On the Advanced X-ray Astrophysics Facility

On April 28, 1993, Space Studies Board Chair Louis J. Lanzerotti sent the following letter to Dr. Wesley T. Huntress, Jr., associate administrator for NASA's Office of Space Science.

In a letter to me dated September 15, 1993, from Mr. Joseph Alexander, Assistant Associate Administrator for Space Science and Applications, NASA requested that the National Research Council (NRC) conduct a scientific evaluation of the restructured Advanced X-ray Astrophysics Facility (AXAF). Working jointly with the NRC's Board on Physics and Astronomy, the Space Studies Board established a Task Group on AXAF to perform this study. I am pleased to enclose the report of this task group.

Please contact me if you have any questions about the report.

SCIENTIFIC ASSESSMENT OF THE RESTRUCTURED PROGRAM FOR THE ADVANCED X-RAY ASTROPHYSICS FACILITY (AXAF)

April 28, 1993

Summary

The Task Group on AXAF (TGA), a joint panel of the Space Studies Board and the Board on Physics and Astronomy, finds that the restructured AXAF program-consisting of AXAF-I, to be launched into a high-Earth orbit in 1998, and AXAF-S, to be launched into a polar, low-Earth orbit in 1999-is fully capable of meeting the primary scientific goals of the former AXAF program. Although the need to reduce substantially the total cost of the program has led to shorter mission lifetimes, the expected increase in operating efficiency partly makes up for this shortfall. The TGA concludes that the revised AXAF program continues to meet the scientific expectations set forth in previous NRC reports, which have recommended AXAF as the highest-priority, new, large-scale program in astronomy.

Thus the TGA urges NASA to proceed with the implementation of the restructured AXAF program and to make every effort to ensure the launch of both AXAF-I and AXAF-S before the end of this decade.

Background

In a letter dated September 15, 1992, from Joseph K. Alexander, Assistant Associate Administrator for Space Sciences and Applications, to Louis J. Lanzerotti, Chair of the Space Studies Board, NASA asked the National Research Council (NRC) to evaluate the scientific content and the expected scientific return of the restructured AXAF program. In response to this request the Space Studies Board and the Board on Physics and Astronomy jointly established the Task Group on AXAF (TGA) as a subpanel of the newly formed Committee on Astronomy and Astrophysics. Arthur F. Davidsen, of Johns Hopkins University, was appointed Chair of the TGA. The full membership of the task group is attached. The TGA was asked to carry out its review and evaluation of the AXAF reconfiguration by the end of 1992.

The TGA held several meetings via teleconference during October and November 1992 and developed a set of questions concerning the reconfigured AXAF. These were addressed to AXAF program officials at NASA Headquarters and AXAF project officials at the Marshall Space Flight Center. In addition, all members of the AXAF Science Working Group were invited to provide to the TGA information and comments concerning the revised program. Martin Weisskopf, AXAF Project Scientist, provided an extensive written response comparing the scientific capabilities of the original and revised AXAF programs, and Peter Ulrich, AXAF Program Manager, provided written materials concerning the programmatic aspects of the restructuring. The TGA discussed all the responses in a teleconference on December 3, 1992, and held a meeting in Washington, D.C., on December 10 and 11, 1992, at which it heard presentations concerning the restructuring and had discussions with the several AXAF scientists and managers who attended part of the meeting. This report presents the TGA's conclusions and recommendations concerning the AXAF program.

This report was reviewed and discussed by the parent boards of the TGA, the Space Studies Board and the Board on Physics and Astronomy, as well as by the new joint Committee on Astronomy and Astrophysics of the two boards (membership lists attached). Each of these reviews concurred fully with the substance and findings of the report.

Previous NRC Recommendations for AXAF

The AXAF mission has been anticipated and endorsed consistently by the decadal studies of astronomy and astrophysics carried out under the NRC's Board on Physics and Astronomy by the Bahcall committee and by the Field committee before that, and by several reports of the Space Studies Board (and its predecessor, the Space Science Board) and its committees:

- In 1979 (just prior to the launch of the Einstein satellite), the Committee on Space Astronomy and Astrophysics of the Space Science Board, in their document entitled *A Strategy for Space Astronomy and Astrophysics for the 1980's* (National Academy of Sciences, 1979), envisioned and recommended "a semipermanent (several-decade) national observatory facility . . . open to all astronomers and with instrument-changing possibilities . . . . More than an order-of-magnitude improvement in sensitivity over HEAO-2 (Einstein) is required to allow high-resolution spectroscopy and in-depth studies of specific objectives such as clusters of galaxies and active galaxies. This can be achieved by a combination of greater telescope size, better optical surfaces, improved focal-plane instrument sensitivity, and longer mission duration compared with HEAO-2." (p. 13)

- The Field Committee report (*Astronomy and Astrophysics for the 1980's*, Volume I, National Academy Press, 1982) identified four key programs of critical importance for the advancement of astronomy and astrophysics in the 1980s. That committee's top priority was AXAF, which was envisioned as "a permanent national observatory in space, to provide x-ray pictures of the Universe comparable in depth and detail with those of the most advanced optical and radio telescopes. . . . [T]his facility will combine greatly improved angular and spectral resolution with a sensitivity up to one hundred times greater than that of any previous x-ray mission." (p. 15)

- In the report *Long-Lived Space Observatories for Astronomy and Astrophysics* (National Academy Press, 1987), the Space Science Board's Committee on Space Astronomy and Astrophysics stated that it "concurred with the recommendations of the Astronomy Survey Committee (1980), which urges the construction of AXAF . . . . [It] will play a fundamental role in the future progress of astronomy and astrophysics." (p. 2)

- In *Space Science in the 21st Century* (National Academy Press, 1988), the Space Science Board's Task Group on Astrophysics and Astronomy found that "[t]he powerful capabilities of AXAF and the wealth of fundamental problems it can address suggest that this facility will advance research [in x-ray astronomy] for a long time to come." (p. 27)

- The Astronomy and Astrophysics Survey Committee of the Board on Physics and Astronomy (*The Decade of Discovery in Astronomy and Astrophysics*, National Academy Press, 1991) found that AXAF "will return the United States to preeminence in x-ray astronomy . . . [and] have a major impact on almost all areas of astronomy . . . ." That committee reaffirmed the Field Committee decision making AXAF "the highest-priority large program" of the 1990s. (pp. 64-65)

The TGA finds that the scientific performance of AXAF that was anticipated by these previous studies will still be achieved by the restructured program. It is obvious, however, that the authors of these earlier reports envisioned AXAF as a permanent or at least semipermanent x-ray observatory, with an associated program of maintenance that would include new focal-plane instrumentation. However, because the costs associated with such a program are too high to sustain in the current budget environment, NASA and the AXAF Science Working Group have decided that a pair of limited-life missions is a preferable scenario for accomplishing the scientific goals of the AXAF program. The TGA endorses this view and believes that the revised AXAF program will satisfy the scientific expectations encompassed by previous NRC committee reports, even though it will not provide a permanent x-ray observatory in space. The new program should be designed to ensure that the capabilities of AXAF will still be made available to the broad astronomical community through a vigorous guest observer program.

Recent Developments in X-ray Astronomy

Since the AXAF program was first conceived in the 1970s, the field of x-ray astronomy has progressed considerably. The TGA finds that recent developments have only strengthened the arguments in previous NRC reports supporting the need for the enhanced imaging and spectroscopic capabilities that the AXAF program can provide. A few examples are cited below.

Several important results have recently come from the imaging detectors on ROSAT. A prime example from galactic studies is the detection of multiple low-luminosity x-ray sources in the cores of globular clusters. These may be the long-sought cataclysmic variables (white dwarfs that have captured binary companions in the dense cluster cores) and are only marginally resolved even with the ROSAT High-resolution Detector. Thus, the much higher spatial resolution of AXAF-I will be critical for more detailed studies.

There are many new extragalactic results: one is the detection of extended x-ray emission around NGC 1068. Coupled with earlier work on NGC 4151, we now have solid evidence that a hot medium exists around the centers of active galactic nuclei (AGNs) and that spatially resolved, moderate-resolution x-ray spectroscopy will be an important tool for studying both the active nucleus and the surrounding medium.

ROSAT has detected substructure in all clusters of galaxies observed. With detectors that provide both imaging and spectroscopic information, AXAF will measure the mass of galaxy groupings within a cluster and trace out the mass distribution. AXAF will provide a consistency check for the assumption of hydrostatic equilibrium, since x-ray-emitting shock waves should be present if hydrostatic equilibrium does not apply.

ROSAT has shown that many, if not most, AGNs are strongly absorbed below 2 keV. With its higher-energy imaging capability, AXAF will not be impeded in its search for distant objects by the opacity of the circumstellar medium of an AGN. ROSAT, with an energy range below 2 keV, has resolved a large fraction of the x-ray background into discrete objects. AXAF, having significantly more sensitivity and angular resolution than ROSAT, should more completely resolve the x-ray background, if it is indeed entirely composed of discrete sources. Furthermore, AXAF results will apply to energies above 2 keV.

The ROSAT all-sky survey has yielded a total of more than 50,000 objects that can be studied in depth with AXAF's broad range of spectroscopic capabilities. The ROSAT catalog is expected to be publicly available by the time AXAF is operating.

The Japanese x-ray satellite Ginga detected 6- to 7-keV x-ray lines from nearby AGNs. This implies that iron lines, probably broadened fluorescence lines from circumnuclear material, are common emission features in AGN spectra, and that AXAF will therefore have the capability to measure redshifts of distant AGNs.

A very recent result from the Broad-band X-ray Telescope (BBXRT) confirms the existence of an x-ray absorption line in the spectra of BL Lac objects. The greater sensitivity and spectral resolution of AXAF is needed to extend this search to other objects and other lines. The detection of other x-ray absorption lines will resolve ambiguities that currently plague the interpretation of these features.

The premier astronomical event of the 1980s was the occurrence of SN1987a, the closest supernova explosion in 400 years. During its planned time in orbit AXAF may have the opportunity to observe an extraordinary phase in the evolution of SN1987a. The expanding shell of debris from the explosion will collide with a slow-moving ring of matter ejected by the star prior to its death. The best estimate for the time when collisions will begin is about the year 2000. Not only will the event be spectacularly bright in x-rays, but it will also be highly variable in intensity and in its spectral line distribution. The resulting display will provide the best determination of the abundances of newly synthesized matter. As collisions of different clumps of ejecta occur, SN1987a will reveal the composition of different parts of the supernova ejecta. AXAF will also have the ability to locate the positions of the discrete clumps as they are heated to temperatures at which x-rays are emitted. By observing how stars make elements, we will better understand how galaxies evolve. Such a direct observational test of nucleosynthesis theory will allow us to apply these models with confidence to abundance patterns in galaxies at high redshift.

Comparison of the Original and Revised Programs

The restructuring of the AXAF program splits the original, single facility (AXAF-O), a low-Earth-orbit serviceable mission, into two nonserviceable simpler missions: one devoted principally to imaging (AXAF-I), which will be launched into a high, elliptical orbit, and one devoted principally to spectroscopy (AXAF-S), which will be in a low, polar orbit. AXAF-I will carry four of the original six mirror-shell pairs that made up the AXAF-O telescope, two imaging cameras-the AXAF CCD Imaging Spectrometer (ACIS) and the High-resolution Camera (HRC)-and two spectrometers-the Low- and the High-energy Transmission Grating Spectrometers (LETGS and HETGS, respectively). AXAF-S will carry a lower-resolution, shorter-focal-length, foil-mirror telescope and the x-ray Spectrometer experiment (XRS). AXAF-O was designed to be serviced at five-year intervals for a total lifetime of fifteen years. The design lifetime of AXAF-I is five years, and the design lifetime of AXAF-S is three years.

Since the technical aspects of the various instrument designs remain almost entirely unchanged, the scientific performance of the unified AXAF program is largely preserved. The principal differences are associated with the changes in the telescope complement and in the mission profile. Specifically:

- The reduction in the number of mirror-shell pairs in the AXAF-I telescope (from six to four) diminishes by about 40% the effective area of the system at low energies. However, this effect is largely offset by the increase in the observing efficiency of the mission brought about by the change to high-Earth orbit. In particular, the number of observations that can be accomplished at fixed sensitivity over an extended period of time is very nearly the same for the original and the revised AXAF missions. At high energies, the effective area of the system has actually been improved, due to the introduction of high-reflectivity iridium coatings in place of the nickel and gold coatings planned for the original telescope's outer and inner mirror shells, respectively.

- The use of the low-resolution foil telescope for AXAF-S affects both the spatial resolution and the effective area of the XRS investigations. Although some capability for spatially resolved high-resolution spectroscopy still exists with this experiment, measurement of spectral variations on fine angular scales is no longer possible. The foil telescope has very high throughput, and so the net effective area is comparable to that for AXAF-O at high energies and is down by a factor of only about 2 at low energies. Most importantly, the XRS is likely to be *more* productive during its design lifetime on the AXAF-S mission than it would have been on AXAF-O, simply because it can be operated continuously, thereby utilizing its limited supply of cryogen more efficiently.

- Another advantage of the restructured program will be the opportunity to conduct simultaneous observations with the two missions. This can be extremely useful for complementary measurements of time-variable sources. As an example, for many sources such as active galactic nuclei, x-ray binaries, and stellar flares, AXAF-S can be used to obtain high-resolution spectra of the Fe K complex near 6 keV ($E/\Delta E \sim 500$), while at the same time the HETGS experiment on AXAF-I is used to make high-resolution observations of the Fe L complex near 1 keV ($E/\Delta E \sim 1000$). The comparison of Fe K to Fe L line fluxes and profiles will prove very useful for constraining plasma conditions in these sources.

- Finally, elimination of the servicing aspect of the program reduces net observing time by a factor that is less than 2, since in the restructured mission, AXAF-S and AXAF-I will be operated independently. Perhaps the most serious loss in this regard involves the capability of fielding new instrumentation that might have capitalized on future technological advances or been designed specifically to follow up earlier AXAF discoveries. It seems likely, however, that alternative, post-AXAF mission scenarios could prove equally effective as platforms for fielding new instrumentation, perhaps even in a more cost-effective manner.

The restructured AXAF mission maintains essentially all of the outstanding scientific capabilities of the baseline mission. The angular resolution of AXAF-I is more than an order of magnitude better than that offered by any other mission under development or even in the planning stages. The U.S. investment in high-precision x-ray optics makes AXAF-I unique in its capabilities to undertake x-ray investigations on the largest scales and at the earliest epochs of the universe.

Similarly, the broad-band, nondispersive spectroscopy enabled by the development of the micro-calorimeter (the XRS) is maintained in the restructured mission. AXAF-S will provide a combination of high sensitivity and high spectral resolution in the important energy region above 4 keV that is unavailable with any other planned missions. Its capabilities for high-resolution spectroscopy of extended sources are particularly notable and unique in comparison with those of dispersive spectrometers.

The restructured AXAF program continues to provide unmatched angular resolution, spectral resolution, and sensitivity that will make it the centerpiece of international efforts in x-ray astronomy for the foreseeable future. When the AXAF-I and AXAF-S spacecraft are launched at the end of this decade, they will provide unique capabilities permitting major advances in our understanding of the universe.

References

1. Committee on Space Astronomy and Astrophysics, Space Science Board, *A Strategy for Space Astronomy and Astrophysics for the 1980s*, National Academy of Sciences, Washington, D.C., 1979.

2. Astronomy Survey Committee, *Astronomy and Astrophysics for the 1980's*, Volume I, National Academy Press, Washington, D.C., 1982.

3. Committee on Space Astronomy and Astrophysics, Space Science Board, *Long-Lived Space Observatories for Astronomy and Astrophysics*, National Academy Press, Washington, D.C., 1987.

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5. Astronomy and Astrophysics Survey Committee, Board on Physics and Astronomy, *The Decade of Discovery in Astronomy and Astrophysics*, National Academy Press, Washington, D.C., 1991.

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