Particle & Nuclear Astrophysics

by Bernard Sadoulet

The author discusses demographics and funding of an emerging field

By its very nature, science is constantly evolving, and new research fields continuously emerge, in part out of the convergence of fundamental questions of several established fields, the combination of their technologies, and the fertile interaction of scientists of different training. The relatively new field of particle and nuclear astrophysics provides an interesting example of such vitality.

OVER THE LAST TEN TO FIFTEEN YEARS, we have witnessed its birth at the borders between particle and nuclear physics, cosmology, stellar astrophysics, high energy astrophysics, and gravitation. With an attendance of 450 physicists, a recent meeting organized by three divisions of the American Physical Society in Snowmass, Colorado ("Particle and Nuclear Astrophysics and Cosmology in the Next Millennium") testified to the vibrant nature of the current inquiries. This article presents data on the demographics and funding of this emerging field, gathered with the help of several colleagues engaged in the field and of many funding-agency officials. Even with their efforts, however, the funding numbers I shall show are only approximate. Particle astrophysics has a distant past in cosmic-ray studies, which have played an important role in the birth of particle physics as a field. With the development of man-made accelerators during the last 50 years, the quest to understand the structure of matter has increasingly relied on accelerators of growing power and size. Recently, however, this movement has been reversed. A new stream of research is now emerging in which the cosmos is used not only as a natural source of high energy particles but also as a laboratory where we can explore temperatures, energies, mass densities, distance, and time scales that cannot be obtained directly on earth. Obvious examples include the early universe, which probes fundamental physics at very high energy; nuclear reactions in the sun; neutron stars and their equation of state; the physics around very compact objects such as black holes; and so on. In this work a dialogue is established between particle and nuclear physics that provides critical information for the understanding of fundamental astrophysics phenomena, and astrophysics which may challenge our current models of particle physics and provide constraints on unification schemes and hint at necessary transformations.

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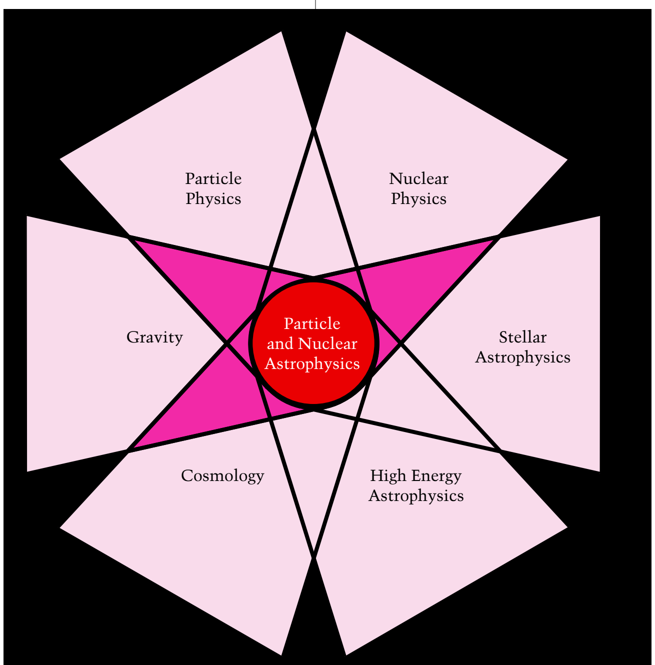
This reverse movement started about 25 years ago with the attempt to detect neutrinos emerging from the sun. Until about a decade ago, however, much of the work in this new field was theoretical in nature, attempting to apply the knowledge gained from nuclear and particle physics research to stellar physics and cosmology in order to widen the range of conditions we understand. This began to change in the early 1980s, when a growing number of experimental particle and nuclear physicists started again to use non-accelerator-based methods and, in many cases, to focus their research on astrophysics. There are at least two major reasons for this recent development: (i) the mismatch between our present accelerator capabilities and the increasingly ambitious theoretical questions we are asking, and (ii) the sociological issue of larger and larger groups (hundreds of physicists) in accelerator-based experiments. The recent work has led to wonderful results, perhaps the most spectacular of which was the detection of neutrinos from the 1987A supernova in two underground detectors that were initially built to search for the decay of the proton. The new detector technologies these experimentalists introduced in astronomy, the powerful computer-reconstruction methods they transposed, and the fertile interaction of their style with that of more traditional astronomers have indeed been a successful combination. An extraordinary amount of new data has been gathered which, combined with vibrant theoretical work, appears to stress our conventional understanding so much that something may have to give!

It is of course difficult to draw a classification of the research activities in such a rapidly evolving field, but we can recognize at least four overlapping categories:

• *Particle cosmology* and the tantalizing questions it tackles: What is the nature of the ubiquitous dark matter and the origin of the predominance of matter over antimatter? What is the explanation for the smoothness of the universe and for the primeval inhomogeneities that triggered the formation of structure and, eventually, galaxies?

• *Neutrino astronomy*. After the pioneering chlorine solar neutrino experiment and the detection of neutrinos from supernova 1987A, neutrino astronomy is coming of age with a new generation of solar neutrino experiments and exploration of ambitious schemes to detect high-energy neutrinos from compact astrophysical sources.

• *Ultra-high-energy astrophysics*. The acceleration mechanisms associated with such compact objects as stellar black holes and active galactic nuclei are poorly understood; the relative role of electromagnetic and hadronic processes is not very well mapped; and the origin of ultra-high-energy cosmic rays and their composition remains a central mystery.



• *Gravitational astrophysics*. There is a continuing challenge to unify gravitation with the other interactions and to make progress in its experimental investigation. The coming generation of gravitational-wave detectors promises to open a new window on violent phenomena in the universe and to provide a complementary source of information on compact objects.

Demographics and Funding

These exciting directions have attracted a number of scientists, primarily but not uniquely from particle and nuclear physics, and with them an already sizable budget. I will try here to provide some quantitative information on these trends. In order to be conservative in summarizing the demographics and budgetary data, I have chosen to restrict the definition of the field to *astrophysics activities explicitly linked by the investigators to particle and nuclear physics*. I have, for instance, only included the studies of the Cosmic Background Radiation at the Center for Particle Astrophysics and at LBL, where connection with particle physics is a primary motivation, and not similar efforts at Princeton, Chicago, and the Goddard Space Flight Center. For similar reasons, only the Large Scale Structure observations at the Center for Particle Astrophysics and at Fermilab enter our data set. An arbitrary energy threshold of 1 GeV has been imposed on cosmic-ray experiments, and only gamma-ray observations from the ground are considered. Even with this

Approximate United States Funding for Particle and Nuclear Astrophysics for Fiscal Year 1994
(thousands of dollars)

Department of Energy	
High Energy Physics	11300
Nuclear Physics	5000
Theory (10 %)	2300
High Energy Laboratories	4400
Weapons Laboratories	3000
Total	*26000*
National Science Foundation	
High Energy Physics	3000
H.E. Theory	1000
Nuclear Physics (incl. 10% theory)	4500
Astronomy	3500
Polar Programs	1000
Gravity (does not include LIGO)	11000
Total	*24000*
NASA	
Cosmic Rays	1500
Theory	500
Total	*2000*

very restricted definition, I estimate the number of experimentalists involved in the United States to be about 300 and the fraction of the theory effort devoted to these problems to be at least 10 percent. These numbers are evolving quickly, and as noted above, the last ten years have witnessed a pronounced shift from pioneering theoretical studies to a large number of experimental investigations. We should also note a growing involvement of the national laboratories: LBL, Fermilab, SLAC, Argonne, Livermore, and Los Alamos.

The total funding of this field by American federal agencies (see table) has also become substantial. The Department of Energy supports such activities at a total level of roughly $26M/yr, with approximately 75 percent spent at universities and 25 percent in national laboratories. The National Science Foundation contributes some $13M, and NASA contributes $2M (restricted to cosmic rays above 1 GeV). Gravitation represents another $11M in the NSF budget, plus the current construction money of LIGO (a $290M project) and GP-B (a $250M satellite). Overall, without counting these major construction projects, this amounts to more than $52M per year that is being channeled to this interdisciplinary field.

I have not systematically gathered any data for the rest of the world. But with active programs in Europe, Japan, and the former Soviet Union, the above numbers would probably have to be doubled.

These numbers are getting impressive, and they testify to the fascination of the subject, the enthusiasm of the scientists, and the ingenuity of the funding officials who have found ways to allow the field to grow. It would, however, be unfair to my colleagues not to report at the same time the present uneasiness of the community, which feels that this emerging field still tends to "fall into the cracks." It does not fit readily within the traditional NSF and NASA astronomy funding categories. Although there is a widening recognition in the Department of Energy that particle and nuclear astrophysics is closely related to its mission of understanding the forces in nature, DOE officials have historically worried that such activities may appear to conflict with its traditional mandate. There is a general perception that the review process could be improved and that there could be tighter collaboration among the various divisions within the funding agencies and between the different agencies. Frustration is also often expressed about the lack of mechanisms to establish a long-term strategy and priorities across the field, as we have no screening mechanism equivalent to the program advisory committees associated with large particle accelerators, and no suitable standing committee advising the agencies, as HEPAP, NSAC, and SSAC do in their respective fields of High Energy Physics, Nuclear Science, and Space Sciences. Finally, there is the worry that in any budgetary arbitration the more traditional fields may enjoy some historical advantage.

In spite of the efforts of agency officials to remedy these problems, from the studies organized, for instance, by the American Physical Society and the reports of the National Research Council, it is clear that we do not yet have in place the reviewing structure nor the advisory process necessary to address in a coherent fashion the large international projects on the drawing boards. Their price tags, which are often between $15M and $100M, are sizable. Our community is actively studying several cosmic microwave background satellites, specialized cosmology telescopes, a new generation of solar neutrino detectors, an air Čerenkov farm to extend the measurement of gamma spectra of active galactic nuclei and black hole candidates, giant extensive air shower arrays to explore the highest energy cosmic rays, and km^3 neutrino detectors to look for high energy neutrino sources, not to mention even more ambitious projects such as a space-based gravitational wave interferometer.

The science is clearly exciting, and the scientific community is voting with its feet. The challenge remains to find the resources and the institutional mechanisms to further decrease the potential barriers encountered by excellent proposals, to welcome young investigators into the field, to optimize the scientific output on a very restricted budget, and more actively to develop the necessary international partnership.