ARTICLE

Far-Ultraviolet Astronomy on the Astro-1 Space Shuttle Mission

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The Astro-1 mission obtained observations related to a wide variety of current problems in astronomy during a 9-day flight of the space shuttle Columbia. Early results from one of the instruments, the Hopkins Ultraviolet Telescope, are reviewed here. Among these are new insights concerning the origin of the ultraviolet light from the old stellar population in elliptical galaxies, new evidence for a hot, gaseous corona surrounding the Milky Way, improved views of the physical conditions in active galactic nuclei, and a measurement of the ionization state of the local interstellar medium.

The National Aeronautics and Space Administration's (NASA's) Astro-1 Observatory was launched aboard the space shuttle Columbia on 2 December 1990, beginning a 9-day mission whose technical problems were widely reported in the press but whose scientific achievements are just now coming into focus. Mounted on two steerable platforms in the cargo bay were three telescopes designed to perform various measurements in the ultraviolet (UV) band of the spectrum and one telescope designed to study astronomical x-ray sources (Table 1). Also on board was a crew of seven astronauts, including four astronomers who had been waiting for this flight since 1984.

One of the Astro-1 instruments was the Hopkins Ultraviolet Telescope (HUT), designed to study stars, planets, nebulae, galaxies, and quasars in a largely unexplored region of the spectrum—the far- and extreme-UV bands (*1*). Important clues to the nature of these objects are potentially available in this spectral region, which is not accessible to other observatories, including the Hubble Space Telescope. During the Astro-1 mission, HUT obtained UV spectrophotometry of 77 objects at wavelengths extending from 1850 Å to the Lyman limit at 912 Å, where the interstellar medium becomes opaque because of photoelectric absorption by atomic hydrogen, and detected a few nearby objects at wavelengths as short as 400 Å. Part of the scientific and technical motivation for this mission and a few of the numerous results derived from the first year of analysis of these data are discussed in this article.

Astronomy from the Space Shuttle

Astro-1 was the first space shuttle mission dedicated exclusively to astronomical observations since the start of shuttle flights in 1981. When development of the Astro telescopes was proposed in the late 1970s, many astronomers hoped that the space shuttle would provide relatively easy and vastly expanded access to space for small and moderate-sized telescopes, such as those that were being launched on sounding rockets. Such vehicles typically provide an experimenter with only 5 min to collect data at high altitudes, enough to get a brief measurement of one or two bright objects. The prospect of a week or more in orbit (actually, up to 28 days were then contemplated by NASA officials), collecting data on hundreds of celestial objects 24 hours a day, was more than enough of an incentive to overcome the concern that working in the shuttle world (as it came to be known at NASA) might not be so easy for academic scientists.

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An additional attraction offered by the shuttle attached-payload program was the promise of multiple flights of an individual instrument. This approach allows for repairs, modifications, and calibrations to be performed between missions. It was also supposed to make space science more like laboratory experimentation and provide opportunities to train graduate students and young scientists in the development of space hardware. Finally, the new approach was expected to reduce the need for extremely high level quality assurance, and its associated costs, because occasional instrument failures could be tolerated in a program of this type.

More than a decade after they were conceived, the telescopes of the Astro-1 mission were finally launched aboard the space shuttle Columbia. During the mission, both of the shuttle computer terminals used by the crew to control the Astro-1 instruments overheated and had to be shut down. We recovered from these events by devising a new operating procedure, in which the crew pointed the UV telescopes at the objects of interest with a joy-stick control (similar to that on a simple video game) while the ground-support team controlled the telescopes by up-linking commands directly to the computers in the telescopes, bypassing the malfunctioning terminals on the shuttle.

Averaged over the 7-day portion of the mission devoted to scientific operations, HUT achieved a net observing efficiency (on-target time divided by total clock time) of 25%, while the three other Astro telescopes simultaneously gathered data. Comparison with other missions reveals that this is an excellent level of efficiency for a complex astronomical satellite in low Earth orbit, especially considering that only 24 hours were used for all the preparations necessary before the observations began. During the Astro-1 mission, HUT obtained observations of 77 different objects, with multiple observations made of some of them, totaling nearly 40 hours. Although only a portion of the data has now been analyzed in detail, it is already clear that HUT and the other Astro telescopes are providing important new insights in many branches of astronomy. Because of this success, NASA officials have decided to conduct a second mission, dubbed Astro-2, currently scheduled for launch in late 1994.

Far-Ultraviolet Spectroscopy

Ultraviolet telescopes such as the International Ultraviolet Explorer (IUE), which has performed outstandingly well in orbit since 1978, and the Hubble Space Telescope (HST), launched in 1990 and now

Table 1. The Astro-1 Observatory.

Instrument	Institution	Principal investigator
Hopkins Ultraviolet Telescope	Johns Hopkins University	A. F. Davidsen
Wisconsin Ultraviolet Photo-Polarimeter Experiment	University of Wisconsin	A. D. Code and K. S. Nordsieck
Ultraviolet Imaging Telescope	Goddard Space Flight Center	T. Stecher
Broad Band X-Ray Telescope	Goddard Space Flight Center	P. Serlemitsos

clearly beginning to overcome its well-publicized problems, have optical coatings of magnesium fluoride and aluminum and detector windows of magnesium fluoride or lithium fluoride whose reflectivity and transmission make them insensitive to UV wavelengths much shorter than 1150 Å. However, the interstellar medium (ISM) remains fairly transparent down to the Lyman edge of hydrogen at 912 Å. At shorter wavelengths, the large photoelectric absorption cross section of hydrogen prevents observations of objects more than about 100 pc (326 light-years) from the sun (the ISM becomes transparent again in the soft x-ray region of the spectrum at wavelengths less than 100 Å). A number of important spectral lines are found in the small portion of the spectrum extending from 1216 Å (the wavelength of the hydrogen Lyman α line) to 912 Å, including the entire Lyman series of atomic hydrogen, the Lyman and Werner bands of molecular hydrogen, and the resonance lines of several abundant elements in various ionization stages. One of the most important features in this band is the resonance doublet of O VI (five-times ionized oxygen) at 1032 and 1038 Å, which arises in gas at temperature $T = 2 \times 10^5$ to 10^6 K under conditions of collisional equilibrium. This feature may be used to probe the highest temperatures accessible to UV and optical astronomy. The study of gas at even higher temperatures generally requires x-ray detectors.

Pioneering work in the wavelength region between the Lyman α line and the Lyman edge was performed with the Princeton experiment on Copernicus, one of the Orbiting Astronomical Observatories (OAOC) (*2*). The Copernicus telescope and spectrometer were designed to perform absorption-line studies, using very bright, hot stars as background sources of light, of the interstellar gas at high spectral resolution. However, only a small region of the spectrum could be covered with its scanning spectrometer in any single observation, and absolute flux measurements of the stars themselves were generally not possible.

The only other satellite instrument that has made extensive astronomical observations at wavelengths near the Lyman edge is the Ultraviolet Spectrometer, which was carried on both the Voyager 1 and 2 spacecraft (*3*). This instrument was designed to study the outer planets during close encounters, but, in spite of its small collecting area, it has also been used to detect a few other celestial objects in the extreme UV, 500 to 912 Å, and many more in the 912 to 1216 Å band (*4, 5*). However, the Voyager instrument achieves only rather low resolution, about 18 Å for stars and 38 Å for diffuse objects such as nebulae. This has made identification of some spectral features with specific emission and absorption lines difficult.

The Hopkins Ultraviolet Telescope

The purpose of HUT was to complement the studies that are being done with IUE and HST by pressing beyond the wavelengths covered by these telescopes, down to the Lyman limit and further into the extreme UV (*1*). The resolution of HUT's spectrophotometry is moderate (3 Å) in the range 830 to 1850 Å in first order, overlapping the long-lived observatories above 1200 Å. The telescope's sensitivity extends down to 415 Å in second order but has been maximized over the 900 to 1200 Å region, resulting in the capability to study objects as faint as 16th magnitude.

This instrument is a prime focus telescope with a diameter of 0.9 m, a Rowland circle spectrograph, and a photon-counting microchannel-plate detector. At the focal plane, there is a choice of several different spectrograph entrance apertures, including round apertures 18 and 30 arc sec in diameter, used primarily to observe stellar objects, and large slits 9.4 arc sec × 116 arc sec and 18 arc sec × 116 arc sec in length, which provide high sensitivity for viewing faint diffuse nebulae. With its very fast focal ratio (*f*/2), HUT outperforms even HST in this nebular mode. One of the apertures contains a thin aluminum filter that passes only extreme-UV radiation in the 400 to 700 Å band (*6*).

The unique characteristics required of an instrument designed for studies near the Lyman limit stem from the lack of any window or lens materials that transmit these wavelengths and from the low reflectivity of radiation in this band by normal mirror coatings. In the design of HUT, we overcame these problems by eliminating the use of a window, keeping the number of reflections to the absolute minimum (one telescope mirror and one diffraction grating), and using coatings of osmium and iridium, heavy metals whose reflectivities are a relatively high 20% at the desired wavelengths. On the ground, the detector and its cesium iodide photocathode are protected from air by a vacuum seal at the spectrograph entrance. This seal is opened after several hours in space, when the ambient density in the shuttle cargo bay has dropped to an acceptable level. The spectrograph is kept at low pressure by attached vacuum pumps, which operate between observations.

A low light level TV camera that provides a view of the 9 arc min × 12 arc min field that surrounds the spectrograph aperture is also incorporated into HUT. The image is used by the payload specialist to find a target object and, as it turned out on Astro-1, to keep the telescope pointed at it. A HUT microprocessor also digitizes the image and transmits it to the ground, where operations personnel can aid in the identification of objects. Amplified pulses from the HUT UV detector are also digitized, and pulse centroids are computed to determine the position of individual photons to a precision of 12.5 μm, which corresponds to 0.51 Å in the spectrum. The final resolution is typically about 3 Å, except for observations of extended objects with the wide slit, for which it is about 6 Å. Photon arrival times are obtained with 2-s resolution for all the data, and 2-ms timing is available for objects whose count rates are less than 500 counts per second. This makes it possible to study rapid variability of UV sources, which has not been possible with IUE or Voyager.

The net effective area achieved with HUT is about 10 cm^2 at 1050 Å and is within a factor of 2 of this value over the range 900 to 1600 Å (*1*). A flat-spectrum object with a magnitude of 12.5 has a flux of 0.01 photon cm^{-2} s^{-1} $Å^{-1}$, yielding nearly 100 counts per second with HUT. The detector background count rate, attributable to cosmic rays, is less than 1 count per second. In a typical observation lasting about 2000 s (limited by the low Earth orbit of the shuttle), HUT obtains an excellent spectrum of such an object with a signal-to-noise (S/N) ratio of about 25 at 3 Å resolution. Much fainter objects can be observed at a lower S/N ratio, and multiple-orbit observations can be combined. Data can also be binned to lower spectral resolution if necessary. Observations may be made during the day as well as during the nighttime portions of each 90-min orbit. Numerous bright airglow emission lines of hydrogen, oxygen, and nitrogen provide a high background signal during the day, however, preventing observations of the faintest objects. This background is much lower when the shuttle is in Earth's shadow.

Ultraviolet spectrophotometry requires that the instrument be carefully calibrated, which has been done with HUT (*1*). The instrumental efficiency function was determined by measurements made in the laboratory both before and after the flight, using light sources and detectors traceable to the National Institute of Standards and Technology. The function was independently determined in flight by comparing the observed spectrum of the hot white dwarf G191-B2B with a model atmosphere calculation believed to provide an accurate prediction of the UV flux distribution of this star. The two methods agree to high precision, with a root-mean-square difference of only 6% over the 912 to 1850 Å range and a maximum deviation of 12%. Thus, absolute fluxes measured with HUT should generally be accurate to better than 10%, a substantial improvement over previous work in the far UV.

Scientific Results

In the 18 months since the Astro-1 mission, analysis of the data obtained with HUT has provided us with new insights into topics in particle physics, cosmology, active galactic nuclei, quasars, normal galaxies, the interstellar medium, stellar astrophysics, and the solar system. I summarize below a few of the interesting results that have been derived so far.

The galactic corona. During the past 20 years, it has been established by several different means that the ISM contains an important gaseous component with temperature T of 10^5 to 10^6 K (*7*). Such gas is called coronal, by analogy with the solar corona. Cooler interstellar gas is heated to temperatures above this range by supernova explosions (*8*). At these temperatures the gas radiates soft x-rays and cools to about 10^4 K, where it may remain until it is heated again by another blast wave. Depending on the mean density of the gas and the rate of energy input by supernovae, a small (10%) to large (90%) fraction of the ISM may be filled with gas at T of about 5×10^5 to 10^6 K (*9*). Under certain circumstances, a galactic fountain might exist, in which the heated gas escapes into the galactic halo, where it could cool and rain down on the disk (*10*).

The sun is thought to be surrounded by a local bubble with a radius of 100 pc containing coronal gas that produces much, if not all, of the soft x-ray background radiation at energies below about 0.25 keV (*11*). The fact that the background is brighter at the galactic poles, however, has led some investigators to suggest that at least some of the radiation is due to coronal gas in the galactic halo, the region that surrounds the main disk, at distances of several kiloparsecs from the galactic plane. Recent ROSAT (Roentgen Satellite) observations of shadows in the soft x-ray background that are attributable to foreground clouds tend to support this view (*12*). Observations with IUE have established that there is indeed ionized gas in the halo but have not established that the temperature of the halo gas is high enough to produce x-rays (*13*).

Ultraviolet observations of interstellar O VI absorption lines with Copernicus first established the existence of coronal gas in the galactic disk but could not determine whether such gas extends far into the halo because the telescope was unable to observe the faint objects needed to probe the distant parts of the halo. Jenkins (*14*) found that the mean density of O VI ions in the disk is 2.8×10^{-8} cm^{-3} and tentatively suggested a scale height of only 300 pc to describe the distribution of this gas away from the galactic plane. Such a small scale height would imply that the hot gas is confined to a region fairly close to the galactic disk.

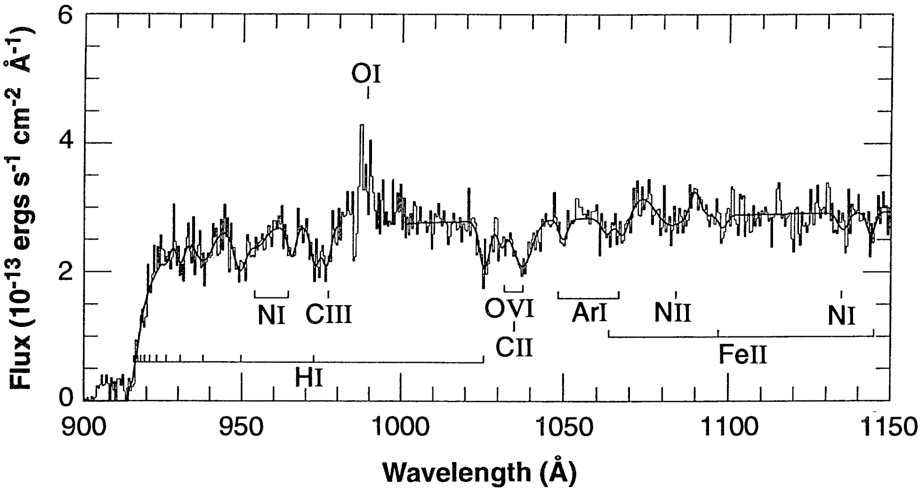

Fig. 1. Far-UV spectrum (wavelength λ < 1150 Å) of quasar 3C273 observed with HUT. The histogram represents the data reduced to absolute flux and corrected for airglow emission lines. The smooth curve is a fit to the continuum and the various spectral features which are attributable primarily to absorption by interstellar gas. Note especially the features attributed to O VI, believed to arise in a hot galactic corona [adapted from (*17*)].

The O VI ion appears with significant fractional abundance only at $T > 2 \times 10^5$ K for gas in collisional equilibrium, and there are no known sources of ionizing radiation that could explain widespread O VI gas by means of photoionization. On the other hand, the lower ionization lines attributed to gas far above the galactic plane, such as C IV and Si IV, can be explained by photoionization from a combination of halo stars and extragalactic UV background radiation. Thus, a crucial test of the nature of the galactic halo can be made by searching for O VI absorption by looking toward extragalactic objects at high galactic latitudes. A hot corona will have a large column density N (total number of particles per unit area integrated along the line of sight) of O VI (*15*), whereas a cooler, photoionized halo, supported at a large distance from the galactic plane by something other than its thermal pressure, will have a much smaller column density of this ion (*16*).

On the Astro-1 mission, HUT was used to observe the far-UV spectrum of the quasar 3C273 (*17*). At galactic latitude $b = +64°$, this line of sight passes almost vertically through the entire halo, providing an excellent probe for coronal gas. The quasar is a good background source for such an observation because it is expected to have an intrinsically smooth spectrum with no features at the rest wavelength where O VI absorption in our galaxy would occur. The HUT spectrum of 3C273 has strong absorption features at 1032 and 1038 Å, the wavelengths of the O VI doublet (Fig. 1). However, there are several interstellar absorption lines that are expected to contribute to the feature at 1038 Å on the basis of absorption lines seen with HST at longer wavelengths. There are also possible contributions to the O VI features from intergalactic hydrogen clouds, whose Lyman α absorption has been seen with HST. The clouds discovered in the Virgo cluster have a redshift that causes their Lyman β lines to contribute to the 1032 Å feature, and Lyman γ lines from a higher redshift cloud may contribute to the 1038 Å feature. It is possible to place strong upper limits on all of these contaminating features, however, and the result is that O VI absorption is required to produce the strong features seen with HUT.

Davidsen *et al.* (*17*) find that N(O VI) is very likely greater than 3×10^{14} cm^{-2}. When compared with the mean density in the disk derived from Copernicus observations (*14*), this suggests a scale height of at least 3 kpc, clearly placing the hot gas in the galactic halo if this line of sight is not atypical. A model for a photoionized halo predicted N(O VI) < 10^{13} cm^{-2} (*16*), whereas a model based on a radiatively cooling corona or galactic fountain predicted N(O VI) = 6×10^{14} cm^{-2} (*15*). Clearly, the former model is excluded by the HUT result, but the latter model is supported. However, the radiative cooling model of Edgar and Chevalier (*15*) does not actually predict enough of the lower ionization species Si IV and C IV to match the observations of 3C273, indicating that the situation is more complicated. Recent work (*18*) on the galactic fountain has shown that self-photoionization of the radiatively cooling gas alters the relative abundances of the lower ionization states appreciably. When this effect is incorporated in the calculations, it is found that the predicted column density ratios of O VI, N V, C IV, and Si IV come into close agreement with the observations. Therefore, HUT has provided new evidence supporting the existence of a hot galactic corona, with $T > 2 \times 10^5$ K, probably originating in a galactic fountain. Of course, it is still necessary to measure the O VI column density along several other lines of sight to prove that the hot gas is widespread in the halo and to map its distribution. These observations will be attempted with HUT on the Astro-2 mission.

The local interstellar medium. We turn now from a consideration of the most global aspect of the ISM to a consideration of its properties in the immediate vicinity of the sun (*19*). As already mentioned, it is believed that the sun is inside a local bubble of hot gas with T about 10^6 K and number density around 10^{-3} cm^{-3}. This gas is highly ionized and therefore provides no opacity for observations within 100 pc or so. Numerous investigations have shown, however, that there is a minimum column density of neutral atomic hydrogen of about 10^{18} cm^{-2} toward all stars observed, and this minimum is all that is seen for stars in the local bubble. Thus, it appears that the sun must be surrounded by a small, at least partially neutral cloud with approximately this column density. An atomic-hydrogen density of about 0.1 cm^{-3} and a bubble size of 3 to 5 pc are consistent with the existing data.

There is completely independent evidence of partially neutral interstellar gas in the immediate vicinity of the sun from observations of solar Lyman α and helium 584 Å resonance radiation scattered by the neutral gas (*19*). Observations made with many spacecraft have indicated a neutral-helium density of about 0.01 cm^{-3} in the gas flowing through the solar system and a neutral hydrogen density about five times as large with a temperature of about 8000 K. The low observed ratio of H to He compared with the nominal cosmic abundance ratio of 10 has usually been interpreted to indicate that the hydrogen is significantly ionized whereas the helium is largely neutral. However, known sources of ionizing radiation in the solar neighborhood are insufficient to maintain such a high degree of hydrogen ionization in the local cloud.

There is a possible solution to this dilemma that does not require the interstellar hydrogen to be highly ionized. Ripken and Fahr (*20*) proposed that the inflowing hydrogen from the ISM undergoes charge exchange with solar wind protons, reducing the observed neutral hydrogen density by a factor of 2 or so from its true value; but their suggestion has remained controversial. According to Ripken and Fahr's calculations, this mechanism requires that the local interstellar hydrogen be 10 to 20% ionized. This degree of ionization is consistent with known sources of ionizing radiation, including the line emission from the coronal gas in the local bubble, which, somewhat surprisingly, produces a slightly higher level of ionization for the helium in the local cloud (*21*).

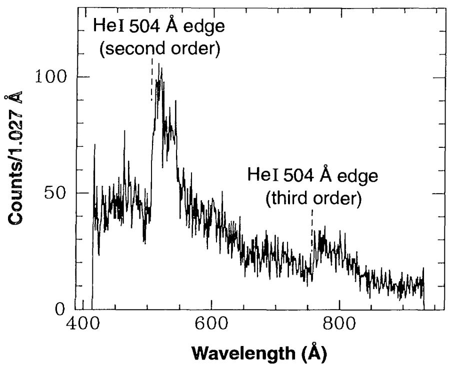

Fig. 2. Extreme-UV spectrum of white dwarf G191-B2B observed with HUT. Raw count data are displayed as a function of the second-order wavelength, which has been binned to 1.027 Å. Absorption by interstellar helium shortward of its 504 Å ionization edge is clearly visible in both second and third order (higher orders of diffraction by the grating). [Reprinted from (*22*) with permission © American Astronomical Society]

The sensitivity of HUT in the 400 to 900 Å portion of the extreme-UV band allows us to make a direct measurement of the neutral hydrogen and neutral helium column densities in the local ISM. The nearby hot white dwarf G191-B2B, located within the bubble but beyond the local cloud, provides a suitable background source for this measurement. It is a DA white dwarf, meaning that it has a pure hydrogen atmosphere whose properties are readily calculated, and is hot enough (60,000 K) to provide a strong signal at 500 Å. Furthermore, the absence of atmospheric helium in such a star avoids potential confusion with interstellar helium.

Absorption by interstellar hydrogen reduces the flux from this star just below 912 Å to an undetectable level, but the decreasing photoelectric cross section at shorter wavelengths transmits an easily detected flux at 500 Å. The helium photoionization edge at 504 Å produces a discontinuity in the spectrum, whose strength is directly proportional to the neutral helium column density. Meanwhile, comparison of the observed spectrum with the theoretical stellar atmosphere for this star permits determination of the hydrogen column density as well.

Isolating the 400 to 700 Å region of the spectrum with its aluminum filter, HUT observed G191-B2B on the Astro-1 mission (Fig. 2). We found a hydrogen column density of 1.69 ($\pm$ 0.12) $\times$ 10^{18} cm^{-2} and a helium column density of 1.45 ($\pm$ 0.065) $\times$ 10^{17} cm^{-2}, giving a H I/He I ratio of 11.6 $\pm$ 1.0. If the total abundance ratio is the usually presumed cosmic value of 10, this ratio of neutral species indicates that helium is preferentially ionized compared with hydrogen, as predicted by Cheng and Bruhweiler (*21*). All the data are consistent if hydrogen is 10 to 20% ionized and helium is 10 to 35% ionized and if charge exchange with the solar wind reduces the neutral-hydrogen fraction of the interstellar gas flowing into the solar system. Only if the helium abundance is less than the primordial value produced in the Big Bang (a situation that is, of course, not expected) can the ionized fraction of hydrogen significantly exceed that of helium. If the helium abundance in the cloud exceeds the normal cosmic value, our results would require the helium to be much more highly ionized than the hydrogen.

The local cloud is found to have a total hydrogen density of about 0.15 cm^{-3} and an electron density of about 0.03 cm^{-3}. With a total column density of 2.2 $\times$ 10^{18} cm^{-2}, the local cloud has an extent of about 5 pc (15 light-years) in the direction of G191-B2B. If this dimension is typical, the total mass of the cloud is about 0.4 $M_\odot$, where $M_\odot$ is the mass of the sun. Of course, it would be interesting to determine the hydrogen and helium column densities and ionized fractions along several other lines of sight, too. This can be done on the Astro-2 mission.

The survival of the local cloud in the environment of the hot local bubble is problematical. If it predated the occurrence of a nearby supernova whose blast wave might have created the local bubble, it should not have survived the blast. Even in the current environment, such a cloud must have a short lifetime because of evaporation by the hot bubble gas, and it is therefore tempting to conclude that the cloud is fairly young. Perhaps it is the remnant of a planetary nebula shed by a nearby star that has recently become a white dwarf (*19*).

Origin of ultraviolet light in elliptical galaxies. Before the advent of space astronomy, it was generally believed that elliptical galaxies would be dark in the UV. Optical spectra of ellipticals showed that their light is dominated by cool red stars whose UV output is negligible. Such stars are very old, and the absence of young blue stars indicated that ellipticals had a quiescent stellar population dating back about 10 billion years. In contrast, star formation in spiral galaxies (including the Milky Way) and irregular galaxies continues quite vigorously to this day. The first UV observations of galaxies made with the OAO-2 satellite (23), and subsequently with the Astronomical Netherlands Satellite (ANS) and IUE, showed, however, that elliptical galaxies become brighter below 2000 Å, with the flux continuing to rise toward the shortest wavelength observed (1250 Å). The strength of this UV upturn varies greatly among different galaxies, and Burstein *et al.* (24) showed that galaxies with higher heavy-element abundances have stronger UV upturns.

These surprising results suggested the possibility that star formation is continuing in giant ellipticals at a low enough rate to be undetectable in the visible spectrum and yet to be dominant in the UV. A young stellar population would be expected to include a certain proportion of massive, very hot O and B stars whose spectral flux distributions could explain the UV upturn. Further support for this idea came from x-ray observations that revealed hot gas in some ellipticals that might cool and condense to form new stars.

Alternatively, the old stellar population might provide enough UV light from dying stars that have shed their cool outer layers in the post–red giant phase of their evolution, revealing their small, hot cores. Such stars are well known in our galaxy. They include the so-called horizontal branch stars in globular clusters and the Milky Way halo, the central stars of planetary nebulae, and similar stars that eventually cool down to become white dwarfs. Until recently, both of these very different ideas—young stars or dying stars—remained as potential explanations of the UV light in elliptical galaxies, though neither could claim compelling agreement with the observations (25).

This problem was originally one of the major motivations for the development of HUT. For example, its *f*/2 focal ratio and large apertures make HUT more sensitive than HST to the diffuse flux expected from large, nearby galaxies, and its wavelength coverage down to the Lyman limit provides an excellent discriminator of the temperature of the stars responsible for the UV radiation. During the Astro-1 mission, HUT obtained the first detailed far-UV spectrum of an elliptical galaxy (26), NGC 1399 in the Fornax cluster, which is known to have one of the strongest UV upturns of any normal elliptical studied with IUE (24). From the absence of any clear absorption or emission feature at C IV (1550 Å), which is strong in hot, young O stars in our galaxy, Ferguson *et al.* (26) were able to exclude such stars as the principal source of the UV light in NGC 1399. The decrease in flux observed in the spectrum below 1050 Å also argues against stars with temperatures greater than about 25,000 K, further proof that O stars are not present. Such

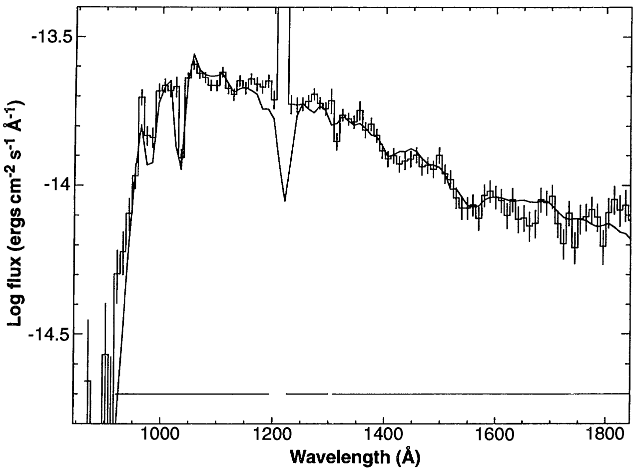

Fig. 3. UV spectrum of NGC 1399 observed with HUT. The histogram shows the flux-calibrated, airglow-subtracted data averaged over 10 Å bins. (Residual Lyman α airglow remains.) Vertical bars indicate statistical error. The smooth curve shows a synthetic spectrum of a population of AGB-manqué stars constructed from the 0.48 $M_{\odot}$, $Y = 0.30$, $Z = 0.02$ model of Castellani and Tornambè (28). Here Y indicates the fractional abundance of helium (by weight) and Z indicates the abundance of elements heavier than helium. The horizontal lines at the bottom show the regions of the spectrum used in fitting models to the data. [Adapted from (30) with permission © Editions Frontières]

stars would be expected if a low level of normal star formation were continuing today, though a burst of star formation that ended about 2×10^7 years ago could possibly explain the data. A population of this age would contain only stars of spectral type B and later ($T < 25{,}000$ K) because the hotter, more massive O stars would all have evolved to produce supernovae by now, leaving behind, as remnants, faint neutron stars and possibly black holes.

Ferguson *et al.* (26) also found that theoretical models based on the evolution of post-asymptotic giant-branch (PAGB) stars (such as central stars of planetary nebulae) do not fit the data obtained with HUT. This is basically because stars that follow the evolutionary paths calculated for this phase spend a large fraction of their time at very high temperatures, $T > 50{,}000$ K, whereas the HUT data indicate that the principal contribution to the UV radiation comes from stars with T about 25,000 K. Although the hotter PAGB stars must be present in the old stellar population of ellipticals, they can contribute only a small fraction of the UV light seen in NGC 1399 if the evolutionary tracks and stellar atmospheres used to model them are correct.

Thus, both of the most popular explanations of the UV light in ellipticals appear to be excluded by the HUT results. Recently, however, there have been new calculations of the late stages of evolution of low mass, high metallicity stars (27–29). These calculations have identified two new types of evolutionary behavior: the post–early-AGB stars and the AGB-manqué stars. The post–early-AGB stars evolve part of the way up the AGB but depart from it at an early stage, before the onset of the thermal pulses that are experienced by normal PAGB stars. They then evolve to higher temperatures at lower luminosity than PAGB stars, with a longer time scale. They maintain two shell sources of nuclear burning (one hydrogen and one helium) during this evolution and consequently emit more UV light over their lifetimes than do the more luminous PAGB stars, making them an excellent candidate to account for the strong UV upturns in ellipticals. The AGB-manqué stars begin on the blue end of the horizontal branch and skip the evolution up the AGB altogether. They evolve slowly toward higher luminosities, becoming even hotter and bluer in their final stages, and then settle on the white dwarf cooling sequence. These stars also provide an interesting, new possible source for the UV light in ellipticals.

We have computed an integrated spectrum of a population of stars evolving along one of these newly identified evolutionary tracks, namely, the one with the largest integrated output in the HUT wavelength band. When the result is compared with the HUT spectrum of NGC 1399 (Fig. 3) (30), the agreement is excellent. Therefore, it appears likely that these new theoretical insights, in combination with the HUT observations, have at last provided a viable explanation for the unexpectedly strong UV light in elliptical galaxies. Observations of a few more elliptical galaxies, including some with lower metallicity and weaker UV upturns, can be made on Astro-2. Such observations will then place important constraints on the theoretical calculations of these late stages of stellar evolution.

Seyfert galaxies. Seyfert galaxies have been among the most intensively studied objects in astronomy, primarily because they are thought to be nearby, low luminosity versions of the same phenomenon observed in quasars. A massive black hole in the nucleus of a galaxy, accreting gas from its surrounding environment, is thought to power all these objects. Of course, we do not see the black hole itself, but the UV continuum radiation is generally presumed to be thermal emission from the hot gas that forms an accretion disk surrounding the black hole. In addition, very broad emission lines are observed, which are thought to come from clouds somewhat farther away, moving at velocities of order 5000 km s^{-1}. These broad-line clouds are photoionized and heated by the extreme-UV radiation from the central source, resulting in the strong, broad resonance line emission observed from hydrogen Lyman α, C IV (1549 Å), and other elements. The permitted lines also sometimes show narrower cores, and there are also narrow forbidden lines, which are thought to arise from more distant, lower density photoionized gas in a narrow-line region.

The broad-line component dominates the spectra of quasars and type 1 Seyfert galaxies, while the narrow-line component dominates in type 2 Seyferts. It is widely believed that the objects may be basically similar but that obscuration of the central region as viewed from certain directions may hide the continuum and broad-line regions in type 2 Seyfert galaxies, leaving a clear view of only the narrow-line region. The luminosity of Seyferts is typically $\sim 10^{11}$ $L_{\odot}$, where $L_{\odot}$ is the luminosity of the sun, making the tiny nuclear region as luminous as an entire galaxy of stars, and the inferred mass of the central black hole is $\sim 10^7$ to 10^8 $M_{\odot}$. The luminosity is proportional to the mass-accretion rate, which is about ~ 1 $M_{\odot}$ $year^{-1}$. Small values of these parameters are associated with low luminosity Seyferts, and large values are thought to characterize the much rarer, high luminosity quasars.

The far-UV spectral region is of fundamental importance in determining the nature of all these active galactic nuclei. The UV continuum radiation may arise in an accretion disk very close to the black hole, whereas UV emission and absorption lines provide the best diagnostics of the surrounding material in the broad- and narrow-line regions. Consequently, observations of Seyfert galaxies and quasars were the goal of one of the major observational programs for HUT on Astro-1.

One of the brightest and best studied Seyfert galaxies is NGC 4151. It has been classified as type 1.5, showing the characteristic features of both types 1 and 2 (*31*). We obtained a high-quality spectrum of NGC 4151 in a 2200-s observation with HUT (Fig. 4). Below 1200 Å, a region in which no Seyfert galaxy has previously been observed, we find strong emission in the O VI doublet and a very complex absorption line spectrum. The Lyman α line and the O VI line are both found to have broad wings with full width at half maximum (FWHM) = 8500 km s^{-1}, identical to the C IV feature, but overlying absorption by numerous lines tends to obscure this fact. Kriss *et al.* (*32*) found that the broad lines have relative intensities similar to those seen in quasars (the large redshift of quasar radiation makes this spectral region accessible to other telescopes) and to theoretical photoionization calculations. All of the permitted lines also have similar cores, with FWHM = 1500 km s^{-1}.

The strongest absorption lines include the Lyman series of hydrogen, as well as features due to C III and N III and higher ionization states, up to N V and O VI. All of the absorption lines are blue-shifted, with respect to the galaxy rest frame, by several hundred kilometers per second, and they appear to have intrinsic widths of about 1000 km s^{-1}. The UV continuum disappears completely below 924 Å, owing to strong absorption by overlapping Lyman lines. The ratio of the strengths of the C III 977 Å line and the C III* 1176 Å line (which arises in an excited state) indicates densities in the absorbing gas greater than 10^8 cm^{-3}. Such high densities are characteristic of the gas in the clouds that yield broad emission lines. Kriss *et al.* conclude that the absorption may arise in the disintegrating remnants of outflowing, radiatively accelerated broad-line clouds. Furthermore, this same material may be responsible for producing the narrow cores of the permitted emission lines. Finally, this material may collimate the ionizing radiation from the central source, explaining the bipolar cone-like appearance of the narrow–emission-line region (*33*). The absorption lines seen by HUT in the far UV thus provide an important new means for studying conditions in active galactic nuclei.

Other Results from HUT

In addition to the topics described above, HUT has been used to address a wide range of problems that can only be mentioned briefly here. For example, observations were made of several cataclysmic variables, or dwarf novae, which consist of a white dwarf accreting matter from a normal red dwarf in a close binary system. The accretion disk surrounding the white dwarf is of considerable interest in its own right and also for what we might learn that would be applicable to the much larger accretion disks in active galactic nuclei. The quasi-periodic outbursts seen in dwarf novae are probably due to an increased rate of mass transfer resulting from an instability in the disk. The American Association of Vari-

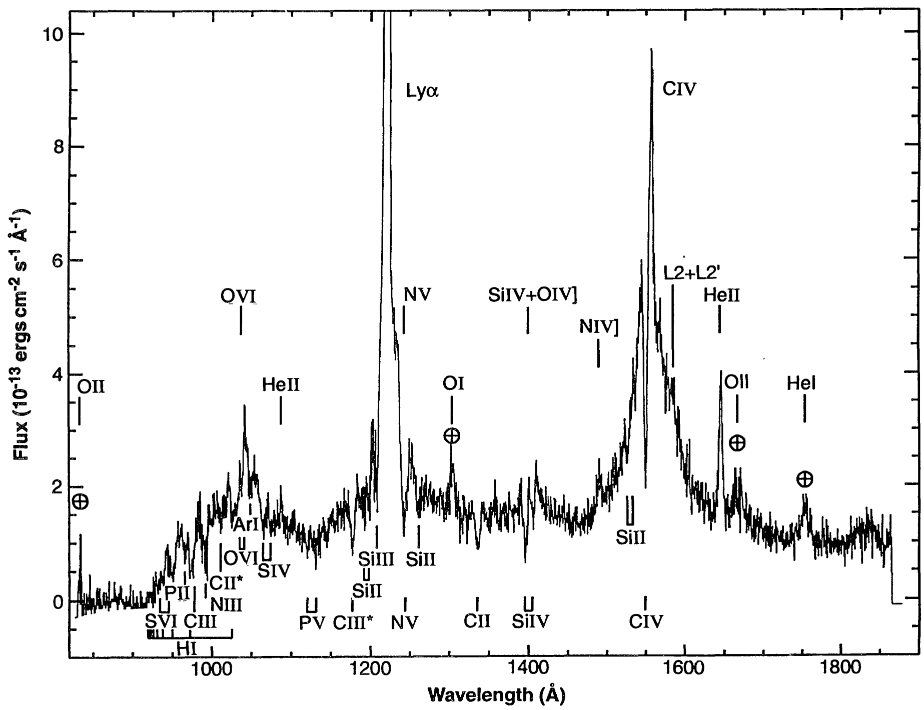

Fig. 4. UV spectrum of Seyfert galaxy NGC 4151 observed with HUT. Geocoronal Lyman α emission has been subtracted, and remaining weak airglow features are indicated with Earth symbols (⊕). Emission and absorption features are marked above and below the data, respectively. Brackets indicate a forbidden transition. A single bracket signifies a semi-forbidden transition. Ions with asterisks are in excited states. The absorbing gas may be responsible for collimating the ionizing radiation from the nuclear source. [Reprinted from (*32*) with permission © American Astronomical Society]

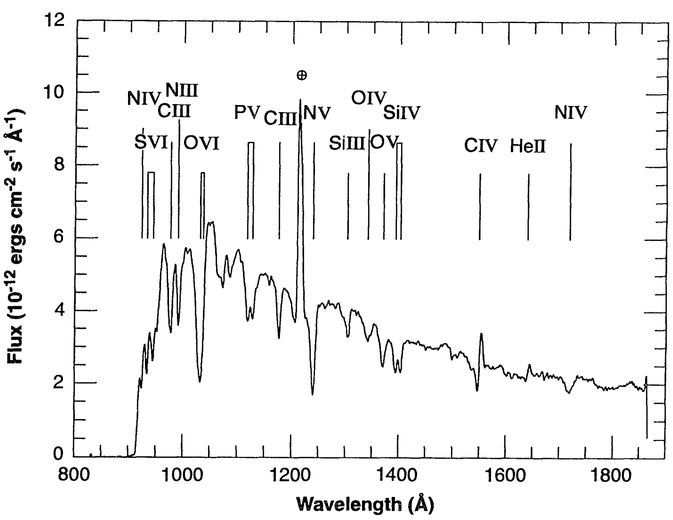

Fig. 5. UV spectrum of dwarf nova Z Camelopardalis observed with HUT near the maximum of an outburst. Many broad absorption lines are present and are attributed to highly ionized elements. Airglow feature marked with Earth symbol (⊕). Geocoronal Lyman α has not been removed. [Reprinted from (*34*) with permission © American Astronomical Society]

able Star Observers (AAVSO) monitored ten dwarf novae throughout the Astro-1 mission and alerted us to each of the outbursts that occurred. As a result, we succeeded in measuring the UV spectrum of Z Camelopardalis at the peak of an outburst (Fig. 5) (*34*). The result is presumably the spectrum of an optically thick accretion disk and shows a strong continuum whose intensity peaks in the far UV around 1050 Å with numerous strong, broad absorption lines of high-ionization species, including C IV, N V, O VI, Si IV, P V, and S VI. These observations provide the first detailed look at the far-UV spectral region of such an outburst. Attempts to model the spectrum with standard accretion disk theory met with limited success and clearly revealed the need for more detailed theoretical calculations of the expected emission.

Another substantial part of the HUT scientific program involves the study of the emission of supernova remnants (SNR) in the far UV. In older remnants, such observations reveal the response of the ISM to the passing blast wave from a stellar explosion. Interstellar gas is compressed and heated by the shock wave, and the subsequent radiation may be used to characterize physical conditions of the gas. Thus, for example, the detection with HUT of strong O VI emission in two filaments in the Cygnus Loop SNR (Fig. 6) indicates a shock velocity of about 175 km s^{-1} and, when combined with optical data, provides new information on the process by which energy is transferred between electrons and ions behind the shock (*35, 36*). We also succeeded in detecting O VI emission from an SNR in another galaxy, N49 in the Large Magellanic Cloud, for the first time (*37*).

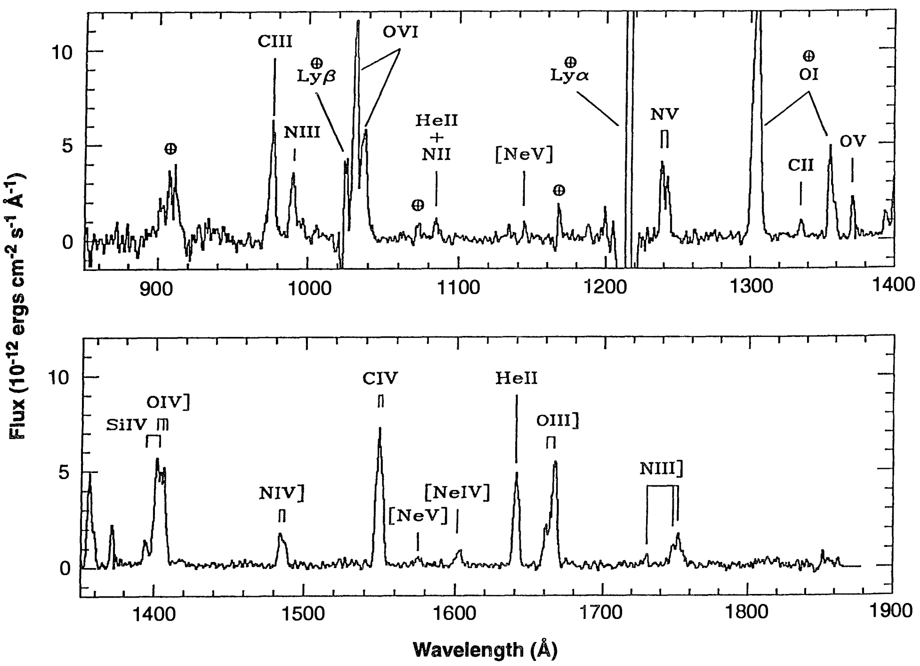

Fig. 6. UV spectrum of a radiative filament in the Cygnus Loop SNR observed with HUT. Airglow features are marked with Earth symbols (⊕). The far-UV emission features due to C III (977 Å), N III (991 Å), and O VI (1032 and 1038 Å) are clearly resolved for the first time. [Reprinted from (*35*) with permission © American Astronomical Society]

We also obtained an interesting spectrum of the Crab Nebula (*38*), the famous remnant of the supernova of A.D. 1054. Although the Crab is one of the brightest x-ray sources in the sky, emitting synchrotron radiation from high-energy electrons accelerated by the pulsar created when the star exploded, it is a difficult target in the UV because of strong extinction caused by interstellar dust along this line of sight. Nevertheless, HUT detected the UV continuum radiation produced by the electrons and also observed a few spectral lines arising in filaments that are photoionized by this radiation. Two velocity-shifted components of the C IV line reveal expansion along the line of sight at ± 1100 km s^{-1}. These observations are the first to demonstrate that relative UV line intensity variations are present in the Crab Nebula. This probably indicates varying carbon or helium abundances in the material observed with HUT (*37*).

A potentially exciting measurement made with HUT was an attempt to detect line radiation from decaying dark matter particles that might dominate the mass of the universe (*39*). The hypothesis of decaying dark matter (*40*) is a clever attempt to explain a number of disparate facts and ideas from astrophysics, cosmology, and particle physics by attributing a mass of about 30 eV to the τ neutrino and assuming that it decays with a lifetime $\sim 10^{23}$ s. The assumed mass would be sufficient to close the universe if the Hubble constant had a value near 50 km s^{-1} Mpc^{-1}, and the hypothesized radiation would explain the degree of ionization attributed to various components of diffuse gas in the universe. We used HUT to search for the emission line that would be expected from a massive cluster of galaxies that would contain a large (and calculable) quantity of dark matter if the theory were valid. No emission was found, limiting the lifetime of any such decaying dark matter particles to at least several times 10^{24} s (*39*).

Closer to home, HUT has also been used for observations within the solar system. Observations of comet Levy (1990c) revealed an extended source of carbon monoxide emission and set upper limits on the abundance of argon and neon in the comet (*41*). A spectrum of the Io plasma torus surrounding Jupiter displayed a large number of lines of sulfur and oxygen in various stages of ionization (*42*). The data have sufficient resolution to allow the ionic abundance ratios to be deduced directly, without recourse to modeling. Even Earth's upper atmosphere has provided interesting new data for HUT. The O^+ recombination spectrum has been resolved for the first time, and the shape of the continuum provides a direct measure of the electron temperature in the ionosphere, which was about 1000 to 1200 K during the Astro-1 mission (*43*).

Future Work and Astro-2

Although detailed analysis of the data obtained by HUT on the Astro-1 mission has barely begun, it is clear that a number of significant results have already been found. Work in progress includes modeling of the spectra of several quasars and Seyfert galaxies to test theories of accretion disks around massive black holes. Several dwarf novae containing small-scale accretion disks are also being studied for new clues to the physics involved in these systems. A great variety of individual stars are being investigated, including cool stars with chromospheres and coronae and very hot Wolf-Rayet stars with strong stellar winds. Studies of the late stages of stellar evolution also include observations of UV-bright stars in globular clusters, central stars of planetary nebulae, and several white dwarfs. Further work is being done on Jupiter and the Io torus, and there is more to be learned from analysis of the airglow spectra observed with HUT.

Before the Challenger disaster changed NASA's view of the shuttle as a platform for astronomical observations, the Astro Observatory was scheduled for at least three missions, and three more were under serious consideration (*44*). Current plans call for just one more flight of the UV telescopes, in 1994. Of high priority for the HUT science team will be a goal that eluded us on Astro-1, namely, an attempt to detect helium in the intergalactic medium by observing its absorption of the far-UV light of a distant quasar. Smoothly distributed intergalactic hydrogen has not been detected, presumably because it is highly ionized, but singly ionized helium may be present at a detectable level. It absorbs at 304 Å, which would be redshifted into the HUT range for redshift $z \geq 2$. Additionally, the hydrogen Lyman α clouds seen in the spectra of quasars are expected to contain singly ionized helium, and these clouds should also be detectable with HUT for $z \geq 2$.

The search for intergalactic helium has been one of the principal goals of the HUT project since its inception. It was not achieved on Astro-1 because we had insufficient time to carry out the very long observation needed to measure the spectrum of a faint, high-redshift quasar. However, this very important project may become feasible on Astro-2, especially if an extended-duration mission can be scheduled. Such a mission could achieve as many as 18 days in orbit, utilizing the new capabilities of the Endeavor or the refurbished Columbia. In addition, many new scientific programs will be introduced on Astro-2 through the inclusion of a guest investigator program. Obviously, these would also benefit greatly from an extended mission. Coupled with improved operating efficiency and new optical coatings that will boost HUT's sensitivity by a factor of 2 or 3, the next mission should obtain an order of magnitude more data than achieved on Astro-1.

This project was begun at a time when multiple space shuttle flights at frequent intervals were presumed possible for the Astro Observatory. It was this prospect that made the investment of years of effort by so many individuals worthwhile. Although 9 days in space has yielded a treasure trove of new discoveries, the Astro-1 mission barely scratched the surface of what can be accomplished with HUT and the other telescopes of the Astro Observatory.

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45. I wish to record my gratitude to the individuals at NASA, in the university community, and elsewhere in private industry whose efforts were responsible for the success of Astro-1 and HUT. I am indebted to my Johns Hopkins colleagues, especially to K. Long, S. Durrance, and G. Fountain, for fundamental contributions throughout the development of this project. I also thank NASA mission manager J. Jones, former mission manager L. Allen, and mission scientist T. Gull for their contributions to Astro-1. Finally, I am grateful for the support of L. Fisk, C. Pellerin, and E. Weiler at NASA. This work has been supported by NASA contract NAS 5-27000 to Johns Hopkins University.