The Presence and Participation of Women in Physics and Astronomy

J. Scott Long, Indiana University

SINCE 1973 there have been rapid and remarkable increases in the presence and participation of women in science and engineering. These changes are documented in a recent NRC report. The report includes data on Ph.D. production and labor force participation for the fields of physics and astronomy. For other career outcomes, there were too few women in physics and astronomy to allow analysis within each field. Accordingly, many of the results given below are based on all fields of science and engineering, often using statistical controls for field differences. These findings should provide insights into what is happening to women in physics and astronomy. The approach in this article is to follow the pipeline, from receipt of degree, to entry into the labor force, and then through the academic ranks.

Figure 1 shows that the percent of Ph.D.s awarded to women in the physical sciences (including astronomy, physics, chemistry, oceanography, and geosciences) grew from 6 percent in 1973 to 24 percent in 1999. The percent of degrees to women was smaller in physics and astronomy, with 20 percent of the degrees to women in astronomy in 1999 and 13 percent of the degrees in physics, which corresponds to only 32 degrees to women in astronomy and 160 in physics. The greater overall increases in the physical sciences as a whole reflects the greater presence of women in fields such as chemistry and geoscience.

Increases in the number of women among new Ph.D.s do not translate directly into increases in the proportion of women in the S&E labor force, as shown in Figure 2.

Figure 2.

There are two basic reasons for the slower increase in labor force participation. First, each new cohort of Ph.D.s is smaller in physics and astronomy, with 20 percent of the degrees to women in astronomy in 1999 and 13 percent of the degrees in physics, which corresponds to only 32 degrees to women in astronomy and 160 in physics. The greater overall increases in the physical sciences as a whole reflects the greater presence of women in fields such as chemistry and geoscience.

Connecting Quarks and the Cosmos:
Committee Recommends Interagency Initiative

Michael Turner, University of Chicago

WE are at a special moment in our quest to understand the universe and the physical laws that govern it. More than ever before, astronomical discoveries are driving the frontiers of physics, and more than ever before our knowledge of physics is driving progress in understanding the universe and its contents. The Committee on the Physics of the Universe, which I chaired, was convened in recognition of the deep connections that exist between quarks and the cosmos. This article is based on the executive summary of the committee’s report.

Both disciplines—physics and astronomy—have seen stunning progress within their own realms of study in the past two decades. The advances made by particle physicists in understanding the deepest inner workings of matter, space, and time and by astronomers in understanding the universe as a whole as well as the objects within it have brought these scientists together in new ways. The questions now being asked about the universe at its two extremes—the very large and the very small—are inextricably
Highlights of the Spring Meeting of the Board on Physics and Astronomy

The BPA convened in Washington on the afternoon of April 26. The afternoon session was dedicated to updates on the status of various programs supporting research in physics and astronomy.

The opening talk was given by Robert Eisenstein, director of Mathematical and Physical Sciences at the National Science Foundation. (Dr. Eisenstein recently announced that he will be taking a sabbatical at CERN.) He framed the strategic goals of the NSF in terms of people, ideas, and tools and organized his presentation around those concepts.

The MPS portfolio of activities includes mathematical sciences, study of the origins of the universe, quantum science and engineering, molecular connections, integrating research and education, and tools. The opportunities that are emerging in these areas include:

- Physics of the universe. This area was identified in a report from the Committee on Physics of the Universe that is discussed in an article on page 1 of this issue of BPA News.

- Quantum information science.

- Laser manipulation of single molecules.

- Few-dimensional quantum systems.

- Complexity, emergent behavior.

- Physical science in biology and medicine.

- Soft condensed-matter physics.

- Simulations.

MPS has become increasingly involved in instruments and facilities. It sponsors the National High Magnetic Field Laboratory. It has partnered with DOE in developing the Large Hadron Collider at CERN, the next major step in experimental high-energy physics. The astronomy division operates the twin Gemini telescopes, which successfully employ adaptive optics to minimize atmospheric aberrations. The Atacama Large Millimeter Array, planned for construction in Chile, is an array of 64 12m antennas that will probe formation processes in the early universe. The Large Interferometric Gravitational Observatory (LIGO) is making progress toward observing gravitational waves from such phenomena as coalescence of two black holes.

Eisenstein concluded the discussion of tools with a review of Amanda and the IceCube proposal. IceCube would be a cubic-kilometer array of photodetectors embedded in South Pole ice to form a huge Cherenkov detector of high-energy neutrinos from such astrophysical phenomena as supernovae. NSF has partnered with DOE on several of these projects and a number of others.

The major NSF-wide priority areas for 2003 are biocomplexity and the environment, information technology research, nanoscience and engineering, mathematical sciences, learning for the 21st century, and social and behavioral sciences. MPS has significant participation in all of these except the last. Mathematical sciences is slated to receive almost a $50 million boost, recognizing the critical role that mathematics plays in advancing interdisciplinary science. The initial focus areas will be on large data sets, modeling uncertainty, and modeling and prediction for complex nonlinear systems. The impact of this initiative could be quite substantial.

Eisenstein was followed by Joseph Dehmer, director of the physics division, and Eileen Friel, executive officer of the astronomy division, with more detailed information on those programs. Friel noted enhanced partnership with NASA in response to the recommendations of the Committee on Organization and Management of Research in Astronomy and Astrophysics (COMRAA). NSF and NASA plan to seek a joint charter for a National Astronomy and Astrophysics Committee to facilitate interagency cooperation and to develop an integrated plan for the field.

Dehmer cited frontier areas in physics and listed a number of new Physics Frontier Centers established to pursue these areas. He related these initiatives to the topics highlighted in Physics in a New Era: An Overview, the summary volume of the most recent physics survey.

Jim Decker, then acting director of the Department of Energy’s Office of Science, gave a very broad overview of DOE pro-
grams.

Pat Dehmer followed with an update on the Basic Energy Sciences program. The 2003 budget request for BES features increases for science at the nanoscale, which will give a boost to condensed-matter physics. Establishment of Nanoscale Science Research Centers is planned, as are increases for general facility operations, upgrades, and construction. Full funding is proposed for the Spallation Neutron Source, and funding has been provided for project engineering and design for the Linac Coherent Light Source at the Stanford Linear Accelerator Laboratory. The LCLS is an x-ray free-electron laser.

Anne Davies reviewed the Fusion Energy Sciences Program. Davies discussed the major facilities and a number of innovative plasma confinement concepts, including a Spheromak and various other configurations. She emphasized the role of advanced computing in scientific understanding and discovery. Scientific understanding of fusion plasmas has increased dramatically. She summarized the goal of the program as “better fusion through better science,” a concept emphasized in the plasma science volume of the physics survey, Physics in a New Era. The next frontier of the field is understanding the physics of burning plasmas. OFES is supporting an assessment to be carried out by a committee under the BPA of the burning plasma experimental program, which will contribute to defining this frontier.

Peter Rosen discussed DOE’s High Energy and Nuclear Physics program. He pointed to the possibility of major discoveries at Fermilab and the Stanford Linear Accelerator. At Fermilab, evidence for the Higgs particle (responsible for particle mass), supersymmetry, and neutrino mass and mixing may be forthcoming in the next few years. The SLAC B factory is studying CP violation. The 2003 budget request provides good support for operation and upgrade of these facilities. It also provides for continuation of the U.S. contribution to work at the CERN Large Hadron Collider. But maintaining these parts of the HEP program in a flat budget scenario means reductions elsewhere. Funding for university research groups and the smaller laboratories will be reduced. HEP research at Brookhaven National Laboratory’s Alternating Gradient Synchrotron will be terminated. The nuclear physics budget request provides support for all the major scientific thrusts in the program, including low- and medium-energy nuclear physics, heavy-ion physics, and theory. The request would ensure effective operation of user facilities, particularly the Continuous Electron Beam Accelerator Facility and the centerpiece of the program, the Relativistic Heavy Ion Collider. The running schedule for RHIC is projected to double.

Guenther Riegler presented the key features of the 2003 budget request for the Space Science Enterprise in the National Aeronautics and Space Administration. Despite the constrained budget environment, OSS emerged with a much more robust program and budget. The new 5-year plan is based on a $682 million increase over that period. New developments include a Nuclear Systems Initiative, cancellation of the Europa mission and its replacement by a New Frontiers Program, and transfer of the Deep Space Network to OSS. (The DSN budget is not counted in the above figure.) The budget supports a final servicing mission to the Hubble Space Telescope in 2004. HST returns to Earth in 2010. The Next Generation Space Telescope, the top priority of Astronomy and Astrophysics in the New Millennium, will be launched as soon as is prudent, but the date is under review. Current thinking puts the launch date in the summer of 2010. There are three missions that have problems, and curing these may have an impact on other areas, since OSS must manage within its overall budget. Riegler also discussed the joint NSF-NASA response to the COMRAA study.

The BPA also heard a policy talk on gender issues by J. Scott Long, who has contributed an article appearing on page 1 of this issue. Michael Turner presented the final report on the Committee on Physics of the Universe, and he too contributed an article starting on page 1. A number of standing committees and other projects and activities of the Board were reviewed. The Board concluded its meeting with a discussion of two new studies mandated by the Office of Management and Budget—a study of neutrino facilities and a study of the research units of the Smithsonian Institution. The BPA website at <www.nas.edu/bpa> has the latest information. ■
only a small fraction of the total number of scientists in the labor force. A change in the percent of women in a new cohort has only a small effect on the total percent of women already in the labor force. Second, women are much less likely to be fully employed than are men, as shown in Figure 3.

The total height of each bar shows the percent of scientists and engineers who are not working full time, with the divisions within each bar indicating the specific labor force status. In 1973 women were 20 percentage points more likely to be less than fully employed, decreasing to an 11 point difference in 1995. Part-time employment for women decreased between 1973 and 1979, leveling off at around 12 percent. There was a steady decrease in the percent of women who were seeking work, from 4 percent in 1973 to 1 percent in 1995. The difference between male and female Ph.D.s in the percent seeking work was reduced to less than ½ point from a difference of 3 points in 1973. There are much larger gender differences in the percent of scientists who are no longer in the scientific labor force.

Overall, differences between men and women in full-time labor force participation add up to less accumulated work experience and less valuable experience for women over the course of their careers, a factor that is important for understanding the gender differences in career outcomes that are described below. While there has been improvement since 1973, female Ph.D.s continue to be substantially less likely than men to be fully employed in scientific occupations, with roughly 10 percent of the potential professional work of female doctorates being lost.

A great deal of the gender differences in full-time labor force participation is associated with marital status and familial obligations. Before examining these effects, it is important to understand that men and women differ in their chances of being married or having children, although these differences have decreased since 1973. Still, male scientists are more likely to be married than female scientists, as shown in Figure 4.

And, given the demands of a scientific career and the greater likelihood that women will undertake more of the responsibilities of raising children, it is not surprising that male scientists are more likely to have children, as shown in Figure 5.

Figure 6 shows that during the first 15 years after the Ph.D., over half of the women working part time indicate that this is due to family obligations, while only around 10 percent of the men give this as the reason for not working.

The same effect is shown in Figure 7, which presents the percent of men and women who are working full time as a function of their marriage and family obligations. Four familial statuses are considered: single without children, married without children, married with one or more children between 7 and 18 living at home, and married with one or more children younger than 7 living at home. Among men, those who are single are least likely to be working full time, with small increases for married men and those with children. In contrast, single women are most likely to be working full time. Being married without children decreases the predicted proportion of women working full time by 5 percentage points. Having older children at home decreases the proportion by 8 more points, while being married with young children decreases the proportion with full-time employment by 22 points. As a consequence of the opposite effects of marriage and children for men and women, an identical 94 percent of single men and single women are expected to be working full time. That is, differences between men and women in labor force participation are eliminated if we compare single men to single women.

Before considering gender differences in career outcomes for academic
scientists, it is important to emphasize that even if these outcomes were identical for men and women (which they are not), they would not reflect the substantial number of women who obtained the doctorate but are not in the full-time labor force.

The rapid change in the percent of academic positions held by women is largely the result of increases in the proportion of new Ph.D.s who are women, which has important implications for the age structure in academia. The average academic woman received her degree more recently than the average academic man, and the difference between the average career age (i.e., years since the Ph.D.) for men and women is increasing. The effects of changes in the growth of academia and the increased entry of women can be seen with a population pyramid, which is a pair of horizontal histograms, one for men and one for women. Each bar represents the percent in an age-sex group (e.g., women between 1 and 3 years from the Ph.D.) relative to the size of the total population. The shape of a pyramid reflects the number of new Ph.D.s entering the population and the number leaving through death or retirement.

Figure 8 shows how the more rapid increase in the number of women with Ph.D.s and their increasing entrance into academia has affected the age structure.

In 1973, men represented a much larger proportion of all academics. The longer bars for young scientists, those with career ages of 1-3 and 4-6, show that incoming cohorts were larger than prior cohorts. For example, 18 percent of academic scientists are men within 3 years of their Ph.D., with women within 3 years of the Ph.D. representing only 3 percent of the academic labor force.

By 1995, things had changed substantially, as shown in Figure 9. First, the proportion of men overall is reduced, as indicated by the lesser difference in the areas of the two halves of the pyramid. Second, the size of incoming cohorts of men has stabilized, as reflected by the similar sizes of the bars for men between career age categories 1-3 and 25-27. For women, in contrast, each younger cohort is larger than older cohorts. By 1995, new female Ph.D.s grew to 4 percent of academics, while new men dropped to less than 8 percent. Even with the rapid increase in the percent of women receiving Ph.D.s and entering academia, women are far from being half of the academic labor force. Further, while there has been a substantial increase in the percent of women with academic jobs, the question remains whether there is a correspondingly large increase in the presence of women among all types of positions and institutions. To address this issue, we examine gender differences in the types of jobs held by men and women in academia.

The most fundamental distinction among academic positions is between tenure-track positions and off-track positions. Scientists with tenure track positions have the possibility of advancing through the faculty ranks and attaining the job security provided by tenure. In comparison, off-track positions have lower pay, fewer resources, and less security. They include temporary teaching positions, research positions funded by soft money, visiting scholars, adjunct faculty without tenure track appointments elsewhere, postdoctoral fellows, and lower level administrative positions. From 1979 to 1995, the percent of all full-time academic jobs that were on-track decreased from 84 percent to 79 percent.

As shown by the light bars in Figure 10, throughout this period men had a 14 percentage point advantage over women in obtaining tenure-track positions. While the lack of change suggests that there has been little progress for women in becoming members of the faculty, these overall figures mask broad differences in the availability of faculty positions at
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(continued from page 5)

different stages of the career (e.g., postdoctoral fellowships are off-track positions that occur within a few years of the Ph.D.). To adjust for age differences we estimated the proportion of men and women in tenure-track positions after statistically controlling for career age. Differences in the adjusted proportions of men and women in their 15th career year are shown by the darker bars. In 1979 there was only a small decrease from the observed to the adjusted difference. That is, the observed gender difference in the percent with tenure-track positions cannot be explained by the younger age of female academics. By 1989, however, the observed difference was substantially reduced by adjusting for age, with a somewhat smaller reduction in 1995. Much, but not all, of the difference between men and women in their success in becoming faculty is due to differences in the stage of the career. The recent entry of women into science and engineering has contributed to the smaller percent of women who are faculty.

The apparent lack of progress for women is due largely to the shifting age structure for women. The increasing entry of women into academia means that they are younger compared to men, which makes the average female faculty member less likely to be tenured than the average male faculty member. Further, there are differences in tenure rates across types of institutions (e.g., major research universities, liberal arts colleges). Adding statistical controls for professional age, type of institution, field, and other variables substantially reduces gender differences in the predicted proportion of scientists and engineers with tenure, as shown by the dark bars in Figure 11. In 1979 the observed difference was reduced from 24 points to an adjusted difference of 17 points; in 1989 the observed difference of 19 points was reduced to 6 points, dropping to 4 points in 1995. Overall, by 1995 gender differences in tenure status are largely the result of differences in career age and, to a lesser extent, to differences in types of employing institutions. However, even after these controls, men continue to be more likely to be tenured.

Progress in an academic career is marked by advancement in rank, culminating in promotion to full professor, and it is here that past research has provided the strongest evidence for the unequal treatment of women in academia. This problem is central, since with rank advancement comes the prestige, resources, and authority that are critical for a successful career in science.

The light bars in Figure 12 show a nearly constant observed difference of 27 points in the percent of men and percent of women who are full professors. But, like tenure, academic rank is highly dependent upon career age. The dark bars show the effects of statistically controlling for differences in the age structures for male and female faculty, as well as differences in field and type of institution. The age-adjusted differences show a decrease in the over-representation of men from 20 points in 1979 to less than 10 points in 1995. Still, even after controlling for gender differences in career age, field of employment, and type of institution, men continue to have an almost 10 percentage point advantage in being full professors.

Overall, there have been remarkable changes in the representation of women in science and engineering. In all aspects of the career, from the receipt of the Ph.D. to entry into the labor force to attaining the rank of full professor, women are an increasing presence, both in absolute number and as a proportion of all scientists and engineers. As positive and encouraging as these changes are, it is equally clear that substantial differences remain. Women as a group remain less well-represented and less successful than men in every dimension of the career. While women have clearly made enormous gains in their participation in science and engineering, it is also clear that these advances represent neither unconditional success in overcoming gender inequalities nor assurance of continuing progress in the future.

Figure 11.  
Adjusted rates controlled for field, age, & Carnegie type.

From 1979 to 1995 there was little change in the percent of tenure-track faculty who had received tenure, as shown in Figure 11. For men, roughly 80 percent had tenure in each year, while for women the number increased slightly, from 56 percent in 1979 to 62 percent in 1989, dropping to 60 percent in 1995. Throughout this period, a nearly constant 20 percentage points more men than women were tenured, as shown by the light bars.

1 This paper is based on the larger study From Scarcity to Visibility: A Study of Gender Differences in the Careers of Doctoral Scientists and Engineers, report of the National Research Council’s Panel for the Study of Gender Differences in the Career Outcomes of Science and Engineering Ph.D.s, J. Scott Long, Chair. Primary data are from the 1973, 1979, 1989, and 1995 panels of the Survey of Doctorate Recipients (SDR), a biennial survey of a sample of doctoral scientists, engineers, and humanists who completed the Survey of Earned Doctorates (SED). Additional data from the SED were also used. For details, see the panel report.
Materials and Society: From Research to Manufacturing
Michael Moloney, BPA Staff

The National Research Council’s 2002 Materials Forum, Materials and Society: From Research to Manufacturing, was held in Washington, D.C., on March 27 and 28, 2002. Materials and Society was part of a continuing series of forums focused on materials science that have been presented approximately every 2 years by the Solid State Sciences Committee and the National Materials Advisory Board. In presenting the 2002 Forum, the SSSC and the NMAB joined forces with the NRC’s Board on Manufacturing Engineering and Design and the University Materials Council. SSSC members Lee Magid (University of Tennessee) and Frank DiSalvo (Cornell University), along with BPA member and NMAB chair Julia Phillips, were members of the organizing committee, which was chaired by Sylvia Johnson (NASA Ames).

The forum brought together over a hundred government policy makers, members of the materials research and manufacturing communities, and end users of materials to review, consider, and discuss the current state of materials science and engineering in the United States and the challenges in the coming years. The agenda was designed to address pressing materials issues through a series of presentations and panel discussions oriented toward materials successes and challenges.

The opening sessions of the forum focused on the impact of materials on the economy, society, and the nation. The presentations pointed to the particularly ripe opportunities that are presented by the physical limits of today's materials and how innovation and discovery are required if the impressive gains made in the last 50 years are to continue. The forum’s agenda was designed to draw attention to the opportunities and challenges for materials in several key areas of national interest.

A special session on Materials in National Security was added to the agenda in response to the events of September 11, 2001. There the attendees heard about evolving national needs in the area of microsystems and biowarfare detection—fields requiring advances in miniaturized power sources, optics and fluidics—and airline security—requiring new blast-resistant materials and new detection and scanning systems. The forum also heard about materials challenges in the auto industry, including the development of new materials for engine and powertrain design.

In the session on energy systems the discussion turned to how the emergence of more efficient, less polluting energy resources will depend in part on the development of new materials that will enable the needed technologies. Examples include improved ionic conductors and electrodes for batteries and fuel cells; advanced and affordable semiconductors for photovoltaic and thermovoltaic generators; and reinforced materials for better electrical transmission cables. The forum also heard about cutting-edge research in nanomaterials, biomaterials, optical materials for communications, and computational materials research.

Congressional staff at the forum discussed recent trends in the funding of research in the physical and materials sciences and—pointing to the recent field surveys, both of astronomy and of physics, as examples—emphasized the need for community input into the legislative decision-making process. The agency leaders attending the forum outlined the priorities for their respective programs.

Much of the discussion time at the various sessions, and in particular during the Workforce and Education session, focused both on the need for federal support so the physical sciences can keep pace with the biomedical sciences and on the need for the U.S. research and educational communities to do a better job of recruiting students at all levels into careers in fields relevant to advancing materials research.

For more information on the forum, its agenda, and its report (due to be released later this summer), see the SSSC website at <www.national-academies.org/bpa/sssc>.
The answers to these questions strain the limits of human ingenuity, but the questions themselves are crystalline in their clarity and simplicity. In framing this report, we have seized on 11 particularly direct questions that capture most of the physics and astrophysics we discuss. They do not cover all of these fields, but rather focus on the interface between them. They are also questions that we have a good chance of answering in the next decade, or should be thinking about answering in following decades. Among them are the most profound questions that human beings have ever posed about the cosmos. The fact that they are ripe now, or soon will be, further highlights how exciting the possibilities of this moment are.

The Questions

1. What is the dark matter?

Astronomers have shown that the objects in the universe—from galaxies a million times smaller than ours to the largest clusters of galaxies—are held together by a form of matter that is not what we are made of and that gives off no light. This matter probably consists of one or more as-yet-undiscovered elementary particles, and aggregations of it produce the gravitational pull leading to the formation of galaxies and large-scale structures in the universe. At the same time these particles may be streaming through our earthbound laboratories.
2. What is the nature of the dark energy?
Recent measurements indicate that the expansion of the universe is speeding up rather than slowing down. This conclusion goes against the idea that gravity is always attractive. This discovery calls for the presence of a form of energy, dubbed “dark energy,” whose gravity is repulsive and whose nature determines the destiny of our universe.

3. How did the universe begin?
There is evidence that during its earliest moments the universe underwent a tremendous burst of additional expansion, known as inflation, so that the largest objects in the universe had their origins in subatomic quantum fuzz. The underlying physical cause of this inflation is a mystery.

4. Did Einstein have the last word on gravity?
Black holes are ubiquitous in the universe, and their intense gravity can be explored. The effects of strong gravity in the early universe have observable consequences. Einstein’s theory should work as well in these situations as it does in the solar system. A complete theory of gravity should incorporate quantum effects—Einstein’s theory of gravity does not—or explain why they are not relevant.

5. What are the masses of the neutrinos, and how have they shaped the evolution of the universe?
Cosmology tells us that neutrinos must be abundantly present in the universe today. Physicists have found evidence that they have a small mass, which implies that cosmic neutrinos account for as much mass as do stars. The pattern of neutrino masses can reveal much about how the Nature’s forces are unified and how the elements in the periodic table were made.

6. How do cosmic accelerators work and what are they accelerating?
Physicists have detected an amazing variety of energetic phenomena in the universe, including beams of particles of unexpectedly high energy but of unknown origin. In laboratory accelerators, we can produce beams of energetic particles, but the energy of these cosmic beams far exceeds any energies produced on Earth.

7. Are protons unstable?
The matter of which we are made is the tiny residue of the annihilation of matter and antimatter that emerged from the earliest universe in not-quite-equal amounts. The existence of this tiny imbalance may be tied to a hypothesized instability of protons, the simplest form of matter, and to a slight preference for the formation of matter over antimatter built into the laws of physics.

8. Are there new states of matter at exceedingly high density and temperature?
The theory of how protons and neutrons form the atomic nuclei of the chemical elements is well developed. At higher densities, neutrons and protons may “dissolve” into an undifferentiated “soup” of quarks and gluons, which can be probed in heavy-ion accelerators. Still higher densities and temperature occur and can be probed in neutron stars and the early universe.

9. Are there additional space-time dimensions?
In trying to extend Einstein’s theory and to understand the quantum nature of gravity, particle physicists have postulated the existence of space-time dimensions beyond those that we know. Their existence could have implications.
for the birth and evolution of the universe, could affect the interactions of elementary particles, and could alter the force of gravity at short distances.

**10. How were the elements from iron to uranium made?**

Scientists’ understanding of the production of elements up to iron in stars and supernovae is fairly complete. The precise origin of the heavier elements from iron to uranium remains a mystery.

**11. Is a new theory of matter and light needed at the highest energies?**

Matter and radiation in the laboratory appear to be extraordinarily well described by the laws of quantum mechanics, electromagnetism, and their unification as quantum electrodynamics. The universe presents us with places and objects, such as neutron stars and the sources of gamma-ray bursts, where the energies are far more extreme than anything we can produce on Earth in order to test these basic theories.

Each question reveals the interdependence between discovering the physical laws that govern the universe and understanding its birth and evolution and the objects within it. The whole of each question is greater than the sum of the astronomy part and the physics part of which it is comprised. Viewed from a perspective that includes both astronomy and physics, these questions take on greater urgency and importance.

Taken as a whole, the questions address an emerging model of the universe that connects physics at the most microscopic scales to the properties of the universe and its contents on the largest physical scales. This bold construction relies on extrapolating physics tested today in the laboratory and within the solar system to the most exotic astronomical objects and to the first moments of the universe. Is this ambitious extrapolation correct? Do we have a coherent model? Is it consistent? By measuring the basic properties of the universe, of black holes, and of elementary particles in very different ways, we can either falsify this ambitious vision of the universe or establish this model as a central part of our scientific view.

The science, remarkable in its richness, cuts across the traditional boundaries of astronomy and physics. It brings together the frontier in the quest for an understanding of the very nature of space and time with the frontier in the quest for an understanding of the origin and earliest evolution of the universe and of the most exotic objects within it.

Realizing the extraordinary opportunities at hand will require a new, crosscutting approach that goes beyond viewing science as astronomy or physics and brings to bear the techniques of both astronomy and physics, telescopes and accelerators, and ground- and space-based instruments. The goal then is to create a new strategy. The obstacles are sometimes disciplinary and sometimes institutional because the science lies at the interface of two mature disciplines and crosses the boundaries of three U.S. funding agencies, DOE, NASA, and NSF. If a cross-disciplinary, cross-agency approach can be mounted, the committee believes that a great leap can be made in understanding the universe and the laws that govern it.

The raison d’être of the Committee on the Physics of the Universe is to create a plan of action. In the first five chapters of the report, it has identified the most important and most timely science opportunities at the intersection of physics and astronomy. These have been encapsulated in the 11 science questions listed above. With the right strategy, all 11 questions are ripe to be answered. In its report, the committee proposes a strategy that will enable each agency to look beyond the traditional boundaries of physics and astronomy within it and take a broader view both of its own mission and of the traditional boundaries between it and the other agencies. Coordination and joint planning are critical. In some instances, it may be essential for two of the agencies (or even all three) to work together. In other cases, one agency, by closing the gap between the disciplines of physics and astronomy, is sufficient. Some projects that are key to achieving the scientific potential of the 11 questions have already been recommended by other studies and reports. New initiatives are needed to achieve other opportunities.

**Recommendations**

Listed below are the committee’s seven specific recommendations for research and research coordination needed to address the 11 science questions.

- Measure the polarization of the cosmic microwave background with the goal of detecting the signature of inflation. The committee recommends that NASA, NSF, and DOE undertake research and development to bring the needed experiments to fruition.

Cosmic inflation holds that all the structures we see in the universe today—galaxies, clusters of galaxies, voids, and the great walls of galaxies—originated from subatomic fluctuations that were stretched to astrophysical size during a tremendous spurt of expansion (inflation). Quantum fluctuations in the fabric of space-time itself lead to a cosmic sea of gravitational waves that can be detected by their polarization signature in the cosmic microwave background radiation.
• Determine the properties of the dark energy. The committee recommends that NASA, NSF, and DOE construct large, wide-field telescopes, both in space and on the ground, to determine the expansion history of the universe and probe the nature of the dark energy.

The discovery that the expansion of the universe is speeding up and not slowing down has revealed the presence of a mysterious new energy form that accounts for 2/3 of all the matter and energy in the universe. Because of its diffuse nature, it can only be probed through its effect on the expansion rate of the universe. To do this requires a new class of large, wide-field telescopes, both in space (such as SNAP) and on the ground (such as the LSST recommended by the Astronomy Decadal Survey).

• Determine the neutrino masses, the constituents of the dark matter and the lifetime of the proton. The committee recommends that DOE and NSF work together to plan for and to fund a new generation of experiments to achieve these goals. It further recommends that an underground laboratory with sufficient infrastructure and depth be built to house and operate the needed experiments.

Neutrino mass, new stable forms of matter, and the instability of the proton are all predictions of theories that unify the forces of nature. Addressing all three issues requires a laboratory that is well shielded from the cosmic-ray particles that constantly bombard the surface of Earth.

• Use space to probe physics. The committee supports the Constellation-X and LISA missions, which have high promise for studying black holes and for testing Einstein’s theory in new regimes. The committee further recommends that the agencies proceed with an advanced technology program to develop instruments capable of detecting gravitational waves from the early universe.

The universe provides a laboratory for exploring the laws of physics in regimes that are beyond the reach of terrestrial laboratories. Astronomy and Astrophysics in the New Millennium (the recent decadal survey of astronomy) recommended the Constellation-X and LISA missions on the basis of their great potential for astronomical discovery. These missions also have unique capabilities for testing Einstein’s theory in regimes where gravity is very strong, near the event horizons of black holes and near the surfaces of neutron stars. For this reason, the committee adds its support to the decadal survey’s previous recommendations.

• Determine the origin of the highest energy gamma rays, neutrinos, and cosmic rays. The committee supports the broad approach already in place, and recommends that the United States ensure the timely completion and operation of the Southern Auger array.

The highest-energy particles accessible to us are produced by natural accelerators throughout the universe and arrive on Earth as high-energy gamma rays, neutrinos, and cosmic rays. A full understanding of how these particles are produced and accelerated could shed light on the unification of nature’s forces. The Southern Auger array in Argentina is crucial to solving the mystery of the highest-energy cosmic rays.

• Discern the physical principles that govern extreme astrophysical environments through the laboratory study of high-energy-density physics. The committee recommends that the agencies cooperate in bringing together the different scientific communities that can foster this rapidly developing field.

Unique laboratory facilities such as high-power lasers, high-energy accelerators, and plasma confinement devices can be used to explore physics in extreme environments as well as to simulate conditions needed to understand some of the most interesting objects in the universe, including gamma-ray bursts. The field of high-energy-density physics is in its infancy, and to fulfill its potential, it must draw in expertise from astrophysics, laser physics, magnetic confinement and particle-beam research, numerical simulation, and atomic physics.

• Realize the scientific opportunities at the intersection of physics and astronomy. The committee recommends establishment of an interagency initiative on the physics of the universe, with the participation of DOE, NASA, and NSF. This initiative should provide structures for joint planning and mechanisms for joint implementation of cross-agency projects.

The scientific opportunities that the committee has identified cut across the disciplines of physics and astronomy as well as the boundaries of DOE, NASA, and NSF. No agency has ownership of the science. The unique capabilities of all three as well as cooperation and coordination between the three will be required to realize these special opportunities.

The Committee on the Physics of the Universe believes that recent discoveries and technological developments make the time ripe to greatly advance our understanding of the origin and fate of the universe and of the laws that govern it. Its 11 questions convey the magnitude of the great opportunity before us. The Committee believes that, by implementing these seven recommendations, this opportunity can be realized.
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