BPA NEWS

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BPA Forum on "Physics in Space" — NASA Administrator Dan Goldin Challenges the Scientific Community

THE Board devoted its November 6-7 meeting to a forum entitled "Physics in Space." The purpose of the forum was to examine the intersection of the fields of physics and astronomy. Although the forum focused on understanding physical phenomena occurring in space, many of the experiments and observations aimed at achieving that understanding are ground based.

The forum opened with a series of science topics that bridge physics and astronomy, including several cosmology talks and discussions of physics in extreme astrophysical environments, ultra-high-energy cosmic rays, gravitation, and neutrinos. The next session featured the perspectives of agencies that support research in this area. Dan Goldin represented the National Aeronautics and Space Administration, Robert Eisenstein represented the National Science Foundation, and Peter Rosen represented the Department of Energy. Spaceborne observational tools and experiments were discussed in the next session. The final session featured organizational bridges between astronomy and physics. The complete program for the forum appears on p. 5. Because of space limitations in the BPA Newsletter, this article only treats the sessions on science and agency perspectives.

Mr. Goldin challenged the BPA to take the lead in formulating an initiative in this area (see the text of Mr. Goldin's address later in this article), with the encouragement of Drs. Eisenstein and Rosen. The BPA concluded that the opportunities to extend the frontiers of knowledge in this area are important and exciting. The Board agreed to respond to Mr. Goldin's challenge and is designing a new kind of assessment process for this multidisciplinary area of research.

Science Topics

Michael S. Turner of the University of Chicago and Fermilab discussed cosmology in a talk entitled "Inner Space/Outer Space." During its earliest moments, the universe was a hot soup of quarks. The behavior of the fundamental particles at high energies and densities is key to understanding the earliest moments of creation and addressing the most pressing issues in cosmology. Conversely, the early universe and other astrophysical environments (the nuclear matter in neutron stars and the event horizons of black holes) offer unique opportunities to probe fundamental physics in regimes that are not accessible with accelerators and other Earth-based experiments. This is the character of the Inner Space/Outer Space connection.

Science at the Inner Space/Outer Space (IS/OS) interface is flourishing. The inflation plus cold dark matter paradigm, which

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Fusion Science Assessment Committee Issues Interim Report

THE Fusion Science Assessment Committee (FuSAC) was formed early in 1999 to repond to a request from the Department of Energy to assess the quality of the science component of the program of the Office of Fusion Energy Sciences (OFES) in the Office of Science. Criteria for the assessment include excellence, impact, role in education, and contribution to strengthening the scientific foundation for fusion. FuSAC plans to develop a science strategy for the program that will provide a context for judgment and a direction for future development. Up-to-date information on the status of the study may be found at http://national-academies.org/bpa/projects/fusac.

The committee held its first meeting on May 16-19, 1999, at the University of California at San Diego. The second meeting was held on July 21-23, 1999, in conjunction with the Fusion Science Summer Study at Snowmass. This meeting provided an opportunity for the committee to gain a broad familiarity with the status of the research effort and to learn about the prospects for future developments.

The membership of the committee was chosen in a somewhat unusual manner. It is somewhat larger in size than most NRC committees, and about half of the members are experts in fusion plasma science. But the remaining half of the committee is made up of scientists working in related areas. The purpose of constructing the committee in this fashion is to ensure objectivity and help the committee to articulate its conclusions in a manner that is broadly persuasive to the research community.

The committee is chaired by Charles F. Kennel, Director of the Scripps Institution of Oceanography. Overall guidance

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In this issue:

The Board on Physics and Astronomy is a continuing interdisciplinary body with expertise spanning the various subfields of physics, astronomy, and astrophysics. It serves as a focal point in the National Research Council for issues connected with these fields. The activities of the Board are supported by funds from the National Science Foundation, the Department of Energy, the Department of Defense, the National Aeronautics and Space Administration, the National Institute of Standards and Technology, and private and other sources, including the Keck Foundation.

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is deeply rooted in fundamental physics, addresses the most pressing questions in cosmology and provides a framework for motivating and organizing the dazzling array of observations that are now coming in. One of the most exciting developments in fundamental physics, evidence for neutrino mass, comes from observations of extraterrestrial neutrinos.

Over the next two decades we can look forward to many more exciting developments, including the identification of the dark-matter particles, the elucidation of the nature of the dark energy that is causing expansion of the universe to accelerate, and testing the hypothesis that all structure in the universe developed from subatomic quantum-mechanical fluctuations. Looking even further into the future, Turner expressed the view that the IS/OS connection will help reveal the quantum nature of gravity and the unification of the forces of nature and shed light upon the ultimate nature of the big bang.

Marc P. Kamionkowski of Caltech discussed the “Cosmic Microwave Background.” Inflation, a period of accelerated expansion driven by the vacuum energy associated with some new fundamental scalar field, can explain the flatness and homogeneity of the universe, and it can also provide the primordial density perturbations from which large-scale structure in the universe grew. Kamionkowski discussed how experiments that map the temperature and polarization of the cosmic microwave background can provide precise new tests of inflation and perhaps determine the physics responsible for inflation.

Roger Blandford of Caltech discussed “Physics in Extreme Astrophysical Environments.” In the history of science, there can have been few disciplinary interfaces more productive of fresh discovery and insight than that between observational astronomy and basic physics. This territory, rightfully claimed by both communities, is inhabited by astrophysicists and it is, arguably, now more fertile than ever. The traffic flows both ways across it. For the physicist, the limitation of not being able to control an experiment is amply compensated by access to cosmic laboratories in which matter can be observed under physical conditions unattainable on Earth; for the astronomer, our secure and tested understanding of physical processes can be applied directly to comprehend the universe around us.

While other speakers emphasized cosmology, relativity, and particle physics, Blandford emphasized some immediate challenges that exist in atomic, nuclear, and high-energy astrophysics. Recent observations of neutron stars probe directly and quantitatively the behavior of cold matter at supranuclear density and magnetic fields with strengths a billion times greater than can be sustained on Earth. Gamma-ray bursts release energy at an observed rate that is some 30 orders of magnitude higher than our most powerful lasers. Space- and ground-based telescopes routinely measure spectral lines whose identity lies outside our laboratory experience.

Blandford argued that there are considerable opportunities for interagency collaboration and cooperation. The challenge for this forum will be to eschew superficial and fanciful connections and to identify those areas where the links are strongest and great progress can be made over a reasonable timescale.

James Hartle of the University of California at Santa Barbara discussed “Gravitational Physics in Space.” His talk reviewed those aspects of gravitational physics that can be usefully done in space. Two points were stressed concerning two frontiers of physics at very large distance scales and very small distance scales:

(1) Increasingly phenomena relevant for both frontiers may be found in space.

(2) Increasingly experiments relevant for both frontiers may best be done in space.

Marc Davis of the University of California at Berkeley discussed “Deep Cosmology.” Over the coming decade, a new generation of astronomical projects will generate new classes of data of importance for the deep universe and fundamental physics. By “astronomical” he referred to instruments connected to large radio/optical/infrared telescopes.

The Next Generation Space Telescope (NGST) will provide information on the

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Gravitational Physics: Exploring the Structure of Space and Time

THE penultimate volume in the *Physics in a New Era* series—*Gravitational Physics: Exploring the Structure of Space and Time*—has been published by the National Academy Press. (The final volume, now in preparation, will be the Overview, which will integrate and synthesize the volumes on the branches of physics.) The book may be viewed and ordered at http://books.nap.edu/catalog/9680.html. This article is based on the Executive Summary of the report, which was prepared by a committee chaired by James Hartle of the University of California at Santa Barbara. The members of the committee were:

James Burkett Hartle, *Chair*, University of California, Santa Barbara
Eric G. Adelberger, University of Washington
Abhay V. Ashtekar, Pennsylvania State University
Beverly K. Berger, Oakland University
Gary T. Horowitz, University of California, Santa Barbara
Peter F. Michelson, Stanford University
Ramesh Narayan, Harvard-Smithsonian Center for Astrophysics
Peter R. Saulson, Syracuse University
David N. Spergel, Princeton University Observatory
Joseph H. Taylor, Jr., Princeton University
Saul A. Teukolsky, Cornell University
Clifford M. Will, Washington University

Gravity is one of the four fundamental forces of nature. It is an immediate fact of everyday experience, yet presents us with some of the deepest theoretical and experimental challenges in contemporary physics. Gravity is the weakest of the four fundamental forces, but, because it is a *universal* attraction between all forms of energy, it governs the structure of matter on the largest scales of space and time and the universe itself. As one of the fundamental interactions, gravity is central to the quest for a unified theory of all forces whose simplicity would emerge at very high energies or, equivalently, at very small distances.

Gravitational physics is thus a *two-frontier science*. On the large scales of astrophysics and cosmology it is central to the understanding of some of the most exotic phenomena in the universe—black holes, pulsars, quasars, the final destiny of stars, and the propagating ripples in the geometry of spacetime called gravitational waves. On the smallest scales it is concerned with the quantized geometry of spacetime, the unification of all forces, and the quantum initial state of the universe. This two-frontier nature means gravitational physics is a cross-disciplinary science overlapping astrophysics and cosmology on large scales and elementary-particle and quantum physics on small scales.

The theory that bridges this enormous range of scales is Einstein's 1915 general theory of relativity. The key ideas of general relativity are that gravity is the geometry of four-dimensional spacetime, that mass produces spacetime curvature while curvature determines the motion of mass, and that all freely falling bodies follow paths independent of their mass, an idea which is called the principle of equivalence.

When gravitational fields are weak and vary only slowly with time, the effects of general relativity are well approximated by Newton's 300-year-old theory of gravity. However, general relativity predicts qualitatively new phenomena when gravitational fields are strong, rapidly varying, or can accumulate over vast spans of space or time. Black holes, gravitational waves, closed universes, and the big bang are some examples. Further, when the principles of classical general relativity are united with quantum theory one can expect quantum uncertainties in the geometry of spacetime itself. The focus of modern gravitational physics has naturally been on exploring such relativistic and quantum phenomena.

Gravitational physics is one of the oldest subjects in physics. Yet the expansion of opportunities in both experiment

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Committees of the Board on Physics and Astronomy

Committee on Astronomy and Astrophysics
John Huchra, Harvard-Smithsonian Center for Astrophysics, and Thomas Prince, Caltech, Co-chairs

Committee on Atomic, Molecular, and Optical Sciences
Wendell T. Hill III, University of Maryland, Chair

Plasma Science Committee
Stephen C. Cowley, UCLA, Chair

Committee on Radio Frequencies
Paul Steffes, Georgia Institute of Technology, Chair

Solid State Sciences Committee
Myriam P. Sarachik, City University of New York, Chair

Astronomy and Astrophysics Survey Committee
Joseph Taylor, Princeton University, and Christopher McKee, University of California, Berkeley, Co-chairs

Fusion Science Assessment Committee
Charles Kennel, University of California, San Diego, Chair

Committee on Gravitational Physics
James Hartle, University of California, Santa Barbara, Chair

Helium Reserve Committee
John Reppy, Cornell University, and Ray Beebe, Homestake Mine (ret.), Co-chairs

Physics Survey Overview Committee
Thomas Appelquist, Yale University, Chair

More information on BPA committees may be found on the BPA Web page at <www.national-academies.org/bpa>.

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first objects to form in the universe. This will be a critical check on our models of structure formation in the universe, which are closely tied to the unseen dark matter.

Weak lensing surveys on ground-based telescopes will provide a close look at the mass distribution in the distant universe, independent of the observed galaxy distribution and the uncertainties in the degree to which galaxies trace the underlying matter distribution.

Millimeter, submillimeter, and infrared wave telescopes such as ALMA and SIRTF will teach us much about the most distant active galactic nuclei and when they were first formed.

DEEP redshift surveys of galaxies at z~1, executed on large telescopes such as Keck, will study the evolution of structure back in time, again a basic test of models. Furthermore, these surveys have the potential to execute powerful tests of fundamental cosmology including precise measures of the “cosmic pressure” in the universe.

Provided that support can be sustained, there is every reason to believe that progress in fundamental cosmology in the coming decade will be as great as it has been in the past decades.

Wick Haxton of the University of Washington discussed “Neutrino Astrophysics.” The current generation of solar and atmospheric neutrino experiments provides very strong evidence for massive neutrinos and neutrino mixing, phenomena beyond the minimal standard model. These results have motivated new proposals for astrophysical neutrino detectors as well as major initiatives for accelerator- and reactor-based oscillation experiments. They have also encouraged theorists to hope that the CKM matrix for neutrinos may soon be known.

The connection between astrophysical neutrinos and particle physics is mimicked by their connection to astrophysics. Neutrinos play a crucial role in the early universe and, if they are massive, perhaps also in its evolution. They control the cooling of red giants and likely drive the supernova mechanism. They also contribute to stellar nucleosynthesis either directly, such as in the neutrino process, or indirectly, by producing the explosive conditions necessary for the r-process. It follows that a variety of astrophysical phenomena that can be studied by other means—optically, by their nucleosynthetic output, etc.—are in principle sensitive to oscillation and other new neutrino physics.

Pierre Sokolsky of the University of Utah discussed “Ultra-High-Energy Cosmic-Ray Physics and Astrophysics.” He described the Fly’s Eye Cosmic Ray Observatory located at Dugway Proving Ground, which is designed to study the nature of the highest-energy cosmic rays. Areas under study at the Fly’s Eye include the cosmic-ray spectrum, composition and anisotropy, and the search for point sources of neutral cosmic rays. Of related interest is the physics of hadronic interactions at energies above those that are reached by accelerators. The Fly’s Eye detector is unique in its use of atmospheric fluorescence to image the development of cosmic-ray cascades in the atmosphere.

Sokolsky also discussed the collaboration building the next generation observatory, called the High Resolution Fly’s Eye (HiRes in short). This new detector is being built by the University of Utah; the University of Adelaide, Australia; Columbia University; and the University of Illinois.

Agency Perspectives

Dan Goldin discussed his enthusiasm for advancing research at the interface of physics and astronomy at some length. What follows is the text of his address.

“I want to thank you all for coming and for responding to the call for this meeting. I want to particularly congratulate [BPA Chair] Bob Dynes for working so rapidly to arrange this special forum on ‘Physics in Space.’

“I made a plea, and you are clearly taking action. So, thank you, Bob, and to all the members of the Board on Physics and Astronomy. I believe the issues you are addressing may lead us to the next breakthroughs in physics.

“Before I begin, let me tell you about a young research assistant who worked at Princeton University. This young research assistant happened to work for none other than Albert Einstein. The young assistant had just finished helping to prepare a paper while Einstein was searching all over the office for a paper clip. When Einstein found one, the clip was too badly bent for use. So Einstein continued to ransack the office in search of a tool to fix the bent paper clip. When he found a whole box of unused paper clips, the young assistant looked on quizzically as Einstein shaped one of them into a tool to straighten the bent one.

“When the young assistant asked him what he was doing, Einstein said, ‘Once I am set on a goal, it becomes difficult to deflect me.’

“It was Einstein’s unquenchable thirst for knowledge and focused tenacity that helped lead Einstein to incredible discoveries. It is also a reminder that it is an asset to think unconventionally in the pursuit of answers and solving problems.

“The physics community has some truly awesome scientific questions on the table today and it seems to me that space may be one venue to get at the answers of questions like:

- Can we use the universe as a laboratory to reveal the laws of nature?
- Can we forecast our cosmic destiny?
- What lies beyond the standard models of particle physics and cosmology?
- Where and what is the dark matter and dark energy in the universe?
- What is the dimensionality of space-time?
- Is our universe unique? And . . .
- Will the Yankees win the World Series?

Wait a second, we know the answer to that. I just love to gloat!

“Think about it — most people are just trying to answer the question, ‘What’s the weather for tomorrow?’ But you are asking monumentally challenging questions! You have your work cut out to answer these questions, but it may take a tool more elegant than Einstein’s paper clip to answer them.

“I feel we have all been underestimating the importance of research into fundamental physics. The problem lies partly in the segmentation of the physics community. It’s almost a vestigial element in some agencies. And as far as space-based research, we need better guidance on how this research fits in among other priorities.

“I’ve been concerned about this area of research for years. When I first came to NASA, we had only one program in funda-

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University of California at Irvine

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Physics in Extreme Astrophysical Environments	Roger Blandford, Caltech
Gravitational Physics	James Hartle, UC Santa Barbara
Deep Cosmology	Marc Davis, UC Berkeley
Neutrino Astrophysics	Wick Haxton, University of Washington
Ultra-High-Energy Cosmic Rays	Pierre Sokolsky, University of Utah
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NASA	Dan Goldin
NSF	Robert Eisenstein
DOE	Peter Rosen
Spaceborne Observational Tools and Experiments	
GLAST	Peter Michelson, Stanford University
OWL	Eugene Loh, University of Utah
LISA	Sterl Phinney, Caltech
AMS and CosmicRay Physics	Sam Ting, MIT
Microgravity Physics	John Reppy, Cornell University
Organizational Bridges Between Astronomy and Astrophysics	
Bridges Between Physics and Astronomy	Tom Gaisser, Bartol Research Institute
Cosmic Genesis Workshop	James Siegrist, LBNL
The DOE Laboratories	Mike Witherell, Fermilab; James Siegrist, LBNL; Jonathan Dorfan, SLAC

mental physics under way — that was Gravity Probe B, the Relativity Mission. Later we added the AMS (Alpha Magnetic Spectrometer) experiment. We had virtually nothing else going on that challenged the basic laws of nature — nothing else that could be called fundamental space-based *physics* research.

"Two years ago, I was approached by a group of scientists who felt we did not have a level playing field at NASA. It was pointed out that we select our priorities in accordance with the findings of the Academy's Decadal Survey reports, but these reports tend to provide only passing mention of the ideas in the areas where particle, nuclear, gravitational, and astrophysics come together.

"Things have changed since then and NASA has some exciting plans on the table for consideration. But NASA, working with the Academy, could still do better.

"I know you're well along in a vigorous Decadal Survey right now. But I'm worried that we're still approaching physics in space in a very segmented way. The area of relativistic physics — early universe physics, gravitation, general relativity — tends to fall in between physics and astronomy and no one seems to put it front and center.

"I have the feeling that there is a 'narrow blinders' view toward nontraditional discipline areas. And this view is not unique to NASA. The challenge is to make non-traditional disciplines part of the mainstream's mind-set. Then we will be able to give them higher priority.

"We need to ask:

- What are the key science questions that need to be answered?
- What's the right venue to provide the answers? Space? Accelerators? Underground detectors?

"We need to bring NASA, DOE, NSF, and the scientific community together to address these issues.

"I went to Fermilab a few months ago, where I was joined by Ernie Moniz (of DOE) and Bob Eisenstein (of NSF). You may recall that I expressed frustration that high-energy physics research has tradi-

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tionally focused on the ground. Instead of lamenting the loss of the superconducting super collider, we need to understand what questions we are asking. And then we need to understand how we are going to get at it. If there is one message you could take away today, it is that we need to embrace new, interdisciplinary ideas.

"Why should exciting areas like gravitational physics, tests of general relativity, cosmic rays, neutrino astronomy, be tucked away in a corner, out of sight, or tacked on to other discipline areas like an afterthought? There is a world, or I should say a universe, of opportunity awaiting scientific discovery.

"This is why I am thankful to be a part of today's discussions. We've got to think boldly about the potential for discovery when we expand our horizons and bring particle physics and astrophysics together. If I could be so bold, I would like to enlist the Academy to play a critical role in putting physics in space front and center.

"The scientific priorities that the Academy provides to NASA are critical. The last report of the Astronomy and Astrophysics Survey Committee gave us a whole list of recommended new initiatives. Let me just go down the list for the NASA-funded items:

- AXAF (Advanced X-Ray Astrophysics Facility) — Check! It's launched and operating beautifully.
- SIRTF (Space InfraRed Telescope Facility) — Check! It's under way and due for launch in December the year after next.
- A dedicated spacecraft for FUSE (Far Ultraviolet Spectroscopic Explorer) — Check! We did that — and it's in orbit now.
- SOFIA (Stratospheric Observatory for Far-Infrared Astronomy) — Check! It's under way and fully funded.
- AIM (Astrometric Interferometry Mission) — Check! We call it the Space Interferometry Mission . . . SIM, but it's a very similar optical interferometer designed to search for Jupiter-like planets around other stars.
- Optical and infrared interferometry technology — Check! We're investing in space interferometry technology for our Origins program.
- Two-Micron All-Sky Survey — Check! This ground-based telescope infrared sky survey accompanies our SIRTF investigations.

"So look at the record. You've told us what the most important initiatives should be — and we do our best to deliver.

"But now I want to raise a series of questions for you:

- Are we fully appreciating the potential importance of fundamental physics?
- Is this area ripe for advancement?
- Are there hints of breakthroughs out there that justify putting physics in space front and center?
- Is this a natural area for the common goals of NASA, DOE, and NSF to come together in a common initiative?

"Take a look at the last Decadal Survey report, *The Decade of Discovery in Astronomy and Astrophysics* (1991). You will hardly find mention of general relativity, the equivalence principle, gravitation, or early universe physics.

"Then take a look at the recent NRC reports "Physics in a New Era." There's practically nothing on gamma-ray bursts, black holes, or gravitational radiation. [Just after this remark, Mr. Goldin was provided with a copy of the just-published *Gravitational Physics: Exploring the Structure of Space and Time*, which was not available when he was composing his remarks.] It's science in a vacuum. Well maybe that's a bad term in this case, because that's exactly where I want it to be — the vacuum of space. But no matter how you categorize it, I'm sure you'll come to the same conclusion.

"The scientific challenges before us require interdisciplinary approaches. Yes, universities are beginning to break down the walls between departments and schools and are developing new ways of training the next generation of scientists. But we can't wait for the next generation of scientists, we must start now with us.

"I have a great faith in human ingenuity to discover revolutionary concepts and new paradigms. We are a remarkably smart species. We have discovered great new ideas: the idea that Earth is not the center of the universe; the idea that humans could fly to the Moon; the idea that the forces of nature lie hidden in the nuclei of atoms.

"Today, we dream that we can understand the architecture of the universe. And we have this incredible, remarkable community of experts skilled in relativistic physics.

"But if we are ever to truly understand the secrets nature still has hidden about the grand design of the universe, we will need to find new answers, and this most likely will require new directions.

"Sometimes we operate in a 'Field of Dreams' mode: 'Build it and they will come.' But I want to suggest a different approach. Let's ask fundamental questions and then seek the best ways to get the answers. Remember the Einstein approach.

"I am convinced that some of these answers to questions in fundamental physics will only come via explorations in space. Space observations are unique in their ability to probe the universe in both time and space. If you want to explore the history of Earth — you're too late. The past is gone and only revealed in the fossil record. But if you want to explore the history of the universe, it's right there for us to witness in real time; in principle, all the way back to the big bang.

"You are the only true historians, because when you look out in space you're looking back in time.

"I see enormous promise in using the laboratory of the universe to explore the laws of physics beyond what our Earth-bound labs could ever do. The physicist Eugene Wigner made this observation: 'Physics can teach us only what the laws of nature are today. It is only astronomy that can teach us what the initial conditions for these laws are.' He was on the right track. Nature has provided us with places where the extremes of gravity, magnetic field, energy, space, and time can all be probed.

"Now, you are the experts, and you can correct me if I'm wrong. But I feel that one of the limitations of our culture is that we have become very compartmentalized. Astronomers tend to focus on their favorite stellar types. High-energy physicists become wedded to the next great ground-based machine and may fail to realize that the ultimate particle accelerators lie in space.

"In seeking progress toward Grand Unification, take a step back and remember that the ultimate quantum gravity event was the big bang itself.

"My point is: if we are to make grand breakthroughs in fundamental physics, we need to pay more attention to this overlap of physics and astrophysics, this inner space-outer space connection. We at NASA believe this connection may hold real potential for testing and advancing our understanding of the laws of physics.

"Already we have the first hints of NEW PHYSICS, physics beyond the Standard Model of high-energy physics, which have come from observations of radiation reaching us from astronomical sources.

"I've talked with Ernie Moniz from DOE and Rita Colwell from NSF. I've asked them to work with us. It's time for a change in perspective; it's time to look to the universe as our new laboratory for discovering new paradigms and revealing the cosmic architecture. We need to pool our talents and join together to create a long-term vision of how to unravel the deepest, darkest mysteries of our universe.

"More than ever we have the technological capability to make amazing progress and to understand what has driven the history of the universe. We have the tools before us — like the paper clip. We just need the will to use them. Only then will we unveil the cloaked rules that govern the creation and evolution of the universe.

"You recall the scene in *The Graduate* where the businessman takes Dustin Hoffman aside and says, 'I have one word for you, son: Plastics!'

"I'm told that Mike Turner (here) takes *his* son aside and says: 'Gravity waves!'

"Maybe we can open a whole new window on the universe through gravitational radiation. Maybe we can investigate string theory by testing the equivalence principle in space. Maybe black holes will provide us with unexpected clues to quantum gravity. Perhaps astronomical observations reveal the real physics behind the cosmological constant. Maybe we can answer the riddle of inflation by measuring the polarization of the cosmic microwave background.

"And when we figure this out, maybe we can let Alan Greenspan in on the secret.

"By daring to look to the heavens for new clues, we may find humanity's next breakthrough in new physics. Imagine the possibilities of harnessing what we discover.

"One person who dares to look to the heavens said this: 'Once we have solved the mysteries of the unification of all forces into a single superforce, we could change the structure of space and time, tie our own knots in nothingness, and build matter to order. Controlling the superforce would enable us to construct and transmute particles at will, thus generating exotic forms of matter. We might even be able to manipulate the dimensionality of space itself, creating bizarre artificial worlds with unimaginable properties.'

"To some it may sound like the bizarre ravings of a mad scientist. Others may think it is something I would say. The author is actually Professor Paul Davies, a respected quantum field theorist.

"Of course he's painting a *long-term* vision for the future. But I believe he may be right — human destiny is to master the unknown and to reach for the stars.

"And maybe someday we will find the secret to developing new energy sources, and even venture from this planet and explore new worlds.

"It is critical in my view that we make the relativistic universe our physics laboratory via gravitational astrophysics, cosmology, particle astrophysics, and high-energy astrophysics. If you share that view, together we can spark broad interest in advancing this field.

"I would like to see the BPA take the lead in putting physics in space front and center. I ask you to organize an assessment of this emerging area of science, an assessment that unites physics, astrophysics, and the latest in space technology capabilities. This assessment should have the best qualities of both the physics and the astronomy surveys. It should provide a science strategy highlighting the most compelling and potentially rewarding questions to answer.

"I would also like BPA to broaden the field beyond high-energy astrophysics or gravitational physics or cosmology to cover the overlap areas. So let's tap the best thinkers in astronomy, astrophysics, and physics, including theoreticians and experimenters — the people who know how to put a fundamental physics project initiative together.

"My hope is BPA will create an initiative to spark new excitement and enthusiasm, as well as cooperation among all the fields involved.

"I'm convinced, as I'm sure many of you are, that there are exciting, and important, breakthroughs in store for us in fundamental physics. But we in the funding agencies need your clear guidance on a broad range of priorities. I'll be very happy when the Academy can provide NASA with priorities spanning astrophysics and fundamental physics. Today, you are taking the first steps toward a new vision of our universe, and I applaud you for that.

"Let's resolve to move forward like Einstein with an unquenchable thirst for knowledge and focused tenacity. The results will be truly out of this world."

Robert Eisenstein, NSF Assistant Director for Mathematical and Physical Sciences, then gave his views on this area from the perspective of the NSF. As subjects, astronomy and astrophysics are in the midst of a golden age of discovery, and our ideas about the formation and evolution of the universe are changing almost on a daily basis. The excitement is contagious, as the public — especially its younger members — has shown a sustained high level of interest in understanding both our origins and our likely fate. Eisenstein presented an overview of NSF's present portfolio of support in astronomy and astrophysics, with an eye toward its possible development in the future. He stressed NSF's interest in close collaboration with the DOE and with NASA in these exciting areas.

Peter Rosen, Director of High-Energy and Nuclear Physics (HENP) at DOE, commented on the DOE perspective. It has always been fascinating that things we learn about the microphysical world using accelerators can have a major impact on the cosmos and vice versa. The connections between HENP and the cosmos go back a long way, from the early days of cosmic-ray physics to modern ground- and space-based experiments. Present-day experiments continue this connection. Rosen discussed the possibilities for the future DOE program. ■

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of the project is provided by a steering group.

Steering Group

Charles Kennel, Chair, Scripps Institution of Oceanography
France Cordova, University of California at Santa Barbara
Robert Socolow, Princeton University
Robert Frosch, JFK School of Government, Harvard University
Albert Narath, Lockheed-Martin (retired)

The steering group will address the question: What is the best structure for a science driven, technology-constrained research program in fusion science?

The remaining members of the committee are divided into three groups: (1) Fusion Concepts, (2) Predictive Capability and Science Infrastructure, and (3) Deep Physics Questions. These groups will assess research in their respective areas. The members of these groups are listed below.

Fusion Concepts

Claudio Pellegrini, University of California at Los Angeles, Group Leader
Stewart Prager, University of Wisconsin–Madison
Linda Capuano, AlliedSignal, Inc.
Andrew Sessler, Lawrence Berkeley National Laboratory

Predictive Capability and Science Infrastructure

James Drake, Chair, University of Maryland, Group Co-leader
Lennard Fisk, University of Michigan, Group Co-leader
Raymond Fonck, University of Wisconsin
George Gloeckler, University of Maryland
Zoran Mikic, Science Applications International Corporation
James Van Dam, Institute for Fusion Studies, University of Texas at Austin

Deep Physics Questions

Robert Rosner, University of Chicago, Group Leader
Patrick Colestock, Fermi National Accelerator Laboratory
Nathaniel Fisch, Princeton Plasma Physics Laboratory
Jonathan Wurtele, University of California at Berkeley

The committee has issued a letter report (August 31, 1999) giving a preliminary assessment. As stated in the cover letter, "The committee prepared the interim report to fulfill the commitment to provide OFES with some initial comments on the quality of the science in its program in time for inclusion in OFES's plans for the next year. A final report will provide a more comprehensive assessment and will address long-term issues facing the field." The text of the cover letter is shown on the facing page (9). The full text of the interim report may be found at the FuSAC Web site (http://national-academies/bpa/projects/fusac). The interim report treated several topics:

- The birth of modern plasma science,
- Fundamental scientific insights from plasma physics and their impact on other scientific disciplines and industry, and
- Outstanding problems.

The following material, quoted from the interim report, describes the development of the field toward a progressively more scientific approach to understanding the plasma dynamics fundamental to fusion. The present state of the field is described in the section entitled "Summary."

The Birth of Modern Plasma Science

"The development of a practical fusion energy source remains one of the most challenging scientific endeavors undertaken by mankind. The early predictions of tabletop-scale fusion energy machines based on 'back of the envelope' calculations very quickly confronted the reality of the plasma state as a complex nonlinear medium. Early plasma experiments more often than not ended with the plasma splattered against the walls of the containment vessels rather than confined within the magnetic bottle as intended. The production of a fusion-grade plasma at a temperature of 100 million Kelvin required the development of the field of plasma science. Scientific tools had to be developed to describe plasma equilibrium, the balance between plasma pressure forces and the confining magnetic forces, and stability. Why do large-scale instabilities cause the plasma to break up and why do instabilities at small scale cause the energy to leak across the magnetic field? How do you heat an essentially collisionless plasma to the temperatures required for fusion and how do you accurately remotely diagnose the complex dynamics of the plasma at both large and small scales to test your understanding of the system? These questions and many more must be answered to establish the firm knowledge base required for the achievement of practical fusion energy production."

Summary

"The worldwide fusion energy program, with vigorous U.S. participation in all areas and leadership in many, has achieved much in its 40-year history. The fusion energy goal also has driven the development of the modern phase of plasma science. Plasma science, in turn, has contributed to many fields of science and technology during this time.

"The reorientation of the U.S. fusion program in 1996 had as its aims the stimulation of innovation and the strengthening of the scientific focus of the program. The extent to which the full promise of this approach has begun to be realized will be addressed in the committee's final report. FuSAC can say with confidence now that the technology needed to create, diagnose, and model sophisticated experiments on fusion-grade plasmas has been developed. The critical materials science issues of fusion energy have been scoped. The progress can be measured in other ways as well: The first preliminary fusion-burning experiments were recently completed. Scientific and engineering understanding of the concepts required for future fusion energy systems is being continually deepened. Nonetheless, the distance to the ultimate goal remains large."■

THE NATIONAL ACADEMIES
Board on Physics and Astronomy

August 31, 1999

Dr. Martha Krebs
Director
Office of Science
Department of Energy
Washington, DC 20550

Dear Dr. Krebs:

National Research Council Chair Dr. Bruce Alberts, in response to your letter requesting a judgement on the quality of the science in the program of the Office of Fusion Energy Sciences (OFES), has established the Fusion Science Assessment Committee (FuSAC). The committee's study will focus primarily on the science of magnetically confined plasmas and the programmatic strategy for long-term progress in this area. The Department of Energy's defense programs also sponsor major inertial-confinement research for stockpile stewardship purposes. Some of the plasma-science issues are common to both magnetic and inertial confinement, but the program structures are quite different. The committee does not directly address inertially confined plasmas in the attached interim report.

The committee prepared the interim report to fulfill the commitment to provide OFES with some initial comments on the quality of the science in its program in time for inclusion in OFES's plans for the next year. A final report will provide a more comprehensive assessment and will address long-term issues facing the field.

In response to congressional direction in 1996, OFES has shifted the focus of its program, emphasizing the effort to build the science and technological foundations for fusion energy and moving the energy technology development effort into the background. The redirection of funds into a broader range of science and technology issues, and to a broader community, is responsive to the report ***Plasma Science: From Fundamental Research to Technological Applications.***[1] The committee finds that this new approach is enabled by recent advances in experiment, diagnostics, theory, and computational modeling.

FuSAC initiated its efforts with a meeting in mid-May 1999 that convened a number of experts on various aspects of the fusion research effort. Discussions with the experts on critical aspects of the program were followed by closed-session discussion by members of the committee about their impressions of the program. On the basis of that work, subsequent telephone conferences, and especially further community inputs and committee discussion at the July 1999 Snowmass meeting, the committee offers a number of observations about the science in the fusion program and about critical unresolved problems. These observations focus on the conceptual advances and the challenges in the program. The connections between experiment, computation, and theory will be discussed in greater depth in the final report.

The committee's final report will be based on an assessment of the past achievements, current strengths and weaknesses, and future prospects of the field. Development of the final report will be guided by broad questions such as: Does the program ask deep physics questions? What are the current role and future potential of a scientific predictive capability for advancing fusion energy? How does one guide the directions of a fusion energy science program if the ultimate goal is to develop a commercially viable fusion reactor? How can the connectivity of fusion science with other scientific disciplines be strengthened? What structural, programmatic, and institutional innovations and international initiatives might strengthen the scientific approach to fusion energy?

FuSAC's Steering Group joins me in transmitting the committee's interim report to you. The committee members have enjoyed interacting with and learning from the fusion community during the past few months. We look forward to continuing these fruitful interactions as we prepare our final report.

Sincerely,

Charles F. Kennel
Chair, FuSAC

Cc: Anne Davies, Director, OFES
Bruce Alberts, Chair, NRC
Peter Banks, Co-Chair, CPSMA
Carl Lineberger, Co-Chair, CPSMA
Robert C. Dynes, Chair, BPA

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[1] National Research Council, *Plasma Science: From Fundamental Research to Technological Applications*, National Academy Press, Washington, D.C., 1995. A new decadal survey of physics entitled *Physics in a New Era* is now in progress; the *Plasma Science* report is part of the series.

Gravitational Physics
(continued from page 3)

and theory has made it one of the most rapidly changing areas of science today. A short list of some of the important achievements of the past decade illustrates this:

- The confirmation of the existence of gravitational waves by the observed shortening of the orbital period of a binary pulsar.
- The detection of the fluctuations in the cosmic background radiation (the light from the big bang) that are the origin of galaxies today.
- The development of a new generation of high-precision tests (to parts in a thousand billion) of the equivalence principle that underlies general relativity, and the verification of its weak-field predictions to better than parts in a thousand.
- The identification of candidate black holes in X-ray binary stars and in the centers of galaxies. Black holes are no longer a theorist's dream; they are central to the explanation of many of astronomy's most dramatic phenomena.
- The use of gravitational lensing as a practical astronomical tool to investigate the structure of galaxies and search for the dark matter in the universe.
- The increasing use of large-scale numerical simulations to solve Einstein's difficult nonlinear equations. These simulations can predict the effects of strong gravity that will be seen in the next generation of experiments.
- The discovery of "critical phenomena" in gravitational collapse analogous to those that occur in transitions between different states of matter.
- The development of string theory and the quantum theory of geometry as promising candidates for the union of quantum mechanics and gravity.
- The first descriptions of the quantum states of black holes.
- The development of powerful mathematical tools to study the physical regimes in which Einstein's theory can break down.

The Committee on Gravitational Physics (CGP) foresees that the transformation of the science of gravitational physics will accelerate in the next decade, driven by new experimental, observational, and theoretical opportunities. A single theme runs through the most important of these opportunities: *the exploration of strong gravitational fields*. Among the specific opportunities the CGP believes could be realized in the next decade if appropriate resources are made available are the following:

- The first direct detection of gravitational waves by the worldwide network of gravitational wave detectors now under construction.
- The first direct observation of black holes by the characteristic gravitational radiation they emit in the last stages of their formation.
- The use of gravitational waves to probe the universe of complex astronomical phenomena by the decoding of the details of the gravitational wave signals from particular sources.
- The continuing transformation of cosmology into a data-driven science by the wealth of measurements expected from new background radiation satellites, new telescopes in space and on the ground, and new systematic surveys of the large-scale arrangements of the galaxies.
- The first unambiguous determination of the basic parameters that characterize the universe, its age and fate, the matter of which it is made, how much of that matter there is, and the curvature of space on large scales.
- The unambiguous measurement of the value of the cosmological constant with profound implications for understanding the fate of the universe and also for particle physics and quantum gravity.
- The use of gamma-ray, X-ray, optical, infrared, and radio telescopes on Earth and in space to detect new black holes in orbit about companion stars and explore the extraordinary properties of the geometry of space in the vicinity of black holes that are predicted by general relativity.
- The measurement of the dragging of inertial frames due to the rotation of the Earth at the one percent level by the Gravity Probe B mission scheduled for launch in 2000.
- Dramatically improved tests of the equivalence principle that underlies general relativity.
- The understanding of the predictions of Einstein's theory in dynamical, strong-field, realistic situations through the implementation of powerful numerical simulations and sophisticated mathematical techniques untrammeled by weak field assumptions, special symmetries, or other approximations.
- The development of current ideas in string theory and the quantum theory of geometry to achieve a finite, workable union of quantum mechanics, gravity, and the other forces of nature, potentially resulting in a fundamentally new view of space and time. The application of this theory to predict the outcome of black hole evaporation and the nature of the big bang singularity.
- The continued development within quantum gravity of a theory of the quantum initial condition of the universe capable of making testable predictions of cosmological observations today.

As a consequence of realizing these opportunities the CGP expects the next decade of research in gravitational physics to be characterized by (1) much closer integration of gravitational physics with astrophysics, cosmology, and elementary particle physics, (2) much larger experiments yielding much more data and requiring international collaboration, (3) a much closer relationship between theory and experiment, and (4) a much wider role for computation in gravitational physics.

In light of such opportunities, the CGP has identified the following unordered list of highest-priority goals for gravitational physics. These assume that a number of projects now under way go successfully to completion, e.g, Gravity Probe B, the first phase of LIGO, the Chandra X-ray satellite, and the MAP cosmic background satellite.

Goals for Gravitational Physics in the Next Decade

- *Receive gravitational waves and use them to study regions of strong gravity.*
- *Explore the extreme conditions near the surface of black holes.*
- *Measure the geometry of the universe and test relativistic gravity on cosmological scales; explore the beginning of the uni-*

verse.

- *Test the limits of Einstein's general relativity and explore for new physics.*
- *Unify gravity and quantum theory.*

Recommendations

To reach these goals the CGP makes the following prioritized list of recommendations:

1. Gravitational Waves

The search for gravitational waves divides naturally into the high-frequency gravitational wave window (above a few hertz) accessible by experiments on Earth, and the low-frequency gravitational window (below a few hertz) accessible only from space. Both windows are important, and the CGP has not prioritized one over the other.

The High-Frequency Gravitational Wave Window

- *Carry out the first phase of LIGO scientific operations.*
- *Enhance the capability of LIGO beyond the first phase of operations, with the goal of detecting the coalescence of neutron star binaries.*
- *Support technology development that will provide the foundation for future improvements in LIGO sensitivity.*

The Low-Frequency Gravitational Wave Window

- *Develop a space-based laser interferometer facility able to detect the gravitational waves produced by merging supermassive black holes.*

2. Classical and Quantum Theory of Strong Gravitational Fields

- *Support the continued development of analytic and numerical tools to obtain and interpret strong-field solutions of Einstein's equations.*
- *Support research in quantum gravity to build on the exciting recent progress in this area.*

3. Precision Measurements

- *Dramatically improve tests of the equivalence principle and the gravitational inverse square law.*
- *Continue to improve experimental testing of general relativity, making use of available technology, astronomical capabilities, and space opportunities.*

4. Astronomical Observations

The astronomical observations recommended below have strong arguments for support from astronomy and astrophysics. The ones listed are those that the CGP expects to have the greatest impact on *gravitational* physics in the next decade.

- *Use gamma-ray, x-ray, optical, infrared, and radio telescopes on Earth and in space to study the environment near black holes.*
- *Measure the temperature and polarization fluctuations of the cosmic background radiation from arcminute scales to scales of tens of degrees.*
- *Search for additional relativistic binary systems.*
- *Launch all-sky gamma-ray and x-ray burst detectors capable of detecting the electromagnetic counterparts to LIGO events.*
- *Use astronomical observations of supernovae and gravitational lenses to infer the distribution of dark matter and measure the cosmological constant.*

If these recommendations are implemented, the CGP believes that the next decade in gravitational physics could see as significant a transformation of the field as occurred in the late 1960s and early 1970s. This transformation will take the subject further into the arena of strong gravitational fields, with stronger coupling with experiment than ever before, leading to a deeper understanding of the central place that gravitational physics occupies in resolving the fundamental questions of contemporary physics.■

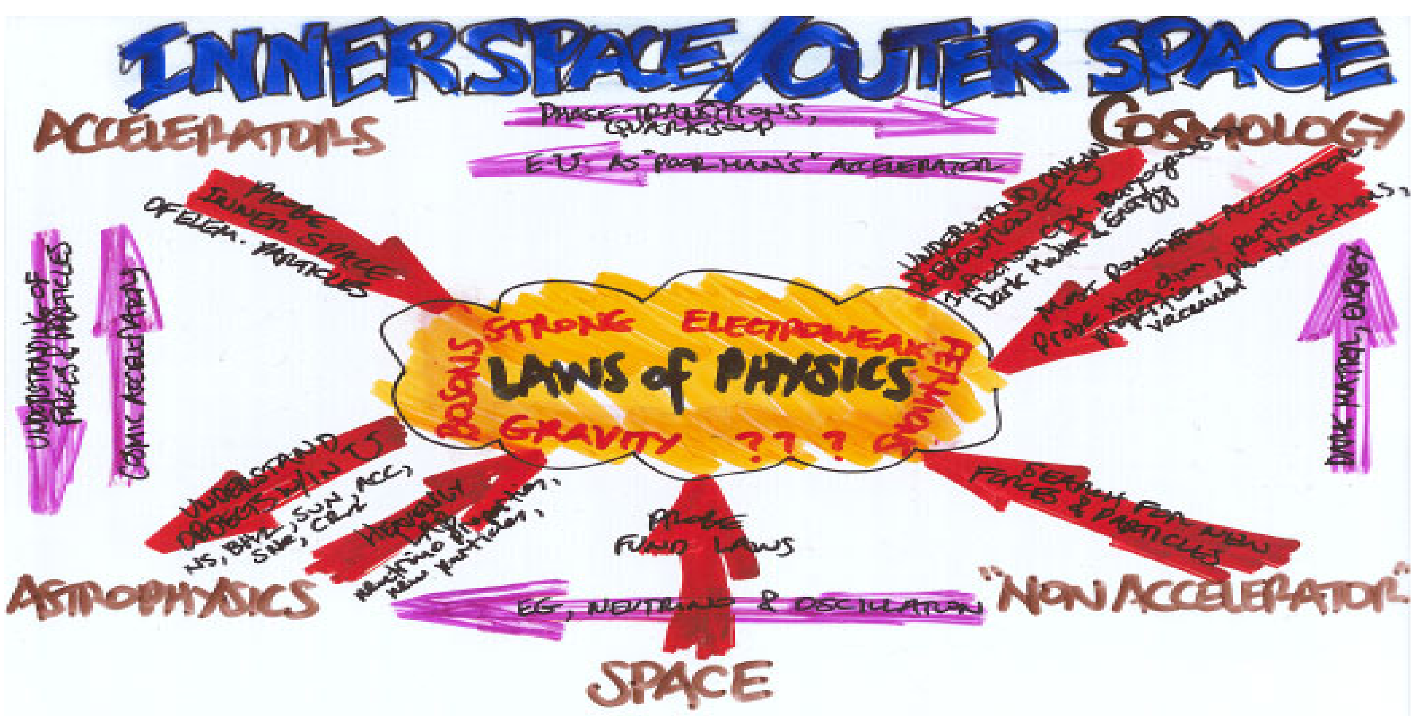

Illustration from Michael Turner's presentation to the "Physics in Space" Forum

THE BPA Web site at **www.national-academies.org/bpa** provides news on recently released reports and other developments. Reports may be ordered at **www.nap.edu.**

New Reports:

- *Gravitational Physics: Exploring the Structure of Space and Time*

Coming Soon:

- *Materials in a New Era: Proceedings of the 1999 Solid State Sciences Committee Forum*
- *The Impact of Selling the Helium Reserve*

Coming Later in 2000:

- *Astronomy and Astrophysics in the New Millennium*
- *Physics in a New Era: An Overview*

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