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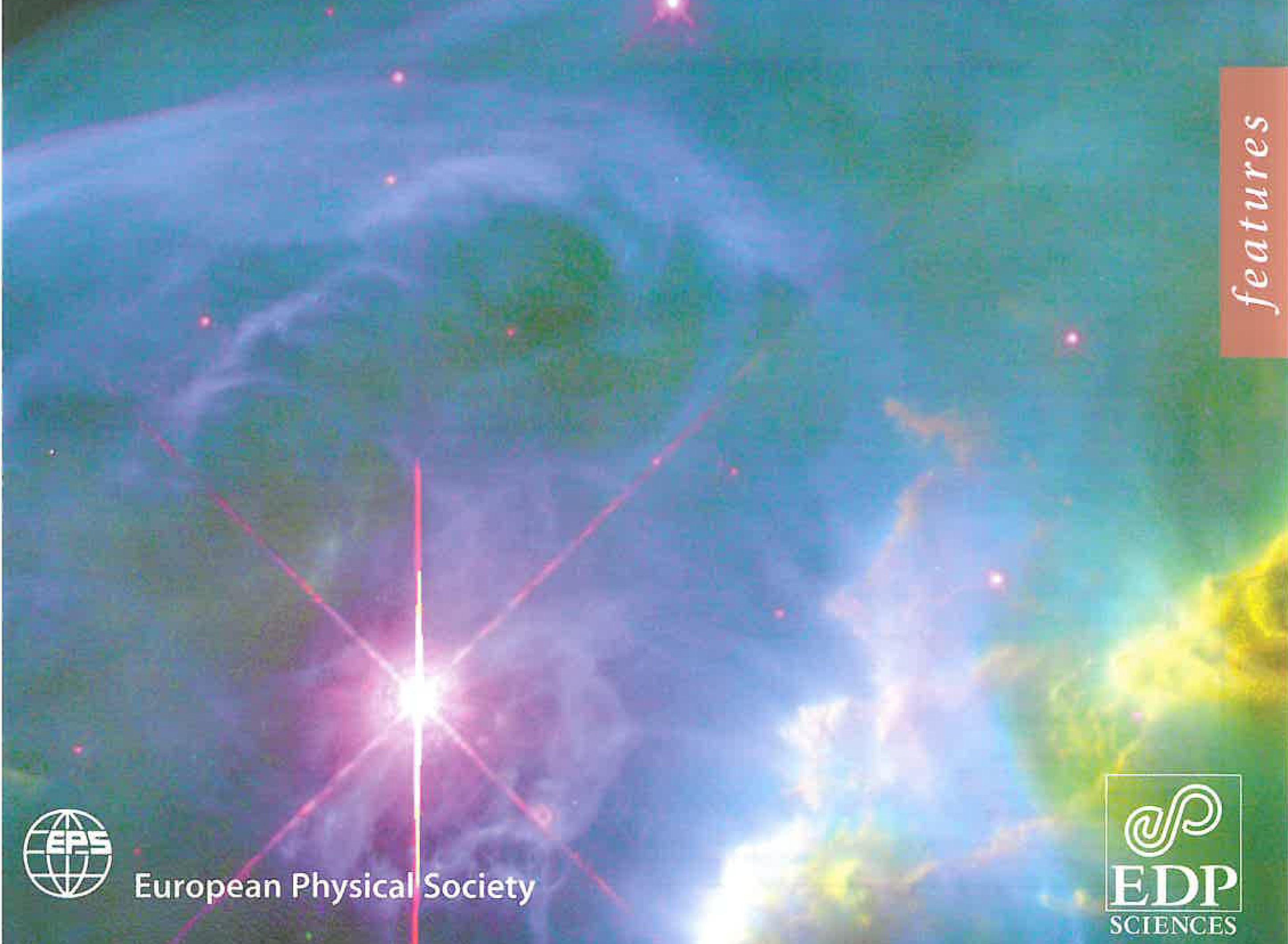
special issue

"Physics and the Universe"
Prepared under the supervision of the EPS Joint Astrophysics Division

features



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Photograph of Bubble Nebula (NGC 7635) taken by astronomers using the Hubble Space Telescope.
(image courtesy of NASA)

features

NEWS FROM EPS

activities

Physics and the Universe

Martin C.E. Huber, Editor of "Physics and the Universe" special issue

The use of physics to interpret observations of the Universe, now including its far away past, has greatly enlarged our knowledge about the origin and history of the Cosmos. These observations, in turn, have also taught us surprising aspects of physics, such as the existence of dark matter and vacuum energy.

At the beginning of the 20^{th} century, Einstein applied to the Universe the laws of physics that were known on Earth, and created the General Theory of Relativity. Here, **Bondi** recalls how cosmology subsequently established itself as a science in its own right and **Silk** reviews today's major issues in cosmology. **Lamarre** and **Puget** then discuss the merit of measuring anisotropies in the cosmic microwave background. This is the most distant, and most ancient source of electromagnetic radiation that can be directly observed.

Watson writes about the highest-energy cosmic rays, and acquaints us with the plans for observing these rare events more extensively. There will be giant detector arrays on the ground, but one also envisages utilising a very large volume of the atmosphere as detector by observing from orbit the fluorescence caused by such particles. **Waxman** and **Mannheim** tell us about the aims of TeV neutrino 'telescopes' that will extend the distance accessible to neutrino astronomy by some five orders of magnitude, to the edge of the observable Universe.

Grenier and **Laurent** present the Universe as seen in X- and γ-rays: "a very exotic place, largely filled with extremely hot gas". **Piro** recounts how the progenitors of gamma-ray bursts were recently located at cosmological distances, and portrays some of the current thought on their cause.

Rauscher and **Thielemann** demonstrate how nuclear astrophysics, after successfully dealing with energy-generation and nucleosynthesis in the Sun and in stars, is now contributing to the study of the early Universe and to the study of matter in neutron stars and matter during the formation of black holes. **Sackett** describes gravitational lensing, an observational method that probes all mass, not only the luminous content of the Universe.

Solar physics, important both for astronomy and physics at large and for 'down-to-Earth' applications, follows: **Christensen-Dalsgaard** reports on probing the interior of the Sun and of stars. Such observations have shown that the so-called neutrino problem cannot be explained by an exotic solar core; oscillations between neutrino species, i.e., a new aspect of particle physics, may now resolve the problem. **Brekke** examines the ever-increasing influence of solar activity on our technical civilisation, particularly on our in-orbit infrastructure, which is exposed to space weather.

Extra-solar planets come next. **Mayor**, who discovered the first such object, and **Santos** present the characteristics of the extra-solar planetary systems found so far. They also touch upon the likelihood of life in the Universe.

Quirrenbach traces the progress in astronomical interferometry since Michelson measured the diameters of Jupiter's Galilean moons 110 years ago, to today's development of imaging and nulling interferometry. Such techniques will help us discover and investigate remote Earth-like planets in the second decade of the 21^{st} century.

Sathyaprakash and **Winkler** expound the impact of gravitational-wave astronomy, an altogether new window on the Universe that is about to be opened. Gravitational waves from merging massive black holes, which can only be observed from space, will give us insight into the realm of strong gravitation.

Ramachers gives an overview of searches for baryonic and non-baryonic dark matter by use of optical telescopes and large underground detectors.

Data from different windows of observation – electromagnetic, cosmic rays, neutrinos, gravitational waves – are complementary, yet accessible through different sub-disciplines of both astronomy and physics. The Joint Astrophysics Division of the EPS and EAS (European Astronomical Society) provides the multidisciplinary forum for the needed dialogue between astronomers and physicists. **Maurice Jacob**, the JAD chairman, presents the Division's aims.

Appropriately, this issue concludes with an article on the origin of cosmic rays by **Erlykin** and **Wolfendale**, the past President of the EPS who has devoted much of his research work to resolving this enigma. They argue here, how one may cut through the fog!

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Cosmology in the first half of the 20th century

Hermann Bondi, Cambridge, UK

In various fields of science an essential early step consists of abandoning a long held assumption that was considered 'obvious', any alternative being viewed as inconceivable and indeed absurd. This happened in celestial dynamics when the notion that the Earth was at rest and was the centre of the solar system had to be given up before a sensible description of its functioning could be formulated. (Interestingly, this development was due to intellectual dissatisfaction with previous attempts at a description of the motion of the planets rather than to a crucial experiment or observation. This only came in 1728 with James Bradley's discovery of the aberration of star light and his explanation of this phenomenon as due to the changes in the velocity of the Earth in its annual orbit)

It happened in atomic physics when the absurd notion of universal determinacy had to be (most reluctantly) abandoned. It was not appreciated that in a fully deterministic Universe experimentation becomes meaningless, since the outcome is the result not of any recent set-up, but of endless chains of causal links starting in the most remote past.

In cosmology the essential step was the abandonment of the 'obvious' assumption that the Universe had to be static, i.e. without any large systematic motions. Even as radical a thinker as Einstein thought that the only way to apply his new General Relativity to the cosmos was to add a 'cosmological' term to his equations so as to balance gravitational attraction. This step indeed made it possible for him to admit as a solution a static uniformly matter-filled model Universe. He expressed the hope that this might in fact be the only solution of his equations with the cosmological term. This hope was soon dashed by de Sitter. He showed, as a mathematical counter example, that another solution was an empty model Universe in an exponential state of expansion. Thus this model of 'motion without matter' was contrasted with Einstein's 'matter without motion'.

In the early 1920's a Russian meteorologist, Friedmann, showed that there existed a range of intermediate solutions. Curiously, though his work was published in widely read journals, it was ignored. Independently of his work and of each other, H.P. Robertson and A.G.Walker found the complete set of solutions of Einstein's equations for a uniform matter-filled Universe in the 1930's, making models with motion familiar to theoreticians. The assumption of uniformity implied that the relative velocity of any two co-moving bodies was along the line joining them and was proportional to their separation.

At the beginning of the 20th century it was still debated among observers whether the 'nebulosities' in the sky were in the main diffuse matter within our galaxy or 'external galaxies' much like our own at very great distances. The second option gradually gained adherents. In 1915 Slipher noted that in the spectra of these external galaxies red shifts were much more common than blue shifts. But it was Hubble's and Humason's remarkable efforts on the then new 100" telescope to define a distance scale for these distant galaxies and measure their red shifts that established beyond reasonable doubt (i) that most of the nebulosities were external galaxies, (ii) that they were reasonably uniformly distributed and (iii) that their red shifts, interpreted as velocities of recession, were proportional to their distance. Though a number of astronomers, including Hubble himself, at first thought that the red shifts should not necessarily be regarded as due to velocities, this alternative interpretation soon lost its popularity.

In the velocity-distance relation, the ratio of velocity to distance is called the Hubble constant and is broadly the same for all galaxies. Its inverse is a time that Hubble evaluated as 1.8 billion (10^9) years. There is of course a corresponding distance, the same number of light years. Accordingly the Universe has a scale.

This is a most important point that is often not sufficiently stressed. In a scale-free cosmos we could never know whether our observations revealed anything about the Universe or only about our local, perhaps unrepresentative, neighbourhood. In a Universe with a scale it is plain whether our observations extend over a significant portion of the whole or not. If the largest red shifts observed were, say, 0.01, we could not infer much about the system as a whole. As red shifts of the order of 5 have been measured, we survey a very significant part of the whole system. Hubble's estimate was in fact difficult to accept as it was hard to reconcile it with the figures then current for the age of rocks, of the Earth, of the Sun. Moreover, it meant that the other galaxies were much smaller than ours. "If they were islands in space, our galaxy was a continent". The upward revision of Hubble's time by Baade and Minkowski in 1952 was therefore greeted with great relief.

The first half of the twentieth century established cosmology as a science in its own right. The universality of the red shift, the large-scale uniformity of the system, the applicability of the geometries of Friedmann, Robertson and Walker were substantial legacies to leave for subsequent researchers. The initial singularity of many of the solutions was first spotted by George Lemaître (followed by George Gamow) as a possible oven for making all the elements from aboriginal hydrogen. Though the output was later seen to be confined to the lightest isotopes, the high temperature and density of the initial 'Big Bang' makes a happy playing field for high-energy particle physicists.

EPN Special Issues

"Physics and the Universe" is the fifth special issue of Europhysics News, conceived and prepared by the EPS Joint Astro Division.

The EPS began publishing special issues in 1998 with Lasers and Quantum Optics, prepared by the QEOD, and have published about one a year since then.

Special issues review the *state-of-the-art* in a particular subdiscipline of physics. They are one important activity of the EPS Divisions, marking the presence and visibility of the EPS in all fields of physics – highlighting their role of providing information to European physicists.

Adapting to the constant evolution of physics requires the creation of new divisions. The EPS is currently studying the creation of two new divisions in emerging disciplines, a first in *physical biology* at the borderline between physics and biology, and another in *nanophysics*, including such applications as nanotechnologies, communication sciences, etc.

The EPS welcomes suggestions and assistance from all interested physicists in these emerging disciplines.

M. Ducloy, EPS President

features

Current issues in cosmology

Joseph Silk
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To illustrate the status of modern cosmology, I have chosen three issues that have played a central role in cosmology ever since the emergence of the Big Bang theory as the dominant cosmological model.

Age of the Universe

The issue of the age of the Universe was the focus of much discussion during the 19th century, centring on the geological age of the Earth. A major breakthrough was the discovery of the longevity of the Sun, via thermonuclear energy sources, in the first half of the 20th century, coupled with the realization that the expansion age of the Universe exceeded the age of the Sun and was comparable to the ages of the oldest stars in our Galaxy. The scene had shifted: from the age of the Earth versus that of the Sun to the ages of the oldest stars versus that of the Big Bang.

During the second half of the 20th century, a controversy raged around the value of the Hubble constant, the inverse of which gives a first approximation to the age of the Universe. One school, led by Gerard de Vaucouleurs, argued vociferously for a high value of Hubble's constant (100 km/Mpc/sec)[1]. If de Vaucouleurs and his supporters had prevailed, the Big Bang would have been in considerable difficulty. However, Allan Sandage, Gustav Tammann and their supporters were equally strong advocates for a low value of Hubble's constant of 50 km/Mpc/sec. Only with the passage of time and the entry into the fray of a new generation of astronomers who exploited new instruments, most notably the Hubble Space Telescope, did the situation converge. High precision observations of key distance calibrators such as Cepheid variable stars and supernovae in distant galaxies resulted in a consensus that Hubble's constant is (70 ± 7) km/Mpc/s, a value that poses no problem whatsoever in reconciling the oldest stellar ages with the age of the Universe.

a controversy raged around the value of the Hubble constant

The canonical cosmological model has an age of 14 Gyr. The cosmological age is consistent with two independent age determinations for the Milky Way galaxy. Stellar evolution applied to the oldest globular cluster stars gives an age of 13 Gyr, and radioactive dating from measuring abundances of U and Th in extremely metal-poor halo stars yield an age of 12 Gyr.

There are also cosmological measures of the Hubble constant that are independent of distance. One utilizes the Sunyaev-Zeldovich effect on galaxy clusters to combine X-ray measurements of galaxy clusters with the microwave (Rayleigh Jeans) decrement in the cosmic blackbody background radiation due to traversal across the hot intracluster gas by the microwave photons to give an absolute distance measurement. Yet another approach makes use of the cosmic microwave background radiation anisotropies, where the height of the first acoustic peak is sensitive to the Hubble constant, given a cosmological model. There is complete consistency between the various Hubble constant determinations. There is no age controversy for the Big Bang.

Galaxy Formation

Galaxy formation theory is not in a very satisfactory state. This stems ultimately from our lack of any fundamental understanding of star formation. There is no robust theory for the detailed properties of galaxies. In contrast, the evolution of the dark matter, which is by far the predominant constituent of the Universe, is well understood. Hierarchical formation of large-scale structure in a cold dark matter-dominated Friedmann-Lemaître Universe has successfully confronted essentially all observations, ranging from deep surveys of the galaxy distribution and the formation of galaxy clusters to the temperature fluctuations in the cosmic microwave background.

The advent of high-resolution N-body simulations has revealed challenges for galaxy formation. Dark halos contain considerable sub-structure, amounting to circa 10% of the halo mass, and continuing down to unresolved scales of 106 M§ or smaller. This has led to two problems. One is that the predicted number of dwarf galaxy satellites exceeds that observed around the Milky Way by an order of magnitude. Even very low surface brightness dwarfs are easily observed in our local environment, and efficient mass loss prior to star formation has been invoked to resolve this discrepancy.

A second problem is that, on the one hand, the initial angular momentum of a typical protogalaxy, when the halo first collapsed, can reproduce the observed size distribution of disks, if angular momentum is approximately conserved during baryon infall and disk accretion, but that, on the other hand, the numerical simulations show that most of the angular momentum is actually lost to the dark halo. The clumpiness induces strong angular momentum transfer via tidal torqueing and dynamical friction from the dissipating baryons to the energy-conserving dark matter. The resulting disks have too little specific angular momentum by an order of magnitude.

Another result from the high-resolution simulations of galaxy halos is that the dark halo has a central concentration and a central cusp. This implies for example that about half the mass within the half-light radius (for our Galaxy this corresponds to near the solar circle) is in the form of cold dark matter (CDM). This apparently contradicts bulge microlensing studies for the Milky Way, which permit a CDM fraction of at most 10% within the solar circle, when combined with the rotation curve and with infrared stellar population modelling derived from the results of the Deep Infrared Background Experiment (DIRBE) that was flown on the Cosmic Background Explorer (COBE). A similar conclusion applies to barred galaxies, for which dynamical studies conclude that self-gravity of the bars, which consist primarily of stars, must dominate the inner gravitational potential. In contrast, a recent study of a non-barred spiral finds that detailed modelling of the rotation curve with a maximal disk requires an axially-symmetric dark-matter contribution of about 30% within an optical radius.

There is another observational hurdle to overcome. Low surface brightness spirals are everywhere dark-matter dominated, and so provide outstanding laboratories for dark matter studies via rotation curves. High-resolution Hα rotation curves reveal a wide array of central profiles. Most systems have soft cores without any indication of a central cusp.

Cold dark matter is seriously challenged. Whether it is actually dead is quite another matter. Nevertheless, to confront this possi-

)nly with the passage of time nd the entry into the fray of a iew generation of astronomers ısing] new instruments, most ıotably the Hubble Space 'elescope, did the situation onverge.

bility, there have been numerous attempts to resurrect CDM. These come under two distinct guises: tinkering with the particle physics or elaborating on the astrophysics. Modified-particle dark-matter can no doubt be developed to explain all of the required dark matter properties. However the seductive simplicity of SUSY, with the lightest stable supersymmetric particle, the neutralino, as an attractive candidate for CDM, is lost.

An alternative approach is via the astrophysics of galaxy formation. Can the dark matter profile be modified by astrophysical processes? The answer is: perhaps. Supermassive black holes, for better or for worse, are intimately connected with the process of galaxy spheroid formation. Whether they aid and abet formation of the first stars remains a mystery. There are certainly dynamical and most likely astrochemical links. The supermassive black-hole (SMBH) merger results in heating of the dark matter cusp. The dark matter is heated and acquires angular momentum. The result is that the concentration and cusp are likely to be modified. However the angular momentum acquired by the halo will help in reinjecting angular momentum into infalling gas clouds that form the disk over a time-scale of a Gyr or longer.

It remains to be seen whether the ultimate answer lies in the dynamical feedback of SMBH formation and evolution on dark halo cores, or on a new prescription that modifies the physics of CDM, or possibly in fundamental physics whereby on large scales unanticipated changes in our 4-d Einstein gravity may be appearing, such as might be associated with the influence of higher dimensions.

Dark Matter

The favoured candidate for CDM is the lightest stable SUSY relic particle. This must be neutral (to avoid already having been detected) and its mass is constrained by accelerator searches and theoretical considerations of thermal freeze-out to lie in the range 50 GeV to a few TeV. The relic density is determined when annihilations and pair production go out of thermal equilibrium in the early Universe at $T \approx m_x / 20$ kK, and one infers that the density in relic particles, relative to the critical density of an Einstein-de Sitter Universe, satisfies $\Omega_x \propto \sigma_{ann}^{-1}$, where σ_{ann} is the annihilation cross-section extrapolated to the low temperature limit and m_x is the mass of the relic particle. For typical weak interaction values of σ_{ann}, one finds that $\Omega_x \approx 0.3$ is required to account for the dark matter content of the Universe. Via studying a grid of supersymmetric (SUSY) models, one can infer a range of particle masses from the annihilation cross-section. Were it not for the accelerator bounds on the sparticle (*i.e.*, supersymmetric partner-particle) masses, the uncertainty in m_x would span some 5 orders of magnitude.

The annihilation cross-section and particle mass is constrained. So also is the elastic scattering cross-section once the annihilation cross-section is specified. This means that one can now consider possible detection schemes. The obvious one is direct detection by elastic scattering. Use of annual modulation of the incident flux on a terrestrial detector has led to a tentative detection (DAMA)[2] that requires an implausibly large cross-section given the suite of minimal SUSY models and is marginally inconsistent with another experiment (CDMS)[3]. Annihilations result in hadronic jets that decay into gamma rays, high-energy electron-positron pairs, proton-antiproton pairs and neutrinos, all of which are potentially detectable as galactic halo signals.

Future observations may greatly help in pinning down the CDM characteristics. Annihilations generate high-energy neutrinos and gamma rays that propagate freely in the halo and detection would provide unambiguous support for annihilating Weakly Interacting Massive Particles (WIMPs). The predicted fluxes are within the anticipated sensitivity of the ANTARES, AMANDA (neutrino) and GLAST (gamma ray) detectors[4], now under construction.

Footnotes

[1] Distances in astronomy are usually given in parsec (pc);
1 pc = $3.085 \cdot 10^{16}$ m = 3.26 light year

[2] 'Particle DArk MAtter searches with highly radiopure scintillators at Gran Sasso', *cf.* article by Y. Ramachers.

[3] The 'Cryogenic Dark Matter Search (CDMS)' experiments aim to measure the recoil energy imparted to detector nuclei through neutralino-nucleon collisions by employing sensitive phonon detection equipment coupled to arrays of cryogenic germanium and silicon crystals.

[4] ANTARES is an underwater neutrino telescope project in the Mediterranean Sea (the 'Astronomy with a Neutrino Telescope and Abyss Environment RESearch'), AMANDA is a neutrino telescope in the South Polar ice cap (the 'Antarctic Muon And Neutrino Detector Array') and GLAST is the 'Gamma Ray Large Area Space Telescope'.

About the author

Joseph Silk is a 58 year old British astronomer currently working at Oxford University. His scientific career led him to positions in the most renowned universities and he has been awarded numerous prizes. In his research he focuses on cosmology, particularly on cosmos background radiation. He has written or co-written more than 300 specialised scientific essays. He is also the author of many popular works and books on science.
In this overview, Silk wants to make basic notions in cosmology clearer and he tries to explain why we will probably never know whether or not the universe is finite.

The cosmic microwave background

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The Cosmic Microwave Background (CMB) is the most distant, and therefore the most ancient source of electromagnetic radiation that can be directly observed from Earth in any frequency range. The Cosmic Background Explorer satellite (COBE) has measured its sub-millimeter emission, which is that of a nearly perfect blackbody at 2.73 K. The relative deviation from a pure Planck spectrum is very small (typically less than 10^{-5}). This emission is attributed to the primordial Universe when it was about 300 000 years old and warm enough (3000K) to ionise the hydrogen gas that constitutes most of its mass. Owing to the expansion of the Universe, this radiation was red-shifted by the Doppler effect by a factor of about 1000, and thanks to the cooling due to the expansion, it could travel and reach us through the very transparent neutral hydrogen. The discovery of the CMB and even more the measurement of its Planck spectrum by the COBE-FIRAS[1] experiment is the most compelling evidence for a hot big bang model. The existence of the CMB was predicted by Alpher, Bethe and Gamow as a very unique feature of a hot big bang in which the nucleosynthesis of most of the He, D and ^{7}Li seen in the Universe (but which cannot be produced in stars) is produced in the early phases of a hot big bang.

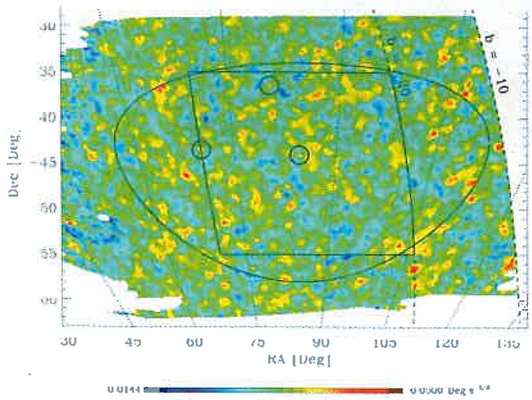

Fig. 1: Map of the Cosmic Microwave Background obtained by the BOOMERanG experiment. The one-degree-like bumps of the CMB emission are tiny local fluctuations of the brightness temperature of the CMB.

Anisotropies in the CMB — and what they tell us

Furthermore, the existence of very small anisotropies was predicted at a level of 10^{-5} in the simplest model to explain large-scale structure formation in the Universe. In this model anisotropies result from the gravitational instability acting on in homogeneities generated in the very early Universe. These anisotropies were indeed found at the right level by the COBE-DMR[2] experiment.

In this model, these fluctuations carry information on the physics of the very early Universe because the spectrum of fluctuations is conserved at least on the largest scale in the expansion. The fluctuations on smaller scales are not gravitationally unstable during the whole history of the Universe preceding recombination. The fluctuations behave as acoustic oscillations leaving characteristic peaks of the anisotropies in the power spectrum. The lowest frequency acoustic peak corresponds to an angular scale, which depends mainly on the geometry of the spatial part of space-time. In fact, in the simplest model of structure formation, this power spectrum, if measures down to small enough scales and with enough accuracy, contains information allowing cosmologists to get very precisely all the cosmological parameters (space-time geometry, relative contribution of the various terms contributing to the dynamics of the Universe, etc.). The measurements of the small-scale anisotropies of the CMB are thus becoming one of the main tools of observational cosmology.

New results from the balloon-borne experiments BOOMERanG[3] and MAXIMA[4] and from ground-based experiments using radio detectors and interferometry[5,6], were recently published. They gave a first view of the small-scale anisotropy of the CMB, unveiling the predicted peaks in the power spectrum of

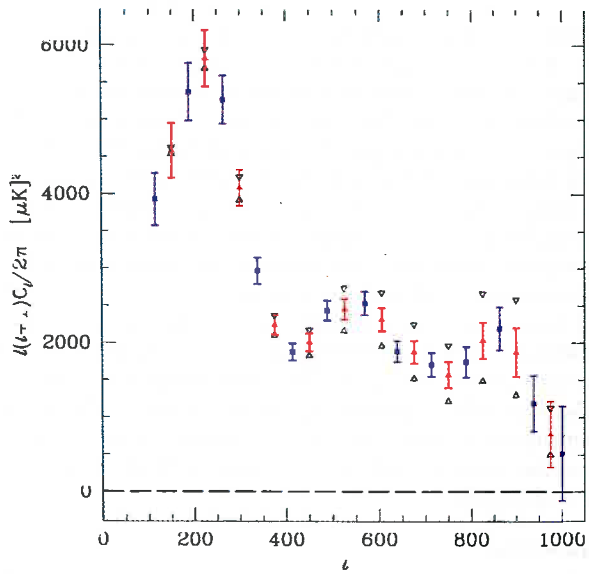

Fig. 2: The power spectrum of CMB anisotropies as seen by BOOMEranG. The first peak corresponds to an angular scale of about 1 degree as predicted for a "flat Universe" (i.e., a Universe where the spatial part of the metric is Euclidean).

its angular distribution. The BOOMERanG CMB map shown in figure 1 is a high-signal-to-noise rendition of the anisotropies of the background radiation as they emerged at recombination when the Universe was a billion times denser than at present. These anisotropies reflect the inhomogeneities of the early Universe. Figure 2 shows the combined power spectrum of these recent experiments. The predicted acoustic peaks are very clearly seen. The most striking result is that the position of the first one is within a few percent of the position predicted for a Universe with a Euclidean spatial part of the metric: "the Universe is flat"!

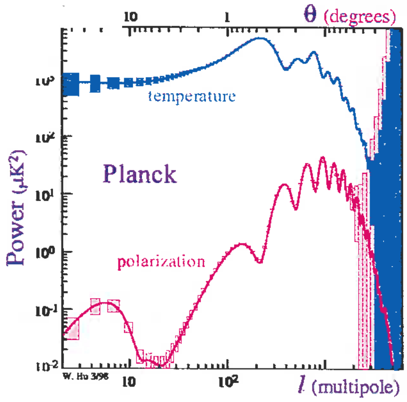

Fig. 3: Simulation of the Planck capability in the domain of angular frequencies. Smaller details will be measured with a much better sensitivity (as compared with BOOMERanG) and on the whole sky. Observations with this accuracy permits the determination of most cosmological parameters with better than 1% accuracy.

Following COBE, NASA launched in the summer of 2001 the MAP satellite[7], which will be a second-generation CMB space experiment. The detectors are passively, i.e., radiatively cooled radio-type receivers with sensitivity comparable to the balloon-borne bolometer experiments but with significantly better capabilities for large-scale measurements and control of systematics.

The ultimate mission: ESA's 'Planck' satellite

The 'Planck' project of the European Space Agency, to be launched in 2007, is intended to be the third generation of CMB space experiments, pushing to its limits the knowledge that will be retrieved from the CMB observation with unprecedented angular resolution and sensitivity.

The six spectral bands of the High Frequency Instrument (HFI) on 'Planck' cover the frequency range between 100 and 1000 GHz with an angular resolution of about 5 arcmin. Its sensitivity will be limited, in the CMB channels, by the statistical fluctuations of the CMB itself, which makes 'Planck' a kind of ultimate experiment. It will also measure the polarization of the CMB in three channels, which will give independent and unique information on the CMB anisotropy.

This kind of accuracy on the CMB can be achieved only by removing the various astrophysical foregrounds emitting at these frequencies. Among these, one expects the emission of dust and gas in our own galaxy and from other galaxies. Clusters of galaxies, that contain high-temperature gas detected in the X-rays, distort the CMB spectrum by inverse Compton scattering. This is the Sunyaev-Zeldovich Effect (SZE), which makes clusters of galaxies good tracers of the dynamics of the Universe at large scales.

The six bands in HFI and four more in LFI (Low Frequency Instrument, also on 'Planck') are needed to characterise and eliminate these various components by use of their spectral and spatial signature. Planck must be considered not only as the third generation of CMB satellites, but also as the first sub-Terahertz all-sky survey of modern astronomy. Several thousands of galaxies, young stellar objects, clusters of galaxies will be detected, many of them for the first time. Nearly every field of astronomy will benefit from 'Planck's' results. The 'Planck' project is committed to deliver a set of well-defined products to the scientific community at large.

The extremely high sensitivity ($dT/T < 2\ 10^{-6}$) as well as the high angular resolution of 'Planck' made possible by the use of "Spider web" type bolometers developed at Caltech and flown on the BOOMERanG, MAXIMA and ARCHEOPS experiments. 'Planck' will also be the first experiment that measures the polarization signal of the CMB on large scales.

For a detailed discussion of all these questions we refer the reader to a more extensive review by Bouchet, Puget and Lamarre.[8]

References and Explanations of Abbreviations

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[2] Differential Microwave Radiometers

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[7] Microwave Anisotropy Probe

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About the authors

Jean-Michel Lamarre, has 20 years of experience in IR and submm space astronomy. He contributed to the development of this field in France by leading or contributing to the conception of a number of experiments: EMILIE at the South Pole, the balloon-borne AROME experiment, and the space projects: CRYOSPIR, AELITA, SAMBA, FIRE and FIRST. He was the PI of the imaging channel of IKS on the VEGA sounder to the comet Halley, and of SPM-PRONAOS that measured the positive part of the SZ effect. He played a major role in the birth of the Planck-HFI concept and design, and is now the instrument scientist of this experiment.

Jean-Loup Puget is an astrophyicist and Research Director at CNRS. He is Mission Scientist for the ESA's Infrared Space Observatory (ISO), and also PI for the High Frequency Instrument (HFI) on ESA's Planck mission. In 1984, together with Alain Leger, he discovered the presence of large quantities of aromatic hydrocarbons in interstellar matter.

The highest energy particles in nature

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The highest energy particles in Nature are cosmic rays. The most energetic one yet detected has an energy of 3×10^{20} eV, a macroscopic energy greater than that of a tennis ball travelling at 250 km h^{-1}. This energy is probably not set by Nature but by the relatively small area (~100 km^2) of the devices that have been used to search for them thus far as the rate above 10^{20} eV is only about 1 per km^2 per century. We do not know how these particles are created, or whether they are photons, atomic nuclei or neutrinos, but experiments underway promise data that may lead us to new understandings of some important astrophysical problems — or even to some new physics.

That we know anything about such extraordinary particles is because of searches that were started for the origin of much lower energy cosmic rays many years ago. In 1938 the French scientist, Pierre Auger, discovered serendipitously that showers of particles, secondaries created in the atmosphere by an incoming cosmic ray, were spread out over distances of 300 m at ground level. The energy of the initiating particles was estimated to be about 10^{15} eV. The particles making up the shower travel through the atmosphere at the velocity of light and are confined to a relatively thin disc, rather like a giant dinner plate. In the 1950s it became possible to find the arrival direction of such particles by measuring the relative arrival times of the shower disc at detectors placed on a widely spaced grid. The detectors of choice have usually been plastic scintillators or water-Cherenkov detectors and with these the direction of the incoming primaries can be measured to about 1°. A shower produced by a cosmic ray of 10^{20} eV contains about 10^{11} particles at ground level spread out over an area of about 20 km^2.

Are there particles with an energy above 5×10^{19} eV?

The Larmor radius of a proton of 10^{18} eV in the galactic magnetic field is about 0.3 kpc. This is comparable to the thickness of the galactic disc and hence it was expected that some features of galactic structure could be mapped out in 'cosmic ray light' if a sufficient number of high-energy particles could be collected. Over the years shower arrays of greater and greater area have been constructed to detect the rare, energetic events but no convincing evidence of an anisotropy or point source of cosmic rays has been found. Although the 'astronomy' of cosmic rays may thus seem a little dull, this turns out to be part of the puzzle about their origin. Indeed the search for sources might well have ended by now had it not been for the discovery of the 2.7 K cosmic background radiation. In 1966 Greisen and Zatsepin and Kuzmin pointed out that there might be a cut-off (the GZK cut-off) in the energy spectrum at about 5×10^{19} eV. By 1966 many events above 10^{18} eV had been detected (with one claimed to be of 10^{20} eV). The view was commonly held that the failure to discover point sources, combined with rather general arguments about source energetics, could most readily be explained if the particles were produced in unusual objects far from our galaxy: quasars, also little understood at the time, were thought to satisfy the requirements. If this was so then sufficiently energetic protons (which see the 2.7 K photons Doppler shifted by a factor proportional to their Lorentz factor) lose energy through photo-pion production and their energies decrease significantly as they travel through space. A similar argument, but invoking photo-production, applies to heavy nuclei. Calculations showed that a 10^{20} eV proton has only a 50% chance of originating further than 20 Mpc from Earth. A few very powerful objects (e.g. Cen A and M87) lie within this distance but the most energetic cosmic rays do not point back to them.

Large ground-based detectors will search for ultra high-energy cosmic rays

The existence, or not, of the GZK cut-off has not been easy to establish. The early experiments at Volcano Ranch (US), Haverah Park (UK) and Yakutsk (Russia) had insufficient area to detect more than a very few particles above the cut-off energy (which is very precisely known because of the blackbody nature of the 2.7 K spectrum and the accurate cross-sections of the interaction processes). Furthermore the need to estimate the energies using Monte Carlo calculations, in which many of the simulated interactions are unstudied by man-made accelerators, made many suspicious of the claims. Fortunately another detection method was invented and became technologically feasible in the late 1970s. This technique uses the fact that the Earth's atmosphere responds to the passage of a shower by emitting fluorescence radiation in the UV part of the spectrum. If the shower is large enough the radiation can be detected with a photomultiplier camera on clear moonless nights and the growth and decay of the cascade can be followed and measured. A model-independent

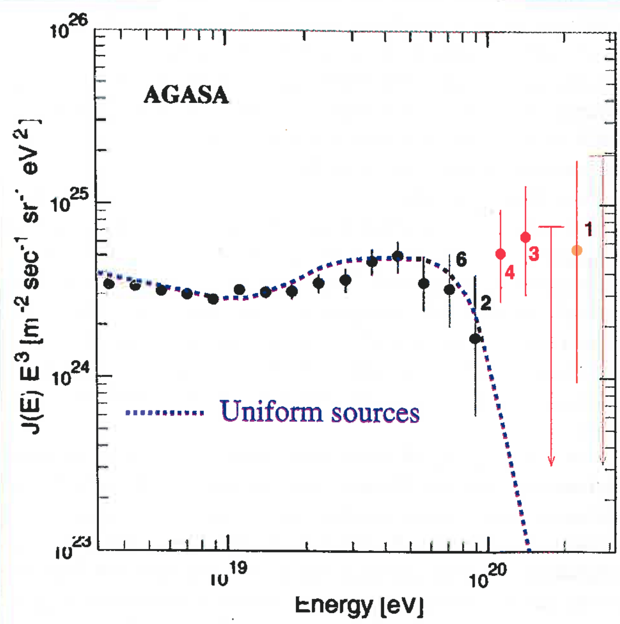

Fig. 1: The energy spectrum as measured by the Japanese shower array known as AGASA. This array comprises 111 × 2.2 m^2 scintillators spread over 100 km^2. The data shown are from Takeda *et al.* (1998). The dashed line indicates the spectrum that would be expected if the ultra high-energy cosmic rays were produced in sources distributed uniformly throughout the Universe, with due allowance for measurement uncertainty. The predicted GZK cut-off, due to photo-pion production on the 2.7 K radiation field is evident in the theoretical curve but clearly absent in the data.

estimate of the energy is in principle feasible so that energies can be measured in a manner similar to the calorimetery approach widely used at particle accelerators. Although many fewer events have been detected by this technique than by the surface arrays a key conclusion is that the fluxes in the critical energy region are very similar. This fact, and the discovery of an event of 3×10^{20} eV in 1993 by the fluorescence group at the University of Utah, have led most people to believe that there are particles at energies well above the GZK cut-off. A striking result, from the 100-km^2 shower array operated by the Japanese AGASA group, is shown in figure 1. With this instrument 8 events have been detected above 10^{20} eV. The data lie well above the prediction made of the spectrum if all of the particles are produced in sources distributed uniformly throughout the Universe.

The existence of events above the GZK cut-off means that the particles must be produced nearby but then why are no point sources seen? This is the enigma of ultra high-energy cosmic rays and hundreds of papers have been written suggesting explanations. The proposals range through modifications to the properties of known particles, speculation about new particles (including massive super-heavy relics created 10^{-35} s after the big bang), radical revisions of our understanding of the magnetic fields in space and even the breakdown of Lorentz invariance. Some argue that the highest energy particles might be iron nuclei. Certainly this would explain the isotropy, as the iron nuclei are more readily bent by the magnetic field, but it is not clear that they would survive the photon field surrounding likely sources.

In an effort to solve the enigma observatories with greater apertures are being developed. A second-generation fluorescence detector, known as HiRes, has been constructed by the Utah group and data from a significant exposure as now been reported. Currently the group have failed to confirm the rate of events above 10^{20} eV seen by the AGASA group but there are unanswered questions about the efficiency of the fluorescence mechanism for turning electron energy into ultra violet photons. The HiRes group do see some events above 10^{20} eV, well beyond the GZK cut-off. A more complex device, that blends the strengths of ground arrays and fluorescence detectors, is under construction at Malargue in Mendoza Province, Argentina. Scientists from 18 countries, including several in Europe, are working on this project. We are building a hybrid instrument of 1600 water-Cherenkov tanks spread over 3000 km^2 (about 30 times the area of the city of Paris) with four fluorescence detectors over-looking the site. There will be dual measurements of the showers in 10% of events so that calibration of the energy deduced from the surface detectors will be possible. Construction of this instrument, the Pierre Auger Observatory, is underway and the prototype fluorescence unit and the surface array have already detected showers. Two of the water-tanks are shown in figure 2. The full instrument should be completed by late 2004.

Plans for observing atmospheric fluorescence from space

To achieve an exposure greater than that targeted by the Auger Observatory may require putting a detector into space. The idea, proposed by Linsley, who was also the first to claim detection of a 10^{20} eV event, is to observe the fluorescence light using a detector mounted in a satellite. As a first stage an instrument with 2×10^5 photomultipliers has been designed for the International Space Station and is the subject of an ESA phase-A study. Called EUSO, for Extreme Universe Space Observatory, it will be come into operation in 2007 and should detect 3000 events above 10^{20} eV in

Fig. 2: Two of the tanks in the Pierre Auger Observatory are shown. They each hold 12 tonnes of clean water and are viewed by 3 × 8" diameter photomultipliers. The electronics for recording and data transmission are powered by solar cells. These tanks are placed close together so that cross-tank measurements of densities and arrival times can be made but the nearest neighbour for all other tanks is 1.5 km away. In this way 3000 km^2 can be covered with only 1600 detectors.

its three-year lifetime. This exceeds the 500 events anticipated from the Auger Observatory from 10 years of operation and the 50 or so events expected from HiRes in a similar period. Again an understanding of the fluorescence emission process is of major importance.

Of the many ideas that will be tested with data from the Auger Observatory, and from EUSO, one is the proposal that Cen A, a very powerful radio galaxy only 3.4 Mpc from the Earth, might be an ultra high-energy cosmic ray source. It is argued by some that we have not seen it because the magnetic field in the space between Cen A and us is stronger than most astronomers believe. However it has also been shown that photo-pion production within Cen A could create neutrons. These live long enough, and could be sufficiently numerous, to give a clear signal. Perhaps a point source of cosmic rays will at last be seen and the problem of the origin of the highest energy particles in Nature will have been, at least partially, solved.

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The Pierre Auger Observatory: www.auger.org/

The EUSO project: www.ifcai.pa.cnr.it/~EUSO/

About the author

Alan Watson did his PhD at the University of Edinburgh where he studied the processes of condensation of water vapour. He has worked in the field of high-energy cosmic rays since moving to the University of Leeds in 1964. He was heavily involved in the construction and operation of the 12-km^2 Haverah Park array, built near Leeds, until its closure in 1987. Subsequently he lead a team from the UK and the USA that built a shower array at the South Pole to look for high-energy gamma rays from the supernova SN1987A. Currently he is co-spokesperson for the Pierre Auger Observatory and was, with Jim Cronin (Chicago) one of the early drivers for this project. He was elected to the Royal Society in 2000.

High-energy neutrinos

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Several neutrino "telescopes" allow today the detection of Solar Mega electron-Volt (MeV) neutrinos, thus enabling direct observations of nuclear reactions in the core of the Sun, which is opaque to photons, as well as studies of fundamental neutrino properties. These telescopes are also capable of detecting MeV neutrinos from supernova explosions in our local Galactic neighborhood, such as the well-known supernova 1987A, at distances $<10^5$ light years. The construction of high energy, Tera electron-Volt (TeV), neutrino telescopes is aimed at extending the distance accessible to neutrino astronomy by some five orders of magnitude, to the edge of the observable Universe, and at opening a new window of observations at high neutrino energy.

an unexplored window of observations is about to be opened, one should be ready for surprises

A kilometer-squared effective area telescope is required to detect estimated neutrino signals. The feasibility of the construction of such large volume detectors in deep water or ice has been demonstrated by the Baikal and AMANDA experiments, and several projects are now under way for the construction of kilometer scale telescopes. Although the expected event rates are small, even a handful of events will have profound implications for both high-energy astrophysics and particle physics. Moreover, as an unexplored window of observations is about to be opened, one should be ready for surprises.

From the Sun to the edge of the Universe: The need for kilometer scale telescopes

Due to the small cross section of neutrino interactions, kilo-tons of detector material are required to observe MeV neutrinos produced in the core of the nearby Sun. The detection of such neutrinos from cosmologically distant sources is impossible using present techniques. This situation changes at higher neutrino energy, due to two reasons. First, the cross section of the interaction increases with energy. Second, at TeV neutrino energy the construction of giga-ton, rather than kilo-ton, telescopes becomes feasible.

Interactions of high energy, >1 TeV, muon neutrinos with nucleons produce muons, which propagate over more than a kilometer through rock, water or ice. The muon track, a straight line co-linear to within one degree with the initial neutrino trajectory, may be identified by an array of photo-multipliers detecting the muon Cerenkov emission of visible light. The DUMAND experiment off the coast of Hawaii demonstrated the feasibility of detection of high energy muons in deep sea water, and the Lake Baikal experiment was the first to detect high energy neutrino induced muons. The AMANDA collaboration has demonstrated that deep ice is also a suitable medium, and that construction of kilometer-scale detectors is feasible, by the construction at the South Pole of the first neutrino telescope with 10^4 m^2 effective area at 1 TeV. Fig. 1 shows a neutrino event detected by the AMANDA telescope.

Nuclear fusion in stars generally ceases to be important at TeV energy. At this high energy, different types of sources are expected to show up. Guidance to estimating the expected neutrino signal is provided by cosmic-ray and gamma-ray observations. The cosmic-ray spectrum extends to energies $\sim10^{20}$ eV, and is likely dominated beyond 10^{19} eV by extra-Galactic protons. Whatever the sources are, some fraction of the protons are expected to produce pions as they escape their source by either hadronic collisions with ambient gas or photoproduction with source photons, leading to electron and muon neutrino production through the decay of charged pions. Waxman & Bahcall have shown that cosmic-ray observations set an upper bound to the neutrino flux from sources which, like candidate sources of $>10^{19}$ eV protons, are optically thin for high energy nucleons to γp and p-p(n) interactions. This upper bound is compared in Fig. 2 with the flux sensitivity of neutrino telescopes, demonstrating the need for a kilometer-scale telescope.

Sources may exist, where pion production losses prevent the escape of high-energy nucleons and allows only neutrinos (and

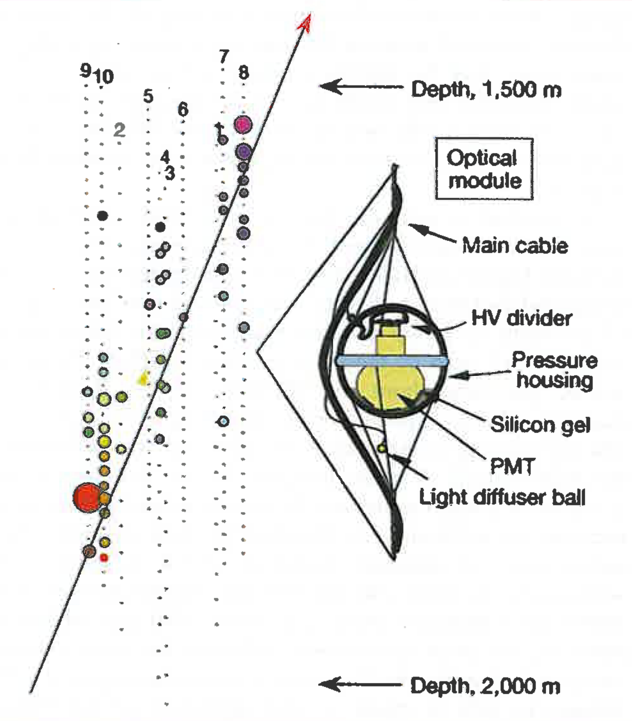

Fig. 1: The arrow indicates the track of a high energy neutrino induced muon passing through the AMANDA detector [E. Andres *et al.*, Nature **410**, 441 (2001)]. The detector is composed of strings of optical modules, represented by dots and shown in detail on the right, deployed 2 km deep under the South-Pole surface. The muon is identified through the detection by photo-multipliers (PMTs) of its Cerenkov emission of visible light. Colored circles show PMT pulses: The size of the circle indicates the pulse amplitude, and its color corresponds to photons' arrival time (earlier times are red and later times are blue). The large background of down moving cosmic-ray muons is rejected by looking for only up moving muons, produced by neutrinos which have crossed the Earth. Above 10^3 TeV, where the Earth becomes opaque to muon neutrinos, a cubic-kilometer Cerenkov telescope may discriminate horizontal and down going neutrino events from the low-energy background by identifying their high energy.

possibly low energy gamma-rays) to escape. While cosmic-ray data do not constrain the possible neutrino flux from such sources, which may therefore exceed the bound shown in Fig. 2, it also does not provide evidence for the existence of such "hidden" sources.

The ANTARES and NESTOR collaborations plan to construct during the next few years 0.1 km^2 detectors in the Mediterranean Sea. The long-term goal of high-energy neutrino astronomy is the construction of 1 km^2 (or cubic-kilometer, after multiplication with the muon range) telescopes. The AMANDA collaboration is planning ICECUBE, a square-kilometer extension of the South-Pole detector, and the NEMO collaboration carries a site study for a square-kilometer Cerenkov telescope in the Mediterranean. Above 10^3 TeV, neutrino detection may be possible also using other techniques, based on horizontal neutrino-induced air showers, radio observations of the moon's limb, and acoustic or radio detection of horizontal events in deep water or ice.

Astrophysics with kilometer scale telescopes

The sources of $>10^{19}$ eV cosmic rays are yet unknown. Gamma-ray bursts (GRBs) and TeV-photon emitting active galactic nuclei (AGN) have been suggested as possible sources. GRBs are transient sources lying at cosmological distances, producing short (typically 1 to 100 s long) flashes of γ-rays with apparent luminosities exceeding that of the sun by 18 orders of magnitude. They are believed to be powered by the accretion of a fraction of a solar mass on second time scale onto a newly born solar mass black hole. AGN are steady sources, with luminosities of the order of 10^{12} Solar, believed to be powered by accretion of mass onto massive, million to billion solar masses, black holes residing at the centers of distant galaxies. Few tens of ~100 TeV events per year, correlated in time and direction with GRBs, are expected in a kilometer-squared telescope if GRBs are the sources of ultra-high energy protons. A lower rate is expected if TeV-photon emitting AGN are producing the ultra-high energy protons.

In both GRBs and AGN, mass accretion is believed to drive a relativistic plasma outflow, which results in the emission of high-energy radiation. A similar process is believed to power Galactic Micro-Quasars, which may be considered as a scaled down version of AGN, with ~1 Solar mass black hole (or neutron star) "engines". In all cases, neutrino observations may provide unique information on the physics of the underlying engine, which is not well understood despite many years of photon observations. In particular, the answer to the question of whether or not the outflowing plasma carries baryons, which has major implications to the energy extraction mechanism, is not yet known. A positive answer implies, for example, that a kilometer-squared telescope may detect tens of events per year associated with Micro-Quasars.

A neutrino beam over cosmological baseline

The production of tau neutrinos, through charmed meson production, is expected to be negligible in astrophysical sources. However, atmospheric neutrino observations suggest muon to tau neutrino oscillations with strong mixing. Thus, a high-energy neutrino telescope would be an "appearance experiment" where equal numbers of ν_μ's and ν_τ's are detected, as long as the neutrino mass difference squared exceeds 10^{-16} eV^2.

A neutrino telescope will operate in coincidence with space and ground based high-energy photon telescopes. This may be particularly valuable for GRB observations. Looking for a neutrino signal in a given time and direction, set by γ-ray observations, implies a background free observation. Moreover, the simultaneity of neutrino and photon arrival times may be tested to ~1 s accuracy. For propagation over cosmological scales this implies checking the assumption of special relativity, that photons and neutrinos have the same limiting speed, to 10^{-16} fractional accuracy, and the weak equivalence principle, according to which photons and neutrinos should suffer the same time delay as they pass through a gravitational potential, to 10^{-6} fractional accuracy. This is many orders of magnitude better than present upper limits (of order 10^{-8} and 10^{-2} respectively).

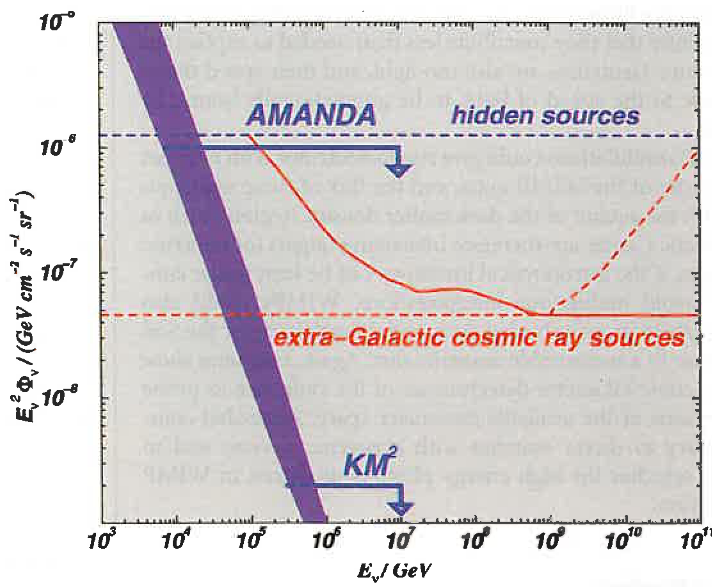

Fig. 2: The experimental upper bound on neutrino intensity established by the AMANDA detector [E. Andres *et al.*, Nucl. Phys. B (Proc. Suppl.), **91**, 423 (2001)], compared to the sensitivity achievable by a 1 km2 detector. The atmospheric neutrino background is shown as a blue strip indicating its variation from vertical to horizontal directions. The sensitivity of the detectors to variable point sources is greater than shown, since the background is much reduced for a search in given time and direction windows.
The solid red curve shows the upper bound imposed by cosmic-ray observations on the intensity of **muon** neutrinos [E. Waxman & J. N. Bahcall, Phys. Rev. **D59**, 023002 (1999); K. Mannheim, R. J. Protheore & J. P. Rachen Phys. Rev. **D63**, 023003 (2001); J. N. Bahcall & E. Waxman, Phys. Rev. **D64**, 023002 (2001)]. The dashed line extension to lower energies is the bound obtained under the assumption that the extra-Galactic proton energy generation rate below 10^{17} eV, which is uncertain due to Galactic cosmic-ray background, does not exceed the generation rate derived from observations at higher energy. The dashed line extension to high energies is obtained under the assumption that the extra-Galactic proton energy generation rate increases rapidly beyond 10^{20} eV, where the cosmic-ray flux is not well constrained by observations. The dashed blue line indicates the maximum intensity allowed for putative extragalactic nucleon accelerators, the existence of which is "hidden" from cosmic-ray detectors due to energy loss which prevents nucleon escape.

Neutrinos and dark matter

Missing mass in the Universe poses a problem for astronomy since Fritz Zwicky's 1933 observations of the velocity dispersion in a cluster of galaxies. There remain sources of gravity unseen at any wavelength despite numerous attempts. This dark matter (and, more recently, also smoothly distributed dark energy) lacks an explanation, but its existence appears naturally in the context of Big Bang cosmology. Approximately 12 billion years ago, the Universe was hot and compact creating particles in pairs at temperatures far above currently available accelerator energies. Supersymmetric extensions of the Standard model indicate that weakly interacting particles created at the electroweak-symmetry breaking scale, i.e. at TeV energies, could have survived until the present day with a matter density of the right order of magnitude, if they carry a conserved new quantum number (the R-parity). The naturalness of producing the correct density makes these weakly interacting massive particles (WIMPs) the currently most favored candidates for non-baryonic dark matter. With the mounting evidence for neutrino mass, one might think of neutrinos as the non-baryonic dark matter. However, given current upper limits on the neutrinos masses and mass splittings, one can infer that they contribute less than needed to explain the dark matter. Neutrinos are also too light, and their speed therefore close to the speed of light, to be gravitationally bound by galaxies.

WIMP annihilations could give rise to neutrinos with energies of the order of the WIMP mass, and the flux of these neutrinos goes with the square of the dark matter density. Regions such as the Galactic Center are therefore interesting targets for neutrino telescopes, if the astrophysical inventory can be kept under control to avoid ambiguous interpretations. WIMPs could also accumulate in massive bodies such as the Earth itself, or the Sun giving rise to a measurable neutrino flux. Again, estimates show that the cubic kilometer detectors are of the right size to probe large regions of the available parameter space, somewhat complementary to direct searches with cryogenic devices and to indirect searches for high energy photons produced in WIMP annihilation.

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Karl Mannheim is professor for astronomy at the University of Würzburg and works mainly in the field of high-energy astrophysics. He was born in Heidelberg in 1963 and studied physics and astronomy in Heidelberg and Bonn, where he received his doctoral degree with a thesis on radio galaxies in 1992.

X-ray and γ-ray astronomy

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The Universe, as seen in X- and γ-rays, is a very exotic place, largely filled with extremely hot gas, with temperatures of 10^6 to 10^8 K, and dotted with cosmic accelerators of all sizes launching particles to relativistic speeds. One can see bright eruptions from young stars, admire cosmic laser shows with beams of radiation circling in the sky from spinning neutron stars, watch matter fall inside a black hole or "miss" the hole and shoot out at nearly the speed of light, follow matter blasted away by giant stellar explosions or by titanic explosions when neutron stars and black holes collide and coalesce. On a quieter but even more energetic scale, one can witness the colossal merging of clusters of galaxies.[1] In these exceptional conditions, far beyond the dreams of the 19th & mid-20th century physicists, both hot gas and relativistic particles are intimately related and their joint observation in X- and γ-rays bears new diagnostics to investigate these extraordinary media.

Most X- and γ-rays are absorbed in the Earth's atmosphere, and so must be detected from space-borne telescopes. Only the highest-energy γ-rays (those above 50 GeV) can be observed from the ground by means of the particle showers they initiate in the upper atmosphere. New X-ray instruments, such as *Chandra* and *XMM-Newton*[2], are revealing hot plasmas with unprecedented angular (sub-arcsecond) & spectral precision. Detailed maps of the density, temperature, "chemical", and velocity distributions of the hot gas are derived from precise spectroscopic line measurements from many atoms in various ionisation states. The γ-ray telescopes still struggle to catch sparse γ-photons one by one and strive for sensitivity and angular resolution in the realm of arcminutes to degrees. Yet, the late *Compton Observatory* in space and the ground-based instruments (e.g. Whipple, CAT, Cangaroo, Celeste)[3] have revealed many powerful cosmic accelerators and have used the penetrating power of γ-rays to deeply probe the conditions inside accelerator cores, otherwise hidden from view at other wavelengths.

Stellar-mass and supermassive black holes

There is now convincing evidence that black holes exist in two varieties: stellar-mass ones, produced by the implosion of the core of a massive star at the end of its life, and super-massive ones weighing 10^6 to 10^9 solar masses, lurking at the centres of galaxies. Whether black holes of intermediate mass exist (with 10^2 to 10^5 solar masses), and why, are still hotly debated. The gathered evidence indicates that black holes of all masses show strikingly similar behaviour. They attract matter from their environment (stellar companion or host galaxy) into a thin disc of gas that spirals inwards; heated by turbulent friction, it brightly shines in UV and X rays. The hungrier the black hole, the softer the radiation! During violent flare episodes, black holes expel highly collimated jets of plasma accelerated to relativistic speeds. Their synchrotron radiation is seen from the radio to X rays. Inside the jets, e^+-e^- pairs are further accelerated to TeV energies and shine profusely in γ-rays. Given these basic ingredients, a source can, however, show up in many disguises from different points of view because of screening by intervening matter and relativistic effects. Sources possess different states and can change from one to another within hours or days, supposedly because they "eat" more or less. Thus it took forty years to disentangle the underlying continuity in the wide variety of sources seen at all wavelengths and this daunting task is far from complete today!

The huge energy release, of 10^{29} W to 10^{31} W in stellar systems and 10^{36} W to 10^{41} W in super-massive ones, originates from the intense gravitational potential of the black hole. Interestingly, neutron stars accreting matter from a companion star develop similar features. With increasing gravitational energy, jet plasma is propelled to $0.5c$ by neutron stars, $0.9c$ by stellar black holes, $0.995c$ by super-massive black holes, and over $0.99999c$ by γ-ray bursts (c being the speed of light). Jets from stellar systems extend over light-years while the galactic ones span millions of light-years. Which mechanisms can generate the acceleration required to maintain jet collimation over such distances? What triggers the ejections? Theorists are at a loss, but answers will hopefully come in the near future with greatly improved observations.

When a star explodes into a supernova, matter is ejected at thousands of km s^{-1} and the released energy of 10^{44} J is enough to power the Sun for 8 billion years! The blast wave rams into the surrounding interstellar gas and heats it up to 10^8 K while a reverse shockwave travels back to the centre and heats the ejecta up to 10^7 K. Thus the whole remnant becomes a bubble of hot gas that brightly shines in X rays. It provides an attractive laboratory for atomic physics and thermodynamics, illustrating how ionisation slowly takes place behind a shock in a rarefied gas (just a few atoms per cm^3), and the distinct thermal responses of ions and electrons.

Nuclei synthesized in the star during its lifetime, or freshly "cooked" in the exploding stellar layers, are ejected into space. They enrich the surrounding medium with elements heavier than hydrogen and helium, but little is known about their ejection and mixing. Recent X-ray maps have revealed complex filamentary structures and marked abundance variations, perhaps even the turnover of the stellar layers before or during the turmoil of the explosion. Next year, a new satellite, *INTEGRAL*[4], will bring precious information from the γ-ray lines produced by the radioactive decay of fresh elements. Those lines will constrain the element densities, but also the temperature, pressure, and isotopic composition at the time of their production, allowing, for the first time, to look back in time into the supernova furnace.

Acceleration of particles

The blast wave can also accelerate electrons and ions up to 10 and 100 TeV, respectively, loosing as much as 10% of its kinetic energy in the process over several hundred years. It is indeed the time required for the particles to bounce back and forth across the wave and steal a little energy at each crossing before finally escaping. The rackets in this ping-pong game are provided by the turbulent magnetic field. The accelerated "cosmic-ray" electrons have long been observed by their radio and X-ray synchrotron radiation inside supernova remnants, or recently in γ-rays when they up-scatter the cosmological microwave background light. Frustratingly, the accelerated "cosmic-ray" ions, which should produce γ-rays by nuclear interactions in the ambient gas, have evaded detection so far. So, we are still unable to prove the origin of cosmic rays nearly a century after their discovery! While waiting for new-generation γ-ray telescopes (such as *GLAST*[5] from space, or HESS[6], VERITAS[7] and others from the ground), new diagnostics on the ion acceleration can be found in X rays since their pumping of energy from the shock-wave leaves an imprint on the thermodynamics of the shocked gas at those energies.

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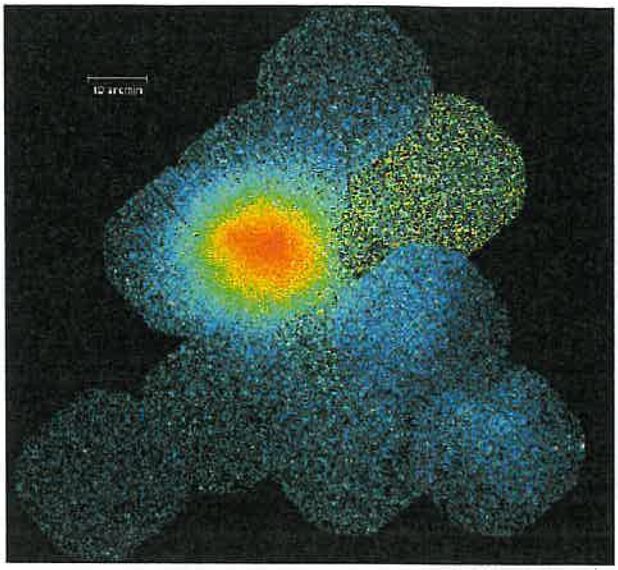

Fig. 1: *XMM Newton* observation of the nearby Coma galaxy cluster. The Coma cluster is one of the most massive clusters in the neighbourhood of our Galaxy. The observed diffuse X-ray emission comes from the hot intra-cluster medium (with a temperature of roughly 10^8 Kelvin), which fills the intervening space between the cluster's thousands of member galaxies. One distinguishes sub-structures in the diffuse emission: this is indeed a group of galaxies (to the lower right of the image) falling onto the cluster. Mapping the hot intra-cluster medium also serves to map the total gravitational potential, both of the visible matter and of the mysterious dark matter. The non-thermal emission of this cluster was also discovered by the Italian satellite *BeppoSAX*, from this last observation, a measure of the intra-cluster magnetic field was obtained.

The collapse of a supernova core may leave an incredibly compact neutron star, with a little more than a solar mass squeezed within 20 km, which spins, like a dazzling top, tens of times per second. Its magnetic field is amplified to 10^8 T, sometimes 10^{11} T! The rapid rotation of this great magnet generates huge electrical fields that accelerate particles to 10 TeV or more. Copious e^--e^+ pair production in the neutron star's magnetosphere creates narrow beams of light emitted in the range from radio- to γ-rays that sweep across the sky like giant lighthouse beacons sending us brief flashes of light, which won them the names of "pulsating stars" or "pulsars". Relativistic particles are blown into a "wind" that powers an energetic nebula around the pulsar and shines at all wavelengths. In fact, the highest-energy photons (~ 50 TeV) ever detected in the sky were produced in the wind of the nebula of the famous Crab pulsar. Yet, little is known about pulsars. Only a handful, the tip of the iceberg, have been seen at high energies where they radiate the bulk of their power. This number is expected to grow by an order of magnitude with *GLAST* within a

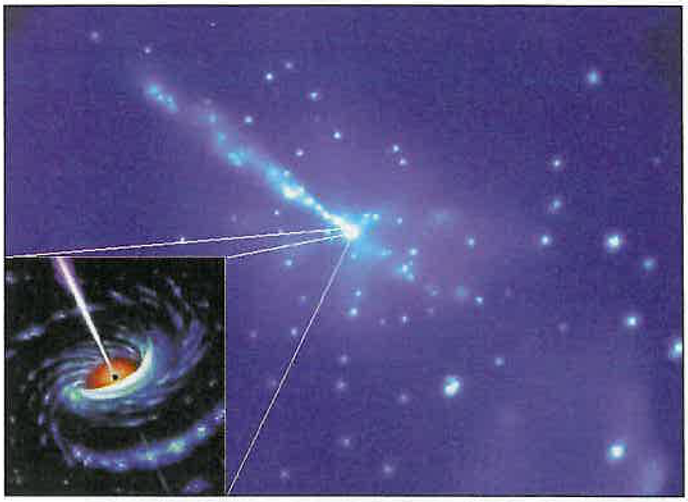

Fig. 2: *Chandra* observation of the active galactic nucleus Cen-A. As shown in the small sketch, this system is thought to be constituted of a super-massive black hole surrounded by an accretion disk. A very long jet, visible in the X-ray image, is produced in the vicinity of the black hole. This jet accelerate particles to very high velocities, which in turn produce γ-rays detected by *CGRO*/EGRET, to be studied in much more detail by *GLAST*, the next generation GeV γ-ray telescope.

few years. In fact, we may have already detected a number of them without recognizing their nature. A few years ago, the Compton Observatory has indeed discovered about 150 mysterious sources of γ-rays in our Galaxy. Some even lie in our backyard, within a thousand light-years from Earth, but their origin remains an enigma. *GLAST* will hopefully tell us what they are and how many of them are γ-ray pulsars to help us understand these fascinating stellar lighthouses.

The hot intergalactic gas

Hot gas (10^5 K to 10^7 K) has been the most abundant form of visible matter in the Universe for at least several billion years. A large fraction is trapped in the vast intergalactic space inside clusters of galaxies. There, it amounts to 2 to 10 times the mass locked inside the galaxies themselves. Clusters are the largest gravitationally bound structures in the Universe. They grow over billions of years to vast assemblies millions of light-years in size, as smaller clusters slowly merge together and through continuous accretion from the surrounding medium. In the process, they release tremendous amounts of energy (10^{56} J per billion years per merger) that heat the cluster gas to 10^7 K to 10^8 K. The typical cooling time of 1 billion years in this extremely rarefied gas (10^{-3} atom per cm^3) is, however, quite unusual in thermodynamics! On the other hand, galaxies inject heavy elements (coolants) and energy into the cluster gas, so that cluster history and galaxy formation are deeply interwoven. Mapping the hot X-ray glowing gas in clusters also serves to map the total gravitational potential, both of the visible matter and of the missing dark matter. The latter contributes from 5 to 8 times more to the total mass of the cluster, so it controls the evolution and fate of structures in the Universe, yet its nature remains elusive. If it is composed of slow, massive, elementary particles left over from the early phases of the Big Bang, there is hope that their annihilation will be detected in γ-rays in the near future paving the way to unravel their mysterious origin.

Hot gas... the most abundant form of visible matter in the Universe for at least several billion years

Massive black holes are also important keys to understanding the evolution of the early Universe. They were already quite numerous a billion years after the Big Bang. If, as currently proposed, mass structures of 10^5 to 10^7 solar masses were formed first, it is unclear what fraction of them turned into clusters of stars and black holes. In other words, whether stars or black holes first populated the Universe continues to be an open question whose answer requires searching for black holes at high energy to very large distances, deep into the past.

Observing the Universe at high energy thus highlights its immense diversity and exuberance, but also the deep unity of physical processes that create such a wealth of phenomena. The current physical laws, developed in terrestrial laboratories, appear to apply remarkably well under conditions far more extreme, billions of light-years away, and into the past. Observational means are still, however, cruelly limited to discover new physical processes. Far more advanced instruments will be needed to allow us to peer near the black hole horizon or form images of high-energy phenomena in the early Universe.

Footnotes

[1] Other highly-energetic phenomena, such as g-ray bursts and ultra high-energy cosmic rays are presented in the articles by L. Piro and A.A. Watson in this issue.

[2] 'Chandra' is NASA's Advanced X-ray Astrophysics Facility and XMM-Newton is ESA's X-ray Multi-Mirror mission, whose emphasis is, respectively, on imaging and spectroscopy.

[3] Cherenkov Telescopes

[4] International Gamma-Ray Astrophysics Laboratory

[5] Gamma Ray Large Area Space Telescope

[6] High Energy Stereoscopic System

[7] Very Energetic Radiation Imaging Telescope Array System

About the authors

Isabelle Grenier is Professor of Astroparticle physics at the University of Paris VII and works in the Service d'Astrophysique at the Centre d'Etudes de Saclay (Commissariat à l'Energie Atomique). Her main field of research are gamma-ray sources, focusing lately on the unidentified sources discovered by GRO-EGRET. She also works on the high-energy aspects of the solar neighbourhood, in particular on the clouds, supernovae, pulsars, and cosmic-ray sources of the Gould Belt. She is also Principal Investigator of the French contribution to the future NASA gamma-ray satellite, GLAST.

Philippe Laurent is an astrophysicist at CEA in France. He has participated to the data analysis of the French SIGMA coded mask telescope, on board the Russian GRANAT satellite. He is now deeply involved in the design and realisation of the INTEGRAL/IBIS telescope, which will produce high resolution images of the sky between 15 keV and 5 MeV.

Quantum Information:
Quantum Entanglement

San Feliu de Guixols, Spain, 23-28 March 2002

Chairs: A. Sanpera & D. Bruss (Hannover, D)
Vice-Chair: S. Huelga (Hatfield, UK)

SPEAKERS WILL INCLUDE

D. Bouwmeester (Oxford, UK); S. Braunstein (Wales,UK); I. Cirac (Innsbruck, A); N. Gisin (Geneva, CH); S. Haroche(Paris, F); P. Horodecki (Gdansk, PL); D. Loss (Basel, CH); M. Lukin (Harvard, US); C. Macchiavello (Pavia, I); D. Mermin (Cornell, US); A. Peres (Haifa, IL); M. Plenio (London, UK); S. Popescu (Bristol, UK); R. Tarrach (Barcelona, E); B. Terhal (IBM, US); H. Weinfurter (Munich, D); D. Wineland (Boulder, US); W. Wootters (Williamstown, US); A. Zeilinger (Vienna, A).

SCOPE

This meeting aims at bringing together experts from various areas in the rapidly growing field of quantum information. This first Euresco conference focuses on the fundamental concept of quantum entanglement, which is at the heart of many tasks in quantum information processing. The main topics include detection, characterization and quantification of entanglement, as well as its experimental creation and manipulation. The aim of this conference is to encourage and promote the interaction between leading figures in the field and young researchers in a friendly environment.

Deadline for Applications: 17 December 2001

Particle Physics and Gravitation*:
EuroConference on Supersymmetry, Gravity and Quantum Cosmology

Bad Herrenalb, Germany, 1-6 June 2002

Chair: H. Nicolai (Golm, D)

SPEAKERS WILL INCLUDE

I. Bakas (Patras, EL); J. Fernandez Barbon (CERN, CH); M. Bianchi (Roma, I); U. Danielsson (Uppsala, S); B. de Wit (Utrecht, NL); M. Gaberdiel (London, UK); A. Giveon (Jerusalem, IL); M. Green (Cambridge, UK); M. Gutperle (Harvard, US); E. Kiritsis (Heraklion, EL); W. Lerche (CERN, CH); D. Marolf (Syracuse, US); N. Nekrassov (IHES, F); B. Pioline (Harvard, US); J. Plefka (Potsdam, D); N. Reshetikhin (Berkeley; US); H. Samtleben (Paris, F); V. Schomerus (Potsdam, D); J. Teschner (Berlin, D); A. van Proeyen (Leuven, B); P. Vanhove (Saclay, F); P. West (London, UK).

SCOPE

Developments in superstring theory over the past years have shown the need for a fully non-perturbative formulation of this theory. The conference will focus on aspects of recent research in this direction, with particular emphasis on D branes and their ramifications (such as non-commutative gauge theories, tachyon condensation, applications of K theory, and black hole physics). It will also cover duality symmetries and supermembrane theory, as well as new developments in integrable systems and super-symmetric quantum field theory relevant to M theory.

Deadline for Applications: 12 March 2002

Fundamental Aspects of Surface Science*: Euroconference on Structure and Reactivity of Oxide Surfaces

Acquafredda di Maratea, Italy, 1-6 June 2002

Chair: G. Pacchioni (Milano, I)

SPEAKERS WILL INCLUDE

C.T. Campbell (Seattle, US); H. Freund (Berlin, D); E. Giamello (Torino, I); W. Goodman (College Station, US); Y. Iwasawa (Tokio, J); N.M. Harrison Warrington, UK); U. Heiz (Ulm, D); C.R. Henry (Marseille, F); U. Landmann (Atlanta, US); F. Netzer (Graz, A); C. Noguera (Orsay, F); J. Rodriguez (Upton, US); M. Scheffler (Berlin, D); C. Wöll (Bochum, D); A. Zecchina (Torino, I).

SCOPE

Oxide surfaces and metal-ceramic interfaces are relevant in corrosion protection, adhesion, microelectronics, photovoltaic cells, sensors, heterogeneous catalysis, but little is known about their atomistic structure. Thanks to a spectacular development of experimental methods in the last decade, today it is possible to prepare oxide surfaces by applying techniques of epitaxial growth. Data coming from these experiments can be compared with more traditional approaches to the surface chemistry of polycrystalline materials and to ab initio modeling. From the interplay of experiment and theory, significant advances in this area have been achieved. This meeting will cover topics like the structural properties of clean and metal covered oxide surfaces, similarities and differences of single crystals, thin films and polycrystalline materials, adsorption and chemical reactivity, point and extended defects, etc.

Deadline for Applications: 12 March 2002

Computational Biophysics: Integrating Theoretical Physics and Biology*:
Biophysics from First Principles EuroConference: From the Electronic to the Mesoscale

San Feliu de Guixols, Spain, 7-12 September 2002

Chairs: F. Seno (Padova, I) & A. Chaka (Gaithersburg, US)

SPEAKERS WILL INCLUDE

R. Car (Princeton, US); P. Carloni (Trieste, I); G. Folkers (Zurich. CH); J. Fraaije (Leiden, NL); B. Honig (New York, US); M. Karplus (Harvard, US); A. Klamt (Leverkusen, D); D. Kleier (Newark, US); M. Klein (Pennsylvania, US); H. Kubinyi (Ludwigshafen, D); B. Lundqvist (Göteborg, S); A. Maritan (Trieste, I); S. Mayo (Pasadena, US); M. Parrinello (Stuttgart, D); J. Rabinowitz (North Carolina, US); U. Roethilsberger (Zurich, CH); C. Rovira (Barcelona, E); K. Schulten (Illinois, US); M. Segall (Cambridge, UK); P. Siegbahn (Stockholm, S); R. Wade (Heidelberg, D); T. Werner (GSF, D); W. Zinth (Munich, D).

SCOPE

The purpose of this conference is to bring together theoretical and experimental researchers from physics, chemistry, biological sciences, and industry to foster interdisciplinary approaches to the study of living systems. The principal focus is on the application of theoretical physics – from first principles to classical simulations, as well as statistical approaches – to understanding biological processes. The conference will include the following sessions: Understanding Biological Mechanisms; Transition Metal Chemistry; Predicting the Activity of Chemicals; Structure and Function of Biomacromolecules; Molecular Interactions and Solvation: Short- and Long-range Forces.

Deadline for Applications: May 2002

Conferences are open to researchers world-wide, whether from industry or academia. Participation will be limited to 100. The registration fee covers full board and lodging. **Grants** *are available, in particular for nationals from EU or Associated States under 35. (*EC support from the High Level Scientific Conferences Activity)*

Scientific programme & on-line application form available at: http://www.esf.org/euresco

or contact: Dr. J. Hendekovic, EURESCO Office, ESF, 1 quai Lezay-Marnésia, 67080 Strasbourg Cedex, France
Tel. (33) 388 76 71 35 Fax.(33) 388 36 69 87 Email: euresco@esf.org

Gamma-ray bursts and afterglows

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Gamma-Ray Bursts (GRBs) are brief, intense flashes of gamma rays, going off at a rate of about one per day all over the sky. For thirty years after their discovery in 1967, the origin of these events has remained a mystery. Hundreds of events were observed by several experiments, but all the information was essentially limited to the few seconds of intense gamma-ray activity, after which the GRB vanished in the background, with no measurable sign of activity at other wavelengths. The lack of any measurement of the distance has left the field open for about a hundred different models as to their origin. The isotropic distribution of these events in the sky measured by the BATSE experiment on board of the Compton Gamma-Ray Observatory was suggesting an extragalactic origin, but a direct determination of the distance of even a single event was lacking.

Establishing the cosmic distances to gamma-ray bursts

A *fast and precise* position of GRB was needed, where the *Holy Grail* of GRB scientists, i.e. *the counterpart*, could have been searched for at all wavelengths. This became possible within a year after the launch on April 30, 1996, of the Italian-Dutch satellite BeppoSAX, named after Giuseppe (Beppo) Occhialini, one of the fathers of high energy astrophysics in Italy. The poor positional accuracy of Gamma-ray instrumentation is circumvented by associating to a monitor of gamma-ray bursts (GRBM, which provides the temporal signature of a GRB), two wide-field X-ray cameras (WFC), able to locate the GRB within 3', in a field of view of 40° × 40°. A deep search of the afterglow emission of the GRB is then carried out with a set of more sensitive, narrow-field (~ 1°) X-ray telescopes (NFI), by re-orienting the satellite towards the location provided by the wide field instruments. On February 28, 1997, the gamma-ray burst GRB970228 was detected by the BeppoSAX GRBM and localized by the WFC. The NFI were pointed to the GRB location 8 hours after burst, leading to the discovery of a previously unknown X-ray source. The new source appeared to be fading away during the observation. On March 3, another observation confirmed that the source was quickly decaying: at that time its flux was a factor of about 20 lower than at the time of the first observation. This was the first detection of an "afterglow" of a GRB (Fig.1). While the X-ray monitoring of GRB970228 was going on, numerous observatories probed the location of the GRB, which had been provided by the BeppoSAX team, at all wavelengths. This campaign led to the discovery of an optical transient associated with the X-ray afterglow by a group led by Jan van Paradijs. Yet, the crucial information on the distance of the GRB was still missing. On 8 May 1997 the second breakthrough came with another BeppoSAX GRB: GRB970508, which was observed by the BeppoSAX NFI 5.7 hours after the burst, and by optical telescopes starting 4 hours after the burst. The early detection of the optical transient, and its relatively bright magnitude permitted a spectroscopic measurement of its optical spectrum with the Keck telescope by a team led by S. Kulkarni. The spectrum revealed the presence of absorption lines at a redshift of $z = 0.835$, produced by the gas of the galaxy hosting the GRB, and therefore demonstrated that GRB970508 was at a cosmological distance. As of today, we have measured the distance of 20 GRB, and all of them are in distant galaxies.

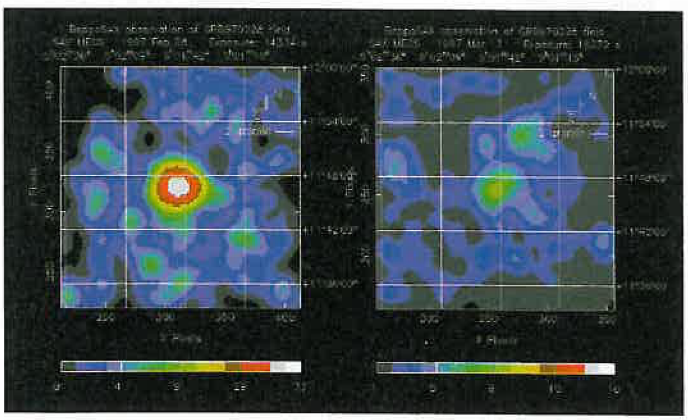

Fig. 1: The discovery of the first X-ray afterglow of a Gamma-Ray Burst: the event of Feb. 28, 1997. The figure shows the image in the 2-10 keV range obtained by the X-ray telescopes of BeppoSAX. A previously unknown bright X-ray source was visible 8 hours after the GRB (left panel). Three days after (March 3. Right panel), the source had faded by a factor of about 20.

The BeppoSAX observation of GRB970228 and GRB970508 have also changed the old concept of a brief - sudden release of luminosity concentrated in few seconds by a GRB. The energy produced in the afterglow phase turns out to be comparable to that of the GRB. The afterglow emission is found when the GRB signal disappears, and lasts for days or even months, decreasing in time according to a power law (Fig.2). These properties are nicely accounted for by the fireball model, proposed by M. Rees, P. Meszaros and others. At cosmological distances the observed fluxes correspond to a luminosity in gamma-rays of ~ 10^{53} erg/s concentrated in a region of the order of a few light seconds. Under such conditions a *fireball* of gamma-rays and electron-positron pairs develops. The initial radiative energy released by the central source is converted to kinetic energy of a shell which expands with relativistic motion (Lorentz factor $\gamma \sim 100$) up to a size of ~ 10^{16-17} cm, where it converts its energy back into electromagnetic radiation (i.e. the GRB and its afterglow).

GRB970508 was the first GRB in which a radio afterglow was discovered by D. Frail and collaborators. But, even more importantly, this measurement yielded direct evidence of a relativistically expanding source, in nice agreement with the fireball scenario. The GRB of December 14, 1997 localized by BeppoSAX introduced a new issue. At a redshift $z = 3.42$ (that corresponds to a look-back time of about 85% of the present age of the Universe), its luminosity would have been about 3×10^{53} erg/s, if the emission were isotropic. Currently, we have other examples of even more luminous GRB. The most extreme is GRB990123. With an isotropic luminosity of ~ 10^{54} erg/s, this explosion would have produced an energy in gamma-rays equivalent to the mass-energy of the Sun. No other known phenomenon in the Universe can compare with this luminosity, but the Big Bang. Indeed, assuming isotropic emission, the energy required, is so high that another possibility needs to be considered. A jet, i.e. a collimated outflow of material producing radiation beamed towards us within a narrow cone, would decrease the energy requirement by a factor proportional to the solid angle of the jet. Some observational evidence suggests a presence of a jet in some, but not all GRBs.

The nature of gamma-ray-burst progenitors

Whether a jet is present or not, the energies required are still compatible with bursts arising from stellar progenitors, which undergo a catastrophic explosion at the end of their evolution. One family consists of very massive stars, usually referred to as *hypernovae* or *collapsars* after B. Paczinsky and S. Woosley. Another consists of a binary system formed by neutron stars or a neutron star- black hole. The end-product of the evolution of both families of *progenitors* is a black-hole surrounded by a disk of very high density. The energy that can be tapped out of this system by extracting either the gravitational energy of the torus or the energy of e.g. a rotating black hole, is comparable to that implied by observations. The radiation physics and energy of all mergers and hypernovae are then, to order of magnitude, the same, so other elements are needed to disentangle the nature of GRB progenitors.

This information can be derived from the study of the GRB environment. In the case of a hypernova, the massive star evolves very rapidly (~ 10^6 years) and therefore GRB should go off in the same site where the progenitor was born, i.e., in a star-forming region. On the contrary, neutron star-neutron star coalescence happens on much longer time scales (billions of years) and the kick velocity given to the binary system by two consecutive supernova explosions should bring a substantial fraction of these systems away from their formation site. In the case of massive progenitors, the large radiation field of hard X-ray photons produced by the GRB, would ionise the surrounding medium, leading to the production of lines, the most prominent being the iron K_α line in X-rays. On the contrary, GRB produced by mergers should go off in a clean environment, and no line is expected. Evidence of iron features in the X-ray spectra of GRB has grown in the last years. Early marginal detections in two GRB by BeppoSAX and the Japanese X-ray satellite ASCA in 1997-1998, have been followed more recently by measurements in other events, like that observed by BeppoSAX in GRB000214 and by the American X-ray satellite Chandra in GRB991216. These measurements are consistent with the line being produced by a material predominantly made up by iron lying within a light day or two of the GRB and with a mass approximately equivalent to one-hundredth that of the Sun. The line width observed by Chandra also indicates that the material is moving very quickly (at approximately 10 percent the speed of light) and that it was probably pre-ejected by the GRB. There is further evidence in agreement with these findings. At early times, during the GRB itself, the photons having an energy near to that needed to ionise the iron atoms, are absorbed by the gas, until the atoms are fully stripped of their electrons. If the gas lies in the line of sight, we then expect to see an iron absorption edge appearing for only a few seconds during the burst, as found in GRB990705 by BeppoSAX. These observations are strongly suggesting that the progenitor of the GRB was very a massive star, but the details of the process require more data and theoretical computations. The large content of iron and the velocity of the ejecta also suggest that the ejection of the material was similar to a supernova explosion.

The extraordinary advances in the GRB field over the last years have also opened new areas of investigations. What is the origin of *GHOSTs* (GRB Hiding Optical Source Transient), a.k.a. *dark GRB*, i.e., events without optical afterglows? If GRBs are indeed associated with massive progenitors and therefore lie in regions of star formation, it is likely that the optical emission is heavily absorbed by dust in a large fraction of events, while the more penetrating X-rays escape the region and are therefore observed. It is also possible that the optical emission is completely absorbed by the intragalactic gas between us and the GRB, that would set the distance of dark GRB at a redshift z > 5. BeppoSAX has also revealed the existence of another new class of events, the so-called *X-ray rich GRB*, characterized by a very faint gamma-ray flux. An intriguing possibility is that these events are located at such large distances (z > 10) that the Hubble expansion shifts the peak of the spectrum from gamma-rays into the X-ray range. Finally, very little is known on *short GRB*, i.e. events lasting less than 1 sec., since no counterpart has been so far identified.

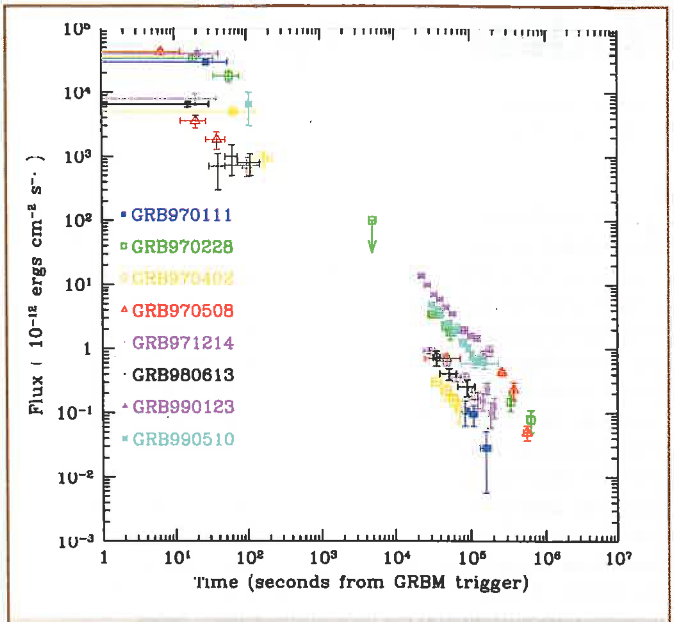

Fig. 2: The X-ray light curves of a sample of afterglows by BeppoSAX. The data points at t<100 sec are gathered by the Wide Field Cameras, that catch the GRB in action. The position derived from these instruments is then followed up by the more sensitive X-ray telescopes, few hours after the GRB (data points in the lower-right part of the image). Note that the light curves follow a power law curve over a range of 6 orders of magnitude in flux and time.

Using gamma-ray-bursts to probe the early Universe

The luminosity of GRBs is so high that they can be detectable out to distances much larger than those of the most luminous quasars or galaxies observed so far. We expect thus, in the near future, to use GRB as beacons to probe star and galaxy formation at much earlier epochs of the Universe evolution, by studying the features imprinted over their spectrum by the gas through which they shine. The future of the GRB field is indeed rich in expectations. The satellite HETE2, launched in Oct. 2000, will transmit the position few seconds after the event for about 20-30 GRB per year. The satellite SWIFT, to be launched in 2003, will provide multi-wavelength data within a minute of the GRB for hundreds of events.

Updated information can be obtained at:
www.ias.rm.cnr.it/sax/grb1.html

Nuclear astrophysics

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In the last decades, the field of Nuclear Astrophysics has greatly expanded its scope and significance. It has developed into a strongly interdisciplinary field in the overlap of astronomy, astrophysics, nuclear and particle physics. The astrophysical sites investigated include the early Universe, stable (hydrostatic) burning and evolution of stellar objects. Explosive events in single and binary systems, like novae, supernovae, X-ray bursters or environments ejecting jets of hot and dense matter are also studied. Understanding the underlying nuclear processes is also important for following galactic chemical evolution, the change of elemental abundances in a galaxy with time. The nuclear equation of state is a third important link between nuclear physics and astrophysics, in addition to energy generation and nucleosynthesis. Matter at nuclear density and beyond is encountered in neutron stars and during the formation of black holes.

Investigations in Nuclear Astrophysics involve stable as well as highly unstable nuclides. In some cases the focus is on a few key reactions, in others thousands of nuclei and tens of thousands of reactions in extended reaction networks are involved. The fact that nuclear physics is so closely related to the astrophysical results makes this interdisciplinary field exciting. Not only the details in the final abundance yields are determined by nuclear reactions but also much of the dynamics. In the following, we present a selection of astrophysical environments to illustrate the main issues.

Hydrostatic burning stages

A star trying to establish equilibrium between radiation pressure and gravitational collapse will experience a series of burning stages, permitting reactions involving nuclides with increasing charge at higher temperatures. H burning, the first burning stage, involves a small network of reactions in the pp-chains (the origin of solar neutrinos) and the CNO-cycles. Famous examples for key reactions in the second burning phase, He-burning, are the reactions $^4He(2\alpha,\gamma)^{12}C$ (triple-alpha reaction) and $^{12}C(\alpha,\gamma)^{16}O$. For the triple-alpha reaction, the existence of a resonance in ^{12}C at the relevant energy for stellar He-burning temperatures ($T\approx1\text{-}2\times10^8$ K) was predicted because vital elements like C and O would not exist otherwise. This prediction from the early days of nuclear astrophysics was later confirmed by a nuclear physics experiment. The reaction $^{12}C(\alpha,\gamma)^{16}O$ has sometimes been termed *the major problem* in nuclear astrophysics. Because it determines the C to O ratio, the fate of a star in its later burning phases is strongly sensitive to the actual value of this rate. Although ^{12}C is stable and the reaction has been well studied at energies $E\geq2.4$ MeV, it has not been measured at the relevant energy of 300 keV due to the low cross section at sub-Coulomb energy. A theoretical treatment cannot provide the necessary accuracy of better than 10% because the cross section at this energy is determined by the interference of tails of three resonances. Although the temperatures of early burning stages are of the order of several 10^7–10^8 Kelvin, the resulting interaction energies are quite low, often below the Coulomb barrier. This leads to problems in prediction as well as measurement of charged particle reaction cross sections even for stable nuclei. Underground laboratories, such as LUNA in the Gran Sasso mountains in Italy, are making advances for reactions on light nuclei by reducing the background significantly [1].

Late burning stages, such as Ne- and Si-burning, exhibiting higher temperatures, allow photodisintegration as an alternative to fusion reactions. A larger number of nuclides is involved but capture and photodisintegration reactions may equilibrate, leading to a simplification of the reaction networks [1]. For instance, Si-burning ends with nuclear reactions in a complete chemical equilibrium (nuclear statistical equilibrium), minimizing the total binding energy with an abundance distribution around Fe. Thus, the sequence of burning stages is terminated. Low mass stars (such as the Sun) will not even reach Ne-burning, whereas stars with masses in the range $8\ M_{sol} \leq M \leq 25\ M_{sol}$ experience a collapse of the Fe-core, leading to a type II supernova explosion and the formation of a neutron star.

The creation of heavier elements has to proceed in a slightly different manner and still poses some puzzles (especially in the r-process, see below). Due to the increased Coulomb barrier, isotopes much heavier than Fe can only be synthesized via reactions with neutral particles, i.e. neutrons. During core and shell He-burning specific α-induced reactions ($^{13}C(\alpha,n)^{16}O$, $^{22}Ne(\alpha,n)^{25}Mg$) can liberate neutrons which then build up elements up to Pb and Bi by subsequent neutron captures on stable isotopes and β-decays, starting on existing heavy nuclei around Fe. The signature of this so-called s-process (slow neutron cap-

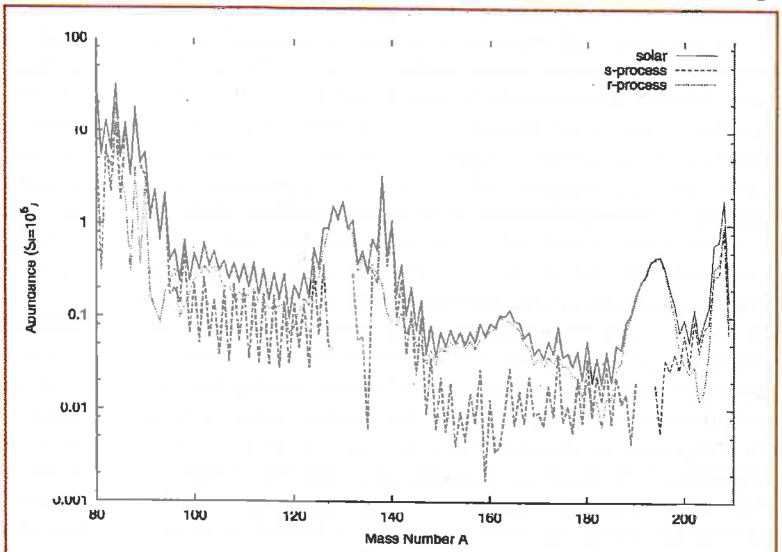

Fig. 1: Abundances for nuclides with mass number $A>80$. Solar system abundances are measured, s- and r-abundances are calculated. The peaks in the solar system abundance distribution around A=88, 138, 208 are formed in the s-process, whereas the broader companion peaks shifted to slightly lower mass number are r-process peaks.

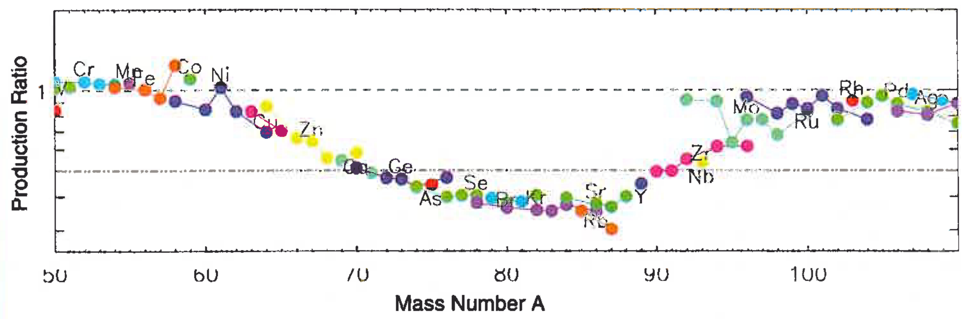

Fig. 2: Nuclides produced and ejected by a type II supernova explosion of a 25 M_{sol} star [7]. Shown are the ratios of two calculations with altered reaction rate sets in the mass range $50 \leq A \leq 110$. The differences are mainly due to a variation in the $^{22}Ne(\alpha,n)^{25}Mg$ rate within current experimental uncertainties.

ture) can be found in the observed elemental abundance distribution in the Solar System (Fig. 1) where peaks are formed due to the small capture cross sections at closed neutron shells. Essential are the accurate (≤1–2%) determination of the neutron producing reactions as well as the relevant neutron capture cross sections for stable and long-lived isotopes. The effective energy is around 20-30 keV and an important contribution can be made by classical nuclear physics experiments on stable nuclei with improved detection techniques and accuracy [2].

Explosive burning

Explosive conditions result in higher temperatures and shorter time-scales, so that often even short β-decay half-lives are longer than the reaction time-scale. This requires the inclusion of short-lived nuclei in extended networks. Two examples are the r-process and the rp-process. In an r-process (rapid neutron capture) the neutron capture times are so short that neutron-rich nuclei far off stability can be reached. An (n,γ)-(γ,n) equilibrium within an isotopic chain is established so that the time-scale is determined by the comparatively slow β^--decay (even if the half-life is of the order of ms and the neutron separation energies are as low as 2-3 MeV). Again, the traces of such a process can be found in the solar abundances (Fig. 1). A companion peak to each s-process peak at slightly lower mass number indicates a contribution from far off stability where the closed neutron shells are encountered at a smaller mass number. Approximately half of the isotopes with A>60 are produced in this r-process but its site remains uncertain (type II supernovae or several sites?) [3]. The search for the actual site(s) is a major focus in the field.
Similarly, the rp-process is characterized by rapid proton captures in a proton-rich, hot environment, moving the effective synthesis path off stability toward unstable proton-rich nuclei. This process occurs in binary systems in H-rich material, which has flown from the atmosphere of a main sequence star onto the surface of its companion neutron star. When reaching a critical mass, such an accreted layer can ignite H-burning and start a thermonuclear runaway [4]. At least one type of X-ray bursts - observed in X-ray astronomy - can be connected to the rp-process. It is yet unclear if any material can attain sufficient kinetic energy to leave the gravitational field of the neutron star during such a burst. Therefore, it remains open whether the rp-process also contributes to nucleosynthesis.

Nuclear properties for nuclei involved in explosive processes mainly have to be predicted by theory [5]. This and therefore also the prediction of reaction rates far from stability for a large number of nuclei remains problematic. Even though microscopic models are continuously improved, phenomenological approaches are still helpful due to the sheer number of reactions to be treated. The proposed radioactive ion beam facilities in Europe, Japan and the USA will highly advance our knowledge of nuclear structure far off stability [1]. Classical nuclear physics experiments can also provide data systematics essential for the theoretical description of certain nuclear properties at energies close to the Coulomb barrier [6].

Hydrodynamic simulations have to include energy generating reaction networks influencing temperature and density profiles. Currently, many of the proposed events cannot be fully self-consistently simulated. Analyses by approximations such as parameterized reaction networks are necessary. Knowledge in nuclear physics can also be gained from analyzing results of astrophysical processes involving unstable nuclei or matter at extreme conditions. For example, the detailed analysis of the r-process has indicated a change of neutron shell closures with distance from stable nuclei [3].

Core-collapse supernovae

The collapse of the Fe-core of a massive star leads to a type II supernova explosion, releasing a total gravitational binding energy of 2–3×10^{53} erg. Neutrinos produced during the formation of the neutron star carry away this energy in the fastest fashion. The apparently most promising mechanism for obtaining explosions is based on the fact that if neutrinos deposit as few as 1% of their energy in the outer layer of the star, the material is sufficiently heated to invoke an explosion. This also leads to explosive burning and nucleosynthesis (Fig. 2) [7]. However, details of the explosion mechanism are still uncertain, as it is not yet possible to consistently simulate all aspects. Core-collapse simulations have to treat convective flows in multidimensional hydrodynamics and include a realistic nuclear equation of state as well as a correct treatment of energy transport [8]. For the latter it is necessary not only to understand radiation transport but also the interaction of neutrinos with matter. Electron captures have to be traced explicitly in the late burning phases because they are not in equilibrium. They also determine the onset of the core collapse by decreasing the stabilizing pressure of the degenerate electron gas [1,9].

Plasma conditions

Of further interest is the modification of nuclear processes in stellar plasmas, which can only be studied in a very limited way in terrestrial laboratories. Target nuclei in a stellar environment are thermally excited and the reaction rate is modified in comparison to the laboratory reaction proceeding on a target in the ground state. Coulomb interactions in the plasma screen the potential of bare nuclei. Electron capture processes, β-decays can also be different for atoms and ions. Therefore, terrestrial half-lives may be different from stellar ones.

Outlook

The potential of nuclear theory and experiment in this field has already been outlined above. Additionally, the evolution of computing power will be an important factor for future progress. Finally, new observational data on abundances and signatures of nuclear reactions will have considerable impact. Such observations can be in the form of spectra across a wide range of electromagnetic wavelengths obtained by terrestrial or satellite-based observatories from stellar surfaces, explosion remnants, and the interstellar as well as intergalactic medium. They can also be of the type of abundance determinations in specific meteoritic inclusions by means of sophisticated chemical extraction methods [10]. Such investigations become increasingly important and provide valuable additional information regarding the products of stellar nucleosynthesis. The increased inflow of such astronomical observations tremendously helps to test stellar nucleosynthesis (and with it stellar and explosive models as well as nuclear input) and, consequently, the role these events play in the evolution of galaxies.

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Huge cosmic lenses

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Cosmic lenses, islands of concentrated mass drifting in the vast void of space, span approximately a factor of 10^{20} in mass and 10^{16} in linear size. This enormous diversity, the long-range nature of the gravitational force, and the simplicity of the underlying physics, make gravitational lensing a powerful tool with which to study a wide variety of astronomical problems.

The Phenomenon of Gravitational Lensing

Astronomical theories are tested primarily through passive observation of the multi-coloured electromagnetic radiation that chances to intercept Earth's orbit on its journey from a distant energetic source. When this radiation passes near a mass concentration, its path is altered by the gravitation field associated with the over-density. The light is bent toward the mass, the effect of an enormous converging lens.

In principle, the bending is gradual and continuous, but because the Universe is so sparse, the thin lens approximation of optics is applicable: the primary effect is a (relatively) sudden bending through an angle α that depends on the size of the impact parameter ξ compared to the Schwarzschild radius R_s of the lens

$$\alpha = 2\,R_s\,/\,\xi = (4\,G\,M)\,/\,(c^2\,\xi)\,,$$

where M is the lens mass (Fig. 1). If the lens is extended over distances comparable to or larger than the impact parameter, the total effect is computed by integrating over the density distribution of the lens.

The ray-tracing process can be expressed as the two-dimensional Jacobian matrix J that describes how positions on the emitting source are mapped onto positions in the image plane. The symmetric piece of the diagonal elements of J is related to the convergence of the lens (isotropic magnification of the images), while the anti-symmetric portion is related to the lens shear (shape of the images). The magnification at any position is given by the inverse of the matrix determinant. The loci of positions in the source plane at which this magnification is formally infinite (because $|J| = 0$), are called *caustics*; the corresponding image positions lie on *critical curves*.

A simple point lens has a point caustic at the angular position of the lens. Due to symmetry, a source located directly behind a point lens will be imaged at very large magnification (finite only due to the non-zero size of the source) into a circular critical curve centred on the lens position. The size of this circle is given by the angular Einstein radius

$$\theta_E = \sqrt{\,[(4\,G\,M\,D_{LS})\,/\,(c^2\,D_{OL}\,D_{OS})]}\,,$$

where D_{LS}, D_{OL} and D_{OS} are line-of-sight distances between the lens, source, and observer. Complicated, multiple and disjoint caustic and critical curves can be generated by compound or extended lenses (see, e.g., Fig. 2).

Geometry of the Universe

Lensing was first observed early in the last century, when a solar eclipse allowed the apparent positions of background stars near

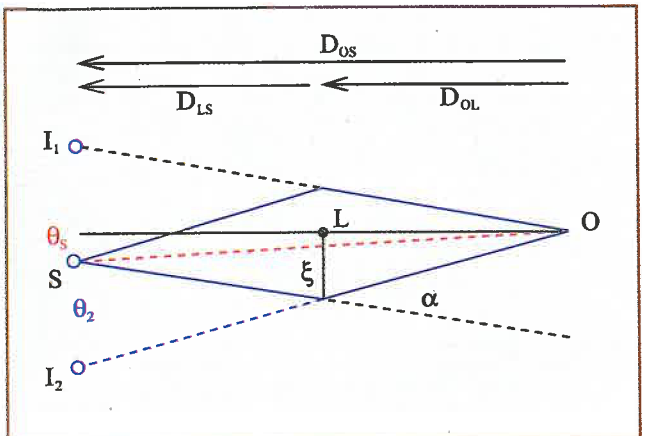

Fig. 1a: When the undisturbed (red) trajectory of light from the source *S* is modified by a simple point lens *L*, rays from different paths (blue) reach the observer at *O*, who interprets the result as images *I* on the sky.

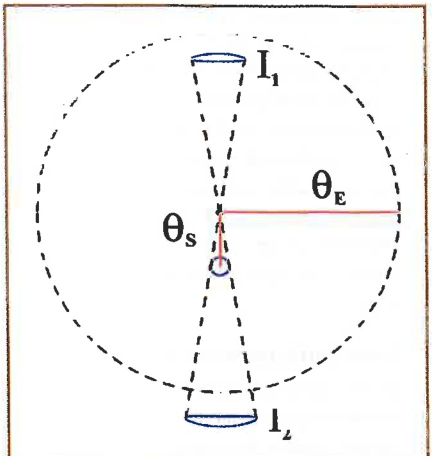

Fig. 1b: On the sky plane, these images are distorted into arclets, with angular separations similar to or greater than $2\theta_E$.

the limb of the Sun to be compared to their relative positions six months later when the (lensing) Sun was no longer in the line of sight. Some researchers anticipated the impact of this phenomenon on astronomy early on, but the potential began to be realized only in the two decades after the first observation of extragalactic lensing — multiple images of distant quasars — by radio astronomers in 1979.

Quasars are compact, extremely energetic, and often variable sources of emission. If lensed by an intervening massive galaxy, multiple images of a quasar can be formed, separated by about an arc second (see Eq. 2). Light associated with each image takes a different path through the lensing potential, resulting in geometric and potential time delays that, for variable quasars, can be measured by correlating the temporal light curves of the images. The total time delay is inversely proportional to Hubble's constant, H_0, the current expansion rate of the Universe. In this way, several lensed quasars with measured lens and source red shifts, and reasonably constrained lens mass models, have been used to infer H_0, resulting in consistent, though often somewhat lower values than those relying on so-called "standard astronomical candles."

The expansion rate changes over cosmic time in a manner that depends on the matter density of the Universe and the value of the cosmological constant, Λ. Since the lensing probability at a given time depends on the volume per unit red shift, it is dependent on Λ. In the early 1990s, several workers used the observed lensing rate as a function of red shift to derive the limit $\Lambda \leq 0.7$, consistent with the value of $\Lambda \approx 0.7$ now inferred from distant supernovae and microwave background studies.

Harnessing the Power of Nature's Telescopes

Focusing celestial radiation into sharp images and detailed spectra has been the work of skilled lens and instrument makers for several centuries. Only recently have astronomers been fortunate enough to catch brief glimpses of the Universe through lenses fashioned by Nature herself. Background galaxies lensed by foreground galaxy clusters, for example, include some of the most distant galaxies known, and are observed easily only with the aid of the cluster-induced magnification (see next section).

brief glimpses of the Universe through lenses fashioned by Nature herself

Closer to home, the sharp differential magnification generated by binary-star caustics is being used to resolve the surfaces of the background stars. To date, the limb-darkening profiles of four stars – three giants near the centre of the Milky Way and one dwarf star at ~60 pc in the Small Magellanic Cloud (SMC) – have

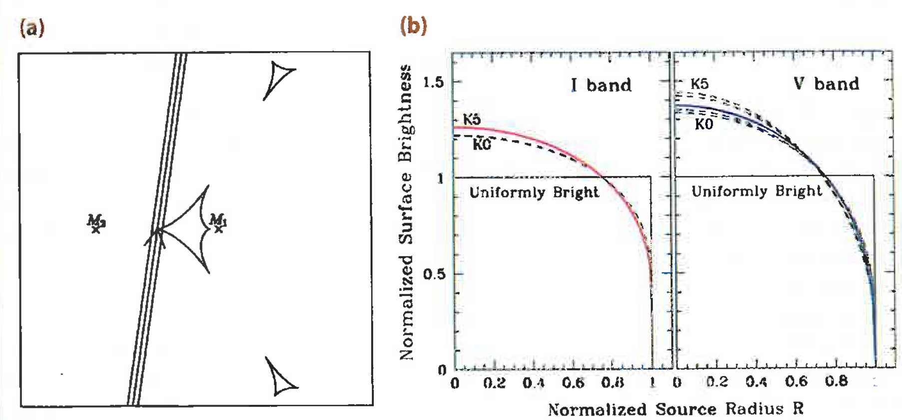

Fig. 2(a): The trajectory of a star (paths of centre and limbs are indicated by the parallel lines) crosses a caustic generated by a foreground binary stellar lens of masses M_1 and M_2.
Fig. 2(b): Measurements every 5 minutes of the resulting rapid rise and decline in brightness of the K-giant source enabled deconvolution of the magnification pattern from the star's surface brightness profile. The results at both wavelengths (red and blue) compared well to theory (dashed). (Adapted from Albrow *et al.* 1999, Astrophys. J. **522**, 1011.)

been measured. Such measurements are precluded by other techniques due to the miniscule angular sizes (radii of 10^{-7} arc seconds at the SMC), and are important since they provide direct tests of theories of stellar atmospheres (Fig. 2). Last year, the high magnification and spatial resolution provided by moving caustics combined with very large telescopes and efficient spectrographs yielded detailed spatially-resolved, spectral information for a giant star in the Galactic Bulge. Qualitatively, the strength of the absorption lines across the face of the giant appears to agree with stellar models; detailed analysis is underway.

Dark and Luminous Lenses of All Sizes

Much of the excitement and potential of this field lies in the lenses themselves. Barring modification of the law of gravitation on cosmic scales, the mass density of the Universe is dominated by unseen, apparently non-luminous, (dark) matter. Lensing, which is sensitive to mass rather than radiation, is thus an unique and welcome probe.

Galaxy Clusters

Based on hydrodynamic studies of their hot X-ray gas and virial motion estimates of their constituent galaxies, rich galaxy clusters were inferred to have masses ~10^{15} times the mass of the Sun ($M_\odot$). Observations of lensing by clusters has now confirmed these estimates directly (to within a factor of two in individual cases), and also allowed detailed mapping of the mass distribution.

Near the cluster centre, where mass densities exceed the critical value required for strong lensing, multiple images of background galaxies are formed (Fig. 3). The position, size, and shape of these giant arcs, especially when they can be associated with their counterpart images, provide information on the asphericity and radial profile of the total cluster mass. In particular, lensing has revealed mass densities that are much more centrally concentrated than previously thought.

Single, small, slightly distorted images are produced by weaker lensing effects in the cluster outskirts. Although individually less dramatic, the statistical orientation of hundreds of these arclets allows mapping of the cluster mass out to several hundred kilo parsecs. Significant substructure is often detected, indicating that, even at the current epoch, many clusters are not dynamically relaxed. Earlier this year, the discovery for the first time of a cluster *via weak lensing* (later confirmed with optical measurements) demonstrated the usefulness of lensing for measuring density contrasts even in seemingly empty or smooth patches of sky.

Individual Galaxies

Isolated galaxies also serve as lenses for background sources, but since they are a factor of 100 or more less massive than clusters, the image separations they generate are ~ 10 times smaller. Multiple images (like those of quasars discussed above) are only formed if the trajectory passes through the very densest centres of galaxies. The detection of weak lensing by individual galaxies (by co-adding the relative orientations of large statistical samples of foreground-background galaxy pairs) has demonstrated that the typical diffuse halo of dark matter around isolated galaxies contains about 10^{12} $M_\odot$, confirming and extending to larger galactocentric radii results derived from the kinematics of gas and stars in the galaxies themselves. The luminous matter associated with galaxies contributes only 3%-30% of this total.

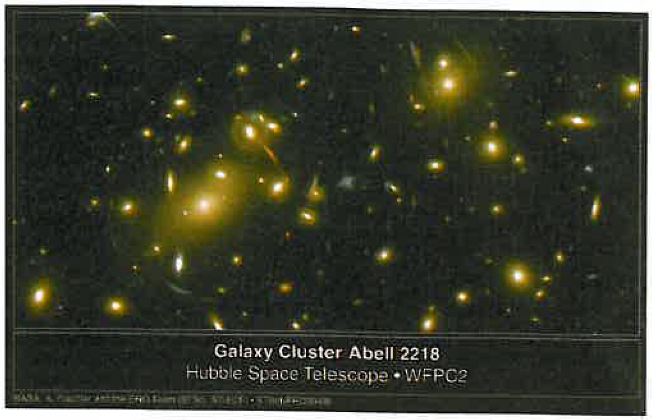

Fig. 3: The cluster Abell 2218 dramatically illustrates the giant arc images of distant background galaxies lensed by the total mass associated with a foreground cluster and its constituent galaxies. (Hubble Space Telescope Archives)

Red, White and Brown Dwarf Stars

So what is the dark matter? Lensing has not provided a definite answer to this question, but has narrowed the list of candidates, at least in our own galaxy, the Milky Way. If compact objects with stellar or planetary masses comprised the dark matter, their motion in the Galactic potential would occasionally bring them across the line of sight to more distant stars, in particular those of the Large Magellanic Cloud (LMC), a small neighbouring galaxy. At any given time, one LMC star in every million would be "microlensed" by such small, moving dark lenses. Separated by about a milli-arc-second, individual images could not be resolved during the lensing event, but a smooth increase and decline would be observed in the total brightness of the background star. The peak amplitude of the variability is set by the impact parameter $u \equiv \theta_S / \theta_E$. The duration depends on θ_E and the relative proper motion of lens and source, and for the Milky Way is typically weeks to months.

A decade ago, massive campaigns began searching for these rare microlensing events in the direction of the Galactic centre and LMC. The first events were announced in 1993. Hundreds followed, the majority toward the Milky Way centre. The measured microlensing probability through our stellar disk toward its centre is about that expected from known stellar populations. Outwards through our dark halo toward the LMC, however, the measured value appears to fall short by a factor five from that expected for a halo filled with unseen low-mass red dwarfs, white dwarf stellar remnants, or sub-stellar brown dwarfs. New microlensing surveys are now underway to perform similar experiments through the halo of the large spiral galaxy Andromeda, while very distant (macro)lensed radio sources are being examined for the "twinkling" that would betray small dark microlenses in the halos of the lenses.

Extra-solar Planets

Extra-solar planets bound to distant stars in the Milky Way would generate small, but extended caustics in the lensing magnification pattern. If probed by a background star, these caustics would cause short-lived (hours to days), but often dramatic, anomalies atop otherwise smooth microlensing light curves. Such planetary signatures are expected to be reasonably frequent for Jupiter-mass planets (10^{-3} $M_\odot$) in orbits similar to those of Mars or Jupiter. Nevertheless, five years of intense monitoring of Galactic microlensing events has yielded no convincing planetary signals. Analysis of this null result published this year implies that no more than one-third of stellar lenses have Jovian-mass planets orbiting in the zone between 1.5 and 4.0 AU[1] from their parent stars. This limit is consistent with the ~60 planets orbiting solar-type stars discovered by the Doppler technique, most of which orbit within 1.5 AU where that method is most sensitive.

What's Next?

What can be expected from lensing studies in the coming decade? Caustics generated by micro-lens networks in distant galaxies may be used to resolve and measure the surface brightness profiles of active galactic nuclei – believed to be associated with massive black holes. Weak lensing measurements over vast portions of the sky may map the large-scale structure of matter (luminous and dark) in the Universe. Advances in observational technique and resource may allow the search for microlensing planetary systems to be pushed into the regime of Earth-mass planets. For a more thorough discussion of these possibilities, and details and references for the scientific work discussed here that were not possible to include in this summary, the reader is referred to the review articles in the bibliography.

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Helio- and asteroseismology

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Modelling of stellar structure and evolution is one of the 'classical' branches of astrophysics, upon which many other areas are based. Important examples are determinations of stellar ages, and studies of element synthesis and galactic enrichment. Yet the physical properties of stellar interiors are highly uncertain. The most important example is probably potential instabilities and the resulting motion that might mix the composition gradients established through the nuclear reactions and hence substantially affect stellar evolution; such effects are usually ignored in modelling of stars. However, even the so-called microphysics, characterizing the thermodynamic properties of stellar matter and its interaction with radiation, as well as the nuclear reactions in stellar interiors, are subject to substantial uncertainties. Thus, although models of stellar evolution generally appear rather successful in reproducing the observed properties of stars, one must worry that the apparent success is in fact coincidental and hides fundamental problems. Indeed, traditional observations of stars are relatively insensitive to the properties of their interiors and hence might not re ect such problems. However, during the last decade observations of stellar oscillations have changed this situation drastically.

Stellar oscillations

Stars have been known to vary in luminosity in a more or less cyclical fashion for several centuries. In most cases, the causes of the variations have been identified as intrinsic pulsations. The periods of such oscillations can be determined with very high accuracy, particularly when compared with the other, rather poorly known, observable quantities that might be used to determine the properties of a star. A measure of the pulsation periods of a star is provided by the characteristic dynamical timescale, $t_{dyn} \approx 30 \min(R/R_\odot)^{3/2}(M/M_\odot)^{-1/2}$ where M and R are the mass and radius of the star and $M_\odot$ and $R_\odot$ are mass and radius of the Sun. Thus the range of observed periods in stars, from minutes to years, immediately corresponds to the extreme range in stellar properties, from very compact objects to extremely extended red giants.

However, the diagnostic potential of stellar oscillation periods is vastly increased when many periods are observed in a given star. Each period provides a unique measure of the stellar interior, and by combining them detailed information about the star can be obtained. This has led to new fields of stellar astrophysics, appropriately known as helio- and asteroseismology.

Seismic investigations of the solar interior

Solar oscillations have been observed with a variety of techniques, although the most detailed data are obtained with Doppler-shift measurements of the surface radial velocity. Very extensive observations have been obtained from the GONG[1] network, funded by the National Science Foundation of the US, as well as the joint ESA-NASA SOHO spacecraft. The Sun shows oscillations with periods between around 3 and 15 mins and

features

mode amplitudes below 15 cms^{-1}. The smallest amplitudes detected so far are of order 0:1 cms^{-1}, and it is likely that longer-period oscillations, of even smaller amplitude, will be detected as the sensitivity is improved. Unlike other stars, the solar surface can be resolved with high resolution; this has allowed observation of oscillations over a broad range of spatial scales, from spherically symmetric modes to waves with a wavelength of a few thousand kilometres. In terms of the degree l of the spherical harmonics characterizing the spatial structure of the modes, the observed modes range from the degree $l = 0$ to degrees of more than 2000.

The modes observed in the Sun are predominantly acoustic modes, excited by convection near the solar surface. They are essentially trapped between the surface and a lower turning point, at a distance r_t from the centre. Low-degree modes penetrate to the solar centre, whereas modes of increasing degree are trapped increasingly close to the surface. Observation of modes over the whole range of l, and hence r_t, therefore effectively scans the solar interior in the radial direction, allowing radial resolution of solar internal properties through the use of suitable inversion techniques. Similarly, the variation of latitudinal extent of the spherical harmonics provides resolution in latitude. As a result it has been possible to determine, for example, the dependence of solar internal rotation on both distance r to the centre and latitude.

Owing to their acoustic nature, the solar oscillation frequencies are predominantly determined by the dependence of adiabatic sound speed c on r; inversion has led to precise inferences of $c(r)$ which may be compared with predictions of solar models. An example is illustrated in Fig. 1. The model is a so-called 'standard solar model'. It is based on up-to-date microphysics, including also effects of element settling and diffusion, and was obtained by following the evolution of the composition profile in the Sun from an assumed initially homogeneous state to the present age. It should be emphasized that, although parameters of the calculation have been adjusted to match the present radius, luminosity and surface composition of the Sun, no direct attempt has been made to fit the oscillation data. In this respect the model can be regarded as a prediction of solar structure, based on current knowledge of the physics of the solar interior. The relatively small discrepancy shown in Fig. 1 is thus a striking example of the power of physics to predict the properties of even a complex object such as a star; it must be admitted, though, that amongst stars the Sun is a rather simple example. It is also evident that the remaining differences far exceed the estimated errors; the physical causes for these differences are as yet uncertain, although it is likely that mixing processes, ignored in the model computation, are at least partly responsible.

a striking example of the power of physics to predict the properties of even a complex object such as a star

The model used in Fig. 1 shares with other solar models predicted neutrino capture rates far exceeding those observed. The helioseismic measurements do not directly constrain the solar internal temperature T, upon which the neutrino fluxes mainly depend. However, since c^2 is approximately proportional to T/μ, where μ is the mean molecular weight, the agreement in Fig. 1 leaves little room for changes to the model reducing significantly the neutrino fluxes. Thus it is very interesting that the recently announced measurements of solar neutrinos at the Sudbury Neutrino Observatory through charge-current reactions indicate that the total flux of high-energy neutrinos from the Sun is consistent with solar models.

In addition to solar structure, the observed frequencies have provided detailed inferences of solar internal rotation, generally in conflict with earlier models of solar rotation. The outer 28% of the solar radius, where energy is transported by convective motions, shows a marked variation of rotation with latitude, the equator rotating substantially faster than the poles. At the base of the convection zone there is a transition over a narrow radial extent, only a few per cent of the solar radius, to essentially uniform rotation of the solar interior; in particular, there is no indication of a rapidly rotating core, left over from a normally presumed earlier phase of more rapid rotation. The origin of this complex pattern of rotation is highly uncertain; it is likely that

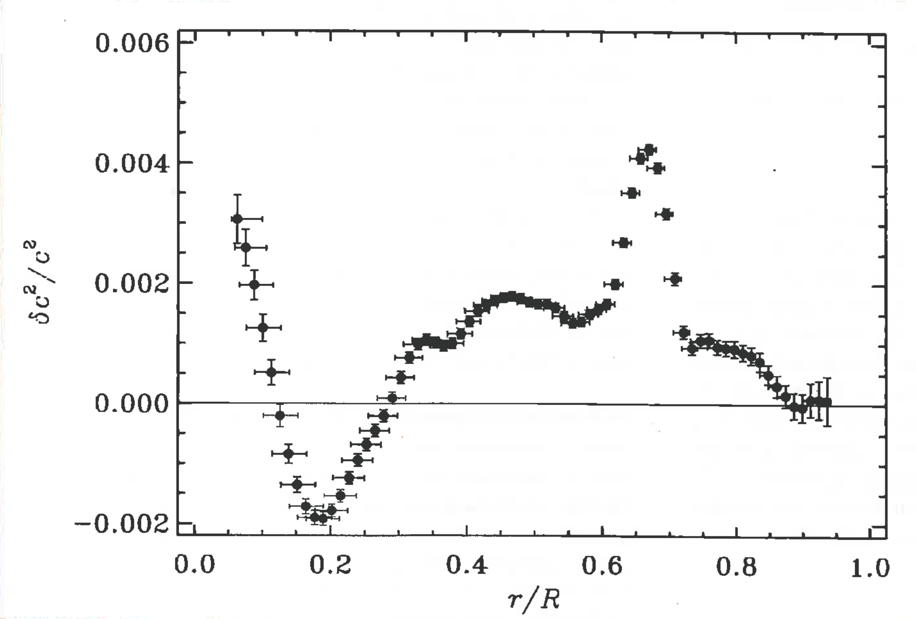

Fig. 1: Difference in squared sound speed c^2 between the Sun and a standard solar model, in the sense (Sun) – (model), inferred from helioseismic inversion of observed solar oscillation frequencies. The abscissa is distance to the solar centre, in units of the surface radius. The vertical error bars are 1-σ errors on the inferred differences, while the horizontal bars provide a measure of the resolution of the inversion. (From Basu *et al.*, 1997; Mon. Not. R. astr. Soc. 291, 243).

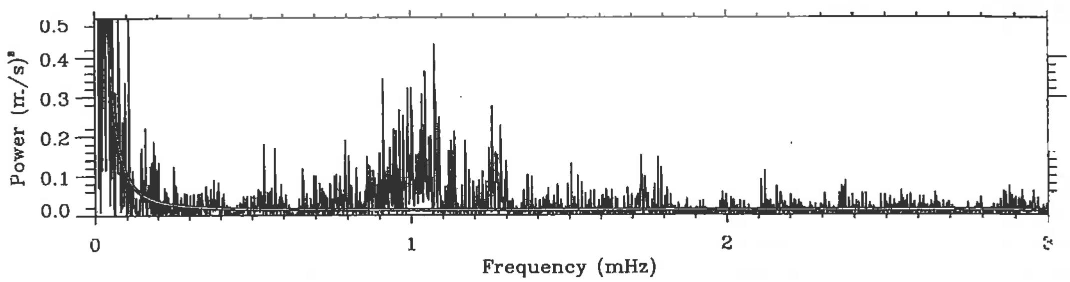

Fig. 2: Power spectrum of oscillations of the star β Hydri, obtained from observations of Doppler velocity at the Anglo-Australian telescope, plotted against cyclic frequency. The power enhancement with a maximum near a frequency of around 1 mHz, corresponding to a period of 17 min, is very similar to that observed for the Sun. (From Bedding *et al.*, 2001; Astrophys. J. 549, L105).

angular-momentum transport by convection causes the variation seen in the convection zone, whereas the rigid rotation of the interior may have been enforced by a weak magnetic field. Observations over the past 5 – 6 years with GONG and SOHO have also shown complex variations with time in the rotation rate within and just beneath the convection zone, likely related to the variations in solar activity reflecting the solar cycle.

Asteroseismology

Given the striking success of helioseismology, it is not surprising that a great deal of effort has gone into extending seismic investigations to other stars. This will allow study of phenomena not observed in the Sun, such as mixing by convective cores, as well as the study of physics under circumstances far more extreme than those attained in the solar case. In fact, a broad range of stars, from red giants to white dwarfs, show oscillations, often with substantial numbers of modes promising detailed information. Major successes have been obtained in the study of white dwarfs, the very compact final stage of evolution for stars of masses below about 10 $M_\odot$. Here the observations have led to precise determinations of the masses and composition profiles of the stars, and hence to important constraints on the late stages of stellar evolution. Measurements of the period changes of the hottest white dwarfs are also providing information about neutrino cooling of these stars, and hence about physical processes under very extreme conditions of temperature and density. Very interesting results have also been obtained in the last few years for hot so-called horizontal-branch stars, in the phase of core helium burning, and extensive data, so far not fully interpreted, are available for several classes of stars on the main sequence.

a great deal of effort has gone into extending seismic investigations to other stars

However, much interest centres on the study of oscillations similar to those observed in the Sun. The excitation mechanism, through turbulent convection, is sufficiently well understood that the presence of such oscillations can be predicted in all relatively cool stars. Also, although only modes of the lowest degrees will be detectable in observations of distant stars, these are precisely the modes that provide information about the cores of the stars reflecting, for example, the age of the star through the change in composition caused by nuclear reactions. The difficulty is the very small amplitudes expected, of order 1 ms^{-1} or less in radial velocity or a few parts per million in intensity. In ground-based observations such small signals are easily masked by effects of the Earth's atmosphere. Even so, over the past decade indications of solar-like oscillations have been found in several stars. Very recently, the first incontrovertible detection was made with Doppler-velocity observations for the star β Hydri, a 1$M_\odot$ star in a somewhat later stage of evolution than the Sun. The observed power spectrum, illustrated in Fig. 2, shows a strong power enhancement corresponding closely to what is observed in the Sun; however, in agreement with theoretical predictions, the observed power is somewhat higher than for the Sun. An even clearer signal has since been obtained for the star α Centauri A, which is quite similar to the Sun. Thus, asteroseismology of solar-like stars is finally set to take off.

Although such ground-based studies are very encouraging, they are limited to the brightest stars. Also, adequate frequency resolution would require extended observations with fairly large dedicated telescopes, suitably distributed around the Earth to avoid daily gaps in the data. Thus, major advances in the field will result from the launch of several small satellites dedicated to asteroseismology over the coming few years: the Canadian MOST mission, the French COROT mission and the Danish Rømer mission, all three to observe the tiny intensity oscillations outside the disturbances of the Earth's atmosphere. In the slightly longer term a very promising prospect is the Eddington project which has been included in the ESA programme as a reserve mission. In addition to searching for Earth-size planets by observing transits, Eddington will provide very accurate asteroseismic data on a broad variety of stars. This will yield a firm observational basis for the study of stellar interiors and the application of the results to other areas of astrophysics.

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Space weather

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For thousands of years, people in the north have marvelled at the space weather seen in the Northern Lights. But auroras never hurt a sailor or a farmer. Only with our modern electrical, electronic and space technologies have the Sun's effects become damaging, and even personally hazardous for astronauts. The more we do in space, the more serious and potentially costly the problems will become. The response of the space environment around the Earth to the constantly changing Sun is known as 'space weather'. Most of the time, space weather is of little concern in our everyday lives. However, when the space environment is disturbed by the variable outputs of the Sun, technologies that we depend on can be affected. This has been demonstrated by the large number of problems associated with the severe magnetic storms between 1989 and 1991, and more recently in 2000-2001 during the maximum of solar cycle 23.

Space weather disturbances are generally caused by transient events in the solar atmosphere. There are two different types of events, which trigger disturbances in the Earth's environment. One type is called a solar flare because the brightening of a small area on the Sun heralds its occurrence. However, not all solar flares result in geomagnetic storms, and, even more significantly, not all geomagnetic storms can be associated with solar flares. Some of the most dramatic space weather effects occur in association with eruptions of material from the solar atmosphere into interplanetary space. These eruptions are known as coronal mass ejections, or CMEs. Such eruptions are sometimes associated with flares and sometimes not, and they now appear to be a primary cause of geomagnetic activity.

The emission from the two types of disturbances can be divided into two classes: electromagnetic radiation and particles, which will have different effects on the Earth's environment, as discussed below.

Particle radiation

A continuous flow of charged particles (protons and electrons) is streaming out from the Sun and is called the solar wind. Several types of solar events can cause particles with high velocities to be superimposed on this background solar wind. CMEs are believed to be caused by sudden disruptions in the Sun's magnetic field. These magnetic fields stretch and twist like titanic rubber bands until they snap. A large CME can contain 1000 million tons of matter that can reach speeds at the Earth of up to 2000 kilometres per second, considerably greater than the normal solar wind speeds of about 400 kilometres per second. The cloud of charged particles (which also bring with them parts of the solar magnetic field) will interact with the Earth's magnetic field when the magnetic clouds reach the Earth's orbit. This results in a disturbance of the Earth's magnetic field, and the auroral particle precipitation into the atmosphere increases. The aurora is a dynamic and delicate visual manifestation of solar-induced geomagnetic storms.

One of the most dramatic effects on ground systems during geomagnetic storms is the disruption of power systems. During a geomagnetic storm the ionospheric currents, or electrojets, reach tens of thousands of amperes and produce fluctuations in the Earth's magnetic field. Such disturbances can induce near DC currents (Geomagnetically Induced Currents, GIC) in long power lines. For instance, during the March 13, 1989, storm, GIC's caused a complete shutdown of the Hydro-Quebec power grid resulting in a nine-hour power outage. The power pools that served the entire northeastern United States came uncomfortably close to a cascading system collapse.

The enhanced particle density within the Earth's magnetic fields during a geomagnetic storm can also cause damage to satellites. Less energetic particles contribute to a variety of spacecraft surface charging problems, especially during periods of high geomagnetic activity.

Under some conditions, solar eruptions can also accelerate charged particles to very high energies (protons and heavier particles, such as helium). These highly energetic particles can penetrate into electronic components, causing bit-flips in a chain of electronic signals that may result in spurious commands (phantom commands), appearing to spacecraft systems as being sent from the ground control. In addition one can experience erroneous data from the onboard instruments. These spurious commands have caused major failures to satellite systems, even causing the craft to point away from the earth direction. Energetic solar protons are also a radiation health hazard for astronauts on manned space flights, in particular for long space missions outside the Earth's protective magnetosphere.

Electromagnetic Radiation

The energetic radiation bursts from flares travel at the speed of light, and so arrive at Earth just eight minutes after leaving the flare site, well ahead of any particles or coronal material also associated with the flare. Moreover, unlike the electrons and ions of the solar wind plasma and the solar energetic particle populations, the passage of electromagnetic waves is not affected by the presence of Earth's magnetic field. The direct response of the upper atmosphere to a burst of solar flare ultraviolet and x-ray emissions is a temporary increase in ionisation (as well as temperature) in the sunlit hemisphere, lasting from minutes to hours and called a sudden ionospheric disturbance (SID). This can cause disruption of short-wave radio communication at HF frequencies (3-30 megahertz), which is still extensively used by the military and for overseas broadcasting.

In general, geomagnetic storms and increased solar ultraviolet emission heat the Earth's upper atmosphere, causing it to expand. The atmospheric density at the orbit of satellites up to about 1000 km from the Earth can increase significantly. This results in increased drag on satellites, and may shift their orbit enough to make them temporarily "lost" to communications links. At times,

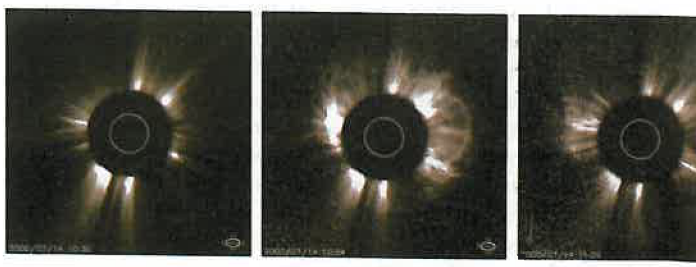

Fig. 1: A full halo coronal mass ejection (CME) was recorded on July 14, 200[…] by SOHO's LASCO/C2 coronagraph. The many speckles in the last two imag[…] are energetic particles bombarding SOHO's electronic detectors. The resulti[…] geomagnetic activity between July 14 and July 19 produced the largest geomagnetic storm observed since 1989, and one of the most intense sola[…] proton events ever recorded. Several satellites experienced problems, and some permanent damages were reported.

these effects may be sufficiently severe as to cause premature re-entry of orbiting objects, such as Skylab in 1979 and Solar Maximum Mission in 1989.

Space Weather Forecast

Today our society is much more sensitive to space weather activity than was the case during the last solar maximum in 1991. An example is the possible disruption of satellites. Our society depends on satellites for weather information, communications, navigation, exploration, search and rescue, research, and defence systems. Thus, the impact of satellite system failures is more far-reaching than ever before, and the trend will almost certainly continue at an increasing rate. Furthermore, safe operation of the International Space Station depends on timely warnings of eruptions on the Sun.

Navigation systems such as LORAN and OMEGA are adversely affected when solar activity disrupts their radio wavelengths. It also introduces position errors and decreases the accuracy and reliability of the Global Positioning System (GPS). Space weather-induced currents can also create galvanic effects in oil and gas pipelines, leading to rapid corrosion at the pipeline joints if they are not properly grounded. Such corrosion requires expensive repairs or can lead to permanent damage. Furthermore signals used during geomagnetic surveys (e.g. search for natural resources such as oil and gas) are significantly affected by the varying magnetic fields during geomagnetic storms.

It is therefore important to forecast and warn for major solar storms. The presence of two satellites located in the L1 Lagrangian point, SOHO and ACE, has definitely improved the accuracy of space weather forecasts. Two instruments on board SOHO have proved to be especially valuable for continuous real-time monitoring of solar storms that affect space weather. One is the Large Angle Spectrometric Coronagraph (LASCO) that takes images of the solar corona by blocking the light coming directly from the Sun itself with an occulter disk, creating an artificial eclipse within the instrument. It is the perfect tool for detecting CMEs heading towards (or away from!) the Earth. The other is the Extreme ultraviolet Imaging Telescope (EIT), providing images of the solar atmosphere at four wavelengths. It reveals flares and other stormy events in the atmosphere, and can usually determine whether CMEs seen by LASCO originated on the near or far side of the Sun, based on the presence or absence of corresponding events on the near side.

Before SOHO was operational, only 27% of major magnetic storms (Kp index of 6 or greater) were correctly forecast, and most forecasts were false alarms. The improvement offered by SOHO is apparent in a study of 25 front-side halo CMEs seen by LASCO and EIT during 1996 and 1997. Over 85% caused major magnetic storms and only 15% of such storms were not predicted.

The Sun has produced a series of large eruptions and flares during 2000-2001 and SOHO's role in the early-warning system for space weather has been demonstrated. On 14 July 2000, SOHO detected the bright flash of a solar flare near the centre of the Sun's disk and just half an hour later SOHO's LASCO instrument detected a mass of gas racing out from the Sun. Next, a burst of energetic particles from the solar explosion hit SOHO. In the imaging instruments it looked like a snowstorm that continued for some hours.

Extra-solar planets

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The generally accepted picture of stellar formation teaches us that a planetary system is a natural by-product of the stellar formation process. When a cloud of gas and dust contracts to give origin to a star, conservation of angular momentum leads to the formation of a flat disk of gas and dust around the central newborn "sun". As time passes, in a process still not completely understood, dust particles and ice grains in the disk are gathered to form the first planetary seeds. In the "outer" regions of the disk, where ices can condensate, these "planetesimals" are thought to grow in a few million years. When such a "planetesimal" achieves enough mass (about 10 times the mass of the Earth), its gravitational pull enables it to accrete gas in a runaway process that gives origin to a giant gaseous planet similar to the outer planets in our own Solar System. Later on, in the inner part of the disk, where temperatures are too high and volatiles cannot condensate, silicate particles are gathered to form the telluric planets like our Earth.

the idea of finding other worlds was until the mid 90's no more than an old and fantastic dream

Recent images taken by the NASA/ESA Hubble Space Telescope (HST) have revealed a multitude of such proto-planetary disks in the Orion stellar nursery, showing that disks are indeed very common around solar-type stars. This supports the idea that extra-solar planets should be common. However, such systems have escaped detection until very recently, and the idea of finding other worlds was until the mid 90's no more than an old and fantastic dream.

Detecting extra-solar planets

The reason why this was so has to do with the difficulty to detect such systems. Planets are cold bodies, and their visible spectrum results basically from reflected light of the parent star. As a result, the planet/stellar luminosity ratio is of the order of 10^{-9}. Seen from a distance of a few parsec, a planet is no more than a small "undetectable" dot embedded in the diffraction and/or aberration of the stellar image.

But a planet also induces dynamical perturbations into its "parent sun", giving the possibility of detecting the presence of a planet by indirect means [1]. Astronomers have long tried to use this fact to measure the small astrometric periodic motion (of the order of 1 milli-arcsecond for the best cases) of a star as it moves around the centre of mass of the star-planet system. The results were quite disappointing, with some false and discouraging detections.

Another technique used to search for stellar motions induced by an orbiting planet is based on the measurement of the star's radial-velocity (in the direction of the line of sight). The biggest challenge of this technique is that one needs to measure the stellar velocity with a very high precision. For example, Jupiter induces a periodic perturbation with an amplitude of only 13 m s-1 on the Sun! For comparison, current techniques have already permitted to achieve precisions of about 3 m s^{-1} ($\Delta\lambda / \lambda = 10^{-8}$).

The first discovery of what could be called a "planetary system" was, however, unexpected and of a completely different nature. By measuring the time delays of the radio pulses of the pulsar PSR 1257+12 (a rapidly rotating and highly-magnetized neutron star) astronomers [2] have detected the presence of three planetary-mass companions, with masses comparable to that of the Earth, orbiting the central object in quasi-circular orbits. These planets, however, have certainly not been formed at the time of the star formation, since the circular orbits could not have survived the strong stellar mass loss at the time of the supernova explosion. These "second generation" planets probably originate from an accretion disk created after the formation of the neutron star.

In any case, it was not until 1995 that the first planet around a "normal" star like the Sun was detected. Using the radial-velocity method, astronomers have induced the presence of an object with only 0.5 times the mass of Jupiter orbiting the solar-type star 51 Pegasi [3]. The curse was broken. Finally an exo-planet! There was, however, a completely unexpected detail: the planet

Fig. 1: Images taken with the ESA/NASA Hubble Space Telescope (HST) of an edge-on proto-planetary disk in the Orion stellar nursery. Both images are of the same object observed at different wavelengths. The disk is seen as a dark "silhouette" against the bright background of the nebula, since the light is absorbed by dust grains. The bright point at the centre is due to light from the central star reflected in the dust. These disks around newborn suns are probably the places of planetary formation, as dust grains coagulate to form the first planetary seeds. The planets in our Solar System, including our Earth, are believed to have formed, about 4.5 billion years ago, out of a structure very similar to the one seen in the images. (Credit: Mark McCaughrean (Max-Planck-Institute for Astronomy), C. Robert O'Dell (Rice University), and NASA.)

around 51 Pegasi orbits its host star every 4.2 days, corresponding to an orbital radius of only 0.05 AU (1 Astronomical Unit, or AU, is the average Earth-Sun distance). This is much less than the distance from Mercury to the Sun. Such a system has nothing to do with our own Solar System and most importantly, following the "traditional" paradigm of planetary formation, a giant gaseous planet is definitely not supposed to be formed in such conditions.

Today, almost 70 exo-planets have been detected using high-precision radial-velocity techniques

Today, almost 70 exo-planets have been detected using high-precision radial-velocity techniques. These detections include 7 multi-planetary systems, the first of which was found orbiting the star υ Andromedae [4]. A significant percentage of the newly found planets belongs to the "hot-Jupiter" class, i.e. jupiter-like giant planets orbiting close to their parent stars (like 51 Pegasi).

Impact on theories of planetary formation and evolution

The major consequence of these detections was the strong need to revise theories dealing with planetary formation and evolution. But soon it was realized that an answer to the origin of the "hot-Jupiter's" could already exist. Work in the early 80's [5] has predicted that a giant planet, formed in the outer regions of the proto-planetary disk, could indeed migrate inwards as the result of gravitational interactions with the latter. This orbital migration could explain the presence of giant gaseous planets so close to their host stars. But that explanation also poses some problems. It is still not completely understood, for example, how the migration can be halted before the planet falls into the star.

Recent observations suggest that planets might in fact be engulfed by their parent stars [6], whether as the result of orbital migration or, e.g., of gravitational interactions with other planets or stellar companions. Astronomers have recently found strong evidence for such an event, by detecting the presence of the lithium isotope ^{6}Li in the planet-host star HD 82843. This fragile isotope is easily destroyed (at only 1.6 million degrees, through (p,α) reactions) during the early evolutionary stages of star formation, when the proto-star is completely convective, and the relatively cool material at the surface is still deeply mixed with the hot stellar interior (this is not the case when the star reaches its "adulthood"). ^{6}Li is thus not supposed to exist in stars like HD 82843, and the simplest and most convincing way to explain its presence is to consider that a planet, or at least planetary material (but perhaps also more than one planet), has fallen into HD 82843 sometime during its lifetime.

One other particularly troubling point related to the newly found systems has to do with their orbital eccentricities [7]. While the major planets in our Solar System all are in nearly circular orbits, most of the currently found planets follow rather elongated trajectories (Figure 2). This may be e.g. the result of the interaction between planets in a multi-planetary system, or with a distant stellar companion. Evidence exists that planets in multi-planetary systems can indeed suffer some orbital evolution; a nice example comes from the discovery of orbital resonances.

Trying to understand how the observed systems, including our own, were formed and evolved can in fact be a particularly arduous task. But current data are already giving us clues about the processes involved. Very important information is brought to us by the mass distribution of the planetary companions (see Figure 3). This distribution is observed to decrease smoothly with increasing mass (note that the higher the mass, the easier it is to find a planet using the radial-velocity technique), reaching "zero" at about 10 Jupiter masses [7]. But from that mass on, and up to masses of around 50 times the mass of Jupiter, there is the so called Brown-Dwarf desert, a mass region for which only a very few companions to solar-type stars were found (Brown Dwarfs are very low mass stars that do not have high enough central temperatures to sustain hydrogen fusion; theoretically they have masses in the range from ~13 to ~75 times the mass of Jupiter). This feature strongly supports the idea that the discovered planets and low mass stellar companions have indeed a different physical origin: stars, even the low mass ones, are thought to be formed as the result of the gravitational collapse and fragmentation of a cloud of gas and dust, while a planet forms in a circumstellar accretion disk.

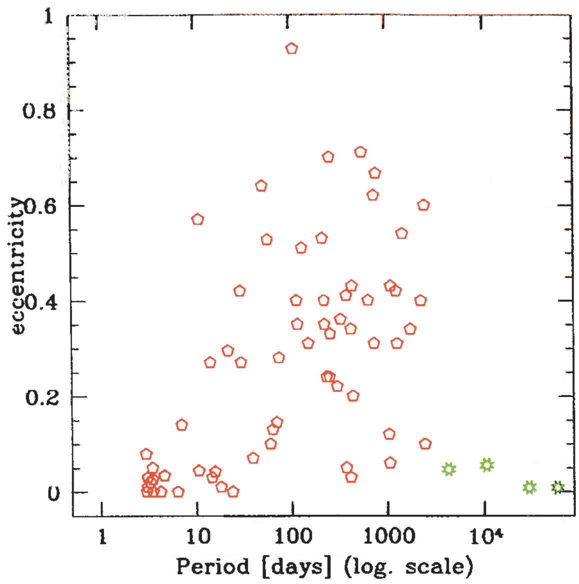

Fig. 2: Eccentricity vs. orbital period (in logarithmic scale) for the discovered extra-solar planets (red pentagons) and for the giant planets in our Solar System (green stars). Although some long-period exoplanets having low eccentricity exist, most of the systems have much higher eccentricities that those of the giant planets in the Solar System. This trend was unexpected before the discovery of the first exoplanets. The explanation may lie in mechanisms capable of pumping the eccentricity, like gravitational interactions between planets in a multi-planetary system, or with a distant stellar companion.

The planet host stars

Another particular fact that is helping astronomers understand the mechanisms of planetary formation has to do with the planet host stars themselves. In fact, they were found to be particularly metal-rich, i.e. they have, in the average, a metal content higher than the one found in stars without detected planetary companions [8], [9]. (In astronomy, all elements heavier than hydrogen or helium are called metals.) The most recent results seem to favour that this metallicity "excess" is actually related to the planetary

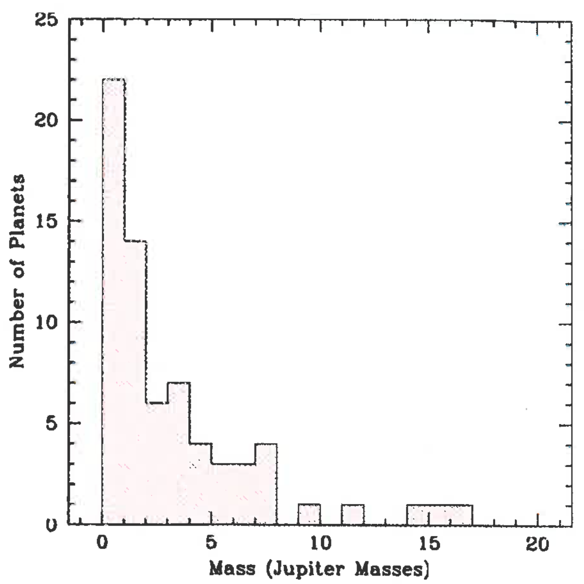

Fig. 3: Distribution of masses for the currently discovered low-mass companions to solar-type stars. Although the radial-velocity method, which permitted the discovery of these systems, has a higher sensitivity to higher mass companions, the observed distribution rises very steeply towards the low-mass domain. The distribution reaches "zero" at a mass of about 10 times the mass of Jupiter, which probably corresponds to the upper limit for the mass of a giant planet. From this mass up to the stellar regime, only a few objects were detected; this region is usually denominated the "Brown-Dwarf desert". The gap in the mass distribution of low-mass companions to solar-type stars shows that the physical mechanisms involved in the formation of the two populations (planets vs. stars) are probably very different.

formation process. The higher the metallicity of the cloud that gives origin to the star/planetary system (and thus the dust content of the disk), the faster a planetesimal can grow, and the higher the probability that a giant planet is formed.

But current observations are also starting to teach us something about the planets themselves. Recently, astronomers have detected the dip in the luminosity of the star HD 209458 as a previously detected planet crossed its disk [10]. This detection not only represents an independent confirmation of the nature of the discovered body, but also permits to precisely constrain some planetary physical properties, like its mass, radius, or mean density.

The study of extra-solar planetary systems is just in its first steps. After only 5 years, we can say that at least 5% of the solar-type stars have giant planetary companions. But the understanding of how giant planets are formed is still wanting in many respects. To help solve some of the problems, several projects are currently in the pipeline.

Huge developments are expected in the radial-velocity surveys by the development of instruments capable of measuring velocities down to a 1 m s^{-1} precision. For astrometric measurements, instruments like the VLTI interferometer (ESO) will permit to combine the light of the four VLT 8-m telescopes, enabling astronomers to obtain unprecedented high-resolution astrometric observations. But even greater hopes come from space missions like GAIA (ESA) or SIM (NASA), that will completely change the current landscape by adding tens of thousands of new planets. On the other side, photometric transit searches, mostly based upon space missions like the European COROT and Eddington or the North-American mission Kepler, achieving a photometric precision better than 0.01%, will permit the detection of transiting earths.

All these steps will give the opportunity to revise the current knowledge about the mechanisms leading to the formation of planetary systems and will thus somehow represent an important step towards the search for life in the Universe. Two similar projects are currently directed towards this goal (Darwin/ESA and TPF/NASA, cf. the article by Quirrenbach). Using nulling-interferometry techniques (to remove the light from the brighter star and leave the one coming from the planet), they will try to find traces of life in the spectrum of exo-earths. In a few decades human beings have to prepare themselves for the prospect that the whole Universe may be teeming with life.

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Astronomical interferometry, from the visible to sub-mm waves

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The history of astronomical interferometry dates back to the 19th century, when Fizeau, Stéphane and later Michelson set out to measure the angular diameters of stars. Whereas Stéphane could only obtain an upper limit of 0.158 arcseconds for the stars he observed in 1874, Michelson published interferometric diameters of Jupiter's Galilean moons in 1891. These early experiments used masks with two small openings placed on the aperture of astronomical telescopes to perform double-slit experiments à la Young. Around 1920 Michelson increased the resolution by placing a periscope on the front-end of the 100-inch telescope on Mt. Wilson; this arrangement enabled him and his collaborators to determine the orbit of the binary system Capella, and to measure the diameter of Betelgeuse. After these initial successes, technological difficulties slowed further progress for several decades. In the 1950's and 60's Hanbury Brown, Twiss, and collaborators invented intensity interferometry[1] and used it to measure the diameters of 32 stars – this is still the best data set on hot stars available today.

The era of modern stellar interferometry began in 1974 when Labeyrie successfully combined the light from two telescopes spaced by 12 m. This breakthrough was soon followed by the construction of similar instruments, which took advantage of modern electronic detectors and computer control to track and stabilize the interference fringes with real-time servo loops, which drive optical delay lines that compensate for the optical pathlength difference and thus maintain coherence between the two arms of the interferometer (see Figure 1). This active pathlength control with millisecond time resolution is a crucial aspect of ground-based astronomical interferometry, because the Earth's rotation and random atmospheric fluctuations have to be tracked continuously.

Interferometry and stellar astronomy

With an angular resolution approaching $\lambda / B \approx 500$ nm / 100 m $\approx$ 1 milliarcsecond, optical and near-IR interferometers have opened completely new avenues for stellar astronomy. A few hundred stellar diameters have been measured with ~1% precision; these data are of fundamental importance for the determination of stellar surface temperatures. The masses of about two dozen stars in binary systems have been derived from the application of Kepler's Laws to their orbits measured by a combination of interferometric and spectroscopic radial-velocity data. Interferometry has been used to infer the distance of a nova explosion, and of Galactic Cepheid stars. These are important measurements because they demonstrate the potential of interfer-ometric techniques to contribute to cosmology: Cepheid distances are the first rung on the cosmic distance ladder, which defines the size and – through the Hubble constant – the age of the universe. Closer to home, interferometric diameters of cool Mira variables hold important clues to the mechanism that makes them pulsate with very large amplitudes.

New experimental techniques usually bring surprises, and optical interferometry is no exception to that rule. When we used the Mark III Interferometer to observe cool giant stars, we found that their diameters vary with wavelength. This effect can in principle be understood by considering the effect of TiO molecules in the stellar photosphere, which blocks the view of lower layers at wavelengths corresponding to the molecular absorption bands. So one sees a higher layer – corresponding to a larger radius – inside TiO bands than in the continuum between the bands. However, we had not expected that the difference would be so large that we could easily measure it! More recently, a near-IR interferometer in Arizona was used to observe a class of stars technically known as Herbig Ae/Be stars. These are young stars with roughly 2 to 5 solar masses, which still show indications of the presence of circumstellar gas and dust – the material from which the star formed in the first place. According to the standard paradigm this circumstellar material should be organized in a disk, and such disks had previously been observed with millimeter interferometry around a number of these stars. But the near-IR interferometer observations indicate that the matter around Herbig Ae/Be stars is distributed in a spherically symmetric way, in apparent contradiction to the millimeter-wave results. A possible solution to this dilemma involves a more complicated structure, in which spherically distributed material is surrounded by a much larger disk. Only future observations will tell whether this is the correct answer.

Imaging interferometry

The results described so far have been obtained with simple "two-element" interferometers. The information that can be obtained with such instruments is quite limited, however; in essence they measure only one Fourier component of the brightness distribution $I(\xi,\eta)$ on the sky at a time:

$$(1) \quad \Gamma(u, v) = Ve^{i\varphi} = \iint I(\xi, \eta) e^{-2\pi i(u\xi + v\eta)} d\xi \, d\eta \,,$$

where (u,v) is the vector connecting the two telescopes, V and φ are the amplitude and phase of the measured fringes, and ξ and φ are the coordinates in the tangent plane of the sky. To make things worse, the phase of this Fourier component is normally corrupted by atmospheric turbulence and thus rendered useless. During the past few years, however, several multi-telescope arrays have been constructed, which can obtain many Fourier components at a time, $n(n-1)/2$ for an n-element array. Furthermore, such arrays can preserve some phase information; taken together these two improvements over single-baseline interferometers allow true imaging of objects whose structure is not known a priori, by inverting Equation (1) through an inverse Fourier transform. So far, only simple objects such as binary stars have been imaged with separate-element interferometers, but experiments with a multi-aperture mask on the 10-m Keck II telescope

features

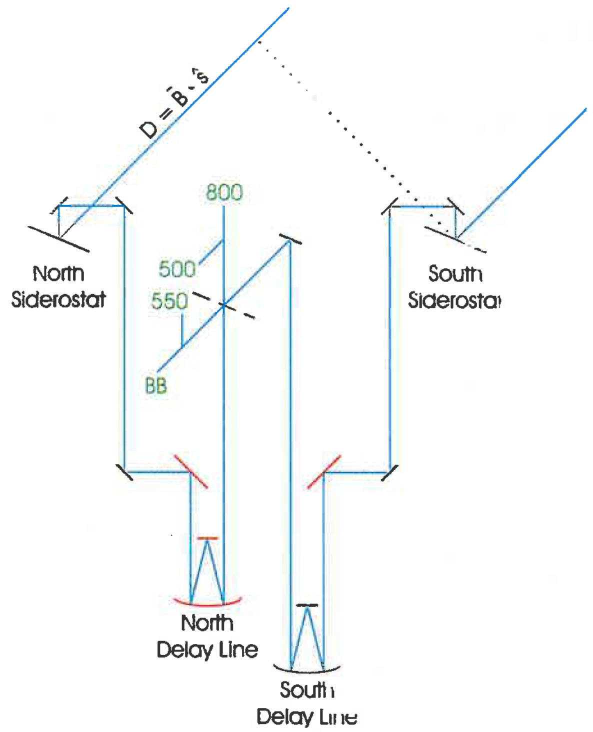

Fig. 1: Schematic drawing of the Mark III Interferometer, a typical two-element stellar interferometer constructed in the 1980's and operational on Mt. Wilson, CA, until 1992. Light collected with the siderostats is fed into the optical delay lines with two (plane) mirrors mounted on piezo-electric actuators (red), which are part of a servo loop that keeps the two images of the star aligned with each other. The positions of the two optical delay lines are continuously monitored with a laser interferometer. They are optically equivalent, but the cart and the small mirror in one of them (red) are actively controlled and are part of the fringe-tracking servo loop. The beams from the two arms are combined with a 50% reflective mirror. The light in each of the two outputs is divided with a dichroic beam splitter, so that four wavelength channels (broad band for fringe tracking, 500 nm, 550 nm, and 800 nm) are available simultaneously. The small mirror in the North delay line is dithered back and forth by one wavelength with a triangle wave at a rate of 500 Hz, so that temporal fringes (alternating constructive and destructive interference) can be detected with photo multiplier tubes in the four channels. The phase of the signal in the broadband channel provides the error signal for the fringe-tracking servo. The useful aperture of the Mark III was 5cm (!), which resulted in a limiting magnitude of 5, i.e., only stars visible with the naked eye could be observed.

have yielded beautiful images of a spiral dust pattern in a binary star system. (Back to the roots and to Fizeau's and Michelson's original masking technique!)

Whereas many interesting observing programs involve bright stars, there is also a strong desire to push interferometry to fainter limiting magnitudes, which means that larger telescopes have to be used. Several projects are now underway to turn some of the world's largest telescopes into interferometer arrays. Most prominent among these are the Keck and VLT Interferometer projects, which both achieved the milestone of "first fringes" in the spring of 2001 (see Figure 2). These facilities will broaden the scope of optical and infrared interferometry by providing sufficient sensitivity to observe rather faint stars and even some extragalactic objects, by offering a suite of beam combiners and detectors covering a wide wavelength range, and by making a fairly complicated technique more accessible to a broad users' community.

Astrometry based on interferometry

In addition to simple parametric measurements and imaging, interferometry can be used for very precise astrometry, i.e., for the determination of positions and motions of stars. The principle of interferometric astrometry can easily be understood from Figure 1. Because a stellar interferometer (unlike a laser interferometer in the lab) works with a very wide bandwidth, typically $\delta\lambda \geq 0.2\lambda$, the coherence length is small, and there is a well-defined central fringe in the fringe packet. When the fringe sensor locks on this central fringe, we know that the total pathlength is zero, which means that the internal pathlength difference given by the delay line positions is equal to the external pathlength difference $D = \vec{B} \cdot \hat{s}$. Since the delay line position is continually measured with an internal laser interferometer, we know D and thus the angle between the baseline vector and the direction to the star; this is a basic astrometric datum. It is possible to perform such delay measurements with a precision of ~10 nm; for a 100 m baseline this results in a precision of ~0.1 nanoradian or 20 micro-arc-seconds. This precision would have enabled Mission Control in Houston to watch Neil Armstrong wiggle his index finger upon leaving the Eagle – without any need for taking a camera along on the ride to the Moon.

Interferometric astrometry has attracted much interest because of its potential to detect extrasolar planets through the reflex motion of their parent stars. This technique is similar to the now-famous radial-velocity method, but it measures the two coordinates of the orbit in the plane of the sky instead of the single radial component. This has the advantage that the orbital inclination i can be determined, which allows deriving planetary masses without the $\sin i$ factor plaguing radial-velocity results. NASA's Space Interferometry Mission (SIM) – a two-element interferometer with a 10 m baseline scheduled for launch in 2009 – will push the astrometric precision down to ~1 microarcsecond from a vantage point above the Earth's atmosphere, sufficient to detect Earth-like planets around a few nearby stars.[2] A subsequent space interferometer operating at mid-infrared wavelengths (~ 7 – 20 μm) may then obtain direct images resolving these planets from their parent stars, and perform low-resolution spectroscopy of their atmospheres. In our wildest dreams, we may hope to discover absorption bands of ozone, signaling the presence of

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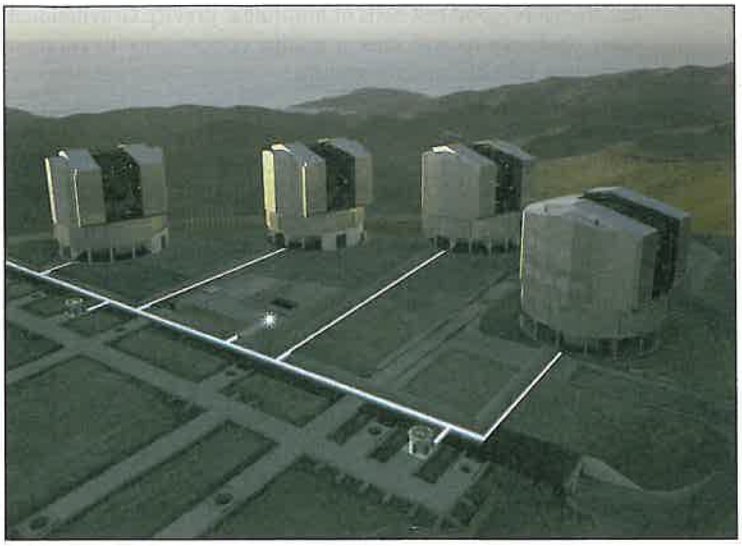

Fig. 2: The Very Large Telescope (VLT) array operated by the European Southern Observatory on top of Cerro Paranal, Chile. This photo shows the four 8.2-m Unit Telescopes (UTs) and various installations for the VLT Interferometer (VLTI). Three movable 1.8-m VLTI Auxiliary Telescopes (ATs), which will be installed in the near future, and paths of the light beams have been superposed on the photo. Also seen are some of the 30 stations where the ATs will be positioned for observations and from where the light beams from the telescopes can enter the interferometric tunnel below. The straight structures are supports for the rails on which the telescopes can move from one station to another. The interferometric laboratory (partly subterranean) is at the center of the platform. The VLTI saw "first fringes" in March 2001. It will be a versatile facility for observations of stars, circumstellar matter, and active galactic nuclei. (Photo courtesy of European Southern Observatory)

oxygen released into the atmosphere by living organisms not too dissimilar from those inhabiting the Earth.

Sub-mm and mm-wave interferometry — the next big leap

Radio astronomers realized in the 1950's that they can take advantage of Equation (1) and build imaging interferometers much more easily than their colleagues working in the visible wavelength region. After all, they have to maintain coherence only on the cm (and not sub-μm) level, and they have to put up with atmospheric fluctuations only on a timescale of minutes, not milliseconds. Radio synthesis imaging has thus become a thriving field, with ever-increasing baseline lengths (now exceeding the diameter of the Earth in ground-space very long baseline interferometry), and at increasingly higher frequencies. There are now a number of mm-wave interferometers that perform imaging of continuum and line emission of objects as varied as nearby star-forming regions and distant galaxies in the young universe, with a spatial resolution of about 1 arc second. These instruments are now beginning to face some of the same difficulties that plague optical and infrared interferometry: fast phase fluctuations induced by atmospheric turbulence, the need to build antennae with smooth surfaces and small thermal and gravitational flexure for use at high frequencies, the large collecting areas required for observations of faint objects, and the limited transparency of the atmosphere in the infrared – sub-mm – mm-wave region.

The next big leap in sub-mm and mm-wave interferometry will therefore require a truly global cooperation. Europe, Japan, North America, and Chile have entered a collaboration to construct the Atacama Large Millimeter Array (ALMA) at a site located at an elevation of 5,000 m above sea level in the Chilean Andes. At this elevation and in an extremely dry climate, the atmosphere is transparent in many frequency bands that are inaccessible from other sites. ALMA will consist of sixty-four 12-m antennas distributed over an area 14 km in diameter and cover the wavelength range from 0.3 – 10 mm (corresponding to frequencies from 30 GHz – 1 THz). ALMA will be complementary to large optical telescopes by giving us a view of cold objects and those regions of the universe that are hidden from our view by large amounts of dust. These are mostly regions of active star formation, both in our own Galactic backyard, and in nascent galaxies giving birth to the first stars during the dawn of the universe. The development of interferometry, from the visible to sub-mm waves, will thus have a profound impact on our view of our place in the cosmic chain of events leading from the formation of the first galaxies out of fluctuations created in the aftermath of the Big Bang to the evolution of life on our home planet.

he next big leap...
vill therefore require a
ruly global cooperation

[1] An intensity interferometer compares the intensities, not the amplitudes, at two points in the wavefront. It is interesting to note that this technique, invented for measurements on astronomical scales, is now widely applied to experiments of sub-microscopic objects. It is possible, for example, to determine the size of the "fireball" in heavy-ion collisions with the Hanbury Brown-Twiss method from correlations between the emitted hadrons.

[2] One may ask how an instrument with a resolution of ~10 milli-arc-seconds may perform measurements with ~1 microarcsecond precision. Note, however, that the centroiding accuracy in any measurement is given by the resolution divided by the signal-to-noise ratio. The trick is to keep systematics at a level that enables photon noise-limited observations with an SNR of 10,000.

About the author

Andreas Quirrenbach is a Professor of Physics and member of the Center for Astrophysics and Space Sciences at the University of California, San Diego. He became fascinated with the concept of milli-arc-seconds as an undergraduate student while attending a summer school at the Max-Planck-Institut für Radioastronomie (MPIfR). After completing his thesis at MPIfR and obtaining a PhD in astronomy from the University of Bonn, he decided to do "fringe science" at shorter wavelengths and joined the optical interferometry group at the Naval Research Laboratory in Washington, DC, which gave him the opportunity to spend 200 nights on Mt. Wilson observing with the Mark III Interferometer. Subsequently he became a staff member at the Max-Planck-Institut für Extraterrestrische Physik in Garching, where he helped shape the scientific program and instrument complement of the VLT Interferometer. He is now Data Scientist and Member of the Science Team for the Space Interferometry Mission.

Gravitational waves

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One of the open fundamental questions in physics is the direct observation of gravitational waves – an observation as important as Hertz's pioneering experiments with electromagnetic waves and the vindication of Maxwell's theory. Existence of gravitational waves is generally accepted, at least since their indirect observation via energy and angular momentum losses in binary pulsars, like in the Hulse-Taylor pulsar. Much more fascinating is the information we will get via direct observation of gravitational waves about the large-scale behaviour of matter under extreme density, temperature and magnetic fields. Examples include normal mode oscillations and quakes in neutron stars, catastrophic astrophysical events like gravitational collapse and the ensuing supernova, black hole formation, mergers of compact binaries, etc. Nowhere else one can learn in more detail about the conditions that prevailed at a time close to the creation of our universe in a big bang. Gravitational waves are hardly dispersed by surrounding matter, far less compared to neutrinos. However, it is only extremely non-linear and/or highly relativistic gravity that can produce detectable amounts of gravitational radiation. Therefore, the information we get from different windows of observation – electromagnetic, neutrinos, gravitational waves - complement each other.

Theory

According to Einstein's general relativity gravitation can be thought of as a consequence of curvature of space and time caused by the presence of matter and energy. The waves associated with gravitation can, therefore, be regarded as an oscillation in the curvature of space-time. One can imagine a passing gravitational wave to effect a strain in space very similar to the tidal deformation caused by an inhomogeneous gravitational field. Any matter present in its path will suffer a tidal force, which is the basic principle used in the construction of gravitational wave antennas or detectors. Gravitation being the weakest of all interactions, gravitational waves are difficult to generate and detect in the laboratory. However, a catastrophic astronomical event in the presence of strong gravitational fields, such as an exploding star or a coalescing and merging binary consisting of compact stars, constitutes a highly luminous source of gravitational radiation. Gravitational waves are characterised by a dimensionless amplitude – a measure of the strain in space they cause as they pass through. A supernova explosion at the centre of our Galaxy will give rise to waves of amplitude $h \sim 10^{-19}$ causing a sub-nuclear displacement of a tenth of a Fermi between two particles separated by a km. Most astronomical sources emit signals that will have even smaller amplitudes. Indeed, the product of the internal (i.e., on a scale equal to the size R of the source) and external (i.e., at the location of the Earth) Newtonian gravitational potentials (which for a source of mass M at a distance r is $G^2M^2/(rR)$), divided by the fourth power of the speed of light, is a good first-order approximation to the gravitational amplitude of a non-stationary source. This immediately implies that unless a source at a given distance is highly compact, hence under the influence of strong gravitational effects, it is unlikely to be a bright source of gravitational waves. Gravitational wave sources are, therefore, good test beds of non-linear gravity. Gravitational wave observations will offer a unique opportunity to conduct many new tests of Einstein's gravity.

Background

Experimental search for gravitational waves began in 1969 when Joseph Weber in the United States used huge aluminium cylinders as resonant antennas. These detectors couple to one axis of the elliptical "deformation" of space induced by a passing gravitational wave. As a consequence, one observes a change in the state of oscillation of the fundamental eigenmode. Since the time of the first experiments, the sensitivity of resonant bars has been improved to a level where rare signals from catastrophic events occurring in our Galaxy could be detected. On the other hand, in the seventies the development of interferometric detectors started. Basically, these detectors are Michelson interferometers wherein a gravitational wave typically changes the lengths of the arms with opposite sign, thus creating an output signal. For isolation against mechanical disturbances the optical components are carefully suspended in vacuum. For the measurement of the strain in space, the signal-to-noise ratio of such a detector improves with increasing light power and with increasing arm-length. In the early eighties the shot noise limited performance was first reached with the Garching 30 m prototype, followed soon by the 10 m experiment in Glasgow.

Ground-based detectors

Thanks to a worldwide effort, five long baseline interferometric detectors are now in operation or nearing completion (Figure 1):

- German-British GEO600 with 600 m arm-length near Hannover,
- American LIGO comprising 2 detectors one in Hanford (State of Washington) and one in Livingston (Louisiana) with 4 km arm-length each,
- Japanese 300 m detector TAMA at Mitaka City in Tokyo, and
- French-Italian VIRGO with a 3km detector in Cascina near Pisa.

Gravitational wave antennas are almost omni-directional. Each interferometric detector has better than 50% sky coverage at sensitivity better than 50% of the rms sensitivity over the entire sky. However, this means a network of gravitational wave detectors will be needed to fully resolve an incident wave. A network of 4 to 5 detectors with a good sensitivity can monitor the entire sky over a wide range of frequencies for both transient and continuous wave sources.

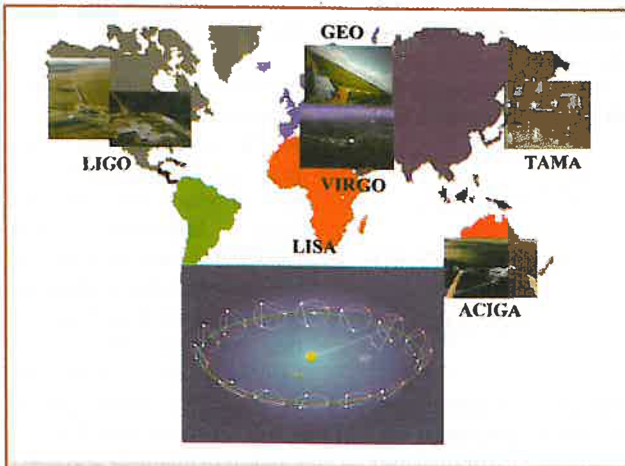

Fig. 1: A geographical view of the interferometer projects together with the orbit of LISA in the foreground.

First coincident observations are expected to take place in 2002 when the GEO and LIGO detectors come on-line. The expected initial sensitivity as a function of frequency is plotted in Figure 2, together with the performance of upgraded detectors. The sensitivity is given in terms of the 1-σ noise background within a bandwidth of 1 Hz (i.e., linear amplitude spectral density) at the output of the interferometer. At low frequencies the performance will be limited by seismic noise, at medium frequencies by thermally induced motions of the optical components and at high frequencies by photo-electron shot noise. This sensitivity of initial instruments is sufficient to detect a rare supernova originating in our Galaxy or coalescence of a binary consisting of two stellar mass black holes at a distance of 100 Mpc.

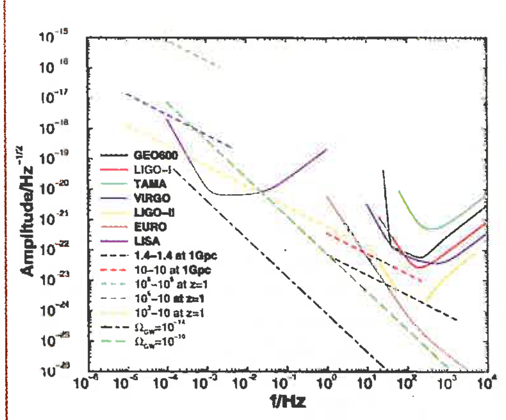

Fig. 2: The amplitude spectral density of noise (solid lines) expected in various ground-based interferometers and LISA. Also plotted are signal strengths (dashed lines) of two types of sources: (1) Inspiral and merger of compact binaries consisting of stars of masses m_1-m_2 (measured in solar masses) at a distance R and (2) primordial stochastic background whose energy density Ω_{GW} is a certain raction of the closure density of the Universe.

To start serious gravitational wave astronomical observations, a careful upgrading of the existing technology has to take place. This includes kW-type lasers to reduce the shot noise level, possibly purely diffractive optics to avoid problems with absorbed light inside optical components, new materials for mirror substrates and cooling of the main optics to reduce internal thermal noise. The fluctuating radiation pressure of the illuminating light requires mirror masses of up to tons.

There are three more or less well defined plans for future upgraded detectors: advanced LIGO, the Japanese Large Scale Cryogenic Gravitational Wave Telescope (LCGT), and EURO – a third generation gravitational wave interferometer in Europe. The performance of EURO, the most ambitious future detector, is described at frequencies above a few hundred Hz by the standard quantum limit, where shot noise and radiation pressure noise are balanced; at lower frequencies there is the Newtonian gravity gradient noise. The sensitivity of EURO as shown in Figure 2 represents the limits possibly reached when different topologies, like recycling parameters, are chosen for optimum sensitivity at each particular frequency. A network of upgraded interferometers and enhanced bar detectors will be able to register signals from stellar mass black holes from cosmological distances, quakes in neutron star cores (and hence an understanding of the state of matter at very high densities) in our Galaxy, supernovae and coalescing neutron star binaries at a redshift of z=1, etc. This is truly an attractive scenario for gravitational wave astronomy.

Space

At low frequencies – below a few Hz - the performance of ground-based detectors is limited by gravitational gradient noise, as caused, for instance, by motions inside the Earth's crust or in the atmosphere. Measurement and subtraction of this disturbance can only work to a certain extent. To enter this very interesting frequency range it is necessary to go into space, as it is planned with the Laser Interferometric Space Antenna (LISA). LISA is a *cornerstone mission* of ESA, and included in NASA's *Structure and Evolution of the Universe Roadmap*. The scheduled launch is around 2011. The technology will be tested in the precursor mission SMART II in 2006. In LISA, three spacecraft are arranged in an equilateral triangle of side 5×10^6 km, trailing the Earth by 20 degrees in a heliocentric orbit (cf. Figure 1). Each of the three craft follows its own elliptic orbit slightly out of the ecliptic. Over the course of a year, the triangle seems to rotate about its centre-of-mass, maintaining the relative distances constant to within a percent, without any active corrections. Under the influence of gravitational waves the relative distances between the craft change. These are, therefore, continuously registered with laser interferometry. To avoid the noise caused by the fluctuating solar-wind and radiation pressure, the distance is measured between free flying test masses, each shielded by its surrounding spacecraft – by use of the so-called drag-free technique.

The sensitive frequency range of LISA is between 0.1 mHz and 1 Hz (Figure 2). For LISA there are guaranteed sources: Galactic compact binaries of period in the relevant range will be observed with a signal-to-noise ratio of up to 1000. But much more fascinating are the signals to be expected from a variety of less well-known origin – namely, events involving super-massive black holes that are believed to exist at the centre of every galaxy in the Universe. It is not clear how such black holes formed. It is possible that a mid-sized black hole forms simultaneously with the formation of the galaxy and then grows in size by accreting matter in the form of ordinary stars and black holes found in their vicinity. If this is so then a small black hole or a neutron star falling into a super-massive black hole emits gravitational waves. As the body slowly spirals into the hole both its orbit and spin are expected to precess, more violently as the body approaches the black hole, and it samples the geometry of space-time as it tumbles round. The dynamics of the body, as well as the nature of the space-time in which the body whirls around will be encoded in the waves we can potentially observe with LISA. In the early history of their formation galaxies are believed to have interacted strongly with one another leading to their mutual collision and merger. Such mergers should also involve the coalescence of the associated black holes. The waves emitted in the process will be visible at a very high signal-to-noise ratio wherever in the Universe the source might be. Thus, LISA should single-handedly give us a complete census of the super-massive black hole population in the Universe. Finally, and most importantly, it is hoped that LISA, or one of its successors, will shed light on the conditions that prevailed when the Universe was born. Nothing could be more exciting.

About the authors

B.S. Sathyaprakash is a Reader at the Department of Physics and Astronomy, Cardiff University. He works on modelling binary black hole orbits and is involved in the development of data analysis algorithms and software for GEO600, LIGO and LISA projects.

Walter Winkler, Max-Planck Institut für Quantenoptik (Garching) and Albert Einstein Institut (Potsdam), was involved in repeating and improving Weber's resonance detector experiments, then the development of the Garching 30 m interferometer, and is now responsible for the optics of GEO600. He was also member of the LISA science team.

features

Dark Matter

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Dark matter is among the hottest topics of research in astrophysics. Although the phenomenon has been noticed the first time almost seventy years ago by F. Zwicky, in recent times dark matter research entered a new era. Its existence is practically accepted due to independent and converging observations in astrophysics (see also the articles in this special issue by J.M. Lamarre and J.L. Puget and by P.D. Sackett). However, the actual composition of dark matter is yet to be determined.

Dark matter as a puzzle inspires astrophysicists and particle physicists

Dark matter as a puzzle inspires astrophysicists and particle physicists, amalgamating these research areas into the rather young discipline of astroparticle physics. To summarize roughly the present status, the overwhelming majority of mass in the universe neither emits nor absorbs light and nobody knows what it is made of. The exercise is clear: to reveal the nature of dark matter and its role in the universe.

Mass and energy budget of the Universe

Fig. 1 shows the mass and energy budget of the universe as known today. Two dark matter problems can be found there (labeled gap I and II).

1. there are dark baryons (gap I), hence missing normal matter. So far, astronomers did not find all the normal matter that should exist in the universe due to the very successful theory of primordial nucleosynthesis.
2. There has to be a non-baryonic dark matter contribution (gap II). The observations today agree on a universe matter content of about 35% of the critical density (the mean matter density to have a flat universe) on average. The maximum allowed amount of baryonic matter, however, is just about 5%. This discrepancy leads to the notion of non-baryonic dark matter – the small syllable 'non' has far-reaching consequences.

Non-baryonic is synonymous with an exotic form of matter that we do not know. It is therefore a main playground for particle physicists entering the field of dark matter. A more detailed presentation of Fig. 1 and the terms used there will be given below.

The main motivation for current experiments to reveal the nature of dark matter or at least some specific properties different than just mass can be understood from Fig. 2. The idea is that all luminous matter is embedded in a huge halo of dark matter. Shown in the right panel one can find the basis for such a model: measurements of the rotation velocity of test bodies (stars, gas clouds) around the center of a galaxy yield its rotation curve. As indicated in the right panel, our galaxy has an approximately flat rotation curve, inconsistent with the expected Keplerian decline (dotted curve) in case all the mass was luminous (velocity ∝ 1/√(distance to center)). Instead, a constant rotation velocity implies a linearly increasing galaxy mass distribution and in fact this has been measured (left panel) up to very large distances of about 200 kpc (our sun is located at the outskirts of the Milky Way galaxy at a radius of about 8 kpc).

Baryonic or exotic?

These observations motivate us on Earth to search for dark matter either in our local (galactic) neighbourhood or even in laboratory experiments. Plenty of candidates for dark matter have been proposed. They can be classified as baryonic and exotic (or non-baryonic).

This distinction is crucial with respect to the two dark matter (DM) problems of Fig. 1. Baryonic candidates can at best fill gap I. These candidates consist of gas, planetary objects and stellar remnants, for example white dwarfs. They would be too dim to be observed with telescopes and therefore would be dark matter by definition. However, the clever idea of microlensing can help to detect such candidates and has been successfully applied.

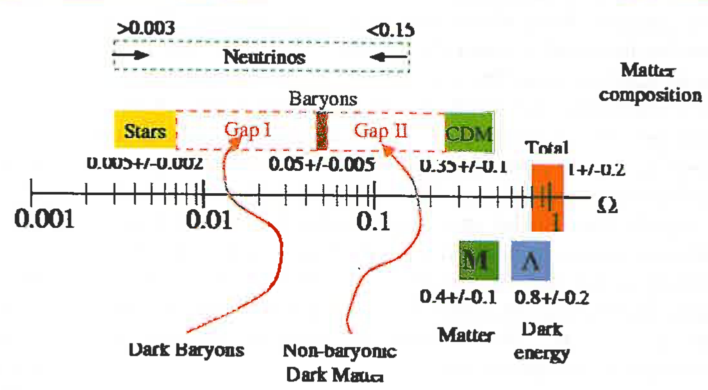
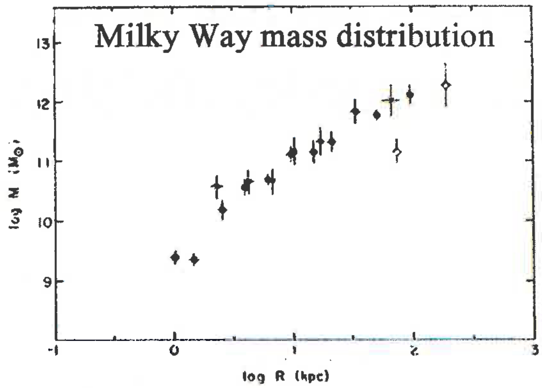
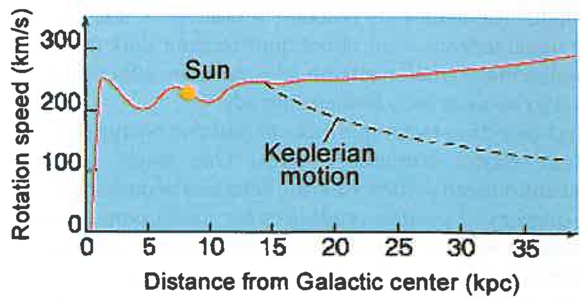


Fig. 1: Mean matter/energy density in the universe normalised to the critical density. A value of $\Omega=1$ means a flat universe topology as the boundary case between a spherical and hyperbolic topology (for simple cosmologies this means closed and open universe). Summaries of measurements for this important parameter are indicated. Below the logarithmic axis is shown an overall account of matter and energy; above the composition of the matter components. The dotted red rectangles, labeled gap I and II indicate the two dark matter problems: dark baryons and non-baryonic dark matter. Colored regions: yellow – range of luminous matter, brown – required range of baryonic matter due to primordial nucleosynthesis, light green – range of non-baryonic cold dark matter (CDM), red – total account of matter/energy density consistent with $\Omega=1$, dark green – total matter content in the universe, blue – dark energy content adding up with matter to the total content. The dashed green rectangle shows the allowed amount of matter density due to neutrinos. Lower bound due to successful neutrino mass measurements, upper bound from failure of structure formation scenarios using neutrinos as hot dark matter. The picture has been adopted from M.S. Turner's dark matter review in Phys. Reports (see references).



Mass increases up to 200 kpc



Schematic flat rotation curve for the Milky Way galaxy

Fig. 2: The right panel shows a schematical rotation curve of our galaxy (from http://www.astro.psu.edu/users/niel/psiwa/darkmatter/mw-rotation-curve.jpg, on Penn State Inservice Workshops in Astronomy). The important observation is that the velocities of stars and gas spinning around the center of the galaxy remains constant up to the largest measured distances. If nothing else but luminous matter was there, the rotation curve should decrease as indicated (dashed line). Therefore there must be much more mass inside and around our galaxy than visible, the dark foundation. In fact, the flat rotation curve implies a linear increase of the total mass with increasing distance from the center. That has been observed as is shown in the left panel up to large distances (from S.M Faber and J.S. Gallagher, Ann. Rev. Astron. Astrophys. 17 (1979) 135, or http://ned.ipac.caltech.edu/level5/Faber/Faber_contents.html).

This technique looks for light amplification of distant stars of the two Magellanic Clouds by massive compact halo objects (MACHOs) from our Milky Way galaxy. This amplification is a generic effect of the gravity field of the MACHO that bends the light and eventually acts as a lens (see also P.D. Sackett's article) for an observer on Earth. The probability that a given star is amplified at a given time is very low; millions of stars have to be monitored for years in order to ever be able to detect such a rare event. The MACHO and the EROS (Expérience pour la Recherche d'Objets Sombres) collaboration have indeed found microlensing events but their interpretation poses some considerable problems. They are consistent with a roughly 50% dark baryon halo but the masses of the lenses needs to be around half a sun mass which would mean they are probably white dwarfs. That turns out to be inconsistent with several astronomical observations, so the latest status is that the nature of the lenses is unknown. Nevertheless, something has caused these microlensing effects and it remains a fascinating challenge to explain them.

Hot and cold non-baryonic dark matter

Non-baryonic candidates are classified as hot and cold DM (also an intermediate state, called warm DM has been proposed), depending on their kinematical state in the early universe at the time of decoupling of light and matter. Hot DM candidates would have been relativistic, cold DM ones non-relativistic. The reason for such a classification originates from the fundamentally different consequences for structure formation in the universe, like formation of superclusters and clusters of galaxies. Hot DM would form huge structures first (top-down approach), cold DM vice versa. The important efforts of research groups using supercomputers for N-body simulations of huge parts of the universe showed that structure formation cannot be understood with dominantly hot DM. A consistent scenario results for a substantial cold DM component and a rather negligible hot DM component.

However, it also turned out that realistic scenarios for structure formation need one mysterious part in addition to cold DM: dark energy. The nature of dark energy is unknown but it can be described as a smooth component which contributes at least 60% of the energy density in the universe (see Fig. 1). It must evolve more slowly than matter not to interfere with structure formation at early times. In addition, it has to have a negative pressure! In order to explain recent cosmological observations (see also J.M. Lamarre and J.L. Puget's article), especially the distant supernova Ia surveys, the universe accelerates instead of slowing down or keeping a constant expansion rate. Initially, this observation led to a revival of Einstein's cosmological constant but soon it has been realized that also time dependent variants, termed quintessence, could explain the dark energy. No conclusion can be given so far about the dark energy but huge efforts are underway to measure the equation-of-state of this phenomenon in order to learn about its nature.

Search techniques

The prime candidate for a hot DM contribution is a massive neutrino. The new results from the Superkamiokande experiment and recently from SNO (Sudbury Neutrino Observatory) seem to prove for the first time that neutrinos are in fact massive although extremely light. Their possible contribution to dark matter is summarised in Fig. 1 as well. Nevertheless, they will not be able to fill exotic matter gap II.

Searches for non-baryonic, cold dark matter exist in a large variety of techniques. One can classify them as three different concepts: production in laboratory experiments (typically at accelerators), indirect and direct detection. These techniques presume that this exotic form of matter consists of unknown particles.

Indirect searches look for products of reactions of these particles. It might be that they decay or annihilate or have inelastic reactions with normal matter, meaning that they might not be 'dark' in the strict sense but shine in 'some' form. Satellite experiments look for radiation from such reactions, for example in the form of high energy gamma rays or antiprotons. Additionally, neutrino 'light' (neutrinos as reaction products) is seen as a promising signal to learn more about non-baryonic dark matter. Large experiments, termed neutrino telescopes, are either in the process to start soon or even measure already.

The direct detection technique seeks to find rare energy depositions from elastic scattering events. One direct search experiment announced evidence for the detection of dark matter. The main category of particle candidates for non-baryonic dark matter are called WIMPs (weakly interacting massive particles). One important signature of WIMP interactions would be an annual modulation of these rare events. The DAMA collaboration, operating almost 100 kg of low background NaI scintillator detectors in the Gran Sasso laboratory in Italy has published evidence for the detection of such a modulation, consistent with the WIMP hypothesis. Now other experiments are bound to confirm or exclude that evidence which promoted large efforts and interest worldwide in inventing alternative and far more sensitive detectors. That compelling development happens at the moment and new results are expected very soon.

To conclude, dark matter appears to be well established as a phenomenon in astrophysics, a fascinating puzzle. Precision cosmological measurements determine the matter and energy content of our universe and reveal the necessity for a substantial amount of unknown matter, a dark side of the universe. Astronomical techniques like supernova searches seem to have detected dark energy, an unexplained phenomenon so far, hinting at new physics beyond current borders. About matter in the universe, we now have a clear picture that the familiar luminous matter represents only a negligible contribution with respect to dark matter. Normal, known forms of matter evaded detection so far and so did an even larger contribution from an exotic form of dark matter. The near future will most probably reveal some pieces of the grand mosaic and it's exciting to follow that development.

dark matter appears to be well established as a phenomenon in astrophysics, a fascinating puzzle

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About the author

Yorck Ramachers has been a research assistant at Oxford University since 1998, working for the direct detection experiment CRESST (cryogenic rare event search using superconducting thermometers) at the Gran Sasso laboratory in Italy in the group of Prof. H. Kraus.
PhD. thesis 1998 at the Max-Planck Institute for Nuclear Physics in Heidelberg on building the HDMS (Heidelberg dark matter search) direct detection experiment in the group of Prof. H.V. Klapdor-Kleingrothaus.

The aim of the Joint Astrophysics Division

Maurice Jacob
Chairman of JAD

There is at present a thriving interface between physics and astronomy and the purpose of JAD is to respond to the need of the fast expanding community of scientists working in that domain by organising workshops and conferences and providing forums for discussion whenever needed. JAD should eventually become a grassroots partner for research organisations that try to co-ordinate their programmes as, for example the newly created AstroParticle Physics European Co-ordination (APPEC). In 2000, JAD organised the first ESA-CERN workshop on "Fundamental Physics in Space", which was held at CERN [1]. The past and present chairmen invested much effort in helping to establish permanent links between ESA and CERN, and the two organisations have actually found several areas of fruitful collaboration.[1]

The Joint Astrophysics Division has two sections:

- one on "Solar Physics", which has long existed and which organises a well-attended European conference in that domain every three years (Chairman: Jan Kuijpers, Nijmwegen);
- the other on "Gravitational Physics" (Chairman: Gerhard Schaefer, Jena), which has been established earlier this year and which brings together gravitation theory and experimentation with, in particular, the search and — hopefully soon — the study of gravitational waves.

The activities of this second section began in 2001. JAD will continue to develop its structure. A new section on "Astroparticle

Members of the Board of the Joint EAS-EPS Astrophysics Division (JAD) met at CERN the day before the ESA-CERN Workshop on "Fundamental Physics in Space and Related Topics". From left to right: Martin C.E. Huber, Michel Spiro, Clare Bingham (ESA), Daniel Enard, Eckart Lorenz, Jean-Pierre Swings, Gerhard Schäfer (Chair, Gravitational Physics Section), Bernard Schutz, Gustav A. Tammann and Jan Kuijpers (Chair, Solar Physics Section) [Photo: Maurice Jacob].

Physics" is at the building stage, to start operating by 2002. This special issue of Europhysics News covers many of the domains where JAD hopes to foster efforts throughout Europe.

Among the main topics at present are: the physics of stellar interiors, plasma astrophysics, neutrinos from space, searches for dark matter and antimatter, high-energy astroparticle physics, very-high-energy cosmic rays, the search for gravitational waves and all the fascinating questions related to cosmology. This latter domain is rich in experimental possibilities, with the improved measurement of key global properties of the Universe such as the Hubble constant, the cosmological constant, the hadronic and the dark-matter densities.

Following the last meeting of the JAD Board in L'Acquila, members visited the Gran Sasso Laboratories together with their guest, the President of EPS. From left to right: Bernard Schutz, Martial Ducloy, Martin C.E. Huber, Daniel Enard, Jean-Pierre Swings, Jan Kuijpers, Roberto Grillo.

As 'astro-physics'[2] should have been a natural subfield for the European Physical Society (EPS), it was deemed appropriate to create an "Astrophysics" Division shortly after the society's founding. However, only solar physicists found their niche there. Night-sky astronomers were — as far as conferences were concerned — mostly oriented towards the US. Therefore, astrophysics within EPS was, for a long time, limited to the activities of the "Solar Physics" Section. When, in the early nineties, the European Astronomical Society (EAS) was in the process of being created, EPS decided to make a special effort in astrophysics. At that time already it was often hard to distinguish astronomy from 'astro-physics' and, therefore, it was decided to act together and create a Joint Astrophysics Division. EPS and EAS entered into a five-year agreement for that purpose in 1992. This agreement has in the meantime been extended for another five years.

The purpose set for JAD, with sections administered either by EPS or EAS, and welcoming members from both societies, was to deal with those topics that benefit from a close collaboration between physicists and astronomers. The joint division has the role of harmoniously co-ordinating the relevant activities of the two societies in that domain, a domain which lately has been expanding, if not exploding, with research on the ground, underground and in space. Such a multidisciplinary activity is not isolated. Back in 1995, ESA created a new Fundamental Physics Advisory Group in addition to its already existing Working Groups on Solar System science and Astronomy. This budding new field was being exemplified and thus defined by a remarkably large number of proposals for space missions, and steps were taken to introduce young researchers to the new field at the 1997 Alpbach Summer School [2]. CERN recently set up the concept of "recognised experiments" for projects corresponding to European collaborations involving particle physicists engaged in astroparticle physics research. The AMS experiment (search for antimatter in space), the Auger project (detection of very high-energy cosmic rays) and the LISA project (search for gravitational waves in space) are already such "recognised" experiments. Although they do not receive any CERN funding, they can use the organisation as a base for their international collaboration.

First chaired by Pierre Léna and then by Martin Huber, JAD has not yet reached cruising speed, and the meetings of the Division Board are still to some extent brainstormings. These meetings take place in different key sites for the community. Past ones were held at ESA/ESTEC (Noordwijk), at CERN and, most recently at the Gran Sasso Laboratories. The next one will be at ESO (Garching).

The field is captivating and thus thriving. Searches for gravitational waves are in a promising development phase. At long last one can match expected signals with achievable detector responses. Instrumentation developed in accelerator-based physics is opening up new windows in astrophysics. Extremely violent events, such as the merging of neutron stars and, even more so, that of very massive black holes, provide (or are soon to provide) data that should improve our understanding of gravitation. The Universe is rich with sources of very-high-energy particles, which are hardly — if at all — understood. The domain covered by JAD with such fascinating questions should be a beacon one, quite capable of attracting young people to physics. It is a challenge to make this division work in the best possible way for the benefit of a fast-moving multidisciplinary community.

References:

[1] Fundamental Physics in Space and Related Topics. ESA-CERN Workshop, ESA SP-469 (2001).

[2] Fundamental Physics in Space, 1997 Alpbach Summer School, ESA-SP-420 (1997).

[1] In order to facilitate a more extensive collaboration, the large European International Research Organisations (EIROs) have recently created the EIROFORUM. The Forum, consisting of the Directors General of the European Organisation for Particle Research (CERN), the European Molecular Biology Laboratory (EMBL), the European Fusion Development Agreement (EFDA), the European Space Agency (ESA), the European Southern Observatory (ESO) and the Institut Laue-Langevin (ILL), meets bi-annually to review and pursue issues of common interest. By exploiting the links between the Organisations and their respective European research communities, they will thus mobilise the substantial combined expertise in basic research and in the management of large international projects for the benefit of European research and development.

[2] A hyphen is used here in 'astro-physics', in order to convey the difference to astrophysics, a sub-discipline of astronomy. Astrophysics began with the development of spectroscopy in the nineteenth century. One of its main aims was determining the abundance of the chemical elements. Today, the expression is often used arbitrarily to describe investigations that are based on a combination of methods employed in physics and astronomy.

features

The European Physical Society is pleased to include in this *special issue* a contribution on the origin of cosmic rays by immediate past President, Professor Sir Arnold Wolfendale and his colleague A.D. Erlykin

The origin of cosmic rays

A.D. Erlykin[1,2] *and A. W. Wolfendale*[1]
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Cosmic rays were discovered in 1912 by Viktor Hess during perilous balloon ascents in which he found that the radiation levels in his electroscope increased with height above about 1 km. The term 'radiation' was used because some form of ultra-hard gamma radiation was thought to be responsible. In fact, it was shown later that most of the radiation comprises nuclear particles, largely protons, at low energies at least. This fact immediately causes problems with determining their origin because, unlike photons, charged particles are deflected by the tangled Galactic magnetic field. Thus, not until the very highest energies might one expect to have near rectilinear propagation and thereby a rather direct source identification. It is evident, then, that 'the origin problem' is a difficult one and one that must rely on indirect methods.

Some facts about cosmic rays

The energy range

Conventionally, the lower limit is taken as mc^2, i.e. ~ 1 GeV for protons and ~ 0.5 MeV for electrons. The upper limit is not known; particles have been detected up to ~ 3×10^{20} eV but this limit is almost certainly set just by statistics.

Particle masses

At low energies protons predominate and electrons constitute about 1% of the flux. The small (~ 10%) fraction of heavier nuclei grows with increasing energy until by 10^{17}–10^{18} eV heavy nuclei – probably iron nuclei – are in the majority. At the highest energy there is argument, as will be described later.

Our own estimate of the mean logarithm of the atomic mass, $\langle \ln A \rangle$, derived from the world's data – comprising direct measurements below about 3×10^{14} eV and indirect EAS studies above – is as follows: $\langle \ln A \rangle$, (E range, log E (GeV)) 1.5 ± 0.15 (4.0-4.5); 1.62 ± 0.12 (4.5-5.0); 1.95 ± 0.10 (5.0-5.5); 1.96 ± 0.10 (5.5-6.0); 2.15 ± 0.15 (6.0-6.5); 2.32 ± 0.35 (6.5-7.0); 2.32 ± 0.4 (7.0-7.6).

Surprisingly, perhaps, the fraction of electrons in the primary beam is very low, specifically e/p is ~1% at several GeV. Figure 1(a) shows the spectrum of electrons, together with that of protons. Below some tens of GeV the spectra are parallel but the electrons steepen at higher energies due to various losses in the interstellar medium.

The nuclear component

Figure 1(b) shows the total spectrum and that of the two important components, protons and iron. There are two major features, the 'knee' at ~3 PeV (3×10^6 GeV) and the 'ankle' at ~3 EeV (3×10^9 GeV). Both will be discussed in more detail later.

Other components

Neutrinos predominate in terms of number, here, as in all astrophysical situations. Cosmic ray (CR) secondary neutrinos are the decay products of secondaries produced in interactions in the upper levels of the atmosphere and differences in the numbers of downward and upward moving neutrinos underground is the source of information about the possible mass of the neutrino (and other neutrino properties). Solar neutrinos are of such low energy as barely to 'count' in a discussion of 'cosmic rays' but they are detected (as are other rare phenomena) against a background of effects produced by 'conventional' CR.

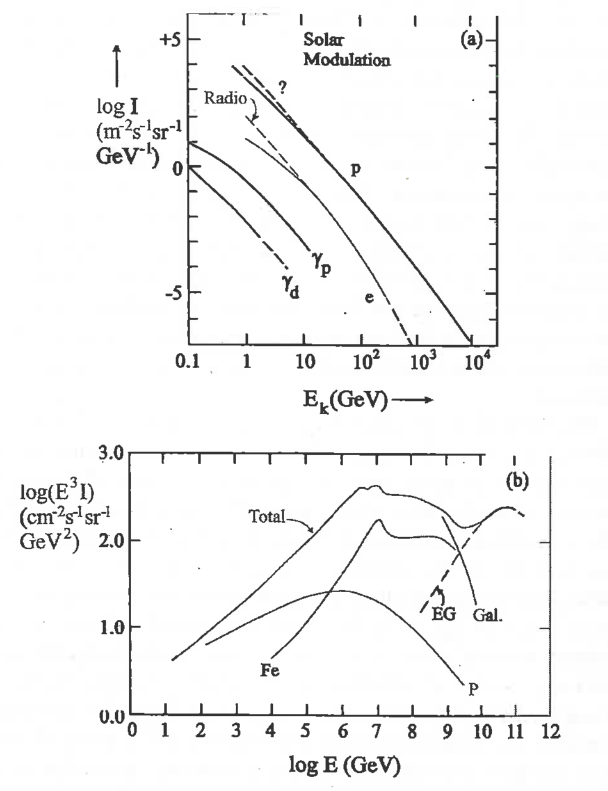

Fig. 1(a): The 'low energy CR spectrum, showing protons, electrons and gamma rays, the last-mentioned being divided into the isotropic diffuse (presumably EG) component, denoted γ_d and the Inner Galaxy Galactic Plane component, denoted γ_p.
Fig. 1(b): The likely spectra of protons and heavy (iron) nuclei over the whole energy range. The division between Galactic and EG components is indicated.

Gamma rays are present in the primary CR beam to the extent of about 10^{-6} of the total (above ~1 GeV) and the spectrum is steep (Figure 1(a)). Although the flux is small it is important from the standpoint of searching for origin, in view of the rectilinear propagation of gamma rays. As with the particles there are two components - of Galactic and Extragalactic origin. In Figure 1(a) the isotropic diffuse gamma ray intensity is indicated (γ_d) which is associated with Extragalactic gamma rays; also shown is the Galactic intensity for a restricted region of space: $|l| < 60°$, $|b| < 20°$ (denoted γ_p). The Galactic intensity, due largely to CR protons and heavier nuclei interacting with the ISM, is sharply peaked about zero Galactic latitude and is much higher in the Inner Galaxy.

The origin of CR

Energetics and the Galactic/Extragalactic question

It is a well known fact that the energy density of the, predominantly nuclear, cosmic rays at the earth is roughly the same as that of the Galactic magnetic field ($B^2/8\pi$), starlight and the average kinetic energy density of gas clouds ($\langle 1/2\ \rho v^2 \rangle$). All are ~0.5 eV cm^{-3}. The cosmic microwave background, the 'CMB', is only a factor two lower, at 0.24 eV cm^{-3}. Presumably these values have relevance to the first question: are CR of Galactic or Extragalactic (EG) origin? An EG origin for the electron component can be ruled out because inverse Compton losses in collisions with the CMB prevent them coming from far distances. On the other hand, protons, and heavier nuclei, *could* be of EG origin. The equalities present a mixed message; the first 3 suggest a Galactic origin and the near-equality with the CMB suggests an EG origin. Further examination of energy densities yields better discrimination, however, as shown below in Table 1.

The Table shows that considering other parameters, some of the equalities disappear. The radial gradient (in terms of fractional change of energy density with Galactocentric distance) is very different for cosmic rays and for gas motion and the CMB; thus a close connection between CR and these two can be ruled out. The same conclusion comes from considering the scale height of the z-dependence of CR and the other properties.

We are thus left with the similarity (within a factor 3) of the radial gradient and $z_{1/2}$ for CR, starlight and magnetic fields. Distinguishing between 'starlight' and 'magnetic fields' is difficult but the former is disfavoured for a simple reason: 'the sun'. The solar radiation energy density is very many orders of magnitude greater than that in CR locally; if there were any subtle connection between CR and starlight then we would expect to see a very high ε_{CR}.

Turning to the magnetic field, *its* relevance is probably that the field acts to trap CR until their energy densities are similar.

Such difference as there is between the radial gradient, and $z_{1/2}$, for the magnetic field and CR is probably associated with the Galactic Halo, which has a smoothing effect on the CR radial gradient.

Other evidence favouring a Galactic Origin

The very fact that CR have a radial gradient in the Galaxy at all shows that an EG origin for all the particles is not possible. A similar conclusion, with more stringent limits, comes from the fact that the flux of gamma rays (in the GeV region) from the Magellanic Clouds is much less than would have been expected if the CR intensity were the same there as locally, i.e. if all CR were Universal. The upper limit to the EG flux for CR below about 100 GeV is approximately 10%. The actual value is almost certainly very much less than this.

The nature of the CR sources

Energies below some tens of GeV

Studies of X- and gamma rays from the Crab, Vela, SN1006 and others suggest that CR (at least electrons) are accelerated by SNR shocks; the correlation of gamma ray excesses with X-ray contours for Loop I supports this view.

The situation near the spectral knee

Many papers have made the case for shock acceleration in SNR being important up to about $4Z \times 10^{14}$ eV, the actual upper limit being dependent on the parameters of the ISM and of the particular SN. The energy spectrum up to the maximum energy is usually considered to follow the standard Fermi-acceleration form: $E^{-2.0}$ (or something close to it - we, ourselves, adopt $E^{-2.15}$ for conventional SNR).

Whilst many support the SNR acceleration model (although there is a lingering doubt connected with the lack of observation of TeV gamma rays coming from the interaction of SNR-accelerated particles with local gas) few, as yet, support our hypothesis that the 'knee' is due, largely, to a single local, recent, SN. The knee itself has been known for some 40 years and has been confirmed time after time. We have argued extensively that it is too sharp to correspond to Galactic diffusion, viz. an increasing inability of the Galactic magnetic field to trap the particles. It appears natural to us to expect some 'structure' in the CR energy spectrum, i.e. it should not be featureless but should demonstrate the essentially stochastic nature of the sources, i.e. that they only occur about once per hundred years somewhere in the Galaxy. In our model

Table 1: Diagnostics of CR Origin

Phenomenon	locally (eV cm^{-3})	Radial gradient (kpc^{-1})	Scale height $Z_{1/2}$ (kpc)
Cosmic Rays	~ 0.5	0.06 ± 0.03	3 ± 1
Starlight	~ 0.5	0.18	6
$(\text{Mag. field})^2$	~ 0.5	0.15 ± 0.05	1.4 ± 0.4
Gas motion $\left\langle \frac{1}{2}\rho v^2 \right\rangle$	~ 0.5	~ 0.9	~ 0.07
CMB	0.24	$\rightarrow 0$	$\rightarrow \infty$

(the 'Single Source Model', SSM, e.g. Erlykin and Wolfendale, 2001) the knee is a 'saw tooth' feature superimposed on a gradually steepening spectrum.

We go further and identify another feature, a factor 3 higher in energy. For good astrophysical as well as CR reasons we identify the first feature (knee) with oxygen nuclei and the second with iron nuclei. It is the second 'peak' that gives rise to the iron spike in Figure 1(b).

The situation above the knee

There is even more discussion about the nature of the sources here. A 'special' variety of SN (which we denote as SSNR – i.e. super-supernovae) and/or pulsars seems likely. A number of general remarks can be made.

(i) Unless the rate of occurrence of the birth of the sources is much greater than that of SN (10^{-2} per year within the Galaxy – a most unlikely situation – the fluctuations in the predicted intensity will be large. By 'fluctuations' is meant the difference between the outcome from one particular configuration of SN and another. Thus, the usual 'leaky box' model prediction, with an *a priori* smooth distribution of SN, can be grossly in error.

(ii) At rigidities above $\sim 3 \times 10^{16}$ V (10^{18} eV for iron) rectilinear propagation will become increasingly important. The fluctuations, then, are even more serious, although if the actual sources are known the situation is clearly eased.

Our model for SSNR is inevitably rather *ad hoc* but one visualises a class of SNR in which strong coupling of CR to the shock results in very strong magnetic fields (Lucek and Bell, 2000). For SN with very high initial shock velocities ($\sim 10^4$ km s^{-1}) it should be possible to just reach 10^{20} eV for iron nuclei. We postulate that the very high energy particles of concern to us are not trapped but escape rather quickly after acceleration (the situation is therefore different from that for 'conventional' SNR). A 'reasonable' dependence of the time interval for emission, tem (E), on energy is $\tau_{em}(E) = 6 \times 10^3 (E/10^8 \text{ GeV})^{-0.5}$ years.

This expression comes from an analysis of the acceleration time for very strong shocks (by analogy with the SNR case).

In view of the comparatively rapid escape the shock acceleration model was taken to be of the straightforward E^{-2} form. The energy required for each SSNR was taken such that there was an approximate fit between the mean of the spectra derived using our Monte Carlo calculations and the observed iron spectrum (by 'observed' we mean that derived by us from a variety of analyses). The normalisation energy was chosen as $\log E = 6$ and the required energy per SSNR is 10^{50} erg $\times\ 15^{-1}$. The factor 15^{-1} is not unreasonable for the fraction of total energy given to the iron component – at lower energies, in the SNR region, the factor is $\sim 10^{-1}$.

Figure 2(a) shows the result of our Monte Carlo calculations for the situation just described. The gap is the transition region where neither the diffusion-mechanism nor rectilinear propagation is appropriate.

It is seen that the 'required' spectrum can be easily achieved in some of the possible SNR and SSNR space-time configurations.

Turning to pulsars, the inevitable uncertainties in the environment of these highly condensed objects means that the acceleration mechanism is uncertain. However, it is apparent from general arguments that a millisecond pulsar should be able to accelerate iron nuclei to 10^{20} eV. The time interval just after the birth of the pulsar when such energetic particles are produced will be very short but it will extend as the energy falls. There is a distribution of energy up to the maximum for geometrical reasons, but the emitted intensity is peaked at this maximum energy. If the emission of the particles were immediate, after production, then for all energies where rectilinear propagation is important, say above $\log E$, GeV = 9, the probability of there being *even one* pulsar anywhere in the Galaxy emitting such particles would be small and the observed spectrum (Figure 1(b)) would not be reproduced.

In fact, although calculations appear not to have been made on this topic, it seems likely that the pulsar-accelerated particles 'leak out' of the environment of the pulsar rather slowly because of the large product of magnetic field strength and linear distance. Presumably this 'emission time' scales, in some way, with the pulsar's age. If it were of order 100 times the age and the ensuing emission spectrum were of the form E^{-2}, the results for rectilinear propagation would be very similar to those for the SSNR case, shown in Figure 2(a). This is as far as we can go at present.

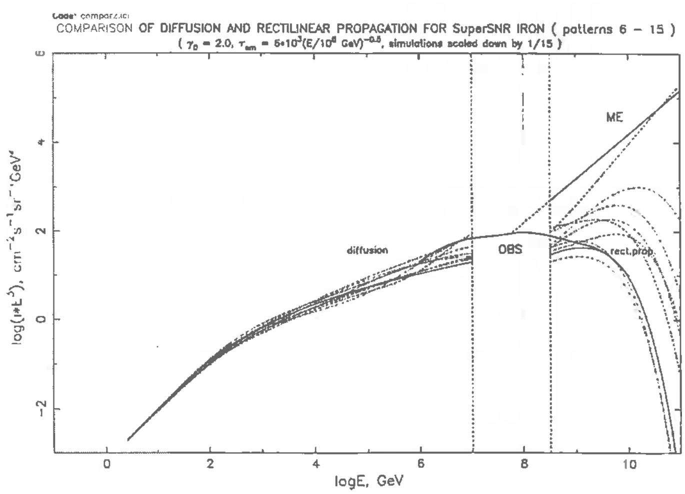

Fig. 2(a): The results of Monte Carlo calculations made by us for the iron component produced by non-conventional SNR in Galactic sources. 10^{50} ($\times\ 15^{-1}$) erg is injected into CR by so-called super-supernova remnants (SSNR). The mechanism is assumed to give an emergent spectrum of the form $E^{-2.0}$ and a limiting energy of 10^{20} eV.
A typical set of ten spectra is shown. The *mean* spectrum expected is indicated by 'ME' (mean expectation). The observed spectrum – at least as inferred by us from the experimental data – is shown as 'OBS'.
The gap marks the intermediate region between the diffusion regime (below) and the rectilinear propagation regime (above).

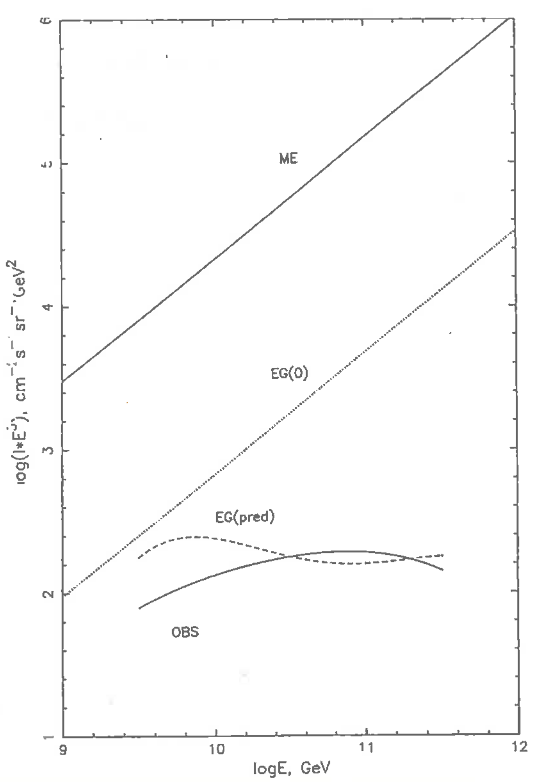

Fig. 2(b): The situation with extragalactic particles. EG(O) is the EG spectrum which would be expected from ME (as in Figure 2(a)) if there were no CMB losses. EG(pred.) is the expected EG spectrum after losses by interactions with CMB photons, assuming that the CR start off as iron nuclei; those emerging will be a mixture of masses (after Wibig, 2001, private communication).

Extragalactic particles

It is true that one *can* design a Galactic Halo of very considerable extent and a high enough, coherent, magnetic field, so that EG particles are not needed, but the energy requirement for the field is very severe; thus, there seems little doubt that the 'ankle' represents the transition from Galactic to EG particles. An interesting feature that follows from the previous analysis – and which seems not to have been appreciated previously – is that it is just possible that the type of source hypothesised for Galactic particles above the knee (SSNR or pulsars) may well be responsible for the EG particles, too.

One can calculate what the EG CR intensity should be if the effective number of galaxies per unit volume were known. We estimate that, when allowance is made for the higher SN rate in Sc galaxies in comparison with our own Sb/Sbc type, this figure is $\sim 2 \times 10^{-2}$ Mpc^{-3}. The result is that, in the absence of EG magnetic fields or radiation fields, the ratio of the EG intensity to the *mean* Galactic intensity for straight line propagation is $\sim 2 \times 10^{-2}$. Allowance for losses on the radiation fields reduces this factor appropriately (see, e.g., Szabelski *et al.*, 2001) – e.g. by ~20 at 10^{11} GeV, if the injected EG particles were mainly iron nuclei, and the resulting predicted EG spectrum (which will contain a mixture of nuclear masses) is not far from that observed (see Figure 2(b)).

The significance of the above is that particles above the knee, whether Galactic or Extragalactic, could originate from the same fundamental mechanism. Thus, Active Galactic Nuclei or galaxy – galaxy collisions may not be necessary, although the latter may be important as regions where the SSNR rate per unit galactic mass (or luminosity) is greater than average. Other systems may also have higher SSNR/pulsar rates and thus simulate specific sources.

Conclusions

Most workers in the field would probably agree with our contention that conventional SNR are prominent sources of CR at energies below the knee. At higher energies, although there is no consensus as to origin, many would agree that iron nuclei become increasingly prominent as one approaches 3×10^{18} eV, above which EG particles rapidly 'come in'. Their mass is uncertain, although we prefer a mixture, such as would come from largely iron nuclei accelerated at their sources. We draw attention to the fact that, because it is the Lorentz factor, *E/Z*, that is important in interactions with the CMB, rather than the energy itself, then very heavy nuclei are less fragile than protons.

Concerning Galactic particles above the knee, whatever the sources, fluctuations in intensity are expected over long periods (10^5 y, or so) and the 'Leaky Box' model is invalid. We have put forward, here, for the first time, a model in which there is only one dominant type of source (pulsar?, super SNR?) for the particles, both Galactic and EG. Our measured Galactic spectrum, with its rapid fall intensity above 10^{19} eV, is simply the result of a not-uncommon downward fluctuation in intensity, viz., by chance, there has been no recent nearby Galactic source at these energies – a situation which is the opposite of the likely situation for the origin of the knee, but not an inconsistent one since the sources are different.

It is not obvious as to how one might confirm, or disprove, the fluctuation hypothesis. The best that we can offer at present is a search for rare energetic cores of radiation-damaged material on the lunar surface; such cores would result from the very considerable concentrated energy deposition caused by the impact of the occasional 10^{18}-10^{19} eV iron nucleus.

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About the authors

Arnold Wolfendale is Emeritus Professor of Physics in the University of Durham. He commenced his research in cosmic ray physics in Blackett's Laboratory in 1948 and is still fascinated by the subject. He has been President of the Royal Astronomical Society, the Institute of Physics and, most recently, the European Physical Society. Arnold Wolfendale is a passionate believer in the importance of Physics – and its adequate funding by Governments – and in the Public Understanding of Science.

Anatoly Erlykin is head research fellow of the P.N. Lebedev Physical Institute in Moscow, Russia. His early work was as an experimentalist at the Tien-Shan and Aragats mountain stations; later, he moved to the analysis of experimental data. He is author or co-author of about 240 publications on high energy interactions, cascade processes and the astrophysics of cosmic rays. Hobbies: history of physics, tennis and jazz.

features

noticeboard

Max Auwärter Award 2002

The Max Auwärter Foundation in Balzers, Principality of Liechtenstein, offers bi-annually the MAX AUWÄRTER AWARD for students and young scientists at universities, vocational colleges and other research institutions, who have published as single author relevant work in the field of surface physics, surface chemistry and organic or inorganic thin films. The award includes a citation and a prize-money of EURO 8.000,-- (EURO eight thousand) and may be split between several candidates.

Applications or proposals for the MAX AUWÄRTER AWARD 2002 should be submitted with four copies of the publication to be considered and the curriculum vitae of the proposed recipient describing his/her previous scientific activities by April 30, 2002 to

Prof. Hannspeter WINTER
Institut für Allgemeine Physik, Technische Universität Wien
A-1040 Wien, Wiedner Hauptstraße 8-10/134
FAX-No. ++43 1 58801-13499, email address winter@iap.tuwien.ac.at

A jury appointed by the Foundation Council will decide finally and indisputably about the awarding of the prize. Presentation of the MAX AUWÄRTER AWARD 2002 is scheduled for 25/26 September 2002 at the Annual Meeting of the Austrian Physical Society in Leoben, Austria.

Human Frontier Science Program

–opportunities for interdisciplinary collaboration and training in the life sciences–

The Human Frontier Science Program is a funding agency whose mission is to promote international collaborations in basic research in the life sciences, with special emphasis on novel and interdisciplinary research involving disciplines outside biology. In addition to its emphasis on interdisciplinary research, the HFSP offers special programs of international support for scientists early in their careers.

The HFSP is an independent agency that receives financial support from the governments of the G7 countries, Switzerland and the European Union. Collaborations are fostered at a global level through support for international, especially intercontinental, research teams focusing on specific interdisciplinary research projects, and through an international postdoctoral program that places special emphasis on encouraging young scientists from non-biological disciplines to apply their expertise to biological problems. It is fundamental to the philosophy of the HFSP that significant advances in the biological sciences will primarily be realized with the involvement of scientists trained in subjects such as physics, chemistry, mathematics, computer science and engineering.

Call for Letters of Intent to apply for a Research Grant:

International, interdisciplinary research teams are invited to submit Letters of Intent for collaborative Research Grants. Letters of Intent must be submitted online in a specific format via the HFSP web site. The deadline for submission is Wednesday April 3rd 2002 for awards to be made in March 2003. After review of the letters of intent, selected teams will be invited at the end of June 2003 to submit a full application in the Autumn. Further information and guidelines for applicants are available at http://www.hfsp.org.

The deadline for Long-term Fellowship applications will be in September 2002. Short-term fellowships may be applied for throughout the year. Calls for applications and other information about the HFSP and the science supported is distributed in an email-based newsletter, which can be subscribed to via the HFSP web site.

Condensed Matter Festival in Brighton

December 10th is the abstract deadline for the 19th General Conference of the EPS Condensed Matter Division, with the conference due to start on 7 April 2002 in Brighton, UK. The meeting is organised jointly with the annual IoP Condensed Matter and Materials Physics Conference, with the combined conference providing an excellent opportunity for meeting with and presenting work to a wide international audience.

The plenary talks at the conference focus on several key recent advances. Bertram Batlogg of ETH Zurich will discuss the sophisticated electronic properties of polymers and molecular crystals. Batlogg and his group have recently opened a whole new research field, demonstrating superconductivity to 50 K, electrically pumped lasing and low temperature carrier mobilities comparable to the highest values observed in semiconductors. Jeremy Baumberg (Southampton) will describe how to play with light-matter interactions in semiconductor microcavity structures, including the formation of bosonic quasiparticles, polaritons, which can be trapped and may allow thresholdless lasing.

The application of physics to biological systems will be another significant theme, including the physics and physical properties of natural and synthetic cells. Several talks will also focus on the ability of scanning microscopy techniques to probe superconductors and magnets on a nanoscale.

The combined meeting follows a similar format to both the CMMP and recent EPS CMD meetings. As well as the invited and Prize lectures, there will be about 15 general symposia covering broad, well-established areas of condensed matter physics, with another 50 mini-colloquia focusing on current and emerging topics.

The meeting offers an ideal opportunity for young researchers to meet with and present their work to a wide international audience. The conference opens with a Student Day on Sunday 11th April, presenting tutorial lectures on the subject of this year's Nobel Prize, Bose-Einstein condensates in condensed matter, as well as on the emerging field of spintronics, and soft condensed matter. For more information, follow the link from www.eps.org to physics.iop.org/IOP/Confs/CMD19.

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10 Job opportunities

The *Laser Physics and Non-Linear Optics* group of the University of Twente has been operating at the frontier of laser physics since the late sixties. The research is mainly focussed on advanced laser systems for identifying novel applications and to employ these systems for fundamental research. *Nederlands Centrum voor Laser Research (NCLR) b.v.* is a dynamic and innovative high-tech company whose mission is to research and develop advanced high power laser systems and to commercially exploit the results. NCLR is located on the premises of the University of Twente and closely collaborates with groups of the University of Twente for its basic research on lasers and applications. NCLR and the Laser Physics group employ a joint staff of 30 scientists in well equipped laboratories.

For the following applied and fundamental projects we are looking for young, enthusiastic *PhD students, Post Docs* and *Marie Curie Fellows*, who are willing to function in a multidisciplinary environment and are capable to contribute to the development of next generation laser systems and their applications.

1. **Novel high performance gas and solid state laser systems with excellent beam quality**
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2. **Fundamental physics with light**
   One project involves research on certain media in which light can be slowed or frozen using electromagnetically induced transparency (EIT). New issues of frozen light, such as novel realisation schemes and the phase and quantum properties of the re-emitted radiation will be studied. Another project researches photonic bandgap materials using ultrashort IR pulses to demonstrate new types of solitons and of optical switching with femtosecond speed.
3. **Electron sources and accelerators**
   One project involves research on and development of large area electron-sources (emitting area of up to 100 cm^2) and their applications as, e.g., X-ray pre-ionization source for kW excimer lasers and novel type of high power gas lasers. Another project studies the formation of a laser induced long plasma channel. This channel will be used to guide a TW femto-second laser pulse to accelerate electrons to ultra-relativistic speeds in the plasma wake of the laser pulse.
4. **Continuous wave microwave free-electron laser for industrial applications**
   In this project a compact cw free-electron laser will be developed in the frequency range from 20 – 100 GHz with an average power of more then 1 kW. Besides studying the physics of this oscillator, the device will also be used to research several applications.

We offer the candidates a stimulating environment and well equipped research facilities in which they can perform their challenging research.

If you are interested or if you want more information please contact

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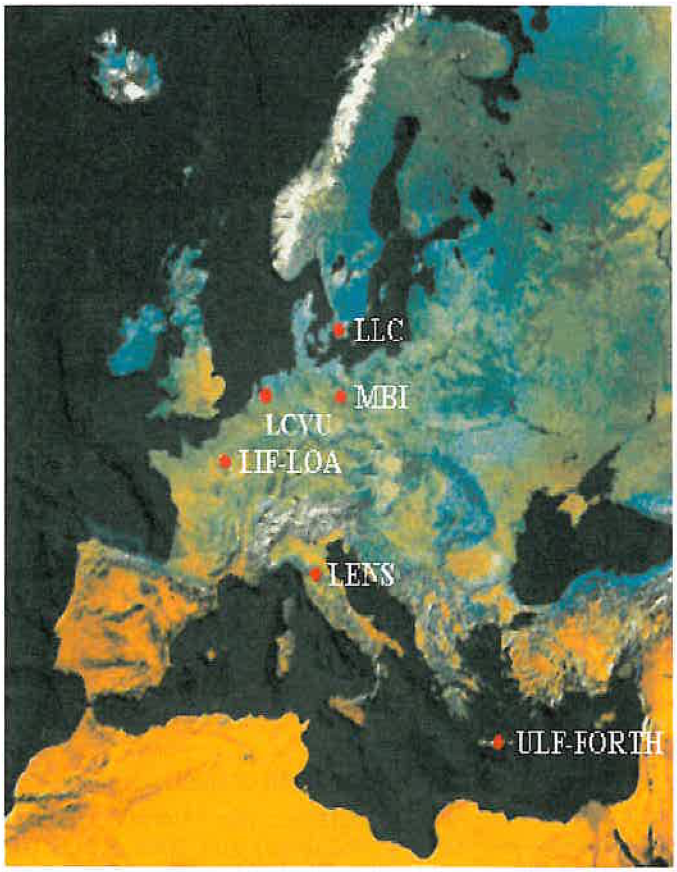
LIMANS III: European Cluster of Large Scale Laser Installations



LCVU:
Laser Centre Vrije Universiteit
Amsterdam, Netherlands

LENS:
European Laboratory for Non-Linear Spectroscopy
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LIF-LOA:
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École Polytechnique
Palaiseau, France

LLC:
Lund Laser Centre
Lund University
Lund, Sweden

MBI:
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for Nonlinear Optics and Short Pulse Spectroscopy
Berlin, Germany

ULF-FORTH:
Ultraviolet Laser Facility
Foundation for Research and Technology - Hellas
Iraklion, Crete, Greece

Call for proposals

The above institutions are funded under the current IHP Programme of the European Union to provide access to researchers or research teams of Member States and Associated States. Within the cluster they offer state-of-the-art scientific laser equipment and research environments with a wide range of research opportunities, allowing for today's most advanced light-matter interaction experiments in broad regimes of power, wavelengths, or pulse durations. Access is provided free of charge; travel and living expenses are covered by the host institution.

Interested researchers are invited to contact the LIMANS III website at **http://limans3.mbi-berlin.de**, from where they find all relevant information about the participating facilities and local contact points. Access is granted on the basis of proposals, which will be reviewed by an external panel of referees. Details about the submission procedure may be found under the LIMANS III website. Applicants are encouraged to contact any of the facilities directly to obtain additional information and assistance in preparing a proposal. Proposals are accepted at any time and from any eligible researcher or research team.

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