Organisation for Economic Co-operation and Development (OECD)

Global Science Forum

Workshops on Future Large-Scale Projects and Programmes in Astronomy and Astrophysics

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Final Report

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Executive Summary

Two Workshops on Future Large-Scale Projects and Programmes in Astronomy and Astrophysics were authorised, following a proposal from Germany, by delegates to the Ninth Meeting of the Global Science Forum in June 2003. It was agreed that there was a need for an OECD-wide consultation (including important non-member countries) to assist national administrations in their strategic planning for large-scale projects and programmes in astronomy and astrophysics. The consensus findings and recommendations from the workshops are summarised below.

Status of Astronomy and Astrophysics

Impressive progress has been made in astronomy and astrophysics in the past few decades. There is now a convincing and coherent model of the origin, evolution and distribution of the visible matter in the Universe, from asteroids and planets to the large-scale structure of clusters of galaxies. This model nevertheless fails to explain the composition or origin of some 96% of the mass/energy in the Universe, and does not explain the distribution or origin of life. Important "Big Questions" remain unanswered. They define the need for new projects and programmes in astronomy and astrophysics, to be developed over the next one or two decades.

Some of the most important future large projects and programmes will have to be organised and financed on a multi-national basis. As research efforts coalesce around a small number of global-scale facilities, national scientific communities and science administrations will face difficult choices about pooling their resources to participate in new international undertakings, involving both challenges (e.g., a loss of autonomy) and opportunities (e.g., access to cutting-edge equipment and technology). Decision-makers will need to ensure that the inventory of resources (facilities, instruments, access rights, observing time) is commensurate with national requirements and the size of the scientific community.

The Need for a Global Consensus Vision

Based on advice of the scientific community, funding bodies should seek to advance astronomy in a balanced, integrated, and globally-coordinated way, from cosmology to planetary studies. Links to other relevant fields such as high-energy and nuclear physics, earth sciences, and biology should be taken into account. A science-based balance should be sought between surveys, special-purpose, and general-purpose projects. For the latter, it is desirable to promote the opening of unexplored "windows" in instrumental parameter space. The selection and operation of new projects should be based both on the science case and on the opportunities for serendipitous discovery, which have proved so valuable in the past.

In this context, a global science-based consensus view on a long timescale, bringing together national and regional strategic plans for both space- and ground-based research, would be invaluable at national levels, giving agencies and governments a broader international perspective, and enabling smaller countries to see what is being planned elsewhere. The desirability and feasibility of a long-term integrated vision for large projects and programmes should be addressed, with the goal of informing funding decisions on the next generation of large projects. Regular community meetings to feed into such a consensus view would be essential to its credibility.

Complementarity of Space- and Ground-Based Observations

Astronomy requires a multi-wavelength approach to address the key scientific questions and to open up new opportunities for observations. Ground- and space-based observations are vital and complementary to the future of astronomy, so good communication and co-ordination between the corresponding agencies are essential. As the costs and timescales associated with the largest ground-based projects increase, it becomes ever more important to ensure that the two modalities develop in a coordinated, mutually-supportive way, based on shared scientific goals, with due consideration of relative costs and technological

feasibility. Therefore, interested countries and regions should establish or strengthen processes through which strategic investment plans for large ground- and space-based astronomy are developed and harmonised. In cases where both approaches may be appropriate for carrying out important observations, support for R&D should be provided such that, ultimately, informed investment choices between space and ground can be made, maximising scientific gain and ensuring optimal use of financial resources.

Key Technological R&D

Progress in astronomy has always been driven by technological innovation, and this will continue to be true for the next generation of big projects. A global strategic view of technological requirements and key R&D areas related to possible new projects (analogous to the scientific strategic view outlined above) would be invaluable at national and regional levels to give agencies and governments a broader perspective. It could also enable smaller countries to see what is being planned elsewhere, and perhaps identify areas for participation. The maximum benefit would come from a strategic view that would transcend the boundaries of individual projects and possibly even subjects.

Selection of Sites

The choice of the best location is vital to the success of a large ground-based astronomical facility. Evaluation and protection of potential sites can begin well before selection and construction. For existing and potential sites at all wavelengths, measures should be taken to limit electromagnetic interference and light pollution, with the involvement and due consideration of the interests of all concerned parties. Interested countries should incorporate open and consensus-based site selection procedures when contemplating new international collaborative projects.

While facilities can bring benefits to host countries and enhance the lives of local inhabitants, the relationship between a facility and its surroundings is multi-faceted and bi-directional. Planning should explicitly anticipate and address local environmental and cultural concerns.

Data Management

The huge volume of digital information flowing from new observatories raises the challenge of collecting, using, storing, and sharing data. The workshops identified a number of major issues in the context of a new community-based vision for a common research infrastructure: the “Virtual Observatory”. Impressive progress has been made and the momentum of the International Virtual Observatory Alliance will ensure sustained progress, provided support and funding are made available.

Agencies and governments should recognise that this is an important long-term issue and should therefore co-ordinate plans on a long-term basis, encouraging the broadening of the existing VO collaboration into a fully representative global activity. New projects and facilities must take data management, storage, maintenance, and dissemination into account at the earliest planning stages, consulting potential users in the process. The workshop participants supported the principle of open access to data, assuming the conventional proprietary period for the data takers.

Generic Issues

In addition to the scientific and technical issues that must be addressed in planning a major new project or programme, there are a range of important generic (i.e., legal, organisational, managerial) issues to be considered by governments and agencies. These are not unique to astronomy and there could be value in OECD compiling and evaluating a data base of current large projects in many fields. A co-ordinated approach across governments in evaluating these issues would provide valuable information and advice to those who will make the final decisions. There are lessons to be learned from the history of the development of large projects in many fields.

A major issue of principle to be settled is that of access and participation of countries outside the inner core of initial advocates, not just in the utilisation of the facilities, but also in the R&D and construction phases. Governments and agencies with an interest in future large projects and programmes could start discussions on the key generic problems, such as access and participation, including issues such as structure, funding, and management of collaborations.

Background/Introduction

The workshops were authorised by delegates to the Ninth Meeting of the Global Science Forum in June 2003, based on a proposal from the Delegation of Germany. The rationale for the activity was stated in the German proposal:

> Earth- and space-based instruments often cost hundreds of millions of dollars, require more than ten years for design and construction, and are often exploited by a world-wide community. Enormous datasets are being archived, and there are ambitious plans for "Virtual Observatories" using the increasing power of the Internet and, in the future, the Grid. Increasingly, projects and facilities are planned and implemented on an international basis, yet at the moment there are only ad-hoc ways to agree on priorities or cost sharing. Long-range priorities are periodically prepared at national or regional levels, but there is a need for an OECD-wide consultation (including important non-member countries) to assist national administrations in their strategic planning.

By design, the workshops were attended by funding agency officials and prominent scientists. They were not intended to be scientific meetings. Special care was taken to not duplicate or interfere with the consultations that take place in the scientific community, or with national or regional priority-setting and planning. The limited goal of the workshops was to examine critically the processes through which decisions about future large facilities will be made. Accordingly, scientific arguments and data were introduced only as needed to shed light on these processes, and specific projects were mentioned only to illustrate past or potential future developments in astronomy[1].

The first of the two workshops was hosted by the European Southern Observatory (ESO) and was held on December 1-3, 2003 in Munich, Germany. It was attended by government-appointed delegates from fourteen Global Science Forum Member countries and Observers[2], three non-OECD countries[3], representatives of ESO, the International Astronomical Union (IAU), invited speakers, and the OECD secretariat. The second workshop was hosted by the Delegation of the United States, and was held on April 1-2 in the Washington, D.C. area. It was attended by government-appointed delegates from seventeen Global Science Forum Member countries and Observers[4], three non-OECD countries[5], representatives of ESO, the IAU, invited experts, and the OECD secretariat. The major space agencies from Europe and the United States (the European Space Agency and the National Aeronautics and Space Administration) declined to send representatives to either workshop.

1 Thus, any mention in this report of a specific project is purely illustrative and does not imply endorsement.

2 Australia, Belgium, Canada, the European Commission, Finland, Germany, Italy, Japan, the Netherlands, Norway, South Africa, Switzerland, the United Kingdom, the United States.

3 Brazil, Chile, India.

4 Australia, Belgium, Canada, Finland, France, Germany, Italy, Japan, Korea, the Netherlands, Norway, Spain, South Africa, Sweden, Switzerland, the United Kingdom, the United States.

5 Brazil, Chile, India.

Both workshops were chaired by Dr. Ian Corbett of the European Southern Observatory. Preparations were supervised by an International Steering Committee appointed by OECD Members. A list of participants is appended to this summary[6].

The Global Science Forum of the Organisation for Economic Co-operation and Development is a venue for consultations among senior science policy officials of the OECD Member and Observer countries on matters relating to fundamental scientific research. The Forum's activities produce findings and recommendations for actions by governments, international organisations, and the scientific community. The Global Science Forum's mandate was adopted by OECD science ministers in 1999, and an extension until 2009 was endorsed by ministers in February 2004. The Forum serves its member delegations by: exploring opportunities for new or enhanced international co-operation in selected scientific areas; by defining international frameworks for national or regional science policy decisions; and by addressing the scientific dimensions of issues of social concern.

The Global Science Forum meets twice each year at OECD headquarters in Paris. At these meetings, selected subsidiary activities are reviewed and approved based on proposals from national governments. The activities may take the form of studies, working groups, task forces, and workshops. The normal duration of an activity is one or two years, and a public policy-level report is always issued. The Forum's reports are available at www.oecd.org/sti/gsf.

This report reflects the consensus of all government-appointed delegates who attended one or both workshops. It was prepared under the supervision of the International Steering Committee.

Overview of the Status of Astronomy and Astrophysics

The entire scientific enterprise has made remarkable progress in recent decades. But a case can be made that astronomy has truly entered a Golden Age, with discoveries and capabilities that amaze and delight expert and layman alike. Neither the OECD workshops nor this report is an appropriate venue for summarising the achievements of astronomy (or its detailed scientific prospects for the future), but a few illustrative examples can convey the context within which the next generation of large projects and programmes are expected to expand and enlarge on recent accomplishments.

Birth of the Universe and its fundamental constituents

Almost all astronomers accept that the Universe began about 13.8 billion years ago in an event, not yet explained or understood, termed the "Big Bang". Approximately 300,000 years later, the Universe had cooled and expanded enough to allow the formation of the first stable atoms (hydrogen and helium). From that moment onwards, photons have travelled freely throughout the Universe. This remarkable transparency makes it possible for astronomers to collect and study radiation that was emitted from objects at all epochs[7].

Measurements of gravitational lensing, velocity distributions in clusters of galaxies, as well as of galaxy rotation curves, have confirmed the existence of gravitationally-interacting "dark matter" of unknown identity, which is five to ten times more abundant than the familiar everyday matter out of which atoms,

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[6] The Steering Committee members are identified with an asterisk in the list of participants.

[7] The transparency of the Universe, and the finite speed of light, enable astronomers to literally look back in time, but they impose limitations as well. For instance, only a small fraction of the Universe may ever be observable. Furthermore, all electromagnetic radiation that existed before the Universe was 300,000 years old was absorbed almost as soon as it was emitted, so there is no chance of ever detecting photons from that early epoch. There is hope, however: neutrinos and even gravity waves from that remote time (including the Big Bang itself) might some day be observable.

molecules, stars and galaxies are made. Even more mysterious is the finding that the Universe appears to be filled with "dark energy" – potentially a property of space-time itself – which comprises the majority of the mass-energy content of the Universe and accelerates its expansion[8]. Furthermore, it has been found that the geometry of the space of the Universe is essentially flat, which means that the Universe probably experienced an extremely fast expansion, termed "inflation", almost immediately after the Big Bang.

Formation of the first stars and galaxies

Shortly after it was born, the Universe consisted of a very hot plasma: ionised gas. But some 300,000 years after the Big Bang, all hydrogen in the Universe was in the form of neutral atoms. As presently observed, all hydrogen between galaxies is ionised, even out to the most distant quasars which are observed less than one billion years after the Big Bang. Therefore, re-ionisation must have happened sometime during the first billion years. Theory predicts that this happened at a redshift somewhere between 10 and 20 and was due to the very large amounts of ultraviolet radiation produced by the first generations of hot massive stars (and, possibly, quasars). Astronomers have, however, no direct observational evidence of what actually happened at that time. New and more powerful generations of optical/infrared telescopes (such as the proposed 30-, 50- and 100-metre telescopes) and radio telescopes (for instance, the proposed "Square Kilometre Array", SKA) will be required to cross the re-ionisation boundary and to bring the earliest objects from the preceding "dark ages" into view. Optical and infrared afterglows of gamma-ray bursts (which for a short while can be a million times brighter than supernovae), associated with highly energetic explosions of short-lived massive stars ("hypernovae") offer great promise for yielding information on the star formation history of the Universe out to redshift 20 and possibly beyond. The proposed new telescopes could probe the complete evolution of large-scale structure at least out to a redshift value of 2, which will yield new information on the distribution of dark matter and dark energy in the Universe.

Extreme objects, extreme physics

Galactic nuclei harbour supermassive black holes that give rise to exotic phenomena: near-light-speed powerful outflows ("jets") of charged particles, and copious emissions of high-energy electromagnetic radiation from X-rays to ultra-high energy gamma-rays that are thousands of times more energetic than those produced at the most powerful accelerators. Collapsed objects – neutron stars and black holes – arise at the end of the thermonuclear evolution of stars. They are the most concentrated forms of matter in the Universe, with the strongest gravitational fields, vastly larger than could ever be produced in a laboratory. Their study opens up new domains of physics and allows unique tests of some of the most exotic predictions of Einstein's Theory of General Relativity, such as the existence of event horizons and the dragging along of space-time around rotating compact objects. The latter is expected to be observable in accreting millisecond pulsars (neutron stars) and in the X-ray spectra of the inner parts of accretion disks around black holes. Furthermore, the formation process of supermassive black holes presumably involves black hole mergers – which should be major sources of gravitational waves, observable with future ultra-sensitive gravitational wave antennas in space, such as the Laser Interferometer Space Antenna, LISA. The accretion process of matter onto black holes is expected to generate ultra-high-energy neutrinos, which could be observable with Earth-based detectors, planned as well as presently under construction.

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8 This expansion changes the frequencies at which spectral features (such as emission or absorption lines) are observed, a phenomenon known as "redshift". For any astronomical object, the value of the redshift is the ratio of the frequency at which the radiation was emitted, to the frequency at which it is observed today on Earth, minus one. This quantity is indicative (in a somewhat theory-dependent way) of the time elapsed since the radiation was emitted. For example, a measured redshift value of one indicates an object observed as it was seven billion years ago, whereas a value of ten corresponds to a "look back time" of eleven billion years. The oldest observed photons (the "Cosmic Microwave Background" (CMB) emitted when the first stable atoms were formed 13.7 billion years ago) have a redshift of approximately 1000.

Astronomy is now intimately linked to elementary particle physics and the study of fundamental phenomena. Physicists have developed the "Standard Model of Particles and Fields"[9] which is often described as reflecting the deepest current understanding of the fundamental laws of nature. But the model does not give a good account of dark energy, dark matter, or gravity – phenomena that are studied chiefly by astronomers. Thus, research in astronomy and astrophysics will be essential for the exploration of new, deeper fundamental theories such as superstring theory, which aims at the unification of gravity and quantum mechanics and which ultimately may offer insight into why the Universe originated with the Big Bang.

Planets and life

One of the most intriguing of all questions is why and how life originated on Earth, and whether life, and particularly intelligent life, exists elsewhere in the Universe. Astronomers are attempting to answer this question in close collaboration with colleagues from molecular biology, geology, chemistry and information theory.

The discovery of more than 100 planets orbiting nearby stars has been an enormous step forward and shows that the formation of planetary systems is a "normal" product of the process of star formation, and that planetary systems are common in the Solar neighbourhood and, by inference, also among the hundred billion stars in the Milky Way galaxy and the billions of other observed galaxies.

The discovery of water and of many types of complex organic molecules (including amino acids, the building blocks of proteins) in asteroids, comets, interstellar space, and in the dusty proto-planetary discs surrounding very young stars – shows that the basic ingredients required for starting life are common throughout the Universe. The next step will be the search for signs of life in the spectra of the atmospheres of planets around other stars. This should be achievable within the coming two decades. The need for a multidisciplinary approach to the problem of the origin of life has led to the new science of Astrobiology for which many new institutes have been recently established in different countries. These centres specialise in astronomical observations, laboratory experiments, theory and computational modelling.

Some unanswered "Big Questions"

The exciting discoveries of the past decades still leave many unanswered "Big Questions". The following is a sampling of such questions. The answers to most of them may well be found in the coming decades, using some of the proposed next-generation projects:

- Why does the Universe have its observed fundamental properties? Why are these properties so finely tuned to permit the emergence and evolution of stars, planets, and even living organisms on Earth? How did such complex structures evolve from the smooth distribution of hot amorphous matter in the infant Universe? When and how will the Universe end? Are there other Universes?
- How can astronomy contribute to the grand challenge of developing a unified theory of quantum and gravitational phenomena? How do dark matter and dark energy fit into the over-all framework of physics? Can the epoch of "inflation" be studied using gravity waves? What signatures did dark energy leave in the evolution of the large-scale structures in the Universe? Do galaxies differ in their dark matter content? Why?
- When and how did some galaxies develop the supermassive black holes in their centres? Can the gravitational wave signals from this process be detected, and is there evidence of event horizons, frame dragging and other general relativistic effects?

[9] The Standard Model is known to be incomplete, and new particle accelerators such as the LHC are being constructed to look at "physics beyond the Standard Model".

- When and how did the first stars and galaxies form? When did the re-ionisation of the Universe take place and what were its causes?
- How do stars and planetary systems form inside dusty molecular clouds? How common are Earth-like planets?
- How common is life in the cosmos? Are there other intelligent beings?

Findings:

Impressive progress has been made in astronomy and astrophysics in the past few decades. There is now a convincing and coherent model of the structure, distribution, origin and evolution of the visible matter in the Universe, all the way from asteroids and planets to huge ensembles of galaxies. Nevertheless the model fails to identify or describe what appears to be some 96% of the mass/energy in the Universe, and does not explain the origin and distribution of life. Many unanswered “Big Questions” remain. They define the need for new projects and programmes in astronomy and astrophysics, to be implemented over the next one or two decades.

Large Projects and Programmes for the Future

Large projects and programmes have been important throughout the history of astronomy. One principal reason is simply that the signals to be detected are extremely weak[10] and the study of faint distant objects requires large structures for intercepting and focussing sufficient quantities of radiation to enable spectra and images to be produced. Astronomical discoveries are often made by pushing the limits of observation with the most powerful telescopes on the ground and the most advanced satellites in space (e.g., the study of high-redshift galaxies, black holes, gamma-ray bursts). However, smaller workhorse telescopes and instruments, used in a new modes of operation, can also produce exciting discoveries, as seen for example in the searches for extrasolar planets.

The OECD workshops focussed on large projects because of their scientific importance, their high costs, and because of certain long-term trends (identified in this report) that deserve the special attention of funding agencies and the organised scientific community. Foremost among these trends is the transition, for the largest “flagship” projects, into the “Big Science” category (defined, roughly, as costing over $500M, with broad international participation, and with lead times of ten or fifteen years from early concepts to “first light”). This transition has implications for the way the big projects are selected, organised, funded, and operated. The following general considerations were identified in the course of the workshops (in addition to the more specific ones discussed in later sections of this report).

Opening new windows and serendipity. A historical view of how major progress in astronomy has occurred is instructive: (1) major progress has often resulted from the opening up of large unexplored “windows” in key parameters (radiation type, frequency, sensitivity, spatial and temporal resolution, polarization); (2) many great discoveries in the new windows were unexpected and unplanned; (3) the key to opening up the new windows has been new technology, much of it acquired from other scientific fields, or the defence sector, or industry, and then adapted to the needs of astronomy. Big projects can be general-purpose observing platforms (usually with multiple instruments/detectors), large-scale survey instruments, and those dedicated to answering specific questions (e.g., observing a certain kind of object, measuring a certain parameter). All have their place in a balanced plan to advance astronomy.

Multi-modal, multi-wavelength approach. To answer the most challenging scientific questions, a broad-spectrum approach is often needed using the most advanced instruments (covering not just the

[10] For example, the total energy collected by all radio telescopes since observations first began in the 1930s would power a flashlight for a mere fraction of a second.

electromagnetic spectrum, but sometimes astroparticle experiments and even gravity). There is no shortage of proposals for such state-of-the-art equipment, each with a convincing scientific case and a prominent constituency in the scientific community. This makes decision-making more complex and underlines the need for strategic planning and a global-scale approach[11].

Competition versus cooperation. Competition has often accelerated scientific discovery, and independent verification of results is a hallmark of the scientific method itself. Nonetheless, in an era of expensive long-term projects, national and regional administrations will have to examine with great care the possibility that some duplication of projects is unjustified. The Atacama Large Millimeter Array (ALMA) is a positive example of the amalgamation of several projects to produce a single enhanced effort with wide international participation. Even when competition is appropriate, the decision should be based on careful analysis and foresight.

Theory and Computation. Any report on large astronomy projects must emphasise the importance of the work of theorists. Much of astronomy is phenomenological (descriptive) but, ultimately, the goal is to conceive and verify universal theoretical constructs that explain the observed behaviour of astronomical objects across the vast scales of the Universe. Accordingly, support for theoretical investigations must be proportional and synchronised with the great data-gathering projects undertaken in laboratories and observatories.

Dramatic advances in computation and information technology have transformed astronomy, which has always been highly data-intensive compared to most other fields of science. The data-related requirements for large new facilities are addressed in a separate section of this report, but it is worth pointing out that astronomy has benefited to an exceptional extent from large-scale simulations, some of which require access to big, expensive computing infrastructures. For example, simulations of the behaviours of large ensembles of gravitating particles have led to important insights in cosmology, galactic structure, and solar system formation.

Findings:

In the future, some of the most important large projects and programmes will have to be organised and financed on a multi-national basis. As research efforts coalesce around a small number of global-scale facilities, national scientific communities and science administrations will face difficult choices about pooling their resources to participate in new international undertakings, involving both challenges (e.g., a loss of autonomy) and opportunities (e.g., getting access to cutting-edge equipment and technology). Decision-makers will need to ensure that the inventory of resources (facilities, instruments, access rights, observing time) is commensurate with national requirements and the size of the scientific community.

[11] By design, this report does not enumerate the various existing proposals for large projects and programmes. As of the date of the report (summer 2004) the reader is referred to the useful – but by no means exhaustive – materials for the conference "Exploring the Cosmic Frontier – Astrophysical Instruments for the 21st Century" (http://www.mpifr-bonn.mpg.de/berlin04/), held in Berlin on May 18-21, 2004.

Recommendations:

Based on advice from the scientific community, funding bodies should seek to advance astronomy in a balanced, integrated, and globally coordinated way, from planetary studies to cosmology, and taking into account the links to other relevant fields such as high-energy and nuclear physics, earth sciences, chemistry and biology. A science-based balance should be sought among surveys, special-purpose, and general-purpose projects. For the latter, it is desirable to promote the opening of unexplored “windows” in instrumental parameter space. The selection and operation of new projects should be based both on the science case and on the opportunities for serendipitous discovery, which have proved so valuable in the past.

Complementarity of Ground- and Space- Based Observations

Planet Earth imposes constraints on astronomical observations; for example, thermal background radiation, man-made radio interference, limited physical space, obstruction of one-half of the sky. Most importantly, the atmosphere absorbs and distorts the paths of electromagnetic waves and particles. Because of this, space missions that observe the Universe from above the atmosphere are a major benefit to astronomers, even though space-based systems have their own drawbacks, among them restricted size/mass of payloads, stubbornly high launch risks and costs, harsh physical environment, limited or zero accessibility for refurbishment or repairs. Space-based systems can today be regarded as a mature technology in to the service of astronomy, providing important capabilities complementary to those of ground-based facilities.

To a first order of approximation, the division of tasks between ground- and space-based astronomy is straightforward: whenever feasible, observations should be done on the ground; otherwise, space is the choice[12]. Discussions at the workshops, however, revealed some nuances and trends that are relevant to decisions about future large projects:

- Even when the choice of observing venue is clear, there can be great value in anticipating complementarity when making long-range plans. For example, the synergy between the two largest optical platforms (the 10-metre Keck telescopes in Hawaii, and the Hubble Space Telescope) has produced many important scientific results. To cite another example, understanding the causal relationship between the physical conditions in the formation of stars and planets, and the emergence of life, will require a coordinated space-based and ground-based programme, exploiting the technical and operational strengths of the next generation of both approaches. The search for extrasolar bio-markers could benefit from links to the space-based remote sensing communities.
- Simultaneous ground and space measurements can lead to results that greatly exceed the value of separate observations. Thus, for example, space/ground synergy has led to great progress in elucidating the nature of ultra-high energy gamma-ray bursts. In the future, combining signals from orbiting radio telescopes and large ground-based arrays offers the prospect of unprecedented spatial resolution.
- In a few specific cases, space- and ground-based systems can be directly competitive. Thus, for example, active wavefront control (adaptive optics) offers the prospect of greatly diminishing the effects of atmospheric distortion for very large ground-based optical telescopes, putting them in direct competition with the inevitably smaller telescopes in space.

Space-based astronomy has generally been managed by national agencies (or, in the case of Europe, by the European Space Agency) which have developed their own planning and review processes and have established many formal and informal links for international co-operation, though in some instances, critics have pointed out duplication of projects. The dialog between space- and ground-oriented agencies, in

[12] The choice is obvious in the case of space missions that can directly access comets, asteroids and planets.

contrast, has been historically weaker and more fragmented, for a variety of technical, institutional, national, and "cultural" reasons. Often, funding comes from separate parts of national budgets. Fortunately, in some countries, steps have recently been taken to strengthen interactions among all agencies that carry out or support astronomical research.

Findings:

Astronomy requires a multi-wavelength approach to address the key scientific questions and to open up new opportunities for observations. Therefore, ground- and space-based observations are vital and complementary for the future of astronomy. It is greatly regretted that neither of the two main space agencies, ESA and NASA, chose to participate in the OECD workshops. As the costs and timescales associated with the largest ground-based projects increase, it becomes ever more important to ensure that the two modalities develop in a coordinated, mutually-supportive way, based on shared scientific goals, with due consideration of relative costs and technological feasibility. There is a compelling scientific and strategic case for strengthening coordination of ground and space investment planning.

Recommendations:

Interested countries and regions should establish or strengthen processes through which strategic investment plans for large ground- and space-based astronomy are developed and harmonised. In cases where both approaches may be appropriate for carrying out important observations, support for R&D should be provided such that, ultimately, informed investment choices between space and ground can be made, maximising scientific gain and ensuring optimal use of financial resources.

Defining a Long-Term Strategic View

Long-term strategic plans completed at national level with wide scientific community participation (which gives the process genuine credibility) produce recommendations that are taken seriously by politicians, funding agencies and the community alike[13].

The selection and phasing of big future projects increases in difficulty as costs go up and timescales stretch out. Decisions cannot be made piecemeal, based solely on arguments of national proponents. The workshops considered whether, in an era of regional and global projects in astronomy and astrophysics, where most large projects intersect with the plans of many countries, it would be valuable to develop a consensus global long-term vision of major large-scale projects. Such a consensus would bring together national and regional priorities, and would naturally provide a powerful tool for national agencies as they approached decisions on funding research and development programmes and on establishing collaborations for the construction and operation of facilities.

Given the wide range of potential large projects in astronomy and astrophysics, a consensus view is unlikely to emerge spontaneously, and a linear prioritisation approach is likely to prove too simplistic. In fact, the scientific cases being advanced for the proposed projects suggest that several of them should, for good scientific reasons, be simultaneously operational. In this, the complementarity of ground and space facilities must be emphasised, and other types of synergy as well, for example, the complementarity of broadly-based survey projects with programmes of deeper observations[14].

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[13] This has been demonstrated in several countries and areas of research, most recently in particle physics, where spontaneous community activities in Asia, Europe, and America (conducted by bodies independent of funding agencies) resulted in a global consensus view on the priority and timescale of the next linear collider.

[14] It is abundantly clear that the space community would be an important contributor to any long-term strategic view. Workshop participants particularly regretted the absence of major space agencies during the discussion of this topic.

The workshop participants agreed that a bottom-up global consensus on large-scale programmes and projects on around a 20-year timescale, bringing together national and regional strategic plans in space and on the ground, would be invaluable at the national level, giving agencies and governments a broader perspective and enabling smaller countries to see what is being planned elsewhere. This could open up opportunities for collaborations.

Workshop participants considered possible mechanisms for achieving a "bottom-up", science-driven consensus view, but an extended debate did not produce a satisfactory conclusion. A key difficulty was identifying a venue with the appropriate mandate and resources. Among the options explored were approaching the International Astronomical Union (IAU), and sponsoring a further workshop of more specialised composition on this topic alone[15].

Findings

A global consensus on a long timescale view, bringing together national and regional strategic plans in both space and ground, would be invaluable at the national level, giving agencies and governments a broader perspective and enabling smaller countries to see what is being planned elsewhere.

Recommendations:

The desirability and feasibility of a long-term integrated vision for large projects and programmes should be addressed, perhaps through the IAU, with the goal of informing funding decisions on the next generation of large projects. Regular community meetings to feed into such a consensus view would be essential to its credibility.

Key Areas for Investment

Progress in astronomy is enabled by technological development, and each generation of telescopes or instruments exploits the latest developments, often borrowed from other domains and adapted for the specific needs of astronomy. Working at the frontiers of technology, astronomy has always benefited from investments in other fields such as defence; for example after World War II, radar technology revolutionized radio astronomy, and space programmes made it possible to observe the Universe in new ways. More recently, astronomy has benefited from defence R&D spending (at levels considerably higher than those available for astronomy) on sensitive infrared detectors and adaptive optics.

In the future, funding in other areas will continue to benefit astronomy; for example, the continued advances in computer technology will be of immense value to all astronomy projects, particularly those that depend heavily on electronics and computing such as large arrays of detectors and the Virtual Observatory projects. Advances in optical communication and data compression are also likely to have spin-off benefits to astronomy. However, certain specific requirements for the next generation of astronomical facilities are such that astronomers will be less able to rely on technological progress in other fields. For example, the bandwidth requirements for phased arrays in radio astronomy considerably exceed military requirements, as do the size requirements for the next generation of astronomical infrared detectors. Astronomy is already funding this R&D directly. A similar situation has existed for optical CCDs for a number of years.

[15] The workshop participants were of the opinion that producing such a global view was not a task for the workshops themselves – in their view this would be outside its remit and an OECD workshop has neither the competence, nor the resources, nor the time, to carry out such a task. However, astronomy meetings to consider a range of topical projects, such as the meeting held in Berlin in May 2004, help to formulate consensus views and the community should be encouraged to hold such meetings and report back to governments and agencies.

Thus there is a need to sponsor technology development aimed specifically at the anticipated needs of the future large-scale projects. A strategic view (analogous to the scientific strategic view) of technological requirements and key R&D areas would be extremely useful at national and regional levels for giving agencies and governments a broader perspective, and enabling smaller countries to see what is being planned elsewhere. Such an approach of course would open opportunities for a range of collaborations.

The usual practice is for each new project to carry out the R&D that it needs. However, such an approach is not as powerful as a potential co-ordinated global strategy to develop key technologies that could benefit multiple projects and that could access significantly more resources. Forefront technologies usually generate spin-off applications, often quite unexpected, and it is probable that some technologies developed through such an exercise would have applications beyond astronomy. Co-ordination does not imply the elimination of competition between alternative approaches to the same goals: such competition is important and usually leads to long-term gains in performance and efficiency.

One of the most significant areas for technology development is detectors. R&D is needed for detectors across the entire electromagnetic spectrum, but there are especially big science gains to be made in the far infrared and sub-mm wavelength regime where large-format detector arrays simply do not exist, and focal plane arrays are relatively rare and correspondingly expensive.

Whilst a comprehensive list of areas is beyond the scope of this report, examples of other key technologies needed are given in the table below.

Facility	Technology	Comment
Large optical and infrared telescopes	Adaptive Optics	Including the development of lasers
	Segment manufacture	
	Large structures	
	Instrumentation	Including detectors, large filters, multiplexing systems
Large radio arrays	Beam-forming in phased arrays	
	Antenna design	Low cost, high reliability
	Instrumentation and signal transport	
Multi-satellite space missions	Formation flying	Also needed for projects such as LISA and XEUS[16]

It is important that industry be a partner in big projects, it is also crucial to have competition in bidding for R&D and manufacturing. Strategic R&D goals should be identified, and incentives for industrial competition should be in place. Intellectual property are important: companies must be able to profit from their R&D investments or they will not undertake the research.

Astronomers are now entering an era where major new facilities on the ground will have billion-dollar budgets comparable to the big space-based projects. An underlying theme in such projects is the need to deal well with immense complexity, and deliver projects on time and on budget. Therefore there is a need for the astronomical community to continue to develop its systems engineering and project management skills. Such developments offer the opportunities for national, regional and global collaborations both with industry and other disciplines.

[16] The X-ray Mission for Evolving Universe Spectroscopy (XEUS) is a proposed ESA orbital observatory.

Findings:

A global strategic view (analogous to the scientific strategic view) of technological requirements and key R&D areas related to possible new projects would be very useful at national and regional level for giving agencies and governments a broader perspective on the requirements and on possible collaborative approaches to them. It could also enable smaller countries that are not already members of international collaborations to see what is being planned elsewhere, and perhaps identify areas for participation.

Recommendation:

A global effort should be undertaken to identify key technologies and strategic R&D goals for large-scale projects in astronomy, and to define the necessary follow-up actions. The maximum benefit would be achieved by transcending the boundaries of individual projects, and addressing needs across the full spectrum of astronomy.

Evaluation, Selection, Protection and Management of Observing Sites

In recent decades, new large ground-based facilities have gravitated towards a small number of sites where observing conditions are particularly favourable[17]. For site selection, scientific criteria are paramount (e.g., geographical location, transparency and stability of the atmosphere, low sky brightness/interference) but other considerations apply as well (e.g., physical accessibility, existing infrastructure, benefits provided by the host country, long-term evolution of the quality of the site). Workshop participants agreed that evaluation and selection processes should be characterised by openness and consensus, so that all international partners can agree in advance on criteria and procedures that will be used (basic definitions, measurement standards and protocols, preservation of data, etc.). Once the site choice is made, data from all candidate locations should be released.

Man-made electromagnetic interference is a growing problem at all wavelengths. It is particularly troubling to radio astronomers who are planning the next generation of large instruments with greatly increased sensitivity and broad spectral coverage. These astronomers view with concern the proliferation of new constellations of low-orbiting communications satellites that are designed to provide planet-wide, around-the-clock connectivity, broadcasting powerful beams to hand-held mobile receiver/transmitters[18]. Commercial and residential lighting directed towards the sky has a negative impact on optical astronomy, as well as wasting energy and depriving the public of the opportunity to view the nighttime sky. There are effective steps that can be taken to reduce light pollution, but they require foresight, and the cultivation of constructive relations with local authorities, residents, and industries. In the long-term, reflections from large amounts of debris in Earth orbit, and laser beams for satellite downlinks, may become additional impediments unless timely, effective measures are taken.

Major observatories are typically located far from large human habitations, but construction and operation can have a significant impact on the natural environment, and on the religious or cultural practices of indigenous inhabitants. Past incidents underscore the great importance of anticipating and managing these impacts.

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[17] This is not to imply that no new optimal sites will be found for future facilities.

[18] This problem was the subject of a recent report by the OECD Global Science Forum's Task Force on Radio Astronomy and the Radio Spectrum. The Task Force consisted of fourteen prominent representatives of industry, as well as the scientific and regulatory communities. The report contains findings and recommendations for actions by governments and the scientific community. It can be found at www.oecd.org/sti/gsf.

Findings:

The choice of the best location is vital to the success of a large ground-based astronomical facility. Evaluation and protection of potential sites can begin well before selection and construction. While facilities can bring benefits to host countries and enhance the lives of local inhabitants, the relationship between a facility and its surroundings is multi-faceted and bi-directional.

Recommendations:

When contemplating new international collaborative projects, interested countries should incorporate open, consensus-based site selection procedures. For existing and potential sites at all wavelengths, measures should be taken to limit electromagnetic interference and light pollution, with the involvement and due consideration of the interests of all concerned parties. When appropriate, formal regulatory measures need to be developed and enforced via recognised channels. The amount of time, effort and resources required for this purpose should not be under-estimated. Facility planners and managers should explicitly anticipate and address local environmental and cultural concerns.

Data Management and Storage

The expansion and globalisation of astronomy research lead to new challenges and new solutions in managing, using, and sharing of the huge volume of digital information flowing from the new observatories. Data volume has a doubling time of six to twelve months, but storage hardware access rates are at a relative standstill, creating a major bottleneck in the transfer of large data sets. A new approach envisages large data sets and computational resources being concentrated at a number of data centres. Through a new software infrastructure, users will transparently interact with these distributed resources as in the existing World Wide Web. However, unlike the Web, data will not be transferred to end users but will be accessed, processed, and explored remotely across the network. The explosion of data volume in all fields is also driving the development of new software tools and mathematical algorithms that will operate in the distributed resource and service environment, creating an integrated hardware and software networked system known as the “Grid”.

Diverse, distributed, and multi-wavelength data sets must interoperate, i.e., allow researchers to have simultaneous access to information from many sources in the same, or readily translatable, systems of coordinates and measured properties (e.g., flux, wavelength). Interoperability will require agreement on international standards for astronomical data across the electromagnetic and particle spectrum.

To maximise scientific return, the Grid-like network of data centres and service providers should be funded for the long-term, with the data centres being assigned an importance that is comparable to that of the observational facilities themselves. Funding is needed for physical storage and computing infrastructure, for staff experts in data maintenance, for user support, and for developing data services. While respecting the proprietary rights of investigative teams, data providers must enable open public access to data, free from constraints that originate in institutional policies and national boundaries. This re-use of astronomical data for new purposes is already a growing trend at some modern data centres.

There are technological barriers to the open access research environment. Many communities of astronomers operate in national IT infrastructures that cannot support Grid-like portals into the network of astronomical data and service providers.

Several independent groups of astronomers from around the world are addressing these issues, and a collective vision of the path forward is now emerging: a new global astronomical research infrastructure called the Virtual Observatory (VO). The goal is to achieve for astronomical data the transparency of the World Wide Web, so that all archives can be accessed through a uniform interface, and data analysed with the same tools, independent of location. A more ambitious long-term goal is a computational Grid, where a set of distributed computers functions like a single supercomputer. Today such analysis is done by end-users after downloading data, but in the future such calculations will be offered by the expert data centres holding the data. The VO will not be a monolithic system, but, like the World Wide Web, will be based on a set of standards that make all the components of the system interoperable.

The VO concept already has a high priority in most national astronomy programmes. The International Virtual Observatory Alliance[19] (IVOA) was formed in June 2002. IVOA is also participating in the Global Grid Forum to ensure that astronomical requirements are discussed in a more global scientific and commercial context, and that the VO provides feedback on prototype Grid middleware. The International Astronomical Union is also playing a major role. An IAU working group examined and endorsed proposed IVOA standards, and at the most recent General Assembly the IAU adopted a comprehensive resolution on the topic.[20]

Findings:

The astronomical community has developed the Virtual Observatory concept in response to the challenges of data management and storage. Impressive progress has been made by the International Virtual Observatory Alliance based on support and funding from science agencies. The workshop participants agreed that the global adoption of the IAU resolution and its support by funding agencies, government bodies, and astronomers is critical to the realization of the VO and the maximal scientific utilization of new astronomical facilities. In the astronomical research environment of the 21st century, the endorsement and financial support of long-term data and data service access cannot be separated from the support of new scientific capabilities.

Recommendations:

New projects and facilities must take the data management, storage, maintenance, and dissemination into account at the earliest planning stages, consulting potential users in the process. Agencies and governments should consider adopting the IAU resolutions as the basis for progress in this field. Agencies should recognise that this is an important long-term issue and should co-ordinate plans, provide adequate funding on a long-term basis, and support development and maintenance of the needed infrastructure. Agencies should encourage broadening of existing VO collaboration into a fully representative global activity.

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[19] ESO/ESA, US, UK, Canada, China, Russia, Korea, Hungary, France, Germany, Italy, Australia, Japan, India

[20] *That data obtained at major astronomical facilities should, after a reasonable proprietary period in which they are available only to observers or other designated users of the facility, be placed in an archive where they may be accessed via the internet by all research astronomers. As far as possible, the data should be accompanied by appropriate metadata and other information or tools to make them scientifically valuable.*

That such data should not be subject to intellectual property rights. The form in which data are made available, and the subsequent processing of such data, may be appropriately protected by copyright laws, but the fair usage (including educational purposes) of the archive data themselves should not be subject to restrictions.

That funding agencies provide encouragement and support to enable data produced by astronomical research that they fund to be deposited, after some proprietary period as defined above, in recognized data archives which provide unrestricted access to these data.

Generic Issues

The generic issues of large projects (i.e., legal, administrative, and managerial issues) have been widely addressed in other fields and are not specific to astronomy and astrophysics. Astronomy has many potential projects spanning a wide cost range. A basic project can be national, regional, or global, although there are wide variations in national or regional capabilities and priorities. The workshops discussed a wide range of generic issues from which the following were selected as worthy of further attention by governments and agencies.

Scale of Projects and Participation An important topic that emerged was the scale of the project and the openness of membership or participation. All projects are developed "bottom up" through the ideas of the astronomy community, and large projects are subjected to extensive debate and scrutiny, as well as negotiations with agencies, before they advance to the decision stages. At this point the project might be defined *ab initio* as national, regional, or global, but other partners might wish to join as contributors and/or users, resulting in a national or regional project becoming *de facto* global or semi-global. In broad terms, the workshops heard that the astronomy community favoured projects being "open" to use, as a matter of principle, but that participation in construction and operations was for the primary funding agencies to decide.

Several delegations, representing countries with active astronomy communities, were concerned that their countries might be excluded from future major projects adopted by a small number of larger countries or regions. In addition, although small countries could contribute to, and benefit from, involvement in advanced projects, the mechanisms for allowing them to do so have yet to be developed. The workshop participants felt that this was a major issue of principle to be addressed at the government or agency level.

Fundamental Structure and Legal Basis. Options for the basic structure vary from project to project, and different structures have been applied to regional and international projects in astronomy and many other fields. The principal options are: an additional project within an existing entity, a new legal entity, or collaboration between existing entities. Examples of all these options exist. A new entity can be an international organisation (like ESO) or a company bound by the law of the host state (like the Canada-France-Hawaii Telescope). The workshop participants agreed that there was no single optimal structure, and that it would be invaluable for governments and agencies, faced with decisions on new projects, to have access to a data base on existing project structures in as wide a range of fields as possible. It was felt that OECD could compile such a data base and, in discussion with governments, seek to establish guidelines for best practice.

In some cases it may be desirable to subdivide the project plan into two or more phases (for example, design, construction and operation) thus allowing interested countries to work together prior to making major financial commitments, and allowing some flexibility in the composition of the collaboration, which therefore need not be fixed from the start. In this case, the decision process in moving from one phase to the next needs to be decided at an early stage. In particular, mechanisms for the coordination of national and regional funding cycles will require study if a phased process to global scale projects is to be feasible.

Just as there are different structures, so there are different ways of funding a project. Projects can be funded on an "all cash" basis, a mixture of cash and in-kind can be adopted, or totally in-kind. Operational costs over the lifetime of a major project often exceed the construction costs, and normally operations cannot be wholly funded on an in-kind basis. A stable and equitable basis must be found for managing in-kind contributions, noting that differing national accounting practices must be incorporated so that an equitable measure of the "value" of relative contributions can be made. Whatever the method adopted, "whole life" costs, including construction costs as well as running costs, must be taken into account on an agreed equitable basis.

The role and contribution of the country in which a project is located has also to be considered. The benefits to the country in which the project is constructed, even if it is not a partner, are usually substantial. There is a certain reciprocity of interests here, which is directly linked to the issues addressed under Site Selection.

Management. The management structure is crucial. It must clearly define responsibilities and authority, but the exact structure adopted will depend on the fundamental structure of the project. Again the OECD could help with a data base of existing approaches.

General Personnel Provisions. There are major issues to be addressed, such as residence and working permits for expatriate and seconded staff, matters affecting spouses and children (work permits, school), health insurance and general benefits, expatriation allowances, etc. These can have a bearing on site selection and on project structure.

Intellectual Property. The partners may claim appropriate intellectual property rights available within applicable national jurisdictions over any device, technology or software tool that is developed while carrying out the work program. Intellectual property rights, whether patented or not, generated by project staff and/or participating teams or individuals need to be available for the purposes of the project free of charge throughout the duration of the project.

Findings:

A range of important generic issues should be considered by governments and agencies before decisions on the next generation of large projects are made. These are not unique to astronomy and there are valuable lessons to be learned from the history of the development of large projects in many fields. A co-ordinated approach across governments in evaluating these issues would be invaluable to the ultimate decision makers.

A major issue is the principle of access to participation in large projects, not just in their use but also in the R&D that leads up to them, and in their construction. This is a separate issue to that of access to data, which was strongly supported by workshop participants, assuming the conventional proprietary period for the data takers.

Recommendations:

One of the first issues of principle to be settled is that of access and participation of countries outside the inner core of initial advocates. Governments and agencies with an interest in future large projects and programmes could start discussions on the key generic problems, such as access and participation, but including issues such as structure, funding, and management. To assist governments and agencies in this process OECD should consider compiling a database on existing project structures in as wide a range of fields as possible. OECD could then, in discussion with governments, seek to establish guidelines for best practice.

Future Large-Scale Programmes and Projects in Astronomy and Astrophysics
1-3 December, 2003, Munich and 5-6 April, 2004, Crystal City, Virginia

Appendix 1: Workshop Documents

The following selected presentations from the workshops are available at www.oecd.org/sti/gsf

Planets, Solar Systems, Life in the Universe	*Willy Benz, University of Bern*
Stars and Galaxies	*Brian Boyle, Australia Telescope National Facility*
Extreme Objects	*Peter Mészáros, Pennsylvania State University*
Cosmology	*Malcolm Longair, Cavendish Laboratory*
Quantum measurement	*Reinhard Genzel, Max Planck Institute*
Wavefront control	*Piero Salinari, Osservatorio astrofisico di Arcetri*
Search for Extraterrestrial Intelligence	*Jill Tarter, SETI Institute*
Virtual Observatories and other data issues	*Andrew Lawrence, University of Edinburgh*

Large-Scale Programmes and Projects in Astronomy and Astrophysics
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Appendix 2: List of Participants

(* = Steering Committee member)

Chairman

Ian CORBETT*

Australia

Matthew COLLESS

Greg HARPER*

Elaine SADLER

Belgium

Marcel ARNOULD

Herwig DEJONGHE

Brazil

Albert BRUCH

Claudia MENDES DE OLIVEIRA

Canada

Isabelle BLAIN

Greg FAHLMAN*

Chile

Maria Teresa RUIZ

European Commission

Elena RIGHI STEELE

Finland

Vilppu PIIROLA

Pentti PULKKINEN

France

Michel BLANC

Jean-Gabriel CUBY

Anne-Marie LAGRANGE

Laurent VIGROUX

Germany

Immo APPENZELLER

Ralf BENDER

Kramer BERND

Andreas ECKART

Michael GREWING

Guenther HASINGER

Thomas HENNING

Rainer KOEPKE

Olaf KÜHNHOLZ

Jurgen SCHMITT

Peter SCHNEIDER

Matthias STEINMETZ

Wolfgang VOGES

Anton ZENSUS

India

Pranab GHOSH

Tushar PRABHU

Italy

Roberto BATTISTON

Piero BENVENUTI

Alessandro BETTINI

Marcello RODONO

Paolo VETTOLANI*

Japan

Masanori IYE*

Hiroshi KAROJI

Masaaki NISHIJO

Korea

Young-Soo KIM

Netherlands

Tim DE ZEEUW

Marijn FRANX*

Roel GATHIER

Ronald STARK

Jan VAN DE DONK

Ed VAN DEN HEUVEL*

Norway

Per Barth LILJE

South Africa

Bernie FANAROFF

Justin JONAS

Anneline MORGAN

Tshepo SEEKOE

Spain

Rafael REBOLO

Sweden

Finn KARLSSON

Switzerland

Boris LARDI

Daniel PFENNIGER

Martin STEINACHER

United Kingdom

Philip DIAMOND

Adrian RUSSELL*

Richard WADE

Martin WARD

United States

Craig B. FOLTZ

Martha HAYNES

Tom MCGLYNN

Christopher MCKEE

Matt MOUNTAIN

Lawrence W. RAMSEY

Alexander SZALAY

Wayne VAN CITTERS*

European Southern Observatory

Catherine CESARSKY

Bruno LEIBUNDGUT

Claus MADSEN

Peter QUINN

International Astronomical Union

Ron EKERS*

Richard SCHILIZZI

Jill TARTER

Invited Experts

Willy BENZ

Brian BOYLE

Reinhard GENZEL

Roberto GILMOZZI

Martin HARWIT

Andrew LAWRENCE

Malcolm LONGAIR

Peter MESZAROS

Piero SALINARI

OECD

Hiroshi FURUTA

Stefan MICHALOWSKI*

Michael OBORNE

Alysia RITTER

Frederic SGARD