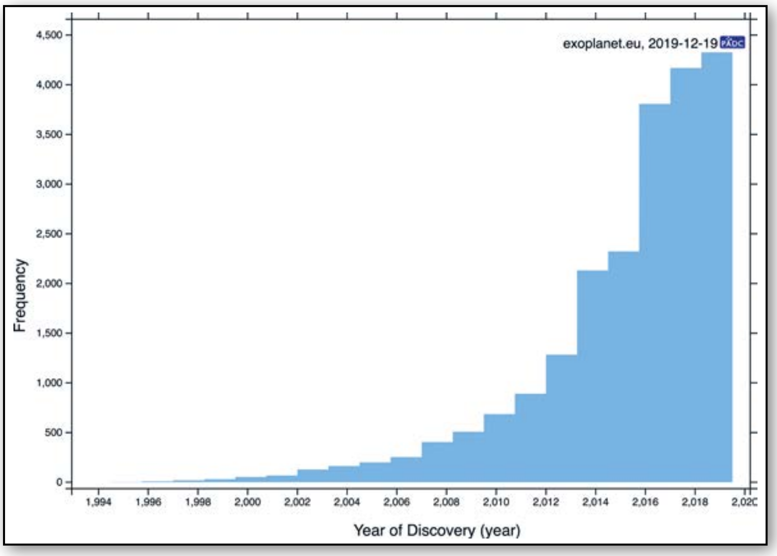
During a transit a planets can be detected by the shadow it casts onto the disc of the host star as its orbit crosses our line of sight to the star. By observing the brightness of a star over a long time, the presence of a planet may be thus inferred by the periodic dimming of the stellar light. Space missions like Kepler have been extremely successful in detecting planets even as small as the Earth, orbiting their host stars at distances where the temperature on their surface could be suitable for sustaining liquid water at their surface. This so-called circumstellar habitable zone or goldilocks zone is the distance of a planet to its host where the temperature might be just right for life to emerge.

To date several terrestrial planets with orbits in the habitable zone of their host stars have been discovered. Figure 2 shows an artist impression of the Trappist 1 system, which was initially discovered by the transit method. This system comprises seven terrestrial planets, three of which thought to be in the habitable zone of the host star. However the Trappist 1 system, and many other discovered habitable zone planets orbit stars that are significantly smaller and thus cooler than our Sun, so-called M-stars. Habitable zones of M-stars are very close to the star itself, as the energy required to keep water liquid on the surface of the planet is only available there. This is potentially a problem for life evolving on such planets as tidal locking may occur, which means that the rotation period of the planet around its axis equals its revolution period around the star. In this case the planet will always keep the same face towards the star, analogous to the Earth-Moon system. Temperatures on the opposite sides of tidally locked planets may be very different causing extreme climates. It is currently unclear if life could develop and thrive on tidally locked planets, which do not have a day-night cycle. Perhaps an even more worrying aspect about M-star planet hosts is their high magnetic activity, which produces strong flares of high energy radiation, which is detrimental to the retention of planetary atmosphere as well as cellular life as we know it on Earth. M-stars, which were the prime targets of the Kepler mission and are very abundant in our Galaxy, might not be the best environment to search for signs of life outside our Solar System after all. The TESS mission will focus instead on planets transiting solar-type stars.

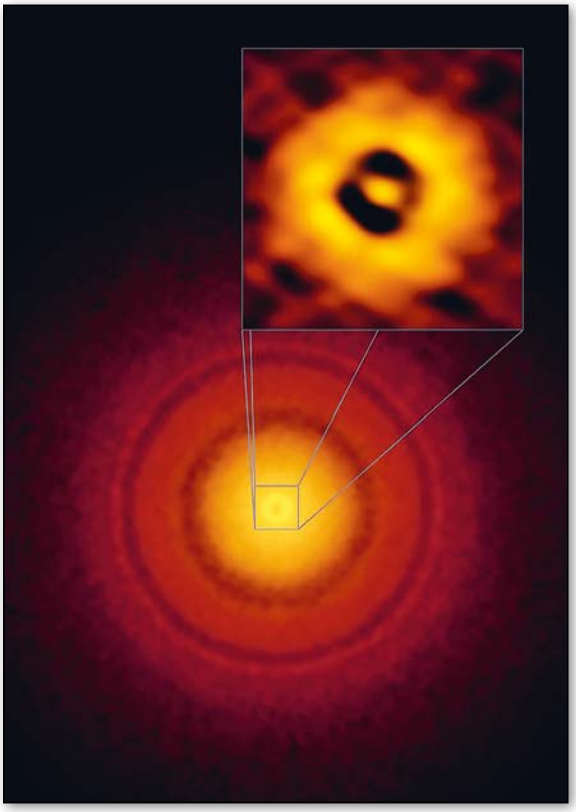
The prime motivation for exoplanet finding missions is the question of whether the Earth may be a unique and special place for life in our Universe. This question continues to be the driving force behind many observational campaigns and theoretical investigations in the field. While a partial answer may have been provided by the recent exoplanet surveys, which have shown that, **statistically speaking, most stars in the Milky Way have planetary companions** (Cassan *et al.* 2012), other surveys have also highlighted the diversity of exoplanetary systems (Mullally *et al.* 2015). This prompted the further question of how did these planets form, and whether some may end up looking like our own and being able to host life.

Diversity and habitability are a consequence of the process of planet formation and subsequent evolution, which is dictated by the physical conditions of the environment where they form. Planets form from the dust and gas contained in the circumstellar discs surrounding nearly all young low- to intermediate-mass stars. These planet-forming disks are a by-product of the star-formation process, since the gravitational collapse of rotating star-forming clumps necessarily needs to redistribute angular momentum. So all stars are born with circumstellar discs, meaning that all stars have at least the potential to host a planetary system. Indeed this theoretical prediction is in line with the observation that on average all stars in our Galaxy host a planet.

Currently, the favourite paradigm for the formation of planets is the so-called core accretion model. In this model micron size dust grains, embedded in the gaseous circumstellar disc, collide against each other and, in some cases, they stick to each other, growing to larger sizes. This "bottom-up" growth process brings dust grains along a journey over at least 12 orders of magnitude as they reach the sizes of thousands of kilometer.



▾ **FIG. 1:** Cumulative distribution of confirmed extrasolar planets. Since the discovery of the first gas giant orbiting a Sun-like star, the rate of discovery has been increasing, with peaks corresponding to the data releases of large space missions likes Kepler. © exoplanet.eu



▸ **FIG. 2:** Atacama Large Millimeter continuum image of TW Hydra. The outer rings are thought to have been carved by forming planets, while the central cavity has been created by photoevaporation from the central star. © S. Andrews (Harvard-Smithsonian CfA), ALMA (ESO/NAOJ/NRAO)

This journey is not easy. Not every collision results in sticking, depending on the velocity of the collision, particles may fragment or just bounce against each other, making the growth process extremely slow. However planet formation has to happen during the lifetime of the circumstellar disc, which holds the reservoir of material from which planets form.

Circumstellar discs are observed to evolve and finally disperse over a timescale of a few million years, which is comparable to the timescales for planet formation by the core accretion process. This implies that the processes driving the evolution and dispersal of discs play a crucial role in shaping new planetary systems and likely contribute to the observed diversity of exoplanets. Studies show that discs mostly disperse from the inside-out via the formation of so-called transition discs *i.e.* discs that have an evacuated inner cavity. These relatively rare objects may be discs caught on the last gasps of their lives and may thus provide key insights on the mechanism responsible for their evolution.

Disc dispersal is thought to be driven by the high energy radiation, particularly X-ray, emitted from the central star, which plays a key role in shaping the evolution of discs and of their planetary progeny. X-rays penetrate the disc, ionising and heating the gas, which then flows away in a thermally unbound and centrifugally accelerated disc wind. This process of disc photoevaporation ultimately causes the dispersal of the circumstellar disc. The Atacama Large Millimeter Array has provided us with exquisite spatially resolved images of transition discs, where the dispersal process and the planet formation process may be occurring simultaneously as in the case of our nearest neighbour, TW Hydra, shown in Figure 3. The outer disc rings have probably been carved out by forming planets, while the central cavity results from the onset of the photoevaporation process, which will finally cause the demise of the disc and pose an end to the planet formation process in this disc (Ercolano *et al.* 2017).

The award of this year's Nobel Prize in Physics to exoplanet science is really just the beginning. The era of exoplanet discovery is giving place to a new era of exoplanet characterisation, with new missions, in the near future, designed to determine the physical properties of these far away worlds as well as starting to study their atmospheric composition in the search for biomarkers (*e.g.* CHEOPS and Ariel). Biomarkers are gas of biological origins that may hint at the presence of life. At the same time theory is advancing fast to explain how these planets may have formed in their natal circumstellar discs and what role the central star plays in determining the habitability of a system. The next two decades will certainly be full of exciting discoveries in this field, which addresses fundamental questions concerning where we came from and what are the perspectives for the emergence of life elsewhere in the Universe.

About the Author

Barbara Ercolano is a Professor of Theoretical Astrophysics at the Ludwig Maximilians University of Munich and leads a DFG Research Unit on transition discs, that are believed to be the natal environments of forming planets. Barbara Ercolano is also a Principal Investigator in the new Origin Excellence Cluster, which is an interdisciplinary Institute joining Astrophysics, Biophysics and Particle Physics in the quest to understand the Origin of the Universe and the building blocks of Life.

She holds a doctoral degree from University College London. She successively held a research position at the Harvard-Smithsonian Center for Astrophysics in Cambridge (MA, USA), an STFC Advanced Fellowship at the Institute of Astronomy of Cambridge University and University College London (UK), and was a lecturer at the University of Exeter (UK). Barbara Ercolano is the 2010 winner of the Fowler Award in Astronomy of the Royal Astronomical Society.

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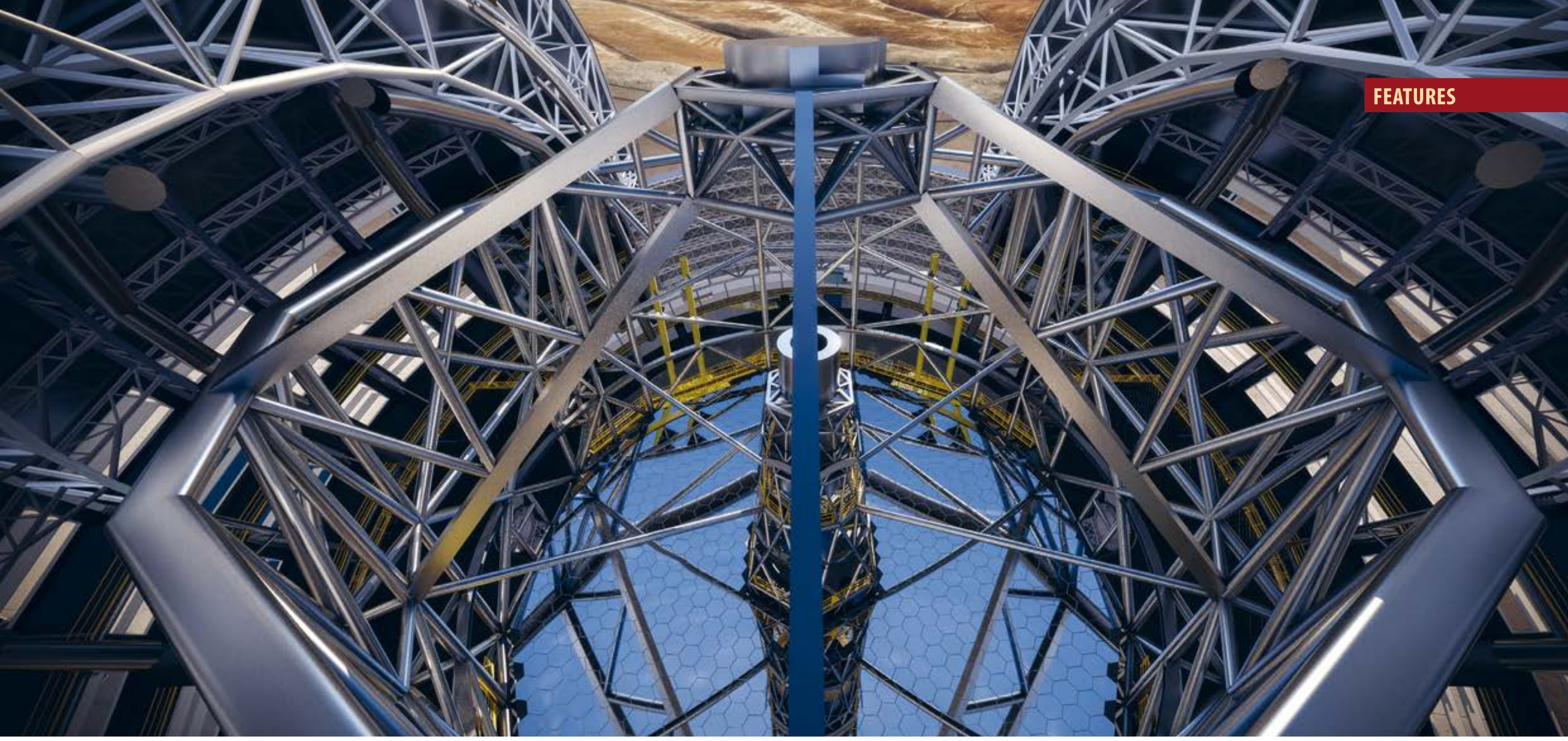


PLANETS ORBITING OTHER STARS

THE SEARCH FOR EXTRATERRESTRIAL LIFE

Ignas Snellen – Leiden Observatory, Leiden University, The Netherlands – DOI: https://doi.org/10.1051/epn/2020102

Since the Nobel-prize-winning discovery of a planet orbiting a sun-like star, the field of extrasolar planets is undergoing a true revolution. Thousands of planets have been found, of which some may be like Earth. Could there be biological activity on any of these, and how do we find out?

▲ Artistic rendering of the European Extremely Large Telescope currently under construction to be operational in the mid 2020s. (Credit: ESO, L. Calcada, ACe consortium)

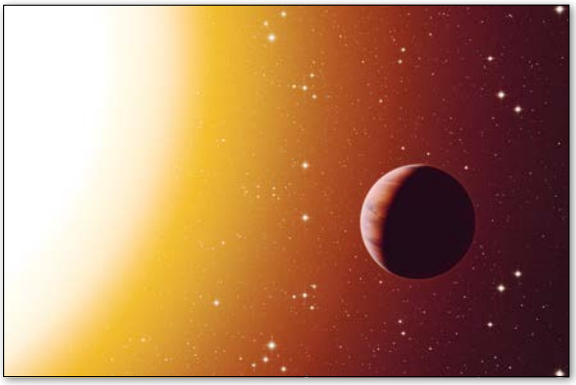
Since the age of Copernicus and Galilei we know that Earth does not form the center of the Universe. We since have found out that it orbits the Sun as one of multiple planets. The Sun is a normal star in the outskirts of the Milky Way, and the Milky Way is one of the billions of galaxies in the observable universe. It may be argued that our home planet is nothing special, and that the universe is teeming with life. In reality, however, the Earth may be quite unique. Circumstances may need to be just right for life to form and evolve, in particular for highly evolved species which may require a stable planetary climate for billions of years. We simply do not know. The search for extraterrestrial life is an important philosophical endeavor, which will shed light on the place of humanity in the cosmos. *Are we alone?*

A particularly complicating aspect of the search for life is that we do not know much about what to expect. Life on Earth is the only reference available. Although many scenarios have been proposed, we do not know how life on Earth initially formed. Also, we cannot yet form living organisms from scratch in the lab. Still, any extraterrestrial organism should obey the laws of chemistry and physics – at least in a scientific context – and any biological function requires complex chemistry. Carbon-based molecules are generally seen as the only way to provide the intricate building blocks for this [1].

Follow the water

We also know that water has been playing a crucial role in the origin and development of life on Earth. Astronomers jump at this aspect. We can identify places in the universe where liquid water could exist, on the surfaces of rocky planets at the right distances from their host stars [2]. These may be places were life can form and evolve. This does not mean that life does not exist in other locations, even in our own solar system, such as deep underground on Mars, or in the sub-surface oceans of some moons of Jupiter and Saturn.

In the case of exoplanets, however, we need to be able to recognize biological activity from interstellar distances, meaning that it must significantly alter the chemical structure of its planet's atmosphere and/or surface – which can potentially be observed from many light years



▸ FIG. 1: Artist's impression of a hot Jupiter (© ESO, L. calcada).

away. This is what astronomers will focus on in the next decade(s). Do rocky exoplanets have atmospheres? What are the main constituencies of these atmospheres? Are the planets wet or dry? Do we understand the atmospheric and geological processes involved? Can we identify gases that may be produced by biological activity, such as molecular oxygen on Earth? Ultimately, we will need a deep understanding of a planet's origin and evolution to make a conclusive case for extraterrestrial biological activity, requiring intensive collaborations between many scientific disciplines, including chemistry, geology, climatology and biology.

Planets everywhere

So, where are we now, and where do we go from here? Since the Nobel-Prize discovery [3], planets have been found everywhere. The two most successful methods are the radial velocity and transit techniques. The first measures the reflex motion of a star around a system's center of mass. This can reveal a planet's orbit, and a lower limit to its mass (depending on the orientation of the orbit). For the second method, the orientation of the planet's orbit needs to be nearly edge-on. The planet then regularly occults a part of the star, resulting in a small dip in the amount of starlight that we see. This reveals the size and orbit of the planet, and in combination with the radial velocity method, also its mass and mean density – providing first clues about its composition.

▾ FIG. 2: Artist's impression of the surface of exoplanet Proxima Centauri b. (© ESO/ M. Kornmesser)

After 25 years of discoveries, we know that planets are very common. About one in ten stars harbor a gas giant like Jupiter, about one in three have Neptune-size planets, and most stars harbor Earth-mass objects. The latter is particularly pronounced around low-mass stars. Our nearest neighbor, Proxima Centauri at about 4 light years, has a small planet [4] in an 11-day orbit. Since the star is more than a thousand times less luminous than our Sun, the planet receives as much stellar energy as if it were a planet in an orbit between that of the Earth and Mars. Very exciting is also the nearby TRAPPIST-1 system [5], which harbors seven sister planets, all about the size of the Earth, and of which at least three could have a climate allowing liquid water on their surfaces. Therefore, even very nearby, we already know of several planetary systems where life possibly could form and evolve. Do note, however, that it is not clear whether the, in some aspects, harsh circumstances around red dwarf stars allow the onset biological activity [6].

Atmospheres

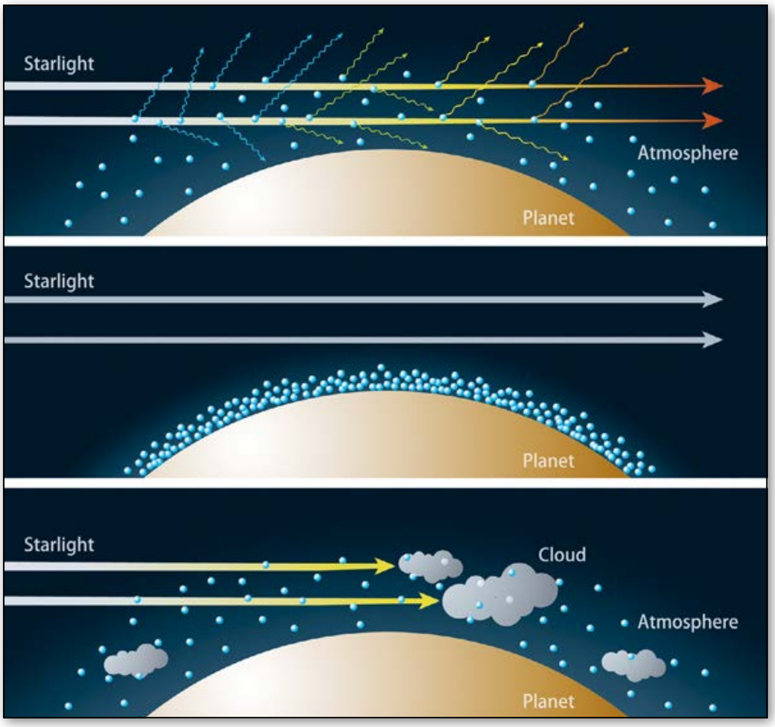
Studying the atmospheres of exoplanets is a whole different ball-game. Almost all planets found to date have been discovered without identifying a single photon from the planets themselves. For atmospheric studies this can no longer be the case – planet light needs to be separated from that of the star, with the latter being many orders of magnitude brighter.

There are basically two families of methods to accomplish this. The first has so far been the most successful and involves transiting systems, making use of temporal variations in how we see the planet. When a planet transits a star, in addition to occulting part of the stellar surface, starlight also filters through the planet atmosphere, leaving an imprint of atomic and molecular absorption and scattering. In addition, half an orbit later, the planet is occulted by the star, meaning that for a few hours the planet's light (either intrinsic thermal emission or starlight reflected off the planet's atmosphere) is missing and can be accounted for. Also during the rest of the orbit, varying parts of the dayside and nightside of the planet are visible, resulting in variations that reveal its heat distribution which can constrain global climate circulation models.

Making direct images of exoplanets, by angularly separating the planet from the star in the sky, is still very difficult. Ground-based telescopes require adaptive optics to mitigate the disturbing influence of our atmosphere, to approach their theoretical angular resolution. This is needed in combination with coronagraphy to block the star light such that a faint orbiting planet can be seen. Telescopes in space have the advantage not to need the former, but are costly, and are therefore smaller and have significantly less resolution, limiting their performance [7].

Most atmospheric characterization has been limited to warm gas giant planets, which have the largest atmospheric scale heights and therefore strongest transit signals, and emit most thermal emission. For direct imaging this needs to be accompanied by a large enough orbital distance to assure angular separation from their host stars, which means that only young gas giants, which are still hot from their formation, can be probed. So far, several different molecules, such as carbon monoxide and water have been identified with both families of methods, in addition to several atoms and ions, and evidence for Rayleigh scattering and the presence of clouds and hazes. Also, vertical and longitudinal temperature structures have been measured, including thermal inversions and atmospheric escape processes.

In the exoplanet group at Leiden University we focus on the use of ground-based telescopes for atmospheric characterization. In particular, performing transit and direct imaging observations at very high spectral resolving powers ($\lambda/\Delta\lambda \sim 100{,}000$) is very effective, revealing the tens to hundreds or thousands of individual rotational-vibrational lines of molecules. This has several advantages. Molecules are uniquely identified, even if their spectral bands overlap. Furthermore, the ground-based calibration is significantly more straightforward in this way, and the spectral features from the planet, our own atmosphere, and the star can be disentangled because of their different Doppler shifts – even if each exhibit features from the same molecule. This has been shown to be very powerful and probes exoplanet atmospheres in unique ways, also being sensitive to exoplanet atmospheric winds and spin rotation [8, 9]. Ultimately, this can also be used to target molecular oxygen, a biomarker gas, in nearby rocky exoplanets – the possible exoplanet-based oxygen and that in our own atmospheres will be separated in velocity and can be distinguished from each other.



▲ **FIG. 3:** Schematic relation between the composition and structure of an exoplanet atmosphere and the observed transmission spectrum. Starlight travels through the planet atmosphere and is being scattered by molecules at certain wavelengths (top), is largely unaltered because of the small scale height of the atmosphere (middle), or absorbed by clouds (bottom). (Credit: NAOJ)

En route to finding life

Atmospheric observations are currently still limited to gas giants, including a recent detection of water vapor in the atmosphere of a temperate mini-Neptune [10, 11]. But this will soon change. Astronomers around the world are eagerly awaiting the launch of the James Webb Space Telescope in 2021 – the successor of Hubble. It will target TRAPPIST-1 planets to see whether they have atmospheres, and if so, get a handle on their constituencies. This will be a major step forward, providing a first assessment of the climates of rocky planets around small red dwarf stars.

Personally, I am even more excited about the next-generation of ground-based telescopes, in particular the 39 meter European Extremely Large Telescope, which is being built in the Atacama Desert of northern Chile (first light in 2026). One of its first light instruments is METIS [12], a mid-infrared spectrograph with high spectral resolving power perfectly designed for atmospheric observations. METIS, and the second-generation optical spectrograph HIRES, can reveal possible water vapour, carbon dioxide, methane, and ultimately oxygen in the atmosphere of our nearest neighbour Proxima Centauri b. A very exciting prospect. If common, and nature is kind to us, we may find the first clues of extraterrestrial life within this decade. ■

About the Author

Ignas Snellen is a professor in astronomy at Leiden University in the Netherlands. He is an expert in the atmospheric characterization of extrasolar planets.

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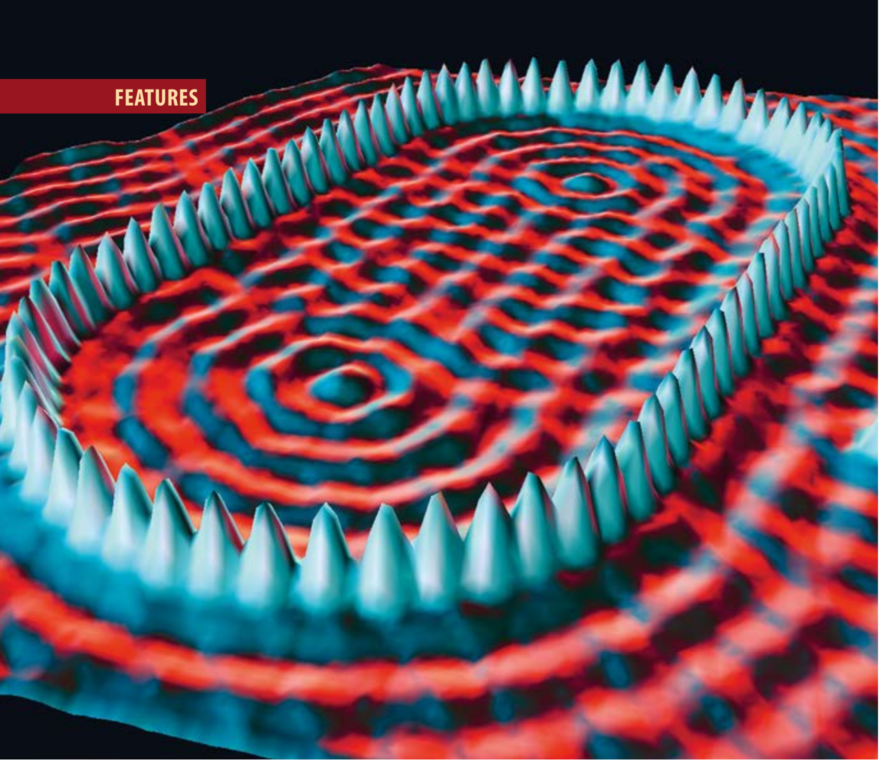

30 YEARS OF MOVING INDIVIDUAL ATOMS

Christopher Lutz[1] and Leo Gross[2]
DOI: https://doi.org/10.1051/epn/2020103
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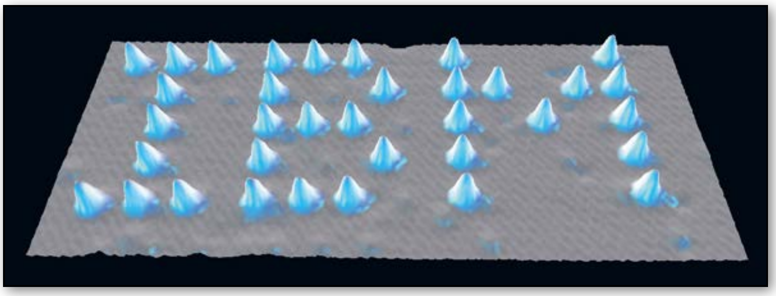
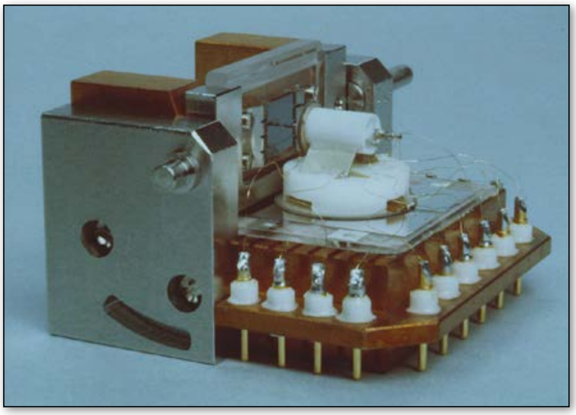
In the thirty years since atoms were first positioned individually, the atom-moving capability of scanning probe microscopes has grown to employ a wide variety of atoms and small molecules, yielding custom nanostructures that show unique electronic, magnetic and chemical properties.

This year marks the thirtieth anniversary of the publication by IBM researchers Don Eigler and Erhard Schweizer showing that individual atoms can be positioned precisely into chosen patterns [1]. Tapping the keyboard of a personal computer for 22 continuous hours, they controlled the movement of a sharp tungsten needle to pull 35 individual xenon atoms into place on a surface to spell the letters "IBM" (Figure 1). Eigler and Schweitzer's demonstration set in motion the use of a newly invented tool, called the scanning tunneling microscope (STM), as the workhorse for nanoscience research. But this achievement did even more than that: it changed the way we think of atoms. It led us to view them as building blocks that can be arranged the way we choose, no longer being limited by the feeling that atoms are inaccessibly small.

It is difficult to believe that only a hundred years ago, when quantum physics and relativity came into focus, the idea that atoms are real individual objects was still viewed with suspicion [2]. As late as 1952, Erwin Schrödinger wrote that "…we never experiment with just one electron or atom or (small) molecule. In thought-experiments we sometimes assume that we do; this invariably entails ridiculous consequences…" [3]. These consequences are not ridiculous, but are profoundly intriguing since many of the early speculations have become experimentally accessible in recent decades. For example, the atoms seen by Erwin Müller's field ion microscope in the 1950s [4], inspired many scientists, who marveled at the nested rings of individual atoms at the apex of the sharp metal tips. The atoms at the most exposed corners could be dislodged by voltage pulses, but could not yet be placed in predetermined arrangements. To achieve this, an invention that could sense and guide the atoms in a much gentler environment was required. This invention was the STM.

▼FIG. 1: Thirty-five xenon atoms arranged on a nickel surface to spell IBM in letters 5 nm tall. (Credit: IBM)





▲FIG. 2: The STM that Don Eigler and coworkers used to position atoms. The tip is seen touching its reflection in the sample's surface. (Credit: IBM)

A tool for imaging and moving atoms

In 1981, Gerd Binnig and Heinrich Rohrer, working at IBM's research laboratory in Zurich, created the first STM by raster scanning a sharp metal tip held just a few atomic diameters away from the surface [5]. They succeeded for the first time to image the atoms of a surface of silicon, an achievement that earned them the Nobel Prize in Physics in 1986. The principle of the STM is to control the narrow gap width between the tip and the surface by measuring the flow of electrons that quantum tunnel across this gap. Holding the current constant, the tip traces out contours that display the pattern of atoms. The key property that allows atomic resolution to be achieved is the exponential dependence of the tunnel current on the gap size. Indeed, if the tip is moved by one atomic diameter towards the surface, the current will increase by a factor 100. This extreme resolution opened the door to the nanoworld.

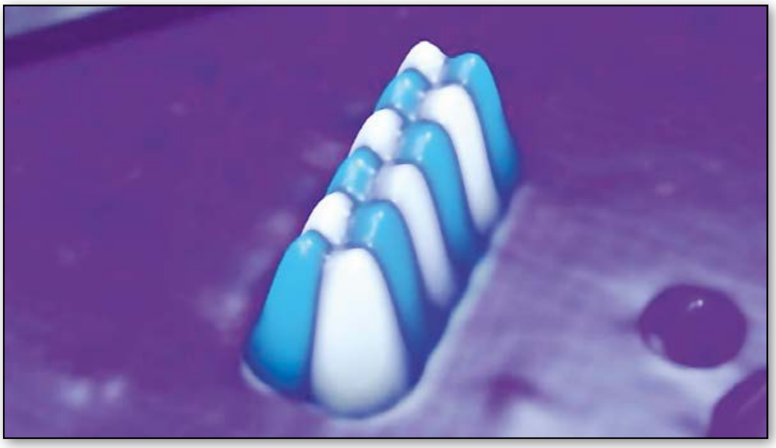
In the late 1980's Don Eigler constructed the first STM operating at liquid helium temperature (4 Kelvin) and under ultrahigh vacuum to keep the surface atomically clean. It was vibrationally isolated so that it had uncontrolled tip-sample motion of only 2 picometers (or 1/100th of a typical atomic diameter). The result was an instrument capable of positioning individual atoms. The whole table-sized STM apparatus is a vacuum chamber bristling with connectors. But the core of the STM – the scanner and sample holder – is small enough to hold in the palm (Figure 2). A sharpened tungsten wire serves as a tip, which is moved in three dimensions by piezoelectric actuators.

Eigler's STM can image individual atoms attached to a surface, even weakly bound elements like the xenon atoms used to write the IBM logo. The controlled motion of atoms depends on the right balance of forces: the atom must not desorb or move spontaneously on the surface while the tip must be able to pull it to a new location with large enough lateral forces. Due to the weak Van der Waals force to the surface, xenon atoms are moved easily by the tip. Other atomic elements require greater pulling forces, reached by bringing the tip in closer contact with the atom on the surface.

The atomic force microscope (AFM) is a sibling of the STM that relies on the force between sample and tip, rather than on the tunneling current. It was demonstrated in 1986 by researchers at IBM and Stanford [6]. The AFM has the advantage of being able to probe insulating surfaces and it provides complementary information to the STM. Nowadays many low-temperature tools measure force and current simultaneously, so they incorporate both AFM and STM capabilities, collectively called scanning probes.

Arranging atoms to control electrons

Controlled positioning of metal atoms has made it possible to construct large atomic arrangements such as the stadium-shaped "quantum corral" of Figure 1, which produces a standing wave pattern of electrons confined inside the corral [7]. Subsequently, various chemical elements were used to assemble a rich variety of structures having well-designed quantum states and band structures [8].



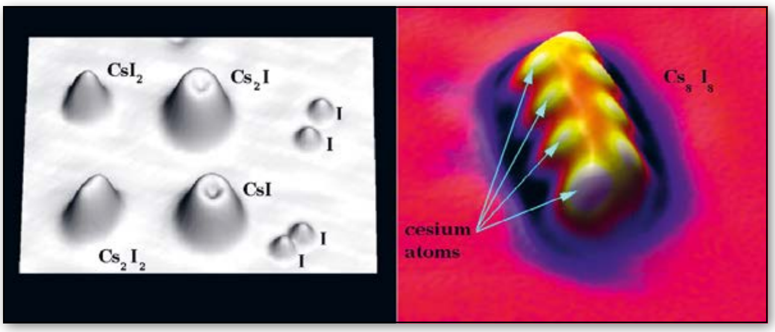
▲ **FIG. 3:** Bistable antiferromagnet made of 12 Fe atoms on an MgO film. Blue/white color shows the measured spin direction. (Credit: IBM)

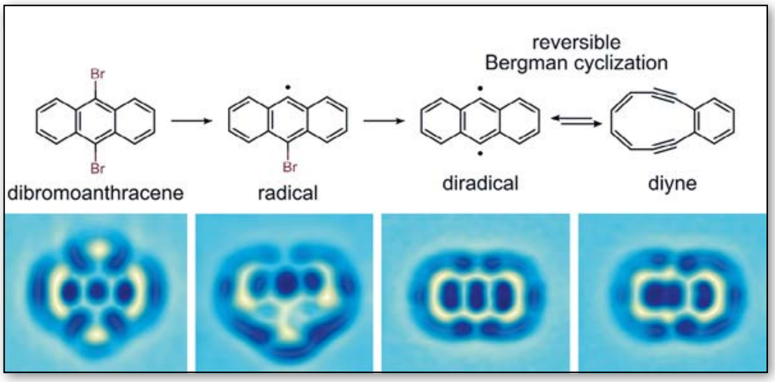
The STM has proven adept at constructing and imaging magnetic nanostructures. Atoms bound directly on the metal surface show many intriguing magnetic properties [8]. Placing them instead on a thin layer of insulating material, such as copper nitride or magnesium oxide (MgO), has yielded long-lived quantum magnetic states. Structures were assembled by transferring each magnetic atom onto the STM tip and back to the insulator, using voltage pulses for each transfer. An example is the antiferromagnet made of 12 iron atoms shown in Figure 3. This tiny magnet can be switched by flipping all the spins at once using a current pulse from the tip, making it a writable magnetic memory bit [9].

From atoms to molecules

A step toward building molecules using STM is to assemble ionic clusters made of alkali halides. Figure 4 shows how cesium (Cs) and iodine (I) atoms were manipulated to form precise molecule-like clusters [10]. The Cs atoms, stable only when attached to an I atom, were moved from one I atom to another by using an I-terminated tip in order to form clusters such as Cs2I and Cs2I2. The Cs2I2 clusters were then pulled along the surface as a unit and attached together into polymer chains. Sodium iodide clusters were also obtained, suggesting that it will likely be possible to build a variety of alkali halide structures in the future.

▼ **FIG. 4:** Assembling planar ionic molecules from cesium and iodine atoms. Left: Small Cs- and I-based structures on a Cu(111) surface. Right: A Cs8I8 chain achieved by sliding four pre-assembled Cs2I2 units together. (Credit: IBM)





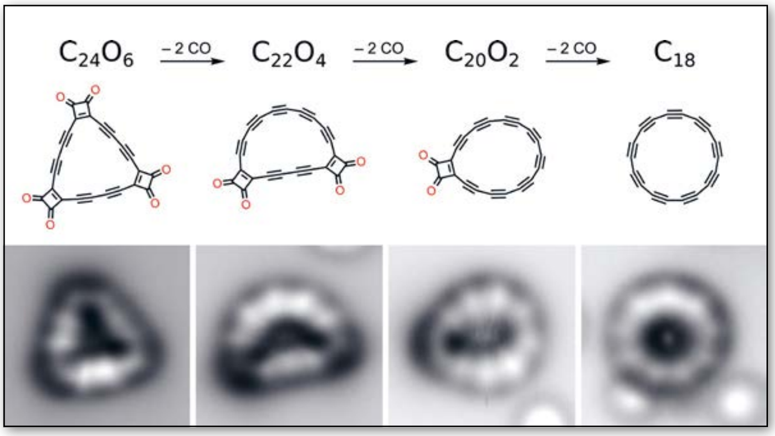
▲ **FIG. 5:** Breaking and forming covalent bonds by atom manipulation. Applying voltage pulses from the tip, two Br atoms are successively dissociated from a precursor molecule to generate a diradical. This diradical can be reversibly and repeatedly transformed into a diyne, breaking and forming covalent carbon-carbon bonds within the molecule. The AFM images are taken using a CO-functionalized tip. Adapted from ref [14], Springer Nature.

Atom manipulation can be used not only to move and place atoms and molecules on a surface, but also to break or form covalent bonds in molecules [11]. The synthesis of a molecule by atom manipulation was demonstrated by Saw-Wai Hla and coworkers in a landmark experiment in 2000, performing all steps of an Ullmann coupling reaction [12].

Recently, molecule and atom manipulation made great progress thanks to high-resolution AFM that uses CO terminated tips, revealing the internal structure and chemical bonds of molecules [13]. This approach permits chemical reactions to be followed step by step and to identify intermediate and final products with atomic resolution. On chemically inert surfaces such as NaCl or Xe monolayers, highly reactive molecules such as radicals and reaction intermediates can be generated, remaining stable enough to be studied. Figure 6 shows bromine (Br) dissociation followed by reversible carbon-carbon bond cleavage and bond formation in an individual molecule [14].

Exploiting the inert surface and the controlled influence of the scanning probe tip, elusive molecules can be generated that cannot be studied otherwise. For example, the cyclo[18]carbon C_{18}, a highly reactive allotrope of carbon, whose structure had been debated for years, was recently synthesized by atom manipulation [15].

▼ **FIG. 6:** Elusive molecules created by atom manipulation. The cyclic carbon C18 was formed by atom manipulation on a bilayer NaCl film on Cu(111). Here CO masking groups from the precursor C2406 were dissociated by voltage pulses. In the AFM images (bottom row) the triple bonds appear with a characteristic bright contrast. Adapted from ref [15], AAAS.



The AFM images (Figure 6) settled a long-running debate by showing that the final structure is not cumulenic with only double bonds but polyynic, consisting of alternating single and triple bonds.

Prospering in the room at the bottom

Richard Feynman's 1959 essay "There's plenty of room at the bottom" looked into a future time when objects will be assembled atom-by-atom. As we strive to approach this ultimate level of miniaturization, we will benefit by making intentional use of every atom. In the last 30 years, scanning probes have led the way forward, and their versatility will surely keep them at the forefront of this exciting exploration. ■

About the Author

Christopher Lutz is a Senior Scientist at IBM Research – Almaden in San Jose, California. He joined the group of Don Eigler in 1990 and has led the group, now the atom manipulation and nanomagnetism project, since 2016.

Leo Gross is a Research Staff Member at the IBM Research – Zurich since 2009, where he is the team lead of the atom/molecule manipulation group.

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ACCRETION DISKS AROUND YOUNG STARS: THE CRADLES OF PLANET FORMATION

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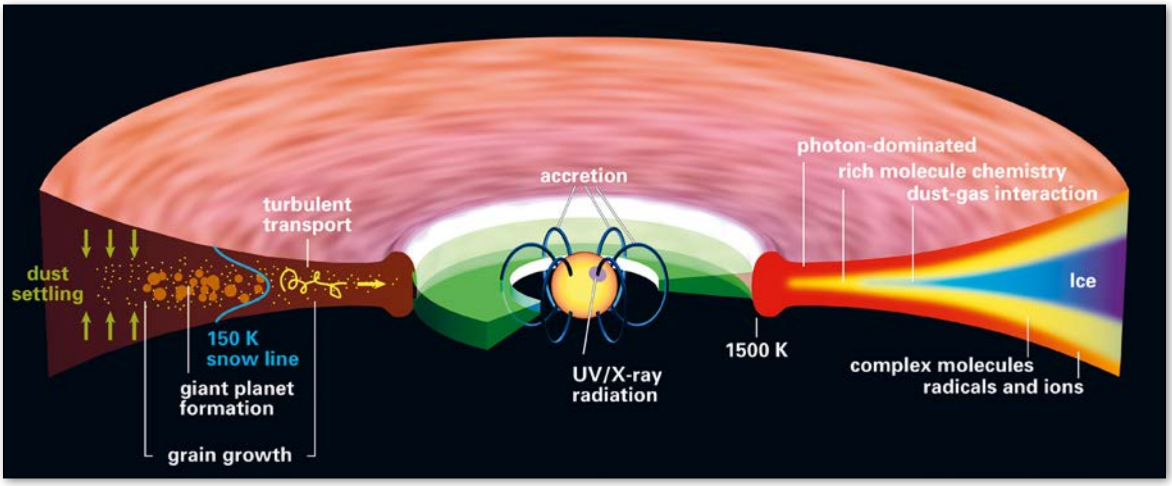
Protoplanetary disks around young stars are the birth sights of planetary systems like our own. Disks represent the gaseous dusty matter left after the formation of their central stars. The mass and luminosity of the star, initial disk mass and angular momentum, and gas viscosity govern disk evolution and accretion. Protoplanetary disks are the cosmic nurseries where microscopic dust grains grow into pebbles, planetesimals, and planets.

▲ The first clear image of a young planet caught in the very act of formation in a protoplanetary disk PDS 70 (SPHERE instrument on ESO's Very Large Telescope). The planet is visible as a bright point to the right of the centre of the image, which is blacked out by the coronagraph mask used to block the blinding light of the central star.

Protoplanetary Disks as Analogues of Young Solar Systems

Protoplanetary disks are believed to be the environments where planets, their satellites as well as comets and asteroids are formed over a timescale of several million years (Myr). Diversity of protoplanetary disks allows us to better comprehend properties of and conditions in the protosolar nebula, out of which our own solar system has emerged [1–3]. Protoplanetary disks are found around young stars with masses between ~0.1 and 2.5 solar masses ($1M_{\rm Sun} \approx 2 \times 10^{30}$ kg). These rotating disks are made of ~99% gas and ~1% dust (by mass) and have typical masses of ~ $0.01–0.1M_{\rm Sun}$. Disks have sizes up to ~1000 au (1 au is the average distance between Earth and the Sun). For reference, Pluto orbits the Sun at ~ 40 au distance, while the Oort cloud of comets is located at distances beyond 2,000-200,000 au.

Protoplanetary disks are a natural outcome of the star formation process. The ~10 Myr evolution of a protoplanetary disk can be divided into three main stages. The newly born star is surrounded by a slowly rotating envelope of material which, due to the conservation of angular moment, flattens out into a circumstellar disk. During the first ~0.1 – 0.5 Myr, the central star continues to grow in mass by accreting matter from the inner edge of the disk, which, in turn, is fed by the remains of the



▸ **FIG. 1:** A protoplanetary disk around a young Sun-like star. The young star illuminates the disk atmosphere, which leads to the flaring vertical structure and strong gradients of physical conditions. The µm-sized dust grains are coupled to the gas and provide opaqueness to the disk matter. The mm-sized dust grains gravitationally settle toward the disk midplane, where they can further grow and drift toward the inner regions. From chemical perspective, a disk can be divided into three layers: (1) a cold midplane where molecules are frozen onto dust grains as ice, (2) a warmer intermediate layer where molecules form and remain in the gas, and (3) a hot irradiated atmosphere with atomic species. Reprinted with permission from [2]. Copyright 2013 American Chemical Society.

extended envelope. Secondly, when the external supply of matter from the envelope onto the disk comes to an end, the star reaches its final mass and the disk mass begins to decrease over a timescale of ~3 – 10 Myr. Sometime during this entire process, the onset of planet formation commences, however it is currently unclear when exactly it begins. During the clearing phase that lasts several Myr, the remaining disk is dispersed by the planet-disk dynamical interactions and photoevaporation by stellar radiation.

Protoplanetary Disk Structure

Protoplanetary disks are accretion disks, which evolution was mathematically described in the "classical" theoretical studies [4–6]. Their fundamental physical properties are described by the conservation laws for energy and angular momentum. An accretion disk is a flat, rotating gaseous structure in orbital motion around the gravitational centre (a star). Usually the central star is much more massive than the disk, and the orbital motion of the gas at a radius R nearly follows the Kepler law: $V_K = GM_*/R$ (where G is the gravitational constant and M_* is the mass of the star). The departure from the perfect Keplerian rotation is due to the thermal gradient, which makes gas orbital velocities to be slightly sub-Keplerian.

Accretion is the loss of potential energy via frictional dissipation. Accretion leads to a net transport of the disk matter toward the gravitational centre, while a minority of the matter carries angular momentum outside of the disk. Measured accretion rates from disks onto their central stars are low, ~10^{-12} to 10^{-8} M_{Sun}/yr [7]. The frictional dissipation is provided by the viscous stresses. The molecular viscosity is too low to drive the disk accretion. Thus, other mechanisms like turbulence or disk winds have been invoked. The origin of disk turbulence or winds are not yet fully understood and likely caused by various (magneto)-hydrodynamical instabilities [8,9]. In massive, cold disks a gravitational instability can occur, driving efficient angular momentum transport and accretion via spiral arms.

Turbulent viscosity in disks is often parameterised by the so-called α parameter: $\nu = \alpha c_s H$, where c_s is the thermal gas velocity (sound speed) and H is the scale height of the disk (local disk extend) [5]. Observations and advanced dynamical models of protoplanetary disks point to a weak subsonic turbulence with $\alpha \sim 10^{-5} - 10^{-3}$ [10]. By knowing the α parameter, the time evolution of the gas density distribution in a geometrically thin disk as a function of radius can be computed by solving for a 1D non-linear diffusion equation [6, 11].

Protoplanetary disks are characterised by the strong gradients of physical conditions and chemical composition, with cold and dense midplanes, warm upper layers, and hot, tenuous atmosphere (Fig. 1). The thermal disk structure is determined by the dissipation of accretion energy in the inner disk region, and by the reprocessing of the stellar and interstellar radiation in the rest of the disk. The dust and gas temperatures are coupled via collisions in dense layers, at particle densities above 10^5 - 10^8 cm^{-3}. The disk gas becomes hotter than the dust in the atmosphere, reaching temperatures >10,000 K. At intermediate heights, where dust grains begin to shield the disk matter from external high-energy radiation, the dust and gas temperatures become close to each other, 20 – 500 K. In the inner disk, midplanes temperatures can reach up to 1,500 K due to accretion heating, while outer midplane regions are cold, 10 – 20 K.

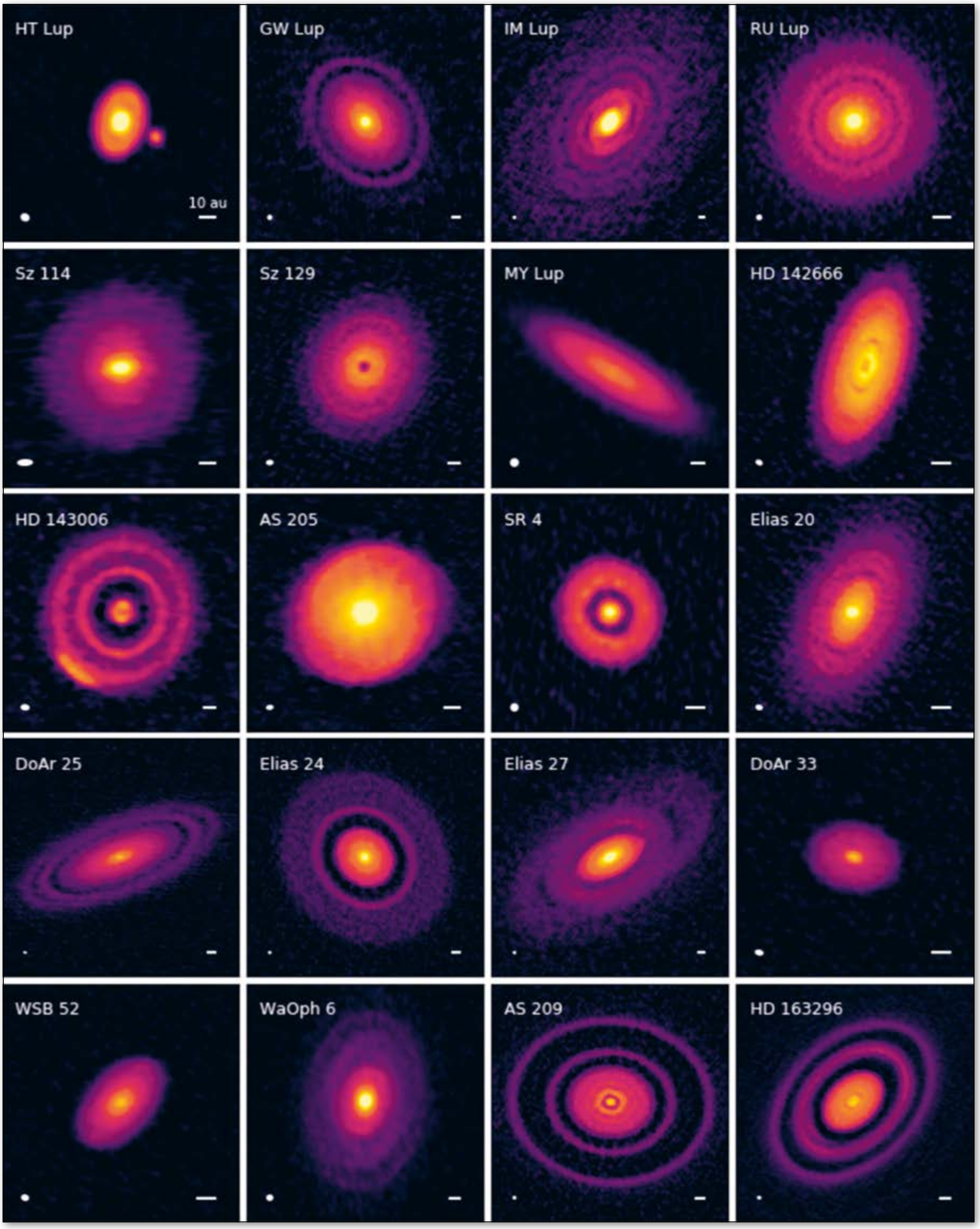
Disk gas density decreases very rapidly in the vertical direction. Assuming hydrostatic equilibrium between gravity and thermal pressure, the vertical gas density distribution can be approximated by a Gaussian function. The vertically integrated gas density also decreases radially outward. This often leads to a situation when more than a half of the disk mass is located inside the planet-forming zone at $\lesssim 20 - 50$ au.

Dust evolution in disks leads to the dust density distribution that differs from the gas density distribution. Micron-sized dust grains remain collisionally coupled to the gas and follow the gas. They can grow through collisions into bigger millimeter-sized grains (pebbles), becoming partially decoupled from the gas and gravitationally settling towards the disk midplane. Pebbles experience a headwind from the gas due to the difference between their perfectly Keplerian velocities and the sub-Keplerian velocity of the gas. This leads to their rapid drift inward and loss, unless they are trapped between the disk gas gaps or grow far beyond 1 m in size. The most robust process for the dust growth beyond this 1 m barrier is the local accumulation of solids in turbulent eddies and other long-lived gas over-densities [12].

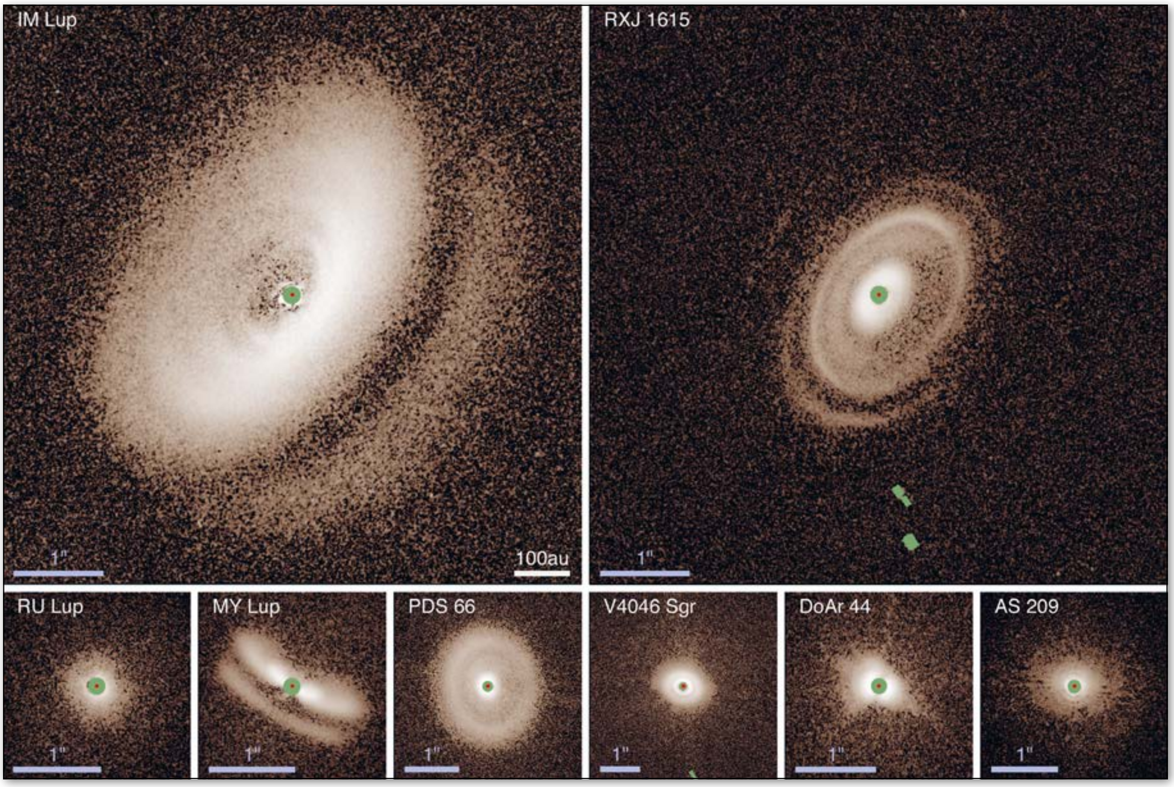
Later, these pebbles can grow into a swarm of km-sized planetesimals, first planetary embryos (~ 100 – 1000 km), and planetary cores (□ >1000 – 3000 km). According to the core-accretion scenario [13], giant planets like Jupiter can form when their solid cores grow above ~ 5 – 20 Earth masses and able to gravitationally attract nearby gas. Otherwise, the planetary cores end up as rocky, Earth-like planets. The planet formation timescale cannot be much longer than the disk lifetime of a ~10 Myr.

Recent Developments

Recent progress in space-born and ground-based observatories like *ALMA, Herschel, NOEMA, Spitzer, VLT* provided images of hundreds of protoplanetary disks in thermal dust



◂ **FIG. 2:** Twenty protoplanetary disks observed at the wavelength of 1.25 mm with the Atacama Large Millimeter Array in Chile (DSHARP project; PI: Sean Andrews, Center for Astrophysics | Harvard and Smithsonian). What is visible in each panel is the continuum emission from ~1 mm-sized dust grains, which gravitationally settled toward the disk center. The detector pixel sizes (lower left corner) and the 10 au scale bars (lower right corners) are shown in each panel, respectively. The dark gaps are believed to be gravitationally cleared by giant planets. Reprinted with permission from [14]. Copyright 2018 Astrophysical Journal.



▸ **FIG. 3:** Near-infrared images of eight protoplanetary disks (SPHERE instrument at the Very Large Telescope in Chile). What is visible in each panel is the stellar light scattered by sub-micron-sized dust grains. The strong emission of the central star is blocked by the coronographic mask. The dark lanes are the disk midplanes where dust absorbs the stellar light. The images are rescaled to represent the same physical size. Green areas mark places where no information is available. Reprinted with permission from [15]. Copyright 2018 Astronomical Journal.

continuum and numerous molecular emission lines (see Figs. 2, 3). Micron-sized grains are best observed at visual and near-infrared wavelengths via scattered stellar light. Solid-state ice and silicate emission bands, and vibrational transitions of gaseous molecules are observed at near- and mid-infrared wavelengths (from ground and space). Bigger mm-sized grains and molecular rotational transitions are observed at (sub-)millimeter wavelengths with radio interferometers such as *ALMA*.

Surprisingly, a majority of disks observed at a high spatial resolution in dust continuum emission reveals a multitude of substructures like dark gaps, bright rings, spiral arms, *etc.*, which are indicative of planet formation (Fig. 2). These circularly-symmetric gaps and rings are likely caused by embedded planets, while spirals could be induced by external perturbers. Ongoing large chemical surveys with *ALMA* and *NOEMA* will allow us to characterise the gas content in protoplanetary disks and to better understand what molecules are being delivered onto the atmospheres of young, forming planets. Recently, the first direct discovery of young, massive Jupiter-like planets in a few Myr old protoplanetary disk PDS 70 has been reported [16, 17]. ■

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Dmitry Semenov is a staff scientist at the Max Planck Institute for Astronomy in Heidelberg. He is interested in high-resolution observations and numerical modeling of various physical and chemical processes in planet-forming disks, star-forming regions, molecular clouds.

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ESRF
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Since 2009, the ESRF is undergoing a major Upgrade Programme, which is foreseen to be completed in 2022. The second phase of this programme, which started in 2015, the so-called ESRF-Extremely Brilliant Source programme (ESRF-EBS), is centred on the construction of a revolutionary low-emittance light source that will increase the brilliance and coherence of the X-ray beams produced by a factor of 100: https://www.esrf.eu/about/upgrade. The facility has currently interrupted its operation until September 2020 in order to proceed with the commissioning of the new storage ring and the adaptation and upgrade of beamlines.

In terms of absolute performance, the new EBS storage ring of the ESRF will be in the coming years the most brilliant high-energy synchrotron radiation source worldwide. Such outstanding equipment is currently undergoing its commissioning phase and is expected to enter into the user-dedicated operation phase by late 2020.

THE FUNCTION:

The ESRF Accelerator and Source Division (ASD) manages the ESRF accelerators complex (comprising the EBS radiation source), and the main objective of the Division in the coming years is to achieve, maintain and further improve the design goal parameters of the new EBS source, and to attain operation availability levels comparable to those attained with the previous storage ring. The ASD Director will have to lead and manage the programme of the ASD to ensure the successful accomplishment of the objective outlined above. He/she manages a dedicated budget to ensure the deployment of a strong preventive maintenance programme and is responsible for the implementation of a strategy for future developments, including new radiation sources, and the perpetuation of ESRF know-how, in relation both with the operation and the development of the radiation source.

The ASD Director reports directly to the Director General of the ESRF, in the same way as the Directors of Research and Administration. He/she directs the ASD, with responsibility for its annual budget. There are about 70 staff members in the Division, but the Director can also call on the technical assistance of both the Instrumentation Services & Development Division and the Technical Infrastructure Division.

QUALIFICATIONS AND EXPERIENCE:

The successful candidate shall be an experienced accelerator scientist with proven knowledge in the management of large-scale accelerator complexes. Expertise in the operation and development of third-generation synchrotron light sources is an important asset. He/she should have proven leadership and managerial and project management skills, including the handling of finances and personnel.

APPLICATIONS:

In order to apply to the position of Director of the Accelerator and Source Division at the ESRF, interested candidates are invited to address by e-mail their CV and motivation letter to the Chair of the Search Committee, Prof. Miguel Ángel García Aranda: g_aranda@uma.es

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