Summary of the ESO-CERN-ESA Symposium on Astronomy, Cosmology and Fundamental Physics

Held at Garching bei München, Germany, 4-7 March 2002

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Astronomy, cosmology and fundamental physics have thriving interfaces and modern research topics that bring together scientists from these different domains. New results and open questions call for meetings covering all of these fields. This year saw the first such meeting jointly organized by the three organizations ESO, CERN and ESA. The symposium took place in Garching on 4-7 March with about 200 participants. It gave a broad overview and so consisted largely of invited talks, with some contributed talks and over 50 posters on display.

The Director General of ESO, Dr. Catherine Cesarsky, opened the Symposium with an overview of the current state of many of the fields to be discussed at the Symposium. She stressed the rapid pace of development in all of these areas, ranging from the spectacular convergence of the major cosmological parameters to the discovery of over 80 extrasolar planets.

N. Turok introduced the cosmology part of the Symposium with a stimulating talk provocatively entitled "The Early Universe – Past and Future". He challenged the relation of the remarkable cosmic concordance picture with standard inflationary models of the Universe, and described a possible alternative involving an infinite recycling of the Universe through colliding branes, in which time is eternal. Possible tests could be provided by a correlation of an all-sky CBR map with X-ray surveys or by CBR polarization measurements.

A series of talks dealt with the evidence for and remarkable convergence of the cosmological parameters. P. de Bernardis described the amazing new results from the current microwave background observations. With the improved data three accoustic peaks in the structure of the microwave background are seen. Results will soon be coming from the MAP satellite, which has already surveyed 85% of the sky. Polarization measurements will be critical in testing the adiabatic inflationary scenario. B. Leibundgut gave the evidence from high-redshift supernova studies for an accelerating Universe. He gave a critical assessment of the steps in this analysis, and stressed the importance of the local calibrators. In the future thousands of distant supernovae will be accessible with the large telescopes. Y. Mellier spoke on the observations of cosmic shear from weak gravitational lensing, stressing the excellent agreement between six different teams working with six different telescopes. He mentioned the problem of biasing, and showed that future large-scale surveys such as that being planned on the CFHT will provide easy discrimination. H. Böhringer provided the evidence from clusters of galaxies, showing that three independent approaches all give a good fit with the concordance model.

A press conference was held during the Symposium. From left to right are Prof. Sir Martin Rees (Cambridge University), Dr. David Southwood ESA), Dr. Catherine Cesarsky (ESO Director General), Dr. John Ellis (CERN), and Dr. Michel Mayor (Observatoire de Genève).

A comprehensive overview of the current state of our knowledge of the cosmological parameters was provided by L. Krauss. He started with the Hubble constant, showing the excellent agreement between different groups. He summarized results from the CMB fluctuations, the ages of the oldest stars, the baryon density from deuterium and ^{3}He measurements, the dark matter density from X-ray clusters, the large scale structure results from the Sloan and 2DF surveys, and concluded that everything fits (the “concordance model”), but that the theoretical basis remains unclear.

A. Vilenkin addressed the Cosmological Constant Problems (CCPs) and their Solutions. The two major problems cited were the value of the vacuum energy density, and the “time coincidence problem” (i.e. why we happen to live just at the time when the vacuum energy dominates). He considered possible particle physics solutions, Brane World solutions, Quintessence models, and the Cosmological Anthropic Principle. He concluded that the anthropic approach naturally resolves both CCPs and opens windows to the super-large scales beyond the visible Universe.

One of the major transition phases of the observable Universe, the “Reionization Epoch” when the first stars formed and ended the “Dark Ages” that followed recombination, was discussed by P. Madau. He described theories for the development of the early massive structures, and reviewed evidence that the helium reionization epoch may already have been detected.

Direct searches for dark matter candidates were reviewed by C. Tao. Gravitational microlensing searches for massive baryonic objects explain at most 20% of the dark matter in our Galaxy. Other searches focus on the possible existence of hypothetical massive, neutral particles which interact only very weakly with matter, such as neutralinos. A claimed signal from the DAMA experiment at Gran Sasso has not been confirmed by other experiments. Several experiments are presently taking data and more sensitive experiments are in preparation.

P. Hernandez summarized the evidence for neutrino oscillations. Recent results using solar and atmospheric neutrinos provide convincing evidence for neutrino oscillations, requiring that neutrinos have a non-zero mass. Neutrino oscillations are probably the most important new phenomenon discovered in particle physics in the last decade (although their masses are not sufficient to provide an appreciable contribution to dark matter). Intense experimental activity is presently in progress. In the longer term, neutrino beams with much higher fluxes will be required to study this phenomenon in detail, including the possible observation of CP violation.

The Standard Model of Particle Physics and the tests performed at low energies were described by A. Pich, highlighting the very impressive precision achieved in comparing measurements with theoretical predictions in particular cases. He also reviewed recent results on CP violation. During the last year large CP violating effects have been reported, and future experiments should clarify the mechanisms responsible for this phenomenon.

High energy tests of the Standard Model were reviewed by F. Gianotti. These include the studies of the W and Z bosons at the e^+e^- collider LEP and the discovery of the top quark at the Fermilab proton-antiproton collider. The W and Z masses are presently known with a precision of 0.05% and 0.0024%, respectively, and other parameters of the Standard Model measured at LEP are measured with typical precisions of the order of 0.1%. In addition, the LEP experiments have provided for the first time a clear demonstration of the existence of the three-boson interaction predicted by the electroweak theory. In the framework of the Standard Model, the LEP measurements have been used to constrain the mass of the Higgs boson, which is the only missing piece of the theory. The prediction is $m_H = 85^{+54}_{-34}$ GeV, giving good hopes for the discovery of this particle at one of the future high-energy colliders (the improved proton-antiproton collider at Fermilab, which is presently in the commissioning phase, or, more likely, the CERN LHC). Gianotti also reviewed the hint for the production of the Higgs boson with a mass of 114 GeV, obtained by the LEP experiments during the last year of LEP operation. Gianotti concluded that the prospects to discover the Higgs boson at the LHC are excellent, as are the prospects to discover the supersymmetric partners of known particles, if they exist.

Pierre Le Coultre showed how one of the LEP detector (L3) can be used as a detector for cosmic ray muons. The results will constrain cosmic ray models which are used to predict the fluxes of atmospheric neutrinos.

Despite its successes, the Standard Model of particle physics contains too many parameters and theorists do not see it as the final theory. In addition, it does not include gravitational interaction, and the mass of the standard Higgs boson becomes unstable when quantum corrections are taken into account. J. Ellis discussed new physics which could solve these problems. The most popular model is Supersymmetry, which adds a new scalar boson to each known fermion, and a new fermion to each known boson. These hypothetical particles have not yet been discovered, but theorists are confident that their masses are lower than 1 TeV, if they exist. The hunt for supersymmetric particles will be one of the main activities at the LHC. Ellis discussed additional theoretical ideas which could give rise to unexpected and spectacular events at the LHC.

Stimulated by a recent claim on the basis of high redshift QSO spectra that the fine structure constant Alpha may be varying with cosmic time, G. Fiorentini reviewed other possible evidence for its variation. So far the only positive claim is that from the QSO spectra, conflicting with the other evidence, and more dedicated experiments will be required to solve this puzzle.

The first of a series of talks on high energy astrophysics was given by E. van den Heuvel. He spoke about Gamma Ray Bursts, the most powerful known cosmic explosions. The models involve relativistic fireballs from either super/hypernovae ("collapsars"), or the mergers of neutron stars with other neutron stars or black holes. A few thousand such bursts have now been observed; the most distant so far known is at $z = 4.5$. The Swift satellite, to be launched next year, will provide rapid response and accurate positions for follow-up by telescopes such as the VLT.

H. Völk reviewed the subject of high-energy γ-rays. In the region up to a few GeV, these γ-rays are detected by measuring their conversion to e^+e^- pairs in satellites, while at higher energies (up to 100 TeV) ground-based Čerenkov detectors are used to detect the electromagnetic showers produced in the Earth's atmosphere. Progress in this field is expected from the future Gamma Ray Large Area Telescope (GLAST) satellite mission which will study γ-rays up to energies of 100 GeV by means of a detector combining large acceptance and excellent angular and energy resolution.

Studies of cosmic rays at extremely high energies (up to 10^{20} eV) were reviewed by A. Watson. The interaction of these particles with the Earth's atmosphere produces extended air showers which are studied by counting the muon multiplicity in a large number of detectors scattered over a large area. The large Pierre Auger Laboratory in Argentina will start data taking soon. Another experiment, EUSO, will measure the nitrogen fluorescence from very high-energy cosmic rays using detectors mounted on the International Space Station, with the advantage of covering a much larger area than ground-based experiments.

The presence of some reported events of extreme energy (above 10^{11} GeV), such that proton primaries should have been stopped by the cosmic microwave radiation, raises an important puzzle. With respect to primary charged particles, high energy neutrinos and γ-rays have the advantage of pointing to the source. Neutrinos interact weakly, so they are the only particles that can provide information from the edge of the Universe and from sources deep inside active regions. However, detectors with very large masses are needed. F. Halzen reviewed the status of AMANDA, a large detector consisting of strings of photomultiplier tubes buried deep in the Antarctic ice cap and looking down to measure Čerenkov radiation in ice from charged particles. Other underwater experiments built on the same principle are operating and in preparation.

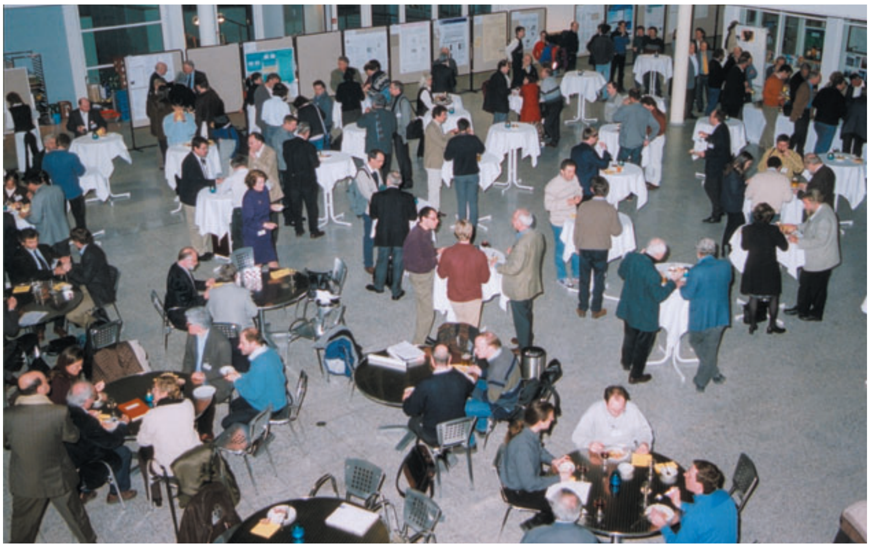
The X-ray background has now been almost completely resolved into discrete sources by the latest satellites, Chandra and XMM. As described by G. Hasinger, many of these sources involve optically obscured active galactic nuclei (AGN), with accretion onto central black holes. The redshift distribution peaks at a surprisingly low redshift, $z \sim 0.6$, and there is a clear deficit at $z > 4$, indicating a decrease in the space density at high redshift, in agreement with earlier results on QSOs. Future missions such as Rosita, Duet and Xeus may find some of the very rare high-redshift X-ray QSOs.

L. Woltjer gave an assessment of our current knowledge of neutron stars. The masses and temperature fit the "standard solution", and there have been many models that agree. Pulsars have provided new constraints and problems, one of which was the relatively few radio pulsars located in supernova remnants. Now it is known that there are objects in about 80% of supernova remnants. There has been a continuing debate over the velocities of neutron stars, and its resolution will be important in the understanding of their origins.

The ubiquity of black holes in the centres of galaxies is now widely believed. R. Bender outlined the evidence for several cases. Spectacular new evidence has come from X-ray spectra, which indicate strong gravitational effects. Only supermassive black holes provide a plausible explanation for all such phenomena, although direct evidence is still hard to obtain. Supermassive black holes appear to be present in most galaxies, and there are certainly enough to explain the QSO phenomenon. A. Eckart showed striking evidence for the black hole in the centre of our own Galaxy. The proper motions of stars in the inner region imply an enclosed mass which is almost certainly a black hole.

Gravitational waves were the subject of the next two talks. B. Schutz reviewed the possible sources of gravitational waves. The merging of two black holes of a million solar masses at $z = 1$ would give an amplitude 5 orders of magnitude higher than the detection threshold of LISA. The merger would take only minutes but the spiral down, with a varying frequency of 0.1 to 10 mHz, would take months. For stable binaries, observing the signal over many periods greatly helps in reaching lower amplitudes. There is complementarity between detectors on the ground (frequencies above 10 Hz) and detectors in space (set at frequencies below 0.1 Hz), The amplitude sensitivity should in both cases reach below 10^{-22} K. Danzmann then outlined the prospects for detecting gravitational waves. He showed that resonating ground detectors were limited to the detection of a supernova in the galaxy but that more promising prospects were offered by interferometers. LIGO should reach to 20 Mpc soon for such a signal, and to 200 Mpc in 2006. For LISA, prospects are great for the observation of massive black holes merging anywhere in the universe.

S. Vitale described other space missions on fundamental physics under study at ESA. STEP should test the equivalence principle at the level of 10^{-18}, 6 orders of magnitude better than



Participants enjoying the Symposium buffet dinner.

the present limit. The ACES mission, on the ISS, should produce a very high precision clock and the HYPER one (free flyer) should study cold atom interferometry in space with the prospect of making very high sensitivity gyroscopes. R. Battiston discussed astroparticle physics from space, pointing out that cosmic ray studies were the beginning of particle physics. He reviewed the studies of cosmic rays made with balloons and satellites, and the prospects for searches for new particles: antimatter, dark matter, and ultraheavy particles. A new detector with a sensitivity to anti-nuclei improved by a factor of 1000 will be installed on the International Space Station.

G. Raffelt discussed how stars can be intense sources of weakly interacting particles. One such particle is the axion, which was conceived to explain the absence of CP violation in the strong interaction. A CERN experiment (CAST) will search for axions using an LHC magnet pointed at the Sun and detecting the axion – X-ray conversion in the magnetic field.

F. Paresce described the first science results from the VLT interferometer. A large number of stellar sources with correlated magnitudes brighter than $K \sim 6$ and $K \sim 3$ have been observed with the 8m and 40cm telescopes respectively, allowing the establishment of tighter constraints on theoretical stellar models. The great scientific potential of the full VLTI system was outlined.

A group of three talks dealt with the exciting new field of extrasolar planets. E. van Dishoeck described observations and theories of forming planetary systems. Infrared and millimetre emission comes from dusty disks surrounding many young stars. The chemistry of these circumstellar disks, deduced from observations of the many molecular lines, provides essential clues to their evolution and planet formation. For future observations high angular resolution will be essential, and ALMA will play a dominant role. Other important facilities will include the VLT/VLTI, SIRTF, NGST and Herschel.

The spectacular advances in the discovery of extrasolar planets (from none in 1995 to over 80 today) were described by M. Mayor. There is a huge diversity, which was unexpected. Many are at 0.03–0.05 AU, many have eccentric orbits, and typical masses are in the range 0.15–10 $M_J/\sin i$. Most have been discovered from radial velocity measurements. Photometric transits have also now been observed – 46 of them from one recent survey alone. And there are now 7 or 8 published systems with multiple planets. Many aspects are now being actively studied – the origins of the "hot Jupiters", the mass functions of substellar companions, the orbital eccentricities, the relation to the metallicity of the star. For the future, M. Mayor mentioned the new HARPS instrument for the ESO 3.6m telescope, the possibility of astrometry with Prima on the VLT, and prospects in space.

M. Perryman followed on from M. Mayor's talk by considering the prospects for the detection of earth-like extrasolar planets – lower mass systems, in particular ones where life might form. He described prospects with the astrometric mission GAIA, due for launch in 2010-2012. With its 1 microarcsec accuracy, it will detect 20,000–30,000 planetary systems, and will find ~10,000 planetary systems by photometry alone. The later Eddington mission will detect photometric transits of 500,000 stars, including some 2,000 due to earth-mass planets. The photometric accuracy will suffice to detect planetary rings and moons. Finally, he considered the conditions thought necessary for life. The DARWIN mission, with a launch date sometime after 2015, would be a 50-250m baseline interferometer employing six 1.5m telescopes. It would make possible direct imaging of solar systems like ours, and seek spectral signatures of possible biomarkers. Surface imaging of earth-like extrasolar planets may be possible with the next generation of extremely large telecopes (OWL, CELT), and very large space arrays.

During the last afternoon there were talks on the future perspectives at ESA, CERN and ESO. Many exciting projects are under construction or at the planning stage in all three organisations. D. Southwood gave a long and impressive list of ESA space missions, present and future, with five launches in just the next year and plans extending well over a decade into the future. He concluded with comments on the role of science in Europe, highlighting the declaration of the EU Council of Ministers that "Europe should become the most competitive and dynamic knowledge based economy in the world".

The future of CERN was reviewed by J. Ellis. In the short term most of the CERN effort is devoted to the construction of the Large Hadron Collider (LHC), a machine where two proton beams, each with an energy of 7 TeV, collide head-on with an interaction rate of $5\ 10^8\ s^{-1}$ in each of two general-purpose detectors. The LHC and detectors are now in the construction phase and physics should start in 2007. The LHC will also accelerate heavy ions to study the so-called "quark-gluon plasma", which is the state of matter of the early Universe before baryogenesis. Ellis also reviewed the R&D activity on accelerator technology which goes on in parallel with LHC construction, to prepare for the post-LHC era.

ESO's current and future programmes were outlined by the Director General, C. Cesarsky. All four 8-meter unit telescopes of the VLT are operating with high efficiency, and the suite of VLT instruments is rapidly increasing. Two survey telescopes are also being added. Adaptive optics systems have given the VLT images added sharpness, and the VLT Interferometer has already started producing science, as outlined earlier by F. Paresce. A major new ESO project is the Atacama Large Millimeter Array (ALMA), which, with its 64 12-meter antennas operating at 5000m altitude, will become a millimeter/submillimeter equivalent of the VLT/VLTI and NGST. It will be an equal partnership with the U.S. and possibly Japan, with completion foreseen for 2011. Further into the future will be OWL, a giant 100-meter diameter optical-infrared telescope, and scientific and technical investigations for this facility are already well underway.

The concluding lecture was given by M. Rees. He saw the Symposium as linking the very small with the very large, and mentioned three major developments discussed at the meeting: the discovery of extrasolar planets, the evidence on neutrino masses, and the determination of important key numbers of the Universe in just the last few years. He remarked on how conclusions regarding the flat Universe and its contents (5% baryons, 25% dark matter, and 70% dark energy) have come from independent sources, with amazing agreement, and the challenges they pose to particle physics. In ten years hence he expects the basic parameters to be well known, and he reflected on the two major challenges that may face us in the post-2010 era: an understanding from the very early ($<10^{-12}$ sec) Universe as to why these numbers have these particular values, and an understanding of cosmic evolution at $>10^8$ yrs. In the latter context he considered the possible detection of the earliest luminous objects, the formation and evolution of galactic nuclei and black holes, the mysteries and potential of Gamma Ray Bursts, and the probable detection of gravitational waves from such objects. Finally, he speculated on the mysteries of the very early Universe. In particular, why do the laws of our Universe have latent in them all the complexity of our Universe? There are now many models, and he wondered how many Big Bangs? According to the Cosmological Anthropic Principle, the laws of our Universe just happen to be "the by-laws governing our patch". With the rapidly increasing data rates he anticipated the development of huge databases making possible a wider participation in science, and he felt that the crescendo of the last few years will continue with the great new scientific facilities becoming available.

Finally, over 50 poster papers were presented, covering a wide range of exciting topics including cosmological models, Quintessence, the CMB, cosmic shear, the cosmological constants, Gamma Ray Bursts, galaxy formation, galaxy clusters, gravitational lensing, new space missions, probes for supermassive black holes, quasar absorption line studies, experiments in fundamental physics, extrasolar planets and others. The programme included a fascinating special evening lecture by Jean-Claude Carrière, well-known author, on the subject of "Time".

The full proceedings of this Symposium will be published in the Springer-Verlag series "ESO Astrophysics Symposia".

The Scientific Organizing Committee was comprised of: R. Battiston (Univ. of Perugia), R. Bender (Univ. of Munich), A. de Rujula (CERN), L. Di Lella (CERN), C. Fabjan (CERN), A. Gimenez (ESA), M. Jacob (JAD), F. Pacini (Arcetri), A. Renzini (ESO), P. Shaver (ESO; chair), M. Spiro (Saclay), B. Taylor (ESA), P. van der Kruit (Univ. of Groningen), S. Vitale (Univ. of Trento), S. Volonte (ESA), and M. Ward (Univ. of Leicester).

We are most grateful to the Symposium Secretaries Britt Sjöberg of the ESO/ESA ST-ECF and Christina Stoffer of ESO for the organizational work before and during the Symposium, and to the ESO students and fellows, led by Harald Kuntschner, who looked after the facilities during the meeting.

The Tarantula Nebula in the Large Magellanic Cloud – ESO/MPG 2.2-m telescope (ESO PR Photo 14a/02.)