Appendix A

The First Paper Reporting Results

from the Hopkins Ultraviolet Telescope

and the Astro-1 Mission

(This paper has been accepted for publication in *Nature.*)

A Test of the Decaying Dark Matter Hypothesis Using the Hopkins Ultraviolet Telescope

A. F. Davidsen, G. A. Kriss, H. C. Ferguson[1], *W. P. Blair, C. W. Bowers, W. V. Dixon, S. T. Durrance, P. D. Feldman, R. C. Henry, R. A. Kimble*[2], *J. W. Kruk, Knox S. Long*[3], *H. W. Moos, and O. Vancura*

Center for Astrophysical Sciences
Department of Physics and Astronomy
The Johns Hopkins University
34th and Charles Streets
Baltimore, MD 21218 USA

In a series of articles[1–4] Sciama has argued that the dark matter in galaxies, clusters of galaxies, and the intergalactic medium consists of τ neutrinos with rest mass $\sim$ 28-30 eV, which are presumed to decay via the emission of ultraviolet photons of energy $E \simeq \frac{1}{2}\, m_\nu \sim$ 14-15 eV. We have carried out a test of this theory using the Hopkins Ultraviolet Telescope which was flown aboard the space shuttle *Columbia* on the Astro-1 mission in December 1990. Straightforward application of Sciama's hypothesis predicts a spectral line from neutrino decay photons in our observations of the rich galaxy cluster Abell 665 with a signal-to-noise ratio of $\sim$ 30. We do not detect the expected emission, and for masses in the range 27.2-32.1 eV our spectrum yields lower limits on the neutrino lifetime (or that of any other decaying dark matter particle in this mass range) that are significantly greater than those required by Sciama.

[1]Current address: Institute of Astronomy, University of Cambridge, The Observatories, Madingley Road, Cambridge CB3 0HA, England

[2]Current address: Laboratory for Astronomy and Solar Physics, Goddard Space Flight Center, Greenbelt, MD 20771

[3]Current address: Space Telescope Science Institute, 3700 San Martin Drive, Baltimore, MD 21218

The idea is based on work by several previous authors[5–7], but Sciama's theory significantly narrows the expected energy range of the decay photon and requires a lifetime for the decay of $\tau \simeq$ 1-3 $\times 10^{23}$ seconds, substantially shorter than lifetimes predicted in most standard theories of particle physics[8], but compatible with some left-right-symmetric models[9]. The severely constrained neutrino mass and lifetime result from Sciama's assumption that the decay photons are responsible for the partial ionization of the HI regions in the galaxy, as well as the ionization of the Lyman α clouds seen in the spectra of quasars at large redshifts. The short lifetime has the added benefit of making the hypothesis eminently testable.

The energy of the decay photons in Sciama's theory is only slightly above the ionization potential of hydrogen, or Lyman limit, at 13.6 eV. Consequently, a cluster of galaxies requires only a modest redshift to place the line emission expected from the decaying dark matter particles longward of the Lyman limit at 912 Å, where the interstellar hydrogen in our galaxy becomes transparent. The Hopkins Ultraviolet Telescope (HUT) (Davidsen *et al.*, in preparation) has been optimized for spectroscopic observations in the 912-1200 Å band (which is inaccessible to other existing telescopes in space apart from the low resolution spectrometer on the *Voyager* spacecraft), and is therefore ideal for searching for the predicted neutrino decay line in clusters with redshifts $z \lesssim 0.5$. The full spectral range covered by HUT extends from 830 to 1850 Å in first order. HUT also includes a large aperture (17×116 arc sec) which projects to a substantial volume within a typical cluster and therefore yields a strong signal for the predicted neutrino decay line.

We selected several rich clusters in the range $0.1 \leq z \leq 0.2$ for potential observation with HUT on the Astro-1 mission. However, as a result of a variety of Spacelab system-level problems and a weather-related shortening of the mission, only one of these clusters, Abell 665, was successfully observed.

Abell 665 is the richest cluster in the Abell catalog[10] and a luminous X-ray source[11,12]. A recent study[13] yields $z = 0.18144 \pm 0.00084$ and a velocity dispersion $\sigma = 1201^{+183}_{-126}$ km s^{-1} for 33 galaxies determined to be cluster members. We assume the projected mass density of the cluster, including both the luminous and dark matter, follows a King model[14] of the form $\mu(r) = 2r_c\rho_0(1 + r^2/r_c^2)^{-1}$ with a core radius $r_c = 0.5$ Mpc measured by Dressler[15]. The central mass density is then $\rho_0 = 1.7 \times 10^8\, \sigma^2/r_c^2\, M_\odot\, \mathrm{Mpc}^{-3} = 1.0 \times 10^{15}\, M_\odot\, \mathrm{Mpc}^{-3}$. The total mass integrated over the large HUT slit, which covered 68×457 kpc at the center of Abell 665, is $2.9 \times 10^{13}\, M_\odot$. (Throughout this paper we assume $H_0 = 50$ km s^{-1} Mpc^{-1} and $q_0 = ½$.)

The uncertainties in this mass estimate contribute a large fraction of the uncertainty in our final result. While Oegerle *et al.*[13] find no evidence for substructure in their distribution of velocities for the galaxies in Abell 665, two separate dynamical systems with dispersions of 900 km s^{-1} and mean velocities separated by 400 km s^{-1} could reproduce their data. This would lower our mass estimate by a factor of two. On the other hand, the central density and the core radius are not tightly constrained by the available data, and the mass enclosed by the HUT slit could well be higher than we have assumed.

If the mass of Abell 665 is predominantly made up of decaying neutrinos, the luminosity of the cluster is $L = 4.0 \times 10^{54} M_{13} \tau_{23}^{-1} (\epsilon/14\ eV)^{-1}$ photons s^{-1} in a line at energy ϵ, where M_{13} is the total mass in units of $10^{13}\ M_{\odot}$, and τ_{23} is the decay lifetime in units of 10^{23} s. The expected width of the decay line is 11 Å (FWHM), or 22 pixels, assuming the neutrino decay emission fills the HUT aperture and that the neutrinos have the velocity dispersion quoted above for the cluster. Using the mass obtained above, the predicted flux at earth is $0.089\ \tau_{23}^{-1}$ $(\epsilon/14\ eV)^{-1}$ photons $cm^{-2}\ s^{-1}$. In the relevant energy range HUT has an effective area of 8.0 cm^2, leading to an expected count rate of 0.24-0.71 counts s^{-1} for Sciama's proposed range for the lifetime $\tau \simeq 1\text{-}3 \times 10^{23}$.

Abell 665 was observed with HUT for a total of 1932 s on 9 December 1990. The aperture was centered at $\alpha_{1950} = 8^h26^m24.46^s$, $\delta_{1950} = +66^\circ 00' 36.0''$, which corresponds to the position of the brightest cluster galaxy (Oegerle, private comm.). Beers and Tonry[16] give the median galaxy position as $\alpha_{1950} = 8^h26^m18.7^s$, $\delta_{1950} = +65^\circ 59' 58''$ and the *Einstein* Imaging Proportional Counter centroid as $\alpha_{1950} = 8^h26^m27.7^s$, $\delta_{1950} = +66^\circ 01' 07''$. The HUT slit was oriented at a position angle of 40° to include both the X-ray center and the median galaxy position. Most of the observation (1378 s) was during orbital night, when airglow line emission is minimized. The spectrum obtained revealed no features other than those expected from the airglow based on observations of other faint sources and blank fields during the Astro-1 mission. The relevant portion of the data from the full 1932 s observation is shown in Figure 1, corrected to the rest-frame of Abell 665. The positions of the known airglow lines Ly β, OI λ989, Ly γ, and Ly δ are indicated. The observed flux of the Ly β airglow line is 0.58 counts s^{-1}, essentially equal to the flux expected for the neutrino decay line. The background count rate (*i.e.* the apparent continuum in Figure 1) of 1.2×10^{-3} cts pix^{-1} s^{-1} is consistent with that observed in other blank sky observations. About one third of this rate is due to internal detector background from charged particles (as measured with the aperture closed), and two-thirds is from grating-scattered geocoronal Ly α.

Emission lines from an extended source filling the 17" $\times$ 116" slit have a FWHM of 5.5 Å (11 pixels) as measured from observations of bright airglow lines through this same aperture on other targets. The Lyman β line in Figure 1 has a FWHM = 5.7 Å. As mentioned previously, emission from decaying neutrinos broadened by the cluster velocity dispersion would produce a line with 11 Å FWHM (22 pixels). At each pixel in the spectrum we calculate upper limits to the intensity of an unresolved spectral feature at that location by computing the flux above the background level in a 19-pixel region surrounding the current pixel. This choice of size maximizes the S/N ratio for detecting a weak feature above the background and is conservative since colder neutrinos would produce a narrower line that would be easier to detect. The 2σ upper limit is then $\left[\sum (C_i - B) + 2\sqrt{\sum C_i} \right] / 0.71t$, where B is the background counts per pixel, the C_i are the number of counts in pixel i, t is the total integration time, and the factor 0.71 is the fraction of the line flux contained in the 19-pixel region. Because this sum averages ~45 counts, the Poisson count distribution closely resembles a Gaussian in its statistical properties, and we have simply used a factor of two times the Poisson standard deviation.

The only spectral features that exceed these upper limits during the orbital night portion of the observation are Ly β and Ly γ. In the full observation shown in Figure 1, airglow features due to O I $\lambda 989$ and Ly δ are also visible, and to be conservative we have used the higher fluxes seen for the whole observation in computing our upper limits. We have not yet developed a detailed model of the expected intensity of airglow features in the HUT spectra for the many relevant parameters, such as orbital position and viewing angle relative to the earth limb and the sun. It is possible that emission from decaying neutrinos could fortuitously lie at the same wavelength as Ly β or Ly γ. However, because we do not observe any of the airglow features to be broader than the instrumental response, the dispersion of the decaying neutrinos in the cluster would have to be much less than the observed cluster velocity dispersion.

The Ly β line is bright enough that we can set a more stringent limit using the shape of the line profile and the observed Lyβ/Lyα ratio from other observations. To be conservative, we compute the expected Ly β flux using the *lowest* observed ratio of Lyβ/Lyα in the airglow observed by HUT. This comes from an observation of the Crab Nebula. (The Crab was within a few degrees of the anti-solar position on the sky, and the viewing angle during orbital night was almost entirely in the earth's shadow.) We therefore presume that any contribution from decaying neutrinos to the observed Lyβ in our observation of Abell 665 can be at most the amount by which the observed flux exceeds this minimum. Within three pixels of the center of the Ly β line we determine our upper limit by subtracting the observed Lyβ/Lyα ratio of $(2.47 \pm 0.23) \times 10^{-3}$ in the orbital night portion of the Crab Nebula spectrum from the ratio $(4.03 \pm 0.16) \times 10^{-3}$ observed during orbital night on Abell 665. Scaling this to the Ly α intensity of 116 cts s^{-1} during orbital night in the Abell 665 observation, we obtain a maximum contribution to the Ly β intensity of 0.181 $\pm$ 0.033 cts s^{-1}. We use 0.247 cts s^{-1} as our 2σ upper limit within three pixels of the Ly β line center. We note that the Lyβ/Lyα ratio observed in the Abell 665 spectrum is typical of that seen in other orbital night observations of the airglow. We may be able to set even lower upper limits at the Ly β line center as we further develop our understanding of the airglow spectrum.

To eliminate the possibility that the decay line could be hiding in the wings of geocoronal Ly β, we compare the Ly β line profile in the Abell 665 spectrum to that observed in other night observations of weak sources. Using a Ly β line profile obtained from observations of the Crab Nebula and of the Perseus cluster that have been summed and smoothed with a three-point boxcar, we fit a 120-pixel region centered on Ly β in the Abell 665 spectrum, allowing the line center, its intensity, and a constant background to vary freely. The resulting $\chi^2 = 126.40$ indicates excellent agreement between the template profile and the Abell 665 Ly β profile. The shift in wavelength between the Ly β line from the Crab and Perseus observations and that of the Abell 665 spectrum is less than one pixel. We then add a second emission line at a fixed offset that is an integral number of pixels from the center of the Ly β emission line. The intensity of the second emission line is increased until $\Delta\chi^2 = 4.2$ (95.4% confidence for one interesting parameter[17]) while all other parameters are re-optimized. This sets our 2σ upper limit in the regions 2-11 pixels above and below the center of the Ly β emission line.

We have converted our upper limits on the decay line intensity for Abell 665 to a lower limit on the lifetime of the neutrino, taking into account the variation in HUT sensitivity with energy (known to $\pm 20\%$ over the wavelength range of interest from laboratory calibrations and in-flight comparison of several white dwarf spectra to theoretical models) and galactic extinction of $E_{B-V} = 0.034$ for a galactic neutral hydrogen column density[18,19] of 4.7×10^{20} cm^{-2}. We use the extinction law produced by Longo *et al.*[20] from the review by Savage and Mathis[21]. The result is shown in Figure 2, along with the range of lifetimes and energies predicted by Sciama's theory. Over most of the range of interest the observational limit on the lifetime exceeds 3×10^{24} s, a factor at least 10 times greater than the value required by the decaying dark matter hypothesis. However, a narrow region of parameter space at E $=14.30 \pm 0.02$ eV, where interference from geocoronal Lyman β is severe, would allow the theory to survive, if we have been so unfortunate as to choose a cluster whose redshift hides the neutrino decay line behind geocoronal Lyman β. (The error in E is dominated by the uncertainty in the redshift of the cluster.) We expect that detailed analysis of the airglow data obtained by HUT throughout the Astro-1 mission, together with further modeling, will allow us to strengthen our limit in the vicinity of Lyman β significantly.

We conclude that highly sensitive observations of the cluster Abell 665 with the Hopkins Ultraviolet Telescope fail to support the decaying dark matter hypothesis. The theory can survive only under one of the two following scenarios, namely: (1) the cluster is several times less massive than we estimate and the redshifted decay photon energy happens to coincide with the Ly β airglow line, or (2) there is substantial absorption of the decay line by previously unsuspected material along the line of sight. The latter has in fact been suggested by Sciama (private communication) in response to our result. We believe we can rule out this possibility, but a discussion must be postponed to a future paper, in which we will derive improved results (Kriss, Davidsen & Ferguson, in preparation). While neutrinos may yet provide the missing mass, they probably do not decay at rates high enough to explain the ionization balance in the interstellar or intergalactic medium.

References

1. Sciama, D. W. *Astrophys. J.* **364**, 549-554 (1990).
2. Sciama, D. W. *Phys. Rev. Lett.* **65**, 2839-2841 (1990).
3. Sciama, D. W. *Nature* **348**, 617-618 (1990).
4. Sciama, D. W. *Astrophys. J. Lett.* **367**, L39-L41 (1991).
5. Cowsik, R. *Phys. Rev. Lett.* **39**, 784-787 (1977).
6. De Rujula, A., & Glashow, S. *Phys. Rev. Lett.* **45**, 942-944 (1980).
7. Melott, A. L., & Sciama, D. W. *Phys. Rev. Lett.* **46**, 1369-1371 (1981).
8. Pal, P. B., & Wolfenstein, L. *Phys. Rev. D* **25**, 766-773 (1982).
9. Maalampi, J., & Roos, M. *Phys. Letters B* **229**, 388-390 (1989).
10. Abell, G. O. *Astrophys. J. Suppl.* **3**, 211 (1958).
11. Johnson, M. W., Cruddace, R. G., Ulmer, M. P., Kowalski, M. P., & Wood, K. S. *Astrophys. J.* **266**, 425-445 (1983).
12. Soltan, A., & Henry, J. P. *Astrophys. J.* **271**, 442-445 (1983).
13. Oegerle, W., Fitchett, M. J., Hill, J. M. & Hintzen, P. *Astrophys. J.* (1991), in press.
14. Rood, H. J., Page, T. L., Kintner, E. C., & King, I. R. *Astrophys.J.* **175**, 627-647 (1972).
15. Dressler, A. *Astrophys. J.* **226**, 55-60 (1978).
16. Beers, T. C. & Tonry, J. L. *Astrophys. J.* **300**, 557-567 (1986).
17. Avni, Y. *Astrophys. J.* **210**, 642-646 (1976).

18. Burstein, D., & Heiles, C. *Astrophys. J.* **225**, 40-55 (1978).

19. Heiles, C. *Astron. Astrophys. Suppl.* **20**, 37-55 (1976).

20. Longo, R., Stalio, R., Polidan, R. S., & Rossi, L. *Astrophys. J.* **339**, 474-478 (1989).

21. Savage, B., D. & Mathis, J. H. *Ann. Rev. Astron. Astrophys.* **17**, 73-111 (1979).

Acknowledgements

This work was supported by the National Aeronautics and Space Administration. We are grateful to R. Lucas for obtaining guide star positions and a finding chart for Abell 665 on short notice, to P. Bergeron for the white dwarf model atmosphere used for the in-flight sensitivity calibration, to W. Oegerle for providing the central galaxy position and cluster velocity dispersion prior to publication, and to D. Sciama for discussions. Finally, we wish to thank all our colleagues on the HUT team at Johns Hopkins and the Applied Physics Laboratory, particularly G. Fountain, B. Ballard, J. Hayes, K. Heffernan, S. Conard, R. Barkhouser and M. Romelfanger, as well as the NASA personnel who helped make the Astro-1 Mission successful.

Figure Captions

Figure 1 — A portion of the Abell 665 spectrum from the full 1932 s observation covering the rest frame energy range 13.6 to 16.1 eV is shown. The ordinate is in observed counts per 0.51 Å bin. Prominent airglow features observed in other HUT spectra are marked.

Figure 2 — The logarithm of the derived 2σ lower limits for the lifetime of decaying neutrinos in seconds is shown as a function of the decay photon energy in eV. The shaded region illustrates the range of energies and lifetimes compatible with Sciama's theory.

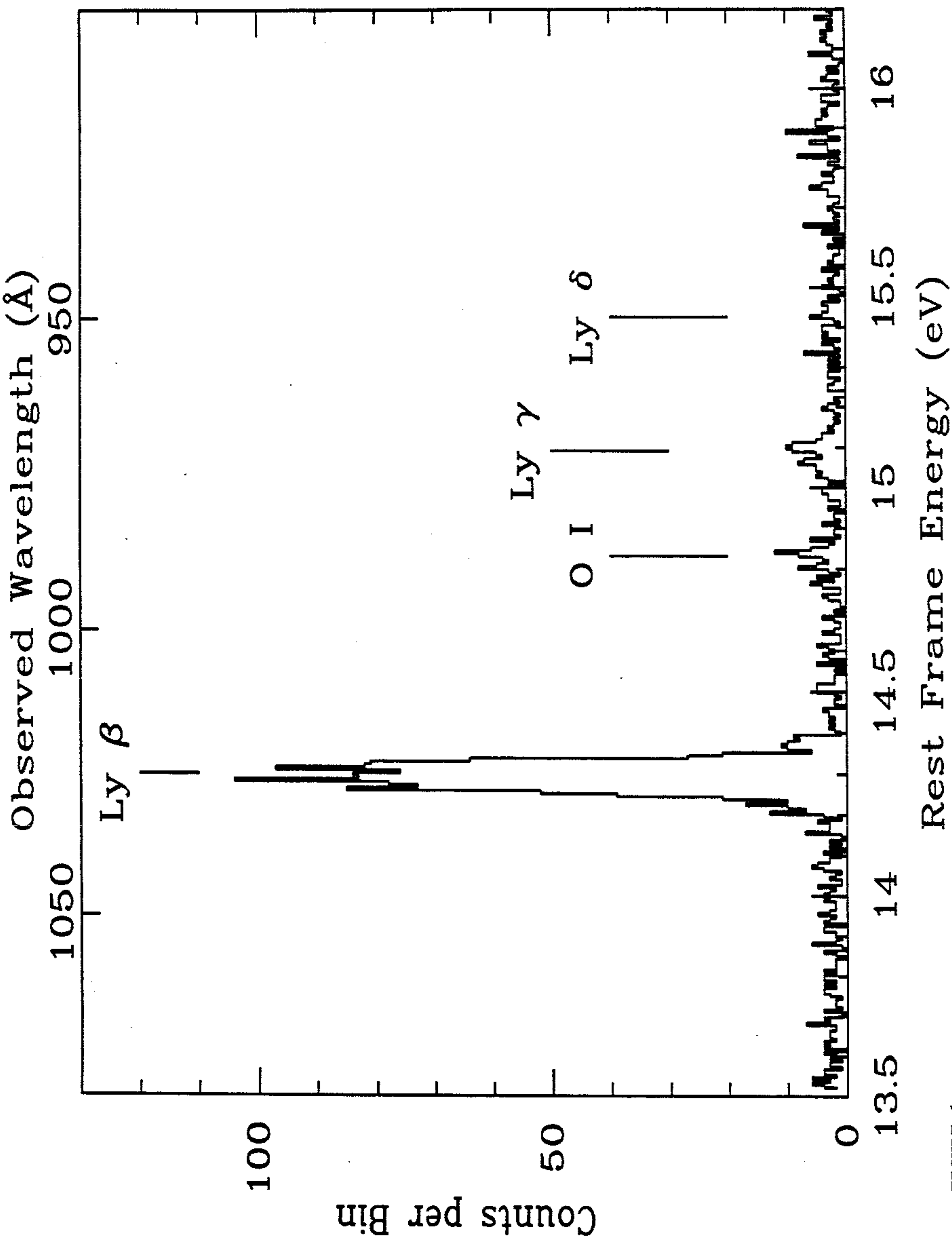
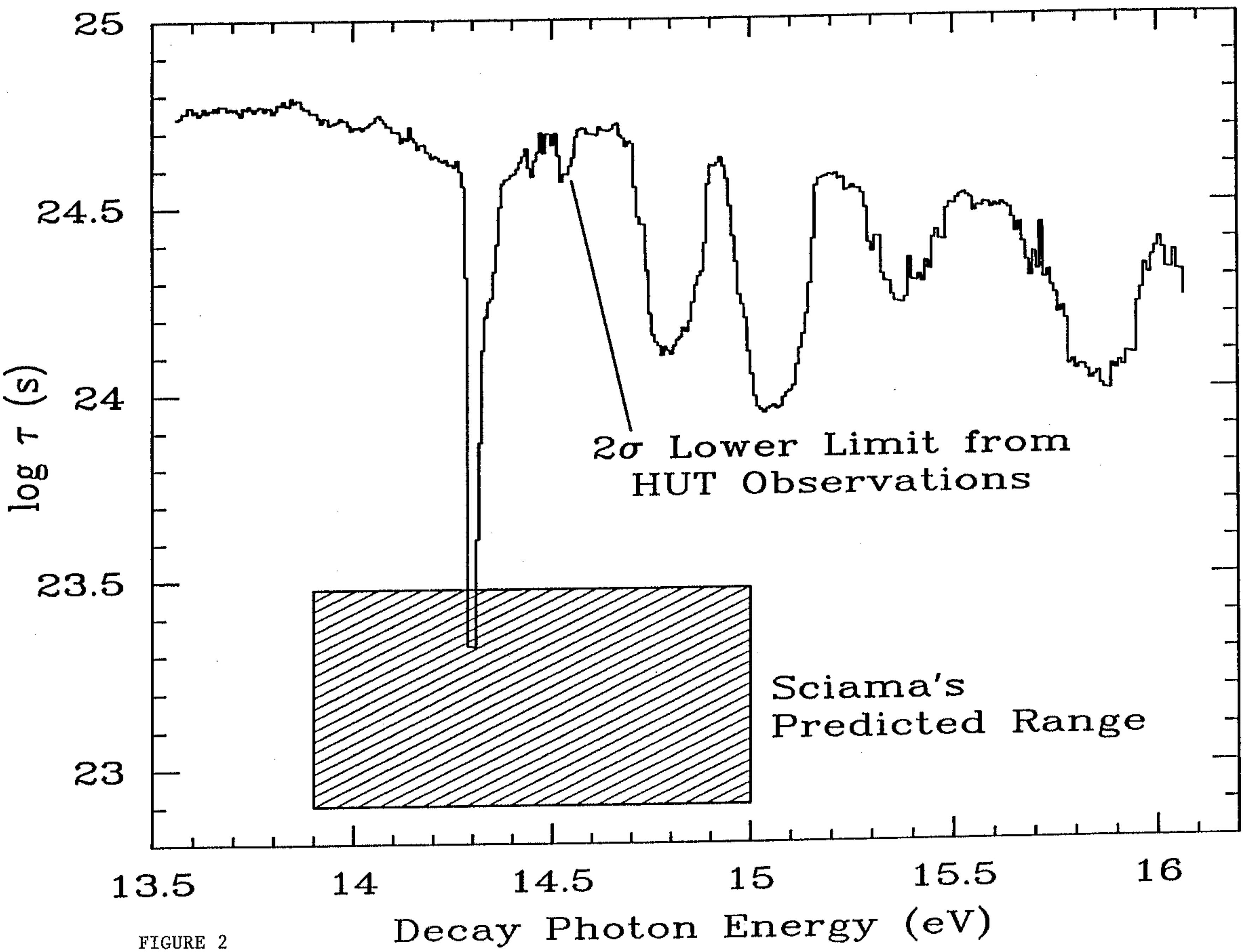

Observed Wavelength (Å)
950
1000
1050
Ly β
O I
Ly γ
Ly δ
Counts per Bin
100
50
0
Rest Frame Energy (eV)
13.5
14
14.5
15
15.5
16

FIGURE 1



25
24.5
24
23.5
23
log τ (s)
13.5
14
14.5
15
15.5
16
Decay Photon Energy (eV)
2σ Lower Limit from
HUT Observations
Sciama's
Predicted Range

FIGURE 2

Appendix B.

Abstracts on HUT Results Submitted for the

178th Meeting of the American Astronomical Society

in Seattle, Washington

May 26-30, 1991

Highlights from the Hopkins Ultraviolet Telescope

A.F. Davidsen (JHU)

The Hopkins Ultraviolet Telescope (HUT) was employed throughout the 9-day Astro-1 space shuttle mission in December 1990 to obtain far ultraviolet spectra (830-1850 Å) of a wide range of astronomical sources at a resolution of $\sim$ 3 Å. A few objects were also observed in the extreme ultraviolet band (415-912 Å), beyond the hydrogen Lyman edge, where HUT's spectrometer yields a resolution of $\sim$ 1.5 Å in second order. HUT's main goal was to explore the astronomically rich but little observed region from Lyman α (1216 Å) to the Lyman limit (912 Å), where most UV telescopes are not sensitive. Spectra were obtained of 77 sources ranging from solar system objects, to stars, nebulae, galaxies, and quasars. For most of these sources the HUT observations were the first sub-Lyman α UV spectra ever obtained.

The performance of the instrument will be described, and highlights of results obtained from a preliminary analysis of a small subset of the HUT data will be presented. These highlights include: (1) measurement of the neutral helium column density toward the nearby hot white dwarf G191-B2B; (2) discovery of a fast radiative shock wave in the Cygnus Loop; (3) the first observation of the absorption line spectrum of the hot stellar component in a giant elliptical galaxy; and (4) measurement of the shape of the continuum at and beyond the Lyman edge in the quasar 3C273; among others. Details of these and other observations with HUT are being presented in various sessions throughout this meeting.

It is a pleasure to acknowledge the contributions of each member of the HUT science and engineering team, as well as those of the many NASA personnel who helped carry out the Astro-1 mission.

The Hopkins Ultraviolet Telescope is supported by NASA contract NAS 5-27000 to the Johns Hopkins University.

Observations of a Bright Radiative Filament in the Cygnus Loop with the Hopkins Ultraviolet Telescope

W.P. Blair (JHU), K.S. Long (STScI), O. Vancura, C.W. Bowers, A.F. Davidsen, W.V. Dixon, S.T. Durrance, P.D. Feldman (JHU), H.C. Ferguson (IoA), R.C. Henry, J.W. Kruk, G. A. Kriss, H. W. Moos (JHU), and R.A. Kimble (GSFC)

The Hopkins Ultraviolet Telescope (HUT), on its maiden voyage as part of the Astro-1 mission in December 1990, was used to observe two positions in the Cygnus Loop supernova remnant, one radiative filament on the eastern edge and a nonradiative filament on the NE edge. Here we report the data on the radiative filament.

The principal advantages of HUT for this work are a) 3 Å resolution, b) a photon-counting detector, c) good diffuse source light grasp, and d) wavelength coverage from 830 to 1850 Å. These advantages have permitted us for the first time to unambiguously identify and measure emission lines predicted in this spectral region, including O VI λλ1032,1038, C III λ977, N III λ991, and many lines above 1200 Å seen in IUE spectra. After correcting for reddening, O VI is roughly a factor of two stronger than any other UV lines at the observed position.

The strength of O VI with respect to other high ionization lines such as N V λ1240 and C IV λ1550 is very large for a radiative filament. Comparison with theoretical shock models such as those of Hartigan, Raymond, and Hartmann (1987, *Ap. J.*, **316**, 323) indicates that the peak shock velocity must be near 170 km s^{-1}, although some mixing of lower velocity material is also indicated. This is a significantly higher velocity than has been suggested for other radiative filaments in the Cygnus Loop. Because of the dominance of the O VI emission in this filament, the importance of far UV line cooling in the evolution of SNRs such as the Cygnus Loop may need to be reassessed.

The Hopkins Ultraviolet Telescope Project is supported by NASA contract NAS 5-27000 to the Johns Hopkins University.

Observations of the Planetary Nebula NGC 1535 with the Hopkins Ultraviolet Telescope

C.W. Bowers, W.P. Blair (JHU), K.S. Long (STScI), A.F. Davidsen,
W.V. Dixon, S.T. Durrance, P.D. Feldman, R.C. Henry,
J.W. Kruk, G.A. Kriss, H.W. Moos, and O. Vancura (JHU),
H.C. Ferguson (IoA), and R.A. Kimble (GSFC)

A 1400 second observation of the high-excitation planetary nebula NGC 1535 was obtained with the HUT spectrograph during the Astro-1 flight in December 1990. A 9" × 116" slit was used producing a resolution of 3 Å. The slit was manually offset by the payload specialist midway during the observation providing separate spectra of the bright central star and the nearby nebulosity.

The central star observation shows a bright UV continuum as well as strong nebular emissions of He II λ1640 and C IV λ1549. The continuum is consistent with model atmospheres of ~ 70,000 K and extinction of $E_{(B-V)} \sim 0.1$. The HUT observations also show P-Cygni profiles at N V λ1240, O IV λ1340, O V λ1370 and the strongest, O VI λ1035, confirming the existence of a stellar wind with a terminal velocity of about 2000 km s^{-1}. The strong O VI feature was predicted in the "hot" wind model for NGC 1535 of Adam and Köppen (1985, A&A, 142, 461). Analysis of these features will permit the characterization of conditions in the wind and in particular help to answer the question of whether the wind is "hot" or "cool". The distinctive absorption pattern of the H_2 Lyman and Werner bands is clearly seen below 1150 Å yielding a column density of $\sim 4 \times 10^{18}$ cm^{-2} at a temperature of ~ 100 K.

The nebular spectra show numerous emission features including He II λλ1085,1640, C III λ1177, C IV λ1549, N IV] λ1487, O III] λ1663, and below 1000 Å, C III λ977 and N III λ991. Longward of 1216 Å, the expected two-photon continuum is clearly seen. Analysis of these features in conjunction with IUE and optical data will be used to characterize both the nebular conditions and composition and the central star.

The Hopkins Ultraviolet Telescope Project is supported by NASA contract NAS 5-27000 to the Johns Hopkins University.

HUT Observations of Ultraviolet-Bright Stars in Globular Clusters

W.V. Dixon, A.F. Davidsen (JHU), H.C. Ferguson (IoA),
W.P. Blair, C.W. Bowers, S.T. Durrance, G.A. Kriss,
P.D. Feldman, R.C. Henry, J.W. Kruk, H.W. Moos,
O. Vancura (JHU), R.A. Kimble (GSFC), and K.S. Long (STScI)

Ultraviolet-bright stars in globular clusters have been studied since the early 1970's. These stars are understood to be post-asymptotic-giant-branch stars which have shed their outer envelopes and are contracting to become white dwarfs. Such stars are interesting not only because they are in a phase of stellar evolution which is poorly understood, but also because they are a possible source of the ultraviolet upturn in elliptical galaxies and spiral bulges. To investigate these questions, far ultraviolet spectra of two UV-bright stars in M3 and NGC1851 were obtained with the Hopkins Ultraviolet Telescope (HUT), which was flown aboard the space shuttle *Columbia* on the Astro-1 mission in December, 1990. The spectra cover the wavelength range between 1850 Å and the Lyman limit at a resolution of about 3 Å. We determine the temperatures, luminosities, and spectral types of both stars and compare their energy distributions to both model spectra and Population I stars of the same effective temperature. The two spectra show strong absorption features shortward of Lyman alpha, attributable to both the stars themselves and the intervening ISM. We detect no emission features other than well-known geocoronal lines.

The Hopkins Ultraviolet Telescope Project is supported by NASA contract NAS 5-27000 to the Johns Hopkins University.

HUT Observations of Neutral Sulfur Emissions from Io

S.T. Durrance, P.D. Feldman, H.W. Moos, A.F. Davidsen,
W.P. Blair, C.W. Bowers, W.V. Dixon, R.C. Henry, G.A. Kriss,
J.W. Kruk, O. Vancura (JHU), H.C. Ferguson (IoA),
R.A. Kimble (GSFC), and K.S. Long (STScI)

The Hopkins Ultraviolet Telescope, on its maiden voyage aboard the space shuttle *Columbia*, as part of the Astro-1 mission in December 1990, made two observations of the Io torus, one near the west ansa and one near the east ansa. The spectra obtained, covering the wavelength range 830-1850 Å (415-925 Å in second order), are used to study the neutral gas component of the torus. To minimize the effects of terrestrial airglow contamination, the observations were made during the nighttime portion of the orbit; however the O I nightglow emission still makes a determination of the neutral oxygen component of the torus difficult. For the first observation near the west ansa, an 17 $\times$ 116 arcsec slit was used (6 Å resolution) and Io was contained within the slit; for the second observation, near the east ansa, a 9 $\times$ 116 arcsec slit was used (3 Å resolution) and Io was not in the slit. Neutral sulfur is detected in the spectrum taken when Io was in the slit. Two emissions from neutral sulfur are identified: the S I (^{3}P–^{3}D) λ1425 multiplet and the S I (^{3}P–^{3}S) λ1474 multiplet. Two other neutral sulfur emissions in this spectral range, S I λ1299 and S I λ1814, are blended with the O I λ1302 nightglow emission and a second-order S II λ909 emission. For the observation made when Io was not in the slit, an upper limit is set to the neutral sulfur emission. The implications of this result for the neutral gas source of ions in the plasma torus will be discussed.

The Hopkins Ultraviolet Telescope Project is supported by NASA contract NAS 5-27000 to the Johns Hopkins University.

HUT Observations of Comet Levy (1990c)

P.D. Feldman, A.F. Davidsen, W.P. Blair, C.W. Bowers,
W.V. Dixon, S.T. Durrance, R.C. Henry, G.A. Kriss, J.W. Kruk,
H.W. Moos, O. Vancura (JHU), H.C. Ferguson (IoA),
R.A. Kimble (GSFC), K.S. Long (STScI), and T.R. Gull (GSFC)

Observations of comet Levy (1990c) were made with the Hopkins Ultraviolet Telescope during the Astro-1 Space Shuttle mission on 1990 December 10. The spectrum, covering the wavelength range 415-1850 Å at a spectral resolution of 3 Å (in first order), shows the presence of carbon monoxide and atomic hydrogen, carbon and sulfur in the coma. Aside from H I Lyman-β, no cometary features are detected below 1200 Å, although cometary O I and O II would be masked by the same emissions present in the day airglow spectrum. The 9×116 arcsecond aperture corresponds to 12000×148000 km at the comet. The derived production rate of CO relative to water, 0.13 ± 0.02, compared with the same ratio derived from *IUE* observations (made in September 1990) which sample a much smaller region of the coma, 0.04 ± 0.01, suggests the presence of an extended source of CO, as was found in comet Halley. Upper limits on Ne and Ar abundance are within an order of magnitude of solar abundances.

The Hopkins Ultraviolet Telescope Project is supported by NASA contract NAS 5-27000 to the Johns Hopkins University.

HUT Spectra of the Hot Stellar Components in the Elliptical Galaxy NGC 1399 and the Bulge of M31

H.C. Ferguson (IoA), A.F. Davidsen, G.A. Kriss, W.P. Blair,
C.W. Bowers, W.V. Dixon, S.T. Durrance, P.D. Feldman,
R.C. Henry, J.W. Kruk, H.W. Moos, O. Vancura (JHU),
R.A. Kimble (GSFC), and K. Long (STScI)

Suggestions for the source of the ultraviolet upturn in elliptical galaxies and spiral bulges include post-asymptotic-giant-branch stars and related objects, hot horizontal branch stars, accreting white dwarfs, and young stars. Each candidate has different implications for the spectral evolution of galaxies. To investigate these possibilities, far ultraviolet spectra of the centers of NGC 1399 and M31 were obtained with the Hopkins Ultraviolet Telescope aboard Astro-1. The spectra were taken through a 9" × 116" aperture and cover the wavelengths from 1850 Å to the Lyman limit at a resolution of about 3 Å. The shapes of the ultraviolet continua in these spectra are consistent with a dominant population of very hot stars. Strong absorption features are shortward of Lyman α in both spectra, attributable both to the intrinsic stellar populations and to the intervening ISM. The lack of detectable C IV absorption at 1550 Å essentially rules out OB supergiants similar to those seen in the Milky Way as significant contributors to the UV flux. No emission features other than well-known geocoronal lines are seen. The continuum shape and the details of the absorption line spectra are quite different for M31 and NGC 1399, suggesting that the UV stellar populations are not the same in these two galaxies.

The Hopkins Ultraviolet Telescope Project is supported by NASA contract NAS 5-27000 to the Johns Hopkins University.

HUT Observations of the Chromosphere of Capella

R.C. Henry (JHU), R.A. Kimble (GSFC), W.P. Blair, C.W. Bowers,
A.F. Davidsen, W.V. Dixon, S.T. Durrance, P.D. Feldman,
G.A. Kriss, J. Kruk, H.W. Moos, O. Vancura (JHU),
H.C. Ferguson (IoA), and K.S. Long (ST ScI)

The Hopkins Ultraviolet Telescope (HUT) was used on three occasions during the Astro-1 space shuttle mission, in December 1990, to observe (for a total of 2400 s) the far ultraviolet (912 - 1850 Å) spectrum of the cool binary star Capella (α Aurigae: G5 III + GO III), and to attempt to observe the extreme ultraviolet ($\lambda < 912$ Å) spectrum. Previous observations of Capella in the ultraviolet are described by T. R. Ayres (1988, Ap J, 331, 476) and A. K. Dupree (1975, Ap J, 200, L27). The hope of detecting extreme ultraviolet emission stems from the very active chromosphere of the fast-rotating secondary, as shown for example by its X-ray emission (R. Mewe *et al.* 1982, Ap J, 260, 233), and from the low interstellar column density (R. C. Henry *et al.* 1986 New Insights in Astrophysics, Proc Joint NASA/ESA/SERC Conf University College London, ESA SP-263, 555) of 1.2×10^{18} cm^{-2} toward Capella. Excellent spectra were obtained, and C III λ 977, O VI λ 1038, and N II + He II λ 1085 emissions are seen, for the first time, from this star. There was no opportunity to use the aluminum filter to exclude wavelengths longer than 912 Å, so the search for extreme ultraviolet features which may be present must be carried out among the airglow emissions and weak chromospheric features of the first-order spectrum; the results of the search will be described.

The Hopkins Ultraviolet Telescope Project is supported by NASA contract NAS 5-27000 to The Johns Hopkins University.

EUV Observations of G191-B2B and the Local ISM with the Hopkins Ultraviolet Telescope

R. A. Kimble (GSFC), A. F. Davidsen, W. P. Blair, C. W. Bowers, W. V. Dixon, S. T. Durrance, P. D. Feldman, R. C. Henry, J. W. Kruk, G. A. Kriss, H. W. Moos, O. Vancura (JHU), H. C. Ferguson (IoA), and K. S. Long (STScI).

During the December 1990 shuttle flight of the Astro Observatory, the Hopkins Ultraviolet Telescope, utilized primarily for far ultraviolet (912-1850 Å) spectroscopy, also undertook a small program of extreme ultraviolet observations of nearby objects in the 420-912 Å range. HUT offered unprecedented sensitivity and spectral resolution at these wavelengths; we applied its capabilities to the observation of several nearby hot white dwarfs and coronal stars. Most successful was the observation of G191-B2B, a hot DA white dwarf, which yielded a strong signal in the 420-650 Å range.

The principal goal of the EUV white dwarf program is to study the physical conditions in the very local interstellar medium (ISM) by measuring the column densities of neutral helium (from direct measurement of the helium absorption edge at 504 Å) and neutral hydrogen (from the shape of the stellar spectrum in the Lyman continuum range). The magnitude of the neutral column densities indicates the spatial extent of the interstellar cloudlet which surrounds the solar system, while their ratio reveals the relative ionization of these two principal constituents of the ISM.

A preliminary analysis of the HUT EUV spectrum of G191-B2B yields column densities of 1.3×10^{17} cm^{-2} for He I and 1.6×10^{18} cm^{-2} for H I, and a neutral helium to hydrogen ratio of 0.08, very close to the canonical cosmic abundance ratio. This latter result is surprising in light of the widespread view that hydrogen is substantially ionized in the local ISM, with helium much less so. The ramifications of these results regarding the pressure in the local ISM and potential sources of ionizing flux will be discussed.

The Hopkins Ultraviolet Telescope Project is supported by NASA contract NAS 5-27000 to the Johns Hopkins University.

HUT Observations of the Far Ultraviolet Spectrum of the Seyfert Galaxy NGC 4151

G.A. Kriss, A.F. Davidsen, J.W. Kruk, W.P. Blair, C.W. Bowers, W.V. Dixon, S.T. Durrance, P.D. Feldman, R.C. Henry, H.W. Moos, O. Vancura (JHU), H.C. Ferguson (IoA), K.S. Long (STScI) and R.A. Kimble (GSFC)

The prototypical Seyfert 1 galaxy NGC 4151 was observed by HUT for ~2200 s on 8 December 1990. Our spectrum spans the wavelength range 830-1850 Å at a resolution of ~3 Å. During the observation, NGC 4151 was slightly above the historical mean in continuum flux level ($f_{1450} = 1.6 \times 10^{-13}$ ergs cm^{-2} sec^{-1} Å^{-1}) and in the flux of broad C IV λ1549 ($\sim 3.0 \times 10^{-11}$ ergs cm^{-2}s^{-1}). The spectrum longward of Ly α is typical of that observed on many occasions with the *IUE.* Shortward of Ly α, however, the continuum shows a pronounced dip centered on ~1125 Å, and then turns over sharply below 1000 Å. Narrow absorption lines are visible in all the highly ionized metallic species — C IV, Si IV, N V, and O VI. In addition, broad (2000 km s^{-1}) hydrogen Lyman lines are seen in absorption slightly blue-shifted from the systemic velocity of NGC 4151. As found in *IUE* spectra, the blue wing of Ly α is strongly absorbed. The emission line profiles exhibit many differences — C IV is unusually strong and broad with a weak central absorption feature; Si IV, N V, and O VI appear narrower with much stronger absorption components; and He II λ1640 and Ly α are dominated by emission from the narrow line region with little emission at the velocities seen in the C IV profile. From the ratio of narrow He II λ1640 to He II λ1085, we set an upper limit on the reddening to the narrow line region of $E_{B-V} < 0.14$. We will discuss possible explanations for the location of the absorbing material and the unusual shape of the far ultraviolet continuum.

The Hopkins Ultraviolet Telescope Project is supported by NASA contract NAS 5-27000 to the Johns Hopkins University.

Far UV Observations of SS Cyg and U Gem in the Low State with the Hopkins Ultraviolet Telescope

K.S. Long (STScI), W.P. Blair, A.F. Davidsen, C.W. Bowers, W.V. Dixon, S.T. Durrance, P.D. Feldman, R.C. Henry, G.A. Kriss, J.W. Kruk, H.W. Moos, O. Vancura (JHU), H.C. Ferguson (IoA), and R.A. Kimble (GSFC)

The Hopkins Ultraviolet Telescope, an experiment flown on the space shuttle as part of the Astro-1 mission, was used to obtain spectra of the dwarf novae SS Cyg and U Gem in the wavelength range 830-1850 Å. Both cataclysmic variables had visual magnitudes which indicate they were in the low state at the time of the observations. In the sub-Lyman α region, which is inaccessible to *IUE*, the spectrum of SS Cyg shows a relatively flat continuum on which are superimposed emission lines of C III, N III, N IV, O VI, S IV, and S VI. The spectrum appears to be dominated by an optically thin accretion disk. The spectrum of U Gem below Lyman α shows absorption lines associated with the higher order Lyman series in addition to metal absorption lines of N III, C III, and O VI. The continuum spectrum is dominated by emission from the the white dwarf, as had been deduced previously with *IUE*. However, the temperature of the white dwarf must be greater than 30,000 K to account for all of the continuum flux near the Lyman limit. Model fits to the continuum spectra of both U Gem and SS Cyg will be reported.

The Hopkins Ultraviolet Telescope Project is supported by NASA contract NAS 5-27000 to the Johns Hopkins University.

HUT Spectra of the Io Torus

H.W. Moos, P.D. Feldman, S.T. Durrance, A.F. Davidsen,
W.P. Blair, C.W. Bowers, W.V. Dixon, R.C. Henry, G.A. Kriss,
J.W. Kruk, O. Vancura (JHU), H.C. Ferguson (IoA),
R.A. Kimble (GSFC), and K.S. Long (STScI)

Since the discovery by *Voyagers 1* and *2* of a very rich emission spectrum of the Io torus at wavelengths below 1200 Å, there has been a need for spectra at a few Å resolution to unravel the details of the torus emissions. The Hopkins Ultraviolet Telescope (HUT), flown on the Space Shuttle *Columbia* as part of the Astro-1 mission in early December 1990, obtained two such spectra (830-1850 Å in first order, 415-925 Å in second order); one at 3 Å resolution (1.5 Å in second order) near the east ansa when Io was well outside the spectrograph slit and one at 6 Å resolution near the west ansa with Io in the slit. In the first case, the 9 $\times$ 116 arcsec entrance slit of the spectrograph was aligned along the torus equator. The observational geometry for the west ansa was similar except that the slitwidth was 18 arcsec. The HUT line-of-sight through the terrestrial atmosphere was not illuminated by the sun so that contamination by airglow was negligible except for a few features. The spectra show a large number of features in agreement with the models used to fit the ~30 Å resolution *Voyager* spectra. There are no strong features other than those due to the ions of sulfur and oxygen. However, the spectrum is quite rich, and weak features due to other species cannot be ruled out at this time. The HUT data permit a determination of relative ionic abundances without the necessity of a detailed model of the plasma distribution.

The Hopkins Ultraviolet Telescope Project is supported by NASA contract NAS 5-27000 to the Johns Hopkins University.