Naval Studies Board


# NATIONAL RESEARCH COUNCIL

COMMISSION ON PHYSICAL SCIENCES, MATHEMATICS, AND APPLICATIONS

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17 March 1991

MEMORANDUM

TO: Panel on ONR Research Opportunities in Astronomy and Astrophysics

FROM: Lee M. Hunt LH

SUBJECT; Draft Report

Attached is a draft of the panel report on ONR research opportunities in astronomy and astrophysics. Please let us have your corrections and additions within the next two weeks or so. We will then incorporate your changes and send the revised draft out to you again for any further modifications prior to its being sent to the NRC reviewers.

We greatly appreciate your participation in this project, and think that you have turned out an excellent report that should have major impact on ONR. My warmest thanks.

Enclosure: 17 March Draft of ONR Research Opportunities in Astronomy and Astrophysics

DRAFT 17 March 1991

NRC:NSB:052

# ONR RESEARCH OPPORTUNITIES IN ASTRONOMY AND ASTROPHYSICS

Naval Studies Board
Commission on Physical Sciences,
Mathematics, and Applications

NATIONAL ACADEMY PRESS
Washington, D.C. 1991

## Commission on Physical Sciences, Mathematics, and Applications



The project that is the subject of this report was initiated under the predecessor group of the Commission on Physical Sciences, Mathematics, and Applications, which was the Commission on Physical Sciences, Mathematics, and Resources, whose members are listed in the Appendix.

**Panel on ONR Research Opportunities in Astronomy and Astrophysics**

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## PREFACE

In the mid-1980s, in response to a request from the Office of Naval Research (ONR), the Naval Studies Board established a series of panels in fields of science and engineering included in the ONR program. Their task was to identify promising research opportunities for consideration by the ONR in planning the future direction of its program and maintaining the strong science base required to support the U.S. Fleet of the 21st century. The panel on astronomy and astrophysics met in July 1987 and issued its report, Research Opportunities in Astronomy and Astrophysics, early in 1988.

In 1990, again in response to a request from the ONR, new panels were appointed to take another look at the ONR program and to update the earlier recommendations in light of developments during the past few years. For continuity, each panel was composed in part of persons who had served on the previous one, and in many instances, including astronomy and astrophysics, chaired by the previous panel chairman.

The new panel on astronomy and astrophysics met on March 14-15. 1991, and was briefed by representatives of the ONR, Naval Research Laboratory, and U.S. Naval Observatory. In executive sessions following the briefing, the panel prepared the following report presenting its recommendations on new research opportunities for the ONR.

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# I. THE NAVY AND SCIENCE: RECOMMENDATIONS

The U.S. Navy has had a long and fruitful relationship with the scientific community, both within its own centers such as the Naval Research Laboratory (NRL) and the U.S. Naval Observatory (USNO), and with the research universities throughout the country. Astronomy and astrophysics, although constituting a relatively small part of the entire effort, have had an important role to play. Accurate navigation required accurate star positions and precise time, and those functions have expanded in recent years to include applications of timekeeping and astrometry to fields far removed from traditional concerns. Astronomy and astrophysics, more generally, require advanced electronic systems and devices, some of which need to be invented and developed, that find applications in a broader range of fields. The Navy's concern with communications, targeting, remote sensing, surveillance, and state-of-the-art performance of weapons systems requires scientific talent of a high order, and its scientists should be able to interact effectively with the best minds in universities, industry, and other government laboratories. After reviewing the promising opportunities for scientific research in light of Navy interests, the panel arrived at the following four major recommendations:

1. A new space initiative, to facilitate the development and launch of small scientific satellites on a short time scale, should be set in motion now. The impact of such a bold new program at this time would be significant, and the rationale for it appears in Section IV.
2. Interferometric arrays for high-resolution imaging

should be constructed. Major scientific opportunities for such developments are to be found at radio, infrared, and optical wavelengths. There should be significant interest in the application of those technologies to other Navy interests. Details are presented in Section V (see subsections D. Infrared Astronomy, E. Radio/ Optical Astronomy, and F. Particle Astrophysics).

3. Device development, particularly for infrared, ultraviolet, and gamma-ray detection should be pursued aggressively. High-energy resolution for gamma-ray detection, arrays for forming images at ultraviolet and infrared wavelengths, and arrays of x-ray detectors with high-energy resolution are examples of detector developments that offer great promise. These are discussed in more detail in Section V (see C. Ultraviolet Astronomy).

4. The ONR should extend its university contacts in astronomy and astrophysics. The in-house programs at the NRL would derive mutual benefit, especially in improving the NRL's ability to attract young research talent.

## II. INTERACTION BETWEEN TECHNICAL DEVELOPMENT AND PURE RESEARCH

New technology comes in part from the perfection of older technology and its modification by invention. But often the most revolutionary technical developments arise from new knowledge and understanding, or from newly developing fields of knowledge. Thus solid state electronics grew from physicists' increased theoretical understanding and interest in solids. Quantum electronics and new optical techniques had their origins in forms of spectroscopy supported in universities by the ONR, as did also atomic clocks. New radio technology and new possibilities for precise navigation have grown from radio astronomy. And there are many other examples. Such connections between research and technology are always seen more clearly in retrospect than in prediction. Yet one can be relatively certain that some new, important forms of technology will indeed grow from fields of research where there are new ideas being proposed and new discoveries being made by productive scientists. In supporting such research and the development of technology from it, the Navy needs to choose wisely those fields that are most likely to be pertinent to its own future, but it also needs to recognize that new breakthroughs are unpredictable in detail, and that the quality of work and richness of research results in a field are some of the best indicators of eventual contributions to valuable new technology.

For perceptive applications of new research ideas or discoveries, there should be both the vigorous pursuit of research for its own sake and thoughtful coupling between the knowledge of new research developments and the technical needs of the Navy or the broader community. Close contact and involvement of Navy personnel with the research community, and awareness on the part of this community of the nation's technical needs are crucial parts of such coupling--and reasons for the Navy to cultivate carefully some involvement in a wide variety of the more active research fields.

## III. THE NAVY AND THE UNIVERSITIES

Through the ONR, the Navy played a critical role in the nation's scientific successes and the strength of university research after World War II. Other agencies have since then become principal supporters of basic research. Nevertheless, the excellent tradition and the importance of the Navy's interaction with basic research remain, as does its general skill and success in selecting and supporting outstanding research. We believe that the cross-cultural interactions within our society, for example, among universities, government, industry, and the military, are crucial to the strength and effectiveness of the nation's efforts. Hence, although university research is substantially supported by agencies created for this purpose, a strong interaction between research and technology of the Navy and what might be considered academic research continues to be important. Through such interaction, the Navy can be in close touch with new scientific or technical developments, it can encourage and benefit from the interest of outstanding technical personnel and students, and they, in turn, can be aware of real Navy needs and problems.

Astronomy is a field that challenges and attracts an increasing number of outstanding physical scientists and imaginative engineers in our universities. Activity in the field has been increasing over the last several decades, and it seems likely to continue to develop in relative importance and attention in the academic community. It is also a field that makes compelling technical demands. For example, it requires sensitive detection of radiation of all types and precision measurement both from the ground and in space, it challenges theorists with types of situations and questions not usually raised by other human activities, and it demands great sophistication in the treatment of complex and large information fields.

The ONR program in astronomy is at present rather modest in size, that is, about 1 percent of its budget, and largely concentrated in the Navy's own scientific establishment. In view of the vigorous developments in astronomy in the university community, particularly new technical developments and ideas, it seems appropriate for the ONR to consider expansion of this program. In view also of the present small size of its astronomy program, even relatively small additional funds could substantially expand the ONR's participation in university development of new astronomical techniques.

## IV. A BOLD INITIATIVE--AN AGGRESSIVE SPACE PROGRAM

A substantial amount of the astrophysical research activity at the NRL depends on opportunities for space flight. Such opportunities have become very scarce in the last decade due to a number of factors that have beset the U.S. space program. The delays, deferments, and cancellations that have characterized the space enterprise have made it difficult to conceive, develop, and launch space experiments in a reasonable amount of time. Many scientists have abandoned the field, and young people are not being attracted to it. Those groups that are left find themselves often participating as "guest observers" or consumers of data rather than as instrument designers and experimental or observational scientists.

The NRL astrophysics group has not been immune from these deleterious trends. Several attempts, such as the SPARTAN development and space-station-attached payloads, have been sterile because of changes in the NASA plans. Some missions have been delayed by many years (e.g., Gamma Ray Observatory [GRO]), and others cannot be carried out within this century.

If, as we understand, the purpose of maintaining a research initiative in astrophysics at the NRL is both to acquire information about natural phenomena of relevance to the Navy mission and to train the NRL scientific staff in the end-to-end execution of space missions that may become relevant in the future, it is obvious that the present program falls short of achieving these objectives. The training of technicians, engineers, and scientists in space endeavors requires practical experience. A vigorous, productive program will attract the excellent engineers and scientists who are needed for the Navy's basic research program.

This modest space program should assure the Navy of having the desired new technology, development, a means of conducting studies in space, and the basis for attracting bright new talent.

We believe that with additional funds the NRL could initiate an in-house small Explorer program of its own. The NRL clearly has the broad range of expertise necessary to conduct such a program. This initiative could add a useful diversity of approach, hence additional robustness, to the nation's overall space effort. It could be styled along the line of the program operated by the University of Tokyo in Japan, which is approximately the proposed size and results in the launch of a scientific satellite per year. Such a program could not only be made available for the NRL scientists but could be kept open to collaborative endeavors with university and other groups. It is pertinent in this respect to consider the very positive image that ROSAT has created for German scientists and ASTRO-D for Japanese scientists.

The scientific space community has advocated small program initiatives for nearly a decade. The Augustine Committee has endorsed them. However, no clear plans at the appropriate level seem to have developed. A bold initiative in this field by the Navy could be as significant for space science of the future as the development of the Aerobee rocket was for the 1960s, and could have the several benefits for the Navy outlined above.

# V. DISCIPLINES

## A. GAMMA-RAY ASTRONOMY

Research on gamma rays is progressing well. The centerpiece of the effort is the Oriented Scintillation Spectrometer Experiment (OSSE), one of the three major gamma-ray telescopes to be flown on the NASA GRO. Bringing this large, low-energy, gamma-ray instrument to its present state required major technical development, excellent scientific coordination, and leadership. The telescope, which is actually a set of four, is performing well and should produce significant new scientific results in several fields of high-energy astrophysics, from the sun through a range of galactic objects to several types of galaxies. The software has been carefully developed and is ready. A good team has been assembled to analyze and interpret the data, including scientists from Clemson University, Northwestern University, and the Royal Aerospace Establishment, as well as the group at the Royal Research Laboratory. If the GRO is successful, a scientifically productive five to ten years lie ahead. Attention should be given to a careful theoretical interpretation of the results.

The group also is looking forward the future by studying new types of detector systems. The high-spectral-resolution detectors they are studying could represent an important advance.

Their work in relation to the Solar Maximum Mission, which reentered the atmosphere on December 2, 1989, was scientifically productive and was valuable to the Navy, the Department of Defense (DOD), and NASA through the identification of nuclear reactors as significant sources of orbital background via emission of gamma rays, electrons, and positrons. Their work was useful in determining the nature of this radiation and the times that it will affect satellite experiments.

In summary, this program in basic research is balanced and productive and shows promise of remaining so through new detector development.

**B. X-RAY ASTRONOMY**

The NRL group continues to play an active role in x-ray astronomy. Having pioneered the use of very-large-area, nonimaging, x-ray detectors with their A-1 detectors on the HEAO-1 satellite (1977-1980), which allowed high time-resolution studies of compact x-ray sources, the NRL group in recent years has pursued detailed time-variability studies of compact x-ray sources using x-ray satellites launched by the Europeans (EXOSAT) and Japanese (Ginga). Their recent work on the nature of the quasi-periodic oscillations (QPOs) in bright galactic x-ray sources has attracted attention and has further constrained models for the puzzling 6 Hz QPO phenomenon that appears to operate at luminosities near the critical Eddington limit. The group continues to make effective use of the HEAO-A-1 data also, having discovered the long-sought, x-ray binary periods in several objects.

It is noteworthy that in the long hiatus of U.S. x-ray missions (since the 1981 demise of the Einstein Observatory, HEAO-2), the NRL group has designed, built, and flown the only U.S. x-ray experiment launched from the shuttle. Their SPARTAN-1 mission (the low-cost SPARTAN concept was proposed and developed by the NRL) returned the first spatially resolved temperatures of galaxy clusters. The group has also made a promising start in planning for participation in the currently operating ROSAT (German-U.S.) x-ray mission.

A number of their x-ray observing proposals have been accepted, and they are undertaking a promising project on the large-scale distribution of galaxy clusters.

New initiatives in the group include an expanded analysis program, with emphasis on development of numerical methods for astrophysical problems on parallel processing computers such as the recently acquired Connection Machine. This computation work is important for a variety of NRL science objectives, including: general algorithms of signal processing, development of statistical methods for recovery of faint signals in noise, treatment of large data bases, and searches for periodic signals. The latter is particularly relevant for the possible new NRL initiative (see Section VII) of conducting a low-frequency survey for millisecond pulsars.

New detector development work for future x-ray astronomy applications is being conducted in several fields (see subsection H. Radio and Optical Astronomy for more detailed discussion). The most promising is the development of Tunnel Junction detectors for high-resolution, nondispersive, x-ray spectroscopy. These devices are extremely promising and, although also being developed by other groups, the NRL should pursue aggressive research on them. The NRL group is also developing multilayer coatings for normal-incidence, soft x-ray mirrors. These have been developed, and flown, by other groups for solar studies, but the NRL program could explore applications for narrow-band cosmic studies (e.g., supernova remnants).

In all the x-ray activity, there is concern that the group might be limited by its small size (a staff of three or four) and lack of future mission opportunities. A dramatic push for new, small-satellite programs at the NRL (see Section IV) could be particularly useful for the x-ray group. By forging collaborative efforts with outside groups, they could marshall a Small Satellite program for a few carefully chosen objectives (e.g., an All Sky Monitor) and thereby reinvigorate the x-ray program.

## C. ULTRAVIOLET ASTRONOMY

The NRL has had a long history of participating in ultraviolet astronomy, using a variety of instruments of their own development launched above the atmosphere on sounding rockets, the Apollo spacecraft, and other satellites. In recent years, the primary vehicle expected to provide access to space for these instruments has been the space shuttle. The NRL was instrumental in developing the shuttle-borne SPARTAN as an obvious extension of its sounding rocket experiment capabilities. Although initially strongly supported by NASA officials, the aftermath of the Challenger disaster has led to the cancellation of the SPARTAN program, with the result that the NRL's ultraviolet astronomy program has been severely curtailed. Other small instruments, with modest astronomical capabilities, have also not yet been flown aboard the shuttle, though the launch of a pair of small, low-resolution, ultraviolet cameras employing film as the recording medium is imminent.

The lack of an effective route to space for NRL instruments in recent years has been a major obstacle to the success of the ultraviolet program at the NRL. Another serious difficulty, however, is the small size of the group compared with other government and university groups conducting ultraviolet astronomy. In the panel's opinion, the small size of the ultraviolet program and the limited scientific scope that this size supports will make it difficult for the NRL to capitalize on opportunities that could develop as a result of the expanded space program that we advocate elsewhere in this report. We believe a vigorous expansion in the scope of NRL research in this field will be necessary to realize the NRL's potential to make significant contributions to ultraviolet astronomy. This expanded research scope could be achieved through the recruitment of young scientists as staff and postdoctoral fellows, and especially, through increasing the NRL's ties to university-based research groups by establishing collaborative programs. Such collaboration would be particularly beneficial, to both the NRL and the astronomical community, if the NRL can succeed in opening the new channel of access to space advocated by this panel.

## D. INFRARED ASTRONOMY

The development of an infrared observational capability is important to the Navy for the surveillance, detection, and identification of targets, for guidance, and for the determination of the environment in which systems operate. The ONR has a long history in the development of infrared detectors and arrays, the measurement of infrared background radiation, and infrared astronomy. The infrared group at the NRL has pioneered the evaluation and testing of new infrared detectors and spectrometers and their introduction into the astronomical community. Laboratory testing and evaluation, as well as astronomical observations using ground-based telescopes, have yielded important data on infrared detector performance and on measurements of the intensity and spectrum of the infrared background radiation. Imaging and spectroscopic observations of astronomical sources by NRL scientists have produced new insights into star formation and evolution, such as the structure of gaseous outflows from young stellar objects, dust ejection from stellar atmospheres, and element production in supernova explosions, and in the structure of interacting galaxies and gravitational lenses. The Navy should promote and expand the present program in infrared astronomy and in array detector development if it is to maintain a state-of-the-art surveillance and guidance capability.

One of the ONR's most active efforts has been the use of optical and infrared interferometry for astrometry, and in particular, for the definition of an inertial reference frame. Such data are most important to the Navy for navigation and guidance. The technical objectives of the present programs include at least a tenfold improvement in the precision of stellar positions at optical wavelengths, with extended wavelength cover anticipated at near-infrared and thermal infrared wavelengths. The infrared interferometer complements the optical interferometer in exploring the quality of astrometry that can be achieved in a window of the atmosphere with quite different seeing characteristics and in allowing examination of stellar objects that are obscured in the optical region and on which little high-angular-resolution work has so far been done. The next step for this instrument is a third telescope that will allow phase closure and a multiplication of the number of baselines by a factor of three.

## E. RADIO/OPTICAL ASTRONOMY

Astronomical research in the radio domain of the electromagnetic spectrum once appeared to be a separate discipline, distinct from conventional astronomy. Its techniques have been, and continue to be, closely related to interests of the U.S. Navy. The technologies that are vital to radar, communications, signal intelligence, remote sensing, and signal processing are frequently the same as those of the radio astronomer whose research programs require state-of-the-art electronics with low noise characteristics, wide bandwidths, high resolution, and just real-time (or near real-time) processing of the received signals.

Sometimes the radio astronomer has been the leader, with benefits to technology, and sometimes the radio astronomer has been the beneficiary. A number of systems are in use that benefitted significantly from the contributions of radio astronomy.

As knowledge and technology progressed in radio astronomy, many linkages with other disciplines developed. Within the U.S. Navy, the responsibility of the USNO to provide precise time and time-interval information, and to determine the position of stars with the rotation of the earth, had traditionally been carried out by optical observations, using technology that had been perfected over many years. Radio interferometry, and especially the techniques of Very-Long-Baseline Interferometry (VLBI), brought a major change in the state of the art. The most precise information on the rate of rotation of the earth and the location of the pole now comes from radio data. The NRL played an important role in developing the VLBI technique and applying it to the earth rotation problems. The practical operation of the VLBI network that carries out the determinations is in the hands of the USNO. In this work, the NRL continues to have an active role.

The NRL is currently the world leader in applying VLBI to determine the celestial coordinate system. Ultimately, it is clear that the fundamental coordinate system will be referred to the distant quasars. Already, the relative accuracy of quasar positional measurements exceeds the traditional optical techniques by an order of magnitude. This does not mean that the optical techniques can be ignored. A number of operational systems use stars as a reference system, or as a backup reference system, in the targeting process, and increased accuracy will be required of such systems. The reference system of stars, and the reference system of quasars, must be tied together. We are pleased to find that the NRL and the USNO are collaborating effectively in this demanding task. Much work remains to be done, and the panel believes that such work will require collaboration with other groups, especially with the university community. Space missions and strategic systems have requirements for more accurate star positions than present methods achieve, and a well-defined fundamental system of reference is the foundation on which the positional network of stars will be based.

The new interferometric systems that the NRL has sponsored on Mt. Wilson are another example of work that builds toward the future. The astrometric optical interferometer, jointly operated by the NRL and Jet Propulsion Laboratory (JPL), which uses the techniques of radio astronomy at visual wavelengths, measures the relative positions of stars with greater accuracy than that achieved by traditional methods. The infrared interferometer, constructed by the University of California at Berkeley, builds on the methods of radio astronomy and applies them at infrared wavelengths. Here, the principal thrust is to use interferometry to construct images of celestial objects with an angular resolution that cannot be achieved with a simple telescope. The present instruments, both optical and infrared, are "proof of concept" prototypes and active research instruments capable of yielding important new scientific results.

The next logical step in the NRL interferometry program will be the "Big Optional Array." The Mt. Wilson interferometer has demonstrated the feasibility of optical interferometry, but a system designed for imaging optical objects with submilliarc-second accuracy requires a larger number of elements, spread over an area that is physically larger than the space at the top of Mt. Wilson. The proposed array of six telescopes, with multiple configurations that can give baselines up to 470 meters in extent, would be capable of generating an optical "picture" with an angular resolution of about 200 microarc-seconds. The key new technology is borrowed in concept from radio aperture-synthesis arrays such as the Very Large Array (VLA), which make full use of the phase information. The utilization of the phase information in optical interferometers is a more challenging problem, and the Big Optional Array should provide the test that can be used to prove the method.

One can foresee that the scientific results from the Big Optical Array should lend to a new era in stellar astronomy. Starspots and other features on the surfaces of stars will be made visible, and their physical characteristics will be accessible to direct study. This ability can be viewed as a new beginning in solar astronomy as well. Our sun is only one example of a star, and there is a strong case to be made that a deeper understanding of the sun's structure should come about through the study of other stars. The scale of the new array is about right for the next step. Ultimately, larger mirrors with seeing compensation will be needed to study fainter objects. The Big Optical Array addresses the key initial issue, which is to recover the phase information after the incoming light has been perturbed by passage through the atmosphere. Once it has been demonstrated that "self-calibration" techniques work, and the new scientific results on stars have been evaluated, a more sensitive and larger array should be planned.

The theme of interferometry, and the full use of Fourier transform methods, is present in two other initiatives in the NRL radio astronomy program. The Fast All-Sky Telescope (FAST) is a creative approach to the problem of observing time-variable phenomena among radio sources. The anomalous scattering phenomenon discovered by NRL researchers using data taken by the Green Bank radio interferometer (operated by the USNO and NRL over the last several years) suggests that such phenomena are ionized gas clouds in the interstellar medium that have anomalously high electron densities and remarkably small size. This new class of object can only be observed at random times, and the FAST array will be able to monitor enough sources to give a more complete picture of the phenomenon. At the same time, the array will accomplish a number of other interesting scientific projects. One especially exciting prospect could be the discovery of a supernova as it explodes, particularly if one occurs in our own Milky Way Galaxy. The dust in the plane of our Galaxy obscures our view of most of the system, and if a supernova were to occur, it is probable that it would be invisible. Neutrino detectors would catch the explosion, but their positional determination capability is so limited that one would only have a crude idea of where the supernova might have gone off. The FAST, since it views the entire sky approximately once per day, would catch the radio flash also, simultaneously with the neutrino detection, but would measure a precise position as well, thus permitting follow-on observations at improved wavelengths. Further, the FAST would be a facility of great interest to the university community. The panel is extremely interested encouraging the building of such ties between the Navy and the universities. University-Navy collaboration is a natural way to accomplish major projects in an era of fixed resources. At the same time, establishing such collaborative ties would facilitate the recruitment of the best young scientists, thereby maintaining a strong renewal process as the older staff of organizations such as the NRL and USNO retire.

The final imaging proposal that falls within the purview of the radio astronomy group is the Low Frequency Space Array. This is a space project and would be carried out in collaboration with the Space Science Division of the NRL. The first step would be to launch a single low-frequency receiver with a simple antenna, with the task of evaluating the radio frequency environment. One can foresee that the eventual design of a station-keeping array of such satellites would be influenced strongly by the experience gained from a simple reconnaissance mission. The eventual low-frequency imaging array, when operating at frequencies below about 20 MHz, would be exploring the radio sky in a little-studied part of the spectrum. At the same time, practical experience would be gained that might well have an impact on operational systems that would be looking toward the earth rather than up at the radio sky.

**F. PARTICLE ASTROPHYSICS**

The study of particle astrophysics is important to the Navy for understanding the nature of the space particle radiation, the radiation hazards to man in space, and the radiation effects on microelectronic circuits in satellites. The NRL has an excellent capability in this field and in the past has made numerous and valuable contributions to such research. Astrophysical applications have produced significant new insight into the origin and propagation of cosmic rays in the galaxy. The NRL group should be encouraged to complete its current studies of the anomalous component of cosmic rays using the Trapped Ions in Space (TRIS) experiment, particularly to determine the presence, ionization state, and intensity of an anomalous component of low-energy oxygen (high-Z) nuclei in near-earth orbit. Recent data from the Heavy Ions in Space (HIIS) experiment, which measured the intensity of very high-Z nuclei in space, are better than anticipated, showing relatively high charge resolution. This work, which will take several years to analyze, will improve not only scientific understanding of the origin and propagation of cosmic rays but the evaluation of the solar-flare and cosmic-ray-particle hazards in space. Future observations include participation, as one of 15 institutions, in the WIZARD experiment, which will involve use of an Explorer satellite to place a large superconducting magnet in space to measure the charge and intensity of the particle radiation with increased accuracy. The NRL group, however, should be alert to the possibility that because of Explorer satellite backlog and limited NASA funding, this mission could be delayed for many years.

The NRL group has also developed the Cosmic Ray Effects on Microelectronics (CREME) model, which is extensively used in government and industry, and should continue to lead the research into radiobiological hazards associated with manned space flight in low-earth orbits, lunar habitats, and a manned mission to Mars. These activities take on increased importance with the development of NASA's plans for the Mission from Planet Earth.

## G. RADIO AND OPTICAL ASTROMETRY

One of the most dramatic results of the ONR's support and assistance to astronomical programs has been the establishment and successful operation of astrometric optical and radio interferometers. The success of these projects rests largely on implementation of recent developments in laser interferometry and computer technology. The work under ONR sponsorship has been carried out with university collaboration and with close NRL and, recently, USNO participation. Both the radio and optical interferometers have achieved precision at the mas (0.001 arc second) level and represent the most precise and advanced instruments in their fields.

Evidence that these programs have been highly successful is the USNO's undertaking the construction of a large optical interferometer for its absolute astrometry and earth motion programs and the completion of the radio program for the Northern Hemisphere. As commendable as are these achievements, they do not imply that the all work in these areas is done. In particular, the radio program is not complete in the Southern Hemisphere, and the radio-optical systems have not yet been successfully coupled. Extension of the radio program to the Southern Hemisphere, already half complete, would produce the first comprehensive mas precision all-sky system. The optical tie in, by determining the systematic errors of bright star catalogs, would make this system accessible to navigation and guidance systems. Both of these efforts may be accomplished through university and USNO collaboration.

Increasing demands of guidance systems also mandate the improvement of the precision of visual star catalogs. Current star positions in catalogs such as the FK5 are approximately 0.1 arc seconds, yet guidance systems now under consideration require precisions of 0.05 arc seconds and better. Thus, if the error associated with the star's position is to be a small fraction of the total error budget of the guidance system, very significant improvements in these catalogs are required. Two approaches to this deficiency are possible. One, the current space-borne system, HIPPARCOS, if successfully completed, will derive (and eventually make available) positions with a precision of several mas at the current epoch. A second approach is to derive these values from the ground within the United States by the extension of the optical interferometer program now being undertaken by the USNO. The latter effort was pioneered under ONR sponsorship and has achieved precisions of 0.005 arc seconds. A major advantage of this system is that, unlike the 2.5-

year duration mission of HIPPARCOS, it will allow the continued monitoring of star motions and the consequent long-term maintenance of the desired precision of these catalogs. An additional and key aspect of the USNO effort is that its ground connection allows the determination of the earth's rather unpredictable motion with respect to the reference frame. Earth motion in relation to the astronomical coordinate system is significant and requires continuous monitoring. The optical interferometer provides the most direct way to determine the total effects of these drifts with respect to the astronomical coordinate system. If we consider the importance of this reference frame and the earth's position within it, this USNO development seems natural. The continued interest and sponsorship of the ONR is both historically and strategically logical, and we encourage its continuation.

## H. TIMEKEEPING

The maintenance of precise time and time interval (PTTI) is a major responsibility of the USNO. This service is vital to a wide variety of military interests, many of which may have limited awareness of how the PTTI service is maintained. The state of the art has advanced through the years to meet increasingly rigorous requirements. An array of precision atomic clocks provides the time base, which must be supplemented by information on earth rotation and proper motion. The product must be disseminated worldwide with as little degradation of precision as possible.

In considering Radio Astronomy Division's work, the panel noted the constructive interaction between the USNO and NRL. The earth rotation work grew from VLBI and other radio interferometer techniques, and the atomic time standards used in VLBI work can be intercompared by proper reduction of astronomical VLBI data. The atomic time standards themselves have been obtained as commercial products, but new and extremely promising methods are appearing in university laboratories. It may be appropriate to encourage development of such devices as time standards; such work might be carried out by the ONR, either at the NRL or through the relevant university laboratories. Laser-cabled atomic beam devices look especially promising. A long-term precision of 1 part in 1015 could be feasible at an early date if such work were encouraged. Two orders of magnitude improvement, to 1 in $10^{18}$, might be achieved on a longer time scale. The laboratories that are conducting the research at present may not be concerned with producing precise time standards; therefore, an investigation of prospects for such a project should be actively pursued.

## I. DETECTOR DEVELOPMENT

**X-Ray Astronomy:** The development of new x-ray detectors is proceeding with work on superconducting detector systems. Particularly promising, and of great current interest to a number of groups, are the Tunnel Junction detector concepts. These offer promise of extremely high-energy resolution (a few eV) and may thus exceed the superconducting bolometer detector now being developed at GSFC for AXAF. Therefore, work on Tunnel Junction detectors at the NRL should be encouraged.

Less clear-cut is the development of multilayer optics for soft x-ray mirrors that allow normal-incidence x-ray telescopes. Here, the NRL effort appears to duplicate what has been done by other groups, who have already flown rocket payloads and obtained narrow-line solar x-ray images. Multilayer normal-incidence x-ray telescopes appear to be useful primarily for solar work, but if larger area or longer duration telescopes could be flown on small satellite missions (see Sections IV and VII), then cosmic x-ray line imaging becomes possible (e.g., on supernova remnants) and would be of great interest. The NRL multilayer effort could make a valuable contribution if it could extend to large-area, or multiple mirror (for multiple spectral line), systems that could be flown on a small satellite, thereby achieving long exposure times.

**Gamma-Ray Astronomy:** The gamma-ray detector development is a needed follow-on to the current major activity with OSSE/GRO at the NRL. The group is correct to pursue new detector technologies not only for use with post-GRO missions (which could include a small satellite mission) but also for future surveillance work. The gamma-ray detector development effort is proceeding with two instrument approaches.

The first, and more conservative, is the eventual development of position-sensitive planar germanium detectors. This collaborative effort with Lawrence Berkeley Laboratory is just beginning. It is promising and should be pushed with the necessary resources. Position-sensitive Ge detectors would allow either or both the coded aperture and Compton telescope imaging techniques finally to achieve factors of 10-100 greater sensitivity and better energy resolution. The key will be the position-resolution achieved in Ge.

The second gamma-ray detector development effort is the program for superconducting grain detectors. This approach is much more demanding technically than the position-sensitive Ge detector and thus a much higher risk. However, the payoff is potentially greater, and the program should be pushed for <u>at least</u> several more years. It should not be terminated too soon to have investigated fully whether a practical large-area detector could be made. The goals of both high-energy resolution and spatial resolution are difficult to achieve in a large area device needed for cosmic gamma-ray detection.

Compromises on spatial resolution could be made initially and would not detract greatly from the promise of such a detector for a future mission. Once again, small satellite programs (see Sections IV and VII) could provide a flight test.

**Infrared Astronomy:** An important aspect of the development of an infrared sensor capability has been the introduction of two-dimensional infrared array detectors for imaging and spectroscopy. A revolution is occurring in the development and application of these devices, with rapid advances not only in the number of detector elements (now exceeding 60,000 per array) but also in the sensitivity of each detector. Such developments significantly enhance the rate of acquisition and the quality of infrared observations and will have major impact on the Navy's mission for target surveillance, detection, and identification and for guidance. The infrared group at the NRL has been at the forefront in the acquisition of new array detectors and should be encouraged to continue its development, testing, and evaluation of these devices, as well as their application to astronomical observations. However, additional manpower and financial support are needed at the NRL to take full advantage of the rapid advances in technology and to expand the capability to build new instrumentation. Collaboration with university scientists has proved valuable in this program and should be strongly encouraged in the future.

## VI. NRL/USNO INTERACTION

In the previous subsections on radio astronomy, astrometry, and timekeeping, numerous instances were given of fields of common interest to the NRL and USNO. The ultimate research goals of the two organizations differ, but there is strong commonality in the techniques they use. A strong communication link between them already exists and should be further encouraged. The completion of the network of precisely located compact quasar sources, with the relative radio positions determined and the optical positions tied to the stellar coordinate system, is an unfinished task, particularly in the Southern Hemisphere. This NRL/USNO program will require the close cooperation of the two organizations. It is a long-term effort that will ultimately become a USNO responsibility, but the organizations will have to work together to establish an ultimate fundamental reference frame.

## VII. PROJECTIONS AND SPECULATIONS: POSSIBLE FUTURE PROGRAMS

The NRL is well-positioned to maintain and strengthen its programs of research in a number of key areas. These extend from most of the research and development programs currently under way to several new ones that would not only further increase the value of NRL work for the Navy but also enhance the nation's science effort as a whole. The panel has identified three future programs that we summarize in order of increasing complexity and possible impact.

### A. NEW ATOMIC CLOCKS

The present performance of working precision oscillators such as hydrogen masers, batteries of cesium clocks, and the like, are impressive, with long-term stability of a few points in $10^{15}$. There are several recent developments that should be investigated seriously; some of them are being considered in a preliminary way now. One especially promising new technique has arisen recently: laser-cooled atomic beams. The work, pioneered by Chu at Stanford, could lead to an improvement in clock stability of several orders of magnitude, and a detailed review, potentially leading to a significant development effort, should be undertaken.

### B. MILLISECOND PULSARS AS PRECISE CLOCKS

A modest effort to extend the low-frequency coverage of the VLA below the current 75 mHz limit to 20-30 mHz would have enormous impact for the rapidly emerging new field of millisecond pulsars. A very low frequency (VLF) extension to the VLA, which would require separate antennas that might be incorporated into the VLA facility to make use of existing resources, could conduct an extremely sensitive survey for millisecond pulsars (MSPs). Current, but necessarily limited, wide-field surveys from Arecibo and Parkes have indicated that there is a very large population of MSPs (at least $10^5$ in the galaxy). These are steep spectrum objects, thus best detected at VLF. The MSPs are increasingly recognized to be exceptionally stable clocks, probably better than the best atomic clocks on timescales of months or years.

The current interest at the NRL in VLF astronomy would thus naturally suggest a pulsar survey. A pulsar survey, in particular a MSP survey, would be of great interest for establishing not only the origin and distribution of these objects but also for establishing a vast network of cosmic clocks. With at least 103 MSPs likely to be detectable from a dedicated galactic survey, these could be used to establish a network of cosmic clocks. Such a "pulsar timing array" (PTA) has been proposed by university groups that might wish to collaborate with the NRL to see it materialize.

The PTA would require extensive data-processing capability, such as that being developed at the NRL with the Connection Machine. It would extend these capabilities in a manner likely to contribute to other large-scale data-processing and data-management tasks carried out by the Navy. By providing what is likely to be the best time base on scales of months to years, the PTA would be of great value to the USNO and to Navy timekeeping interests in general.

## C. ADAPTIVE OPTICS AND PRECISION

Any long-range prediction of the development of science or technology must first forecast profound surprises, along with major growth and changes. Our penetration of the future is likely to be obscured for any time beyond one decade. But probably on about that time scale one development that can be expected is marked progress in precision imaging through the atmosphere. This advance is likely to be coupled also with detectors of great sensitivity, dynamic range, and a large number of pixels. Consider precision imaging.

Optical components of very large systems can now be kept accurately in precise position regardless of thermal drifts or mechanical instabilities by laser interferometry. This capability opens the possibility of optical instruments with almost indefinitely large apertures or interferometry with almost indefinitely large baselines and angular resolution. Radio astronomers have well demonstrated the precision production of complex images from interferometers with a finite number of elements. In the optical and infrared regions, similar principles have been applied to a modest extent; as compared with the radio region, the quality of such results has been limited in part by atmospheric "seeing" problems or fluctuations. However, we know in principle how to compensate for most of these fluctuations by using laser "guide stars," adaptive optics, and phase closure techniques. In principle, interferometry can produce excellent images by multiple apertures, if each is sufficiently small to be diffraction limited. Theoretically, relative phase of sets of fringes can be obtained by phase closure. With adaptive optics operating well on each of a number of apertures, interferometric imaging should also be possible with with much larger apertures and with vastly improved sensitivity. Furthermore, work in the near infrared provides many of the benefits one expects from visible light but with substantial amelioration of atmospheric problems, greater ease in providing adaptive optics and phase measurements, and ability to penetrate dust more successfully.

It appears that, in principle, enormous improvements can be made in imaging through the atmosphere for the optical and infrared regions. Already, there has been successful experimentation with systems oriented toward such improvements, including some important ones supported by the Navy. Although great rewards from such work can be predicted with certainty, yet much difficult development and experimentation, and also substantial experience, will be needed to achieve the full potential of such systems. The astronomical community is one of several that are vitally interested in the success of such developments, as is our military establishment. It appears to be an field in which support and development should be extremely rewarding.

**APPENDIX**
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Neal F. Lane, Rice University
Christopher F. McKee, University of California at Berkeley
Richard S. Nicholson, American Association for the Advancement of Science
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