Organisation for Economic Co-operation and Development

Global Science Forum

Report of the Working Group on Astroparticle Physics

Executive Summary
(Final version of October 4, 2010)

Background and Rationale

Astroparticle physics is the study of particles and radiation from outer space, and of rare, cosmologically-significant elementary particle reactions. The scales of distance examined range from the realm of elementary particles to the outer reaches of the observable Universe, placing the field at the intersection of cosmology, astrophysics, particle physics and nuclear physics. The importance of the field has increased steadily in recent years, for two principal reasons:

(1) Major fundamental research challenges are within the scope of the field, notably, understanding the properties of dark matter, dark energy, and gravitational radiation, and exploring the unification of the fundamental forces of nature. To meet these challenges, it is sometimes necessary to perform measurements at energies far higher than those of present-day accelerators, either directly in cosmic radiation interactions, or indirectly through the study of rare decays in deep underground laboratories.

(2) Extreme astrophysical phenomena that produce high-energy particles and radiation (for example, the collapse, explosion, or merger of stars and black holes) are of intrinsic interest since they have had, and continue to have, a major influence on the structure and evolution of the Universe.

Astroparticle physics started as a specialised endeavour, pursued by a few charismatic pioneers who reached out beyond traditional disciplinary boundaries and used unconventional, innovative experimental techniques. Since then, the field has become a mature, globally-integrated research activity, involving approximately 4000 researchers, with experiments being conducted underground, underwater, on the Earth's surface, in the atmosphere, and in space, and funded at the level of some 400 million dollars per year (excluding space launch costs). Some emerging countries are entering the field with high ambitions; proposing relatively large infrastructures that they will use to train a new generation of scientists. Today, astroparticle physics stands on the threshold of an era of discovery, with a new generation of proposed instruments that are likely to deliver scientific breakthroughs based on enhanced sensitivity and resolution.

While the scientific prospects for the future are exciting, it is important to ensure that this potential is fully realised via a corresponding effort in the domain of science policy. A globally coherent approach is needed, using an optimal set of national, regional, and international projects and facilities. Agencies currently manage a field in which many small projects have to be considered alongside a few very large, multi-year international (or potentially international) undertakings. Indeed, some of the existing and proposed projects enumerated in this report are in the "megascience" category, with costs of several hundreds of millions of dollars.

To address the policy challenges, the OECD Global Science Forum established, in October 2008, the Working Group on Astroparticle Physics. It brought together government-nominated representatives of eighteen countries, two intergovernmental organizations, an independent scientific organisation, and invited experts. The Working Group's final report presents the results of the consultations, and contains a strategic vision of needed large research infrastructures, as well as findings and recommendations addressed to governmental funding agencies and to the scientific community.

Scientific Prospects

During the past two decades, scientists have gradually arrived at a consensus about the structure and history of the Universe. Remarkably, this **Standard Model of Cosmology** merges elementary particle physics, astrophysics, and cosmology into a single coherent intellectual framework. These three domains can be combined because the entire Universe began in a state of high energy and density of subatomic dimensions (the Big Bang), during which many of its fundamental properties resulted from the interactions of elementary particles. Among these properties are the large-scale distribution of matter in space, and the preponderance of matter over anti-matter. These fundamental features of the Universe can be observed today, some fourteen billion years after the Big Bang.

While the broad outlines of the cosmological model are widely accepted, many of its elements are still poorly understood. As is often the case in science, advancement to a higher level of understanding leads to new, even more profound questions. Thus, for example, the Standard Model of Particles and Fields – a major achievement of modern physics – does not explain, or even incorporate, the crucial phenomena of dark energy or dark matter. The answers to many of the new, deep questions can be sought through the pursuit of astroparticle physics, whose central role in the scientific enterprise, and connections to neighbouring disciplines, can be illustrated by citing a few key episodes in the history of the Universe:

- It is believed that some 10^{-35} seconds after the Big Bang, the embryonic Universe underwent a process of "inflation", which magnified tiny quantum-mechanical fluctuations to macroscopic scales. At that time, unlike today, the fundamental forces of nature were presumably unified into one, and whatever particles were present were interacting at energies that cannot be attained by present-day accelerators. It is hoped that the physics of this primordial epoch can be accessed indirectly through the search for the exotic, exceedingly rare phenomena **proton decay** and **neutrinoless double beta decay**.
- As the early Universe expanded and cooled, its physical structures began to emerge (e.g., galaxies and clusters of galaxies), seeded by miniscule fluctuations present in the blazingly hot primordial mixture of particles and radiation. This process of aggregation, dispersal and growth was primarily driven by gravitation and strongly influenced by the presence of a substance whose properties differ markedly from those of standard matter. Dubbed **dark matter**, it appears to be five to six times more abundant than standard matter, and constitutes approximately one quarter of the total mass/energy of the Universe. Moreover, a decade ago astronomers discovered that the Universe is undergoing an accelerated expansion, as if it were filled with a **dark energy** repulsive field, making up the remaining 70% of its mass/energy density. Most of the properties of dark matter and dark energy, and their place in the overall scheme of modern physics, are still deep mysteries. Astroparticle physics is a major contributor to the effort to understand these fascinating phenomena.
- An intriguing cosmological enigma relates to the nature and role of **high-energy ("violent") phenomena** in the evolution of the Universe. Using the assumed generic properties of dark matter, scientists can model many aspects of the formation of large cosmic structures through gravitational contraction. But they also know that high-energy phenomena modulate the emergence and evolution of these large structures. High-energy phenomena produce intense accelerating fields, far stronger than those created in the laboratory, and these fields can propel particles to extremely high energies. The study of these phenomena has astrophysical implications, and it also provides a unique testing ground for the study of deviations from known fundamental physical laws, including gravitation. These experiments are carried out using unconventional "messengers": **very high-energy photons and charged cosmic ray particles, neutrinos, and gravitational waves**.

These are just an illustrative sampling of the many scientific challenges that were considered by the OECD Working Group. In response to the challenges, the Group developed a strategic vision of the future of the field for the 2010 - 2030 timeframe, enumerating desirable generic scientific capabilities, programmes, and infrastructures. The Group did not wish to pre-empt or interfere in any way with national or regional procedures for planning, prioritising, authorising, funding, managing, or evaluating specific projects. Accordingly, the strategic vision is not a roadmap, i.e., no specific projects are endorsed, since the Working Group did not have the mandate or resources for assessing individual initiatives. When projects are mentioned, it is in the context of describing decisions that will need to be made in the near- or medium-term future, with special emphasis on the potential for international coordination and co-operation.

A Strategic Vision of the Future of Astroparticle Physics

The Working Group adopted a definition of astroparticle physics that comprises six domains: dark matter, dark energy, high-energy cosmic messengers, gravitational waves, proton decay, and the properties of neutrinos. The Group decided to classify experiments and infrastructures into three categories, based on their size, cost and complexity: (1) first-generation projects that are currently taking data; (2) second-generation projects that are in R&D or construction phases; and (3) third-generation initiatives with superior sensitivity and resolution, which are proposed for implementation during the next 10 to 20 years. The main focus of the Working Group was on the infrastructures of the last category since (with a few exceptions) they are the most likely to benefit from international coordination and/or collaboration.

1. Dark matter

Astroparticle physics experiments in this domain attempt to directly detect interactions between particles of dark matter and those of ordinary matter. Thus far, the few claims for positive observations of such rare events have not been universally accepted. Like all searches for signals which are both rare and weak, these experiments are inherently subject to systematic errors that are notoriously difficult to calculate and manage. At the present stage – and probably also at the next stage – multiple efforts, using diverse techniques, are highly desirable. Competition and diversity will increase the likelihood of success. In addition to detecting naturally occuring dark matter particles, it may be possible to produce them in accelerator-based experiments, or to infer their properties from observations at ground- and space-based cosmic ray observatories. Maintaining several potential sources of funding will allow unconventional but important experiments to be implemented.

It is highly probable that the complexity of future dark matter experiments, the potential worldwide scarcity of target materials (e.g., germanium or noble liquids) and the funding required (with budgets projected between 50 and 100 million dollars) will necessitate global collaborations. If, as is likely during the next few years, a dark matter discovery claim is made, independent confirmation will be needed using a wide variety of techniques, including different target nuclei.

2. Dark energy

The accelerated expansion of the Universe due, presumably, to dark energy, was discovered through the study of very distant (and, therefore, very ancient) supernovae. Since then, new methods for studying this acceleration have been devised, using powerful ground- and space-based telescopes. Among the new methods are the study of the imprint of primordial fluctuations on the distribution of visible matter ("Baryon Acoustic Oscillations", or BAO) and the study of the formation of cosmic structures through measurements of weak gravitational lensing and galaxy clustering. These methods give complementary information on the nature of dark energy: e.g., supernovae and BAO address the kinematics of the expansion, while weak lensing and galaxy clustering address the dynamics of general relativity. Most of the studies have been conducted as international collaborations of scientists, but with little coordination of entire projects by the funding agencies. To date, with the cost of individual projects not exceeding a few tens of millions of dollars, this arrangement has worked well, and has resulted in vigorous competition and cross-checking of results. However, fundamental questions about dark energy (for example: does it require new particle physics fields, or a modification of the theory of General Relativity?) have remained unanswered.

Most of the projects proposed for the future have a considerably increased cost (exceeding 100 million dollars and, in some cases, approaching or exceeding one billion) which makes international coordination highly desirable. Even for future large telescopes that will be implemented on national or regional bases, joint global-scale planning can prevent unnecessary duplication of the scientific capabilities. The design parameters, and the specialised instruments, of the large telescopes should be such that the complementary aspects of the above methods are fully exploited. There should also be complementarity in statistical and systematic errors, as well as sensitivities, between ground and space telescopes. Likely candidates for future coordination are the proposed billion-dollar-scale multi-purpose space-based telescope initiatives in Europe (EUCLID) and the United States (WFIRST), as well as complementary large-scale ground-based surveys (e.g., those conducted with the proposed Large Synoptic Survey Telescope (LSST)).

Systematic consultations among the relevant agencies could ensure that the future array of ground- and space-based telescopes exploits the full spectrum of desirable capabilities and experimental methodologies. In some cases, pooling of funds and merging of projects could be the optimal solution.

3. High energy cosmic messengers

High-energy cosmic rays have been studied for nearly a century. Soon after their discovery, they were the principal source of progress in understanding elementary particles; then, for many years, research shifted to experiments performed at energy-frontier accelerator laboratories. In recent years, however, cosmic rays have attracted renewed attention, due in part to the enormous energies that they can attain. Basic questions about them remain unanswered: where do they originate? can the known laws of physics account for their acceleration and propagation through space? what is their exact composition? There is the intriguing possibility that some of the particles are decay products of dark matter, antimatter, or other exotic entities. It is typical of astroparticle physics that finding the answers to these questions would advance both astronomy and elementary particle physics. Research in this domain has been, and will continue to be, complementary to that carried out using the traditional tools and methods of these neighbouring fields, such as optical and radio telescopes, X-ray satellites, and particle accelerators.

Nearly all of the advanced second-generation projects have been implemented as international collaborations (e.g., the Auger Observatory, the Fermi satellite, and the International Space Station cosmic ray experiments). Any new large project in the field (with anticipated investments in the 100 to 300 million dollar range) should build on this tradition. Thus, the next-generation high-energy gamma ray telescope is expected to be a single observatory, with partners from Europe, North and South America, Asia, and Africa (CTA or Cherenkov Telescope Array). Complementary, smaller observatories optimized either for the very highest energy range or for the lower energy regime, could be implemented in India and China, respectively. There is also European convergence around KM3NeT, an ambitious project that would instrument a cubic kilometre (or larger) volume of water in the Mediterranean with light sensors. This observatory would complement and extend the results from IceCube, which has started taking data at the United States' Amundsen-Scott South Pole research station.

In this domain, coordination and coherence among scientists has been achieved. For the funding agencies, challenges for the future include configuring truly international institutional arrangements (when desired), managing international facilities (including issues of access, operating costs and data availability) and developing procedures for resolving site selection issues.

4. Gravitational waves

Gravitational radiation is a direct prediction of Einstein's General Theory of Relativity. Detecting these waves is extremely difficult, and has not yet been achieved despite decades of effort. Today, there is a strong expectation among physicists that success will finally be achieved during the next ten years, using a network of second-generation (or "advanced") laser interferometers in the United States, Europe, and Japan. The long-awaited confirmation of Einstein's prediction will not only be hailed as a great achievement in itself, but will inaugurate an entirely new way of studying the Universe.

The scientific community has pioneered a closely connected network between the gravitational wave antennas in Europe and in the United States, with sharing of information and techniques, coordinated data-taking, immediate exchange of data, and joint publication of results. If other ground-based antennae come on-line (e.g., in Australia or India) they are expected to join the network. The community has also prepared a convincing world-wide roadmap for the future of the field. In addition to laser interferometry, the roadmap describes an innovative detection methodology that takes advantage of the clock-like precision of the periodic emissions of radio waves from pulsars (i.e., rotating neutron stars).

Coordinated R&D efforts are already in place for designing and implementing third-generation gravitational antennas at a time near the end of the current decade, following the first series of confirmed detection events. These would be used to study exotic objects that emit gravitational radiation, such as black holes or merging neutron stars. There is a high level of expectation that gravitational wave astronomy will become a scientific field in its own right.

The projected size and billion-dollar cost of third-generation facilities makes them candidates for global-scale planning, funding, and implementation. This applies to the proposed constellation of laser interferometer satellites (dubbed LISA) that would, presumably, be jointly realised by ESA and NASA, and to an advanced large underground interferometer, such as the so-called Einstein Telescope (a current European conceptual design). Overall, international coordination in gravitational wave astroparticle physics is advanced and healthy, both in the scientific and policy communities, but would benefit from strengthening and consolidation in view of the ambitious plans for the future.

5. Extending the Standard Model of Particles and Fields: neutrino properties, and proton decay

The Standard Model of Particles and Fields is one of the greatest scientific achievements of the 20^{th} century, even though physicists know that it does not constitute the ultimate description of elementary particles and their interactions. There is a need to extend its validity to the smallest distance scales (that is, to the highest energies). The formal mathematical similarity of the three known fundamental subatomic interactions (electromagnetism, weak, and strong interactions) suggests that they are unified at a high energy scale (approximately 10^{16} GeV) and that the Standard Model may be embedded in a larger theoretical framework: that of a Grand Unified Theory (GUT). Some potential GUTs posit the existence of an entire new class of particles (as yet unobserved) called “supersymmetric”, the lightest of which is a strong candidate for the chief constituent of dark matter. The experimental confirmation of supersymmetry would be a major breakthrough, not only for cosmology, but also for particle physics since it would clarify the physics of intermediate energy scales, and would constitute a major step towards understanding grand unification.

Even among the known particles of the Standard Model, the neutrino is an elusive entity. There are three types of neutrino. As they propagate through space, they change from one type to another (they “oscillate”). This is possible only if the neutrinos have masses, albeit much smaller than those of the other Standard Model particles. Since the Standard Model, in its most basic versions, stipulates zero neutrino mass, an extension mechanism must be invoked. In Grand Unified Theories, such a mechanism is possible if the neutrino is its own antiparticle (that is, it is a so-called “Majorana” particle). The same mechanism could account for the preponderance of matter over antimatter

The only known experimental approach to testing the Majorana nature of neutrinos is the detection of so-called neutrinoless double beta decays (which would also provide information about their masses). The cost of the individual present generation double-beta experiments is on the order of 50 million dollars , which can reasonably be funded at a national or regional level, as is already the case for a multiplicity of current projects. If needed, generation three experiments involving large amounts of separated isotope, could have projected costs of approximately 200 million dollars, and could benefit from international coordination and collaboration. Furthermore, the theoretical uncertainty regarding certain nuclear effects makes it difficult to designate the best isotope for this research and imposes diversity in the choice of target materials. There are two encouraging examples of international coordination in this domain. The first is the close collaboration among germanium-based projects, where there is currently an open exchange of knowledge and technologies, and a strong likelihood that they will merge for a large future ton-scale experiment. The second example is the worldwide collaboration for the procurement of enriched neodymium. These could serve as examples of intercontinental coordination of experiments that use other isotopes, such as germanium or xenon.

Healthy competition among projects is the rule in the investigation of neutrinoless double beta decay. However, global-scale coordination and avoidance of duplication would be beneficial, especially for the procurement of crystals and scarce enriched isotopes. A future generation experiments, using target masses of approximately one ton of isotope, will certainly need international coordination.

Unlike the Standard Model, Grand Unified Theories allow for the transmutation of quarks into leptons (electrons, muons, neutrinos) – which implies that protons are unstable. The experimental observation of proton decay would be a fundamental discovery for physics and cosmology, providing insight into the physics of the Big Bang (including inflation, matter/antimatter asymmetry, and the ultimate fate of the Universe).

The leading second-generation proton decay detector is Super-Kamiokande, operating in the Kamioka mine in Japan (with international participation). Design studies for third-generation experiments are under way in Japan, the United States and Europe, with detecting volumes ranging from 100 to 500 kilotons, and different target materials, from water (as in Super-Kamiokande) to liquid scintillator and liquid argon. The different target materials provide sensitivity to different potential decay modes of the proton. These large devices could also be used as detectors of neutrinos created in a powerful proton accelerator (e.g., JPARC in Japan, Fermilab in the U.S., or CERN in Europe). The projected cost of the third-generation detectors is 300-500 million dollars, making it unlikely that more than two of them will be deployed in the near future. The fact that a proton decay detector can do double duty as the distant target of a long-baseline neutrino beam experiment will be a major consideration in a decision concerning any facility of this size and cost. The timeline will become clearer only after 2012-2013, when the value (or limits) of currently missing neutrino oscillation parameters will be known from the present neutrino programme. Multiple neutrino energies and, possibly, more than one baseline, are necessary to fully disentangle the neutrino oscillation parameters and their potential degeneracies. Combinations of two detector technologies are proposed for the full coverage of the proton decay and neutrino oscillation programme.

The "megaton-scale" proton decay and neutrino physics and astrophysics projects are clearly of the type that will require worldwide coordination. The technical challenges, financial investments, and the scientific context (synergy with accelerator particle physics) are high. A substantial improvement in interregional co-operation is necessary for optimal decision-making.

Searches for dark matter particles, neutrinoless beta decay, and proton decay need to take place in underground laboratories in order to shield the detectors from cosmic rays. Most of the underground physics laboratories in the world already host, or intend to host, a combination of these experiments. Despite high demand for underground space, progress will not be limited by space constraints for the next decade, if the new infrastructures and extensions now planned become operational. The need to avoid unnecessary duplication, and to optimise the scientific return on investments, brings the coordination of underground laboratory utilisation to the forefront of the astroparticle physics policy agenda. As a first step, the directors of the Western European underground laboratories, encouraged by ApPEC, ASPERA and the EU, have begun taking steps to coordinate some of the activities and to optimise the use of resources.

The coordination of underground laboratory operations, exchange of knowledge, and policy harmonisation are desirable at the world level. The goal should be to raise the level of international coordination for underground experiments to the same level that characterises other astroparticle physics activities, such as gravitational wave experiments.

Overall conclusions

The astroparticle physics community, despite its relatively short history, has achieved good levels of international coordination. Regional and thematic roadmaps have been formulated. One important large infrastructure (the gravitational wave experiments) operates as a worldwide network. Some experiments are global-scale endeavours (e.g., the Auger Observatory). Nevertheless, the scale of the next generation of large infrastructures will require enhanced forms of international coordination. The high diversity of promising experimental methodologies implies that no single, universal degree of coordination will be appropriate across the entire field of astroparticle physics. In some areas (e.g., dark matter, or neutrino mass searches) a healthy diversity and competitiveness is desirable for the instruments under construction, even while procurement of rare materials needs to be coordinated, and convergence should be encouraged for future very large third-generation experiments. In other areas (high energy gamma rays, charged cosmic rays, or high-energy neutrinos) the small number of existing observatories worldwide already operate (or intend to operate) as single integrated worldwide networks. In these areas, the planning of future projects should include consideration of enabling policy issues such as governance, site selection, access to the experimental resources and to data, and operating costs. Lastly, there are very large-scale projects (e.g., dark energy observatories, third-generation gravitational wave experiments and "megaton"-scale proton decay and neutrino detectors) whose cost, complexity and multiple links to neighbouring scientific disciplines (astrophysics, cosmology, particle physics) present a strong case for worldwide convergence or, at a minimum, for avoidance of unnecessary duplication.

Policy Recommendations

To address the policy challenges enumerated above in each of the six scientific domains of astroparticle physics, the Working Group recommends the establishment of a venue for consultations among officials of funding agencies that make significant investments in the field. The overall goal should be to ensure that, during the next 10-15 years, progress in astroparticle physics will be a globally coherent response to the scientific challenges, using an optimal set of national, regional, and international projects. The new consultative group would be called the Astroparticle Physics International Forum (APIF), and would be a subsidiary body of the OECD Global Science Forum. Funding agency officials would be nominated by the delegations to the GSF, and by the governments of interested non-OECD member countries. Once the nominations were accepted by the GSF, all members of APIF could participate in the activities with identical rights and standing. APIF would be created for a period of three years. It would meet at least once per year, elect its own Chair and other officers, define its own rules and procedures, establish subsidiary bodies as needed, and be self-financing. The members of APIF would report to their respective agencies, and the APIF Chair would report annually to the Global Science Forum. When necessary, APIF could request a modest level of in-kind support from the GSF secretariat.

The activities of APIF could include, inter alia:

1. Exchange information about relevant national and regional developments, plans and priorities. Regularly review and update the strategic vision described in the OECD report.
2. Explore the prospects for joint actions (for example, design studies for experiments, research and development) with special emphasis on large programmes and projects.
3. Study options and solutions for governance structures and mechanisms for potential new international collaborative projects.
4. Consult on relevant generic science policy issues, such as access to research facilities and to data, or contributions to operating costs of facilities by users.
5. Analyse the needs and requirements for rare resources such as isotopes for detectors and, if appropriate, promote sharing or joint procurements. Discuss the optimal utilisation of infrastructures (observatories, antennas, underground laboratories)
6. Engage in a collective dialogue with governmental and non-governmental entities in areas that have a strong impact on astroparticle physics, for example, space agencies, and agencies that are responsible for research in high-energy physics, nuclear physics, astronomy and astrophysics.
7. Develop strategies and procedures for promoting transfer of technology and other benefits to industry and to society in general. Jointly develop educational and outreach materials.

The activities of APIF would not pre-empt or interfere with national or regional mechanisms for planning, prioritising, authorising, funding or overseeing specific research projects. Negotiations for new international collaborations could begin in APIF, but would be pursued in other venues.

As needed, APIF would seek information and advice from the international scientific community. It could invite individual experts, spokespersons of projects or members of scientific bodies (e.g., scientific unions or national advisory groups) to attend APIF meetings or to participate in subsidiary activities. It could commission analyses and reports from scientific groups.

The Working Group also recommends that the scientific community strengthen its activities aimed at ensuring vigorous, globally coherent progress in astroparticle physics. Specifically, the International Union of Pure and Applied Physics (IUPAP) could review and, if appropriate, adjust its mechanisms for promoting international scientific co-operation and discussions among scientists about the future of the field. The latter activities could include maintaining and elaborating the strategic vision described in this report. Under the aegis of IUPAP, data-gathering, analysis, and structured deliberations could produce information and advice for policymakers. The community-based consultations would need to be characterized by openness and inclusiveness, involving scientists from all of the relevant scientific disciplines, with representation from major geographic regions, and with transparent procedures for the selection of participants in the activities.