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ULTRAVIOLET ALBEDO OF THE MOON WITH THE HOPKINS ULTRAVIOLET TELESCOPE

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ABSTRACT

During the 1995 March flight of the Hopkins Ultraviolet Telescope, as part of the Astro-2 Space Shuttle mission, we observed the Moon over the wavelength range 820–1840 Å, with a resolution of 3–4 Å, finding the ultraviolet albedo of the Moon to be 0.038 ± 0.0038 at 1700 Å. We also find a gentle increase in the albedo toward shorter wavelengths. Ultraviolet albedo measurements may represent a useful tool for selenographic exploration.

Subject headings: Moon — ultraviolet: solar system

1. INTRODUCTION

The final observation of the Astro-2 mission was an observation of the nearly full Moon. That the albedo of the Moon, and particularly the albedo of the Moon in the ultraviolet, is a subject of some importance has been emphasized by Wagner, Hapke, & Wells (1987). They pointed out both the general importance of reflectance spectroscopy for the remote sensing of solid bodies in the solar system and the particular virtues of *ultraviolet* spectroscopy. Their argument is that light is reflected by two processes, surface scattering and volume scattering. In the far-ultraviolet (FUV), surface scattering is the dominant process. Thus, the albedo is almost entirely determined by the bulk index of refraction of the material of the surface. It has been argued by Henry et al. (1976a) that, for this reason, FUV mapping of the Moon would be a useful tool for selenographic exploration.

The intensity of light that is observed from the Moon depends not only on the albedo but also, in a complicated way, on the angles of illumination and observation. This has been expounded and illuminated by Hapke (1963) and adapted to the UV by Lucke, Henry, & Fastie (1976); rather than repeat the equations, we illustrate them in a practical sense in Figure 1 (Plate L5), where the shading indicates the angular variation that might be expected in the FUV, according to Hapke's equations. We show the mare areas as brighter (rather than darker) because Henry et al. (1976a, b) found Mare Crisium in particular to be brighter in the FUV than surrounding highland areas. The difference (∼5%) is exaggerated in Figure 1, although relative brightnesses within both highland and mare regions are accurate. Henry et al. emphasized that the (inverse) correlation with optical albedo is imperfect, and they pointed out that this presumably means that the UV data contain information that does not exist in the optical albedo data. Had we observed with the Hopkins Ultraviolet Telescope (HUT) just past last-quarter Moon, e.g., in 1994 July 1 (the specific [arbitrary] date for which Fig. 1 illustrates the Hapke-function variation), at the indicated position (*small projected square*), HUT would have obtained an intensity of 0.02 of the maximum possible (which is the intensity that is observed at full Moon). All of these angular dependences are expected to vanish at full Moon (Hapke 1963).

The idea that in the FUV there is, to some extent at least, a reversal in the sense that regions of the Moon that are relatively bright in the optical are relatively dark in the FUV has been supported by Wagner et al. (1987) in their examination of the reflectance spectra of lunar fines; they report that "lunar soils exhibit the property of 'spectral' reversal first noted by Lucke et al. (1974): soils that are lighter in the visible and near-infrared are darker in the far-ultraviolet. This relationship does not occur in the spectra of powdered lunar rocks." It is hoped that the Astro-2 Ultraviolet Imaging Telescope (UIT) observation of Gladstone et al. (1995), obtained simultaneously with the present observation, will result in maps of the variation; however, there is some indication (G. R. Gladstone 1995, private communication) that a red leak in the UIT FUV imager may preclude this.

Lucke, Henry, & Fastie (1973) reported laboratory measurements of the FUV reflectivity of lunar fines (dust), obtaining an albedo in the FUV of about 4%–6% depending on wavelength. The albedo quoted is the so-called geometric albedo, which is the ratio of the brightness of a full Moon to the brightness of a perfectly diffusing disk (100%, Lambert's-law reflector). This is as distinguished from the Bond albedo, the ratio of the total amount of light the Moon reflects to the amount of light incident upon it. We will use geometric albedo exclusively throughout this paper. The reflectivity of lunar samples in the FUV has also been measured by Wagner et al. (1987) with similar results. As for the Moon itself, its UV albedo has been measured previously using the UV spectrometer on *Apollo 17* (Fastie 1973). The results have been reported by Lucke, Henry, & Fastie (1975) and by Lucke et al. (1976), who discussed earlier observations (which show considerable scatter) and who also provided additional laboratory measurements of lunar samples. The albedo in the extreme-UV falls to much lower values (Gladstone et al. 1994), while toward longward wavelengths the albedo increases (see Fig. 14 of Wagner et al. 1987, Fig. 6 of Lucke et al. 1976, and new observations by Andrews & VanHoosier 1995 [and also C. A. Barth 1995, private communication]).

2. OBSERVATIONS

We observed the Moon with the HUT spectrometer at 1995 March 17 0457 UT for 428 s. In Figure 2 (Plate L6), we show a simultaneous visible photograph of the Moon obtained with the HUT entrance-aperture television camera (*left*). The dark

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patch in the middle is the HUT 12″ entrance aperture (field of view 2.8×10^{-9} sr, covering a 28 km diameter patch on the lunar surface), while the dark streak is a fiducial. The region observed is near Flammarion-C, which is a border area between mare and highland regions. In Figure 2 (*right*) we also show the very uniform Hapke-function plot for the time of observation, which was just a few hours after full Moon. As in Figure 1, the HUT observing location is indicated by a projected square. The telescope stayed accurately pointed at this location throughout the observation, and there is no evidence in the data for time variation.

An overview of the Astro observatory is given by Blair & Gull (1990). HUT, described by Davidsen et al. (1992), consists of a 0.9 m f/2 telescope and a prime-focus spectrograph with a photon-counting microchannel-plate intensifier that feeds a Reticon photodiode-array detector. Spectra were obtained at 3–4 Å resolution over the range 820–1840 Å. Modifications for the flight of Astro-2 and the present instrument calibration are described by Kruk et al. (1995). There is a time dependence in the HUT calibration during the Astro-2 mission, which was monitored with repeated observations of the white dwarfs HZ 43 and GD 394. The lunar spectra were corrected to 358 hr (Mission Elapsed Time) with the procedure of Kruk et al. (1995). The extrapolation beyond the 329 hr correction benchmark differed little from spectra obtained by simply correcting to 329 hr. The spectrum of the Moon is shown in Figure 3 and, of course, is simply a solar spectrum as modified by reflection from the lunar rock and dust.

3. RESULTS

In order to obtain an albedo, we must have a measurement of the incident light from the Sun. For the spectral region of Lyα and longward, that has kindly been provided by T. Woods and G. Rottman, in the form of 1.5 Å resolution spectra obtained with *UARS*/SOLSTICE, a three-channel solar spectrometer that makes solar measurements during daylight portions of each orbit of the *UARS* spacecraft. We have used in particular data from March 16 (March 17 UT). We have examined similar spectra for March 14, 15, 17, and 18, finding rms variations of only $\sim$1% at any wavelength, which is better than our absolute instrument calibration. The absolute uncertainty in the SOLSTICE measurement is $\pm$3%–5% (Woods, Rottman, & Ucker 1993). The spectra provided us are not yet fully calibrated; the long-term calibration of the instrument (below $\sim$2500 Å) will possess additional uncertainties of $\lesssim$2%, which is insignificant for our albedo determination. The SOLSTICE spectrum was convolved to the HUT spectral resolution of 3–4 Å.

The HUT lunar spectrum was first corrected for grating-scattered Lyα using a scattered-light profile derived from an observation of geocoronal Lyα against a blank sky made with the same aperture 25 hr earlier (see, e.g., Kruk et al. 1995) and normalized to the total number of counts in the line. Scattered light accounts for $\sim$20% of the measured flux at 1280 Å. The spectrum was then multiplied by 1.073 to account for the Hapke scattering function of a few hours past full Moon and was then divided by the SOLSTICE solar spectrum (divided by π sr, multiplied by 0.995 to allow for the greater distance of the Moon, and divided by 0.99 to allow for the closeness of Earth to the Sun on March 17) to obtain the albedo that is displayed in Figure 4. The albedo is $\sim$4%, almost independent of wavelength between 1250 and 1840 Å. The jitter in Figure 4 is

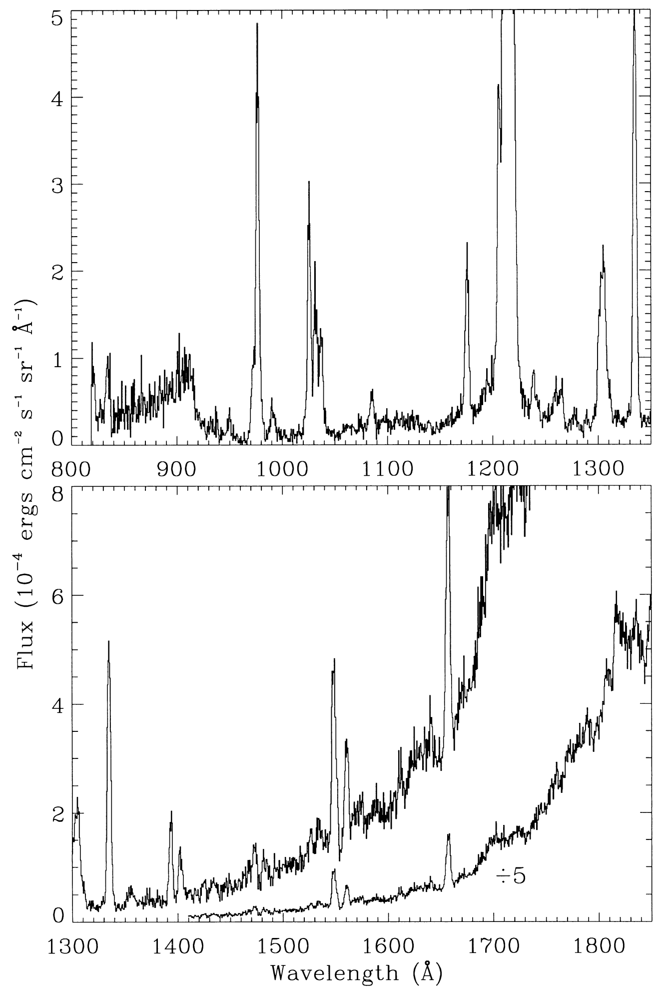

FIG. 3.—Spectrum of the Moon observed with the HUT spectrometer on the Astro-2 mission. The spectrum is essentially solar, modified by the reflectance properties of the lunar surface. The Lyman continuum shortward of 912 Å is prominent.

mainly an artifact of the division since the HUT spectral resolution varies over this spectral range and there is a 0.2 Å rms uncertainty in the HUT wavelength scale (Kruk et al. 1995). In addition, the structure in the albedo between 1290 and 1315 Å is an instrumental artifact that results from the degradation of the gain of the detector's microchannel plate in the vicinity of 1304 Å due to prolonged exposure to daytime terrestrial O I λ1304 airglow emission. In Table 1 we give the results of integrating the continuum data of Figure 4 over broad bands and also the *Apollo 17* numbers for comparison.

4. DISCUSSION

Our main comparison is with the *Apollo 17* observations. The work of *Apollo 17* is described by Fastie et al. (1973a, b, c), and the calibration (which is critical to the present discussion) is described by Fastie & Kerr (1975) and was confirmed in flight by Henry et al. (1975).

In Figure 5, we compare our present albedo (*filled circles*; averages over broad wavelength bands) with the albedo previously reported by Lucke et al. (1976). Although we are close to the *Apollo 17* error bars longward of 1400 Å, we obtain an albedo that is systematically lower than the *Apollo 17* albedo by $\sim$0.5%, which is a 10% relative disagreement. The *Apollo*

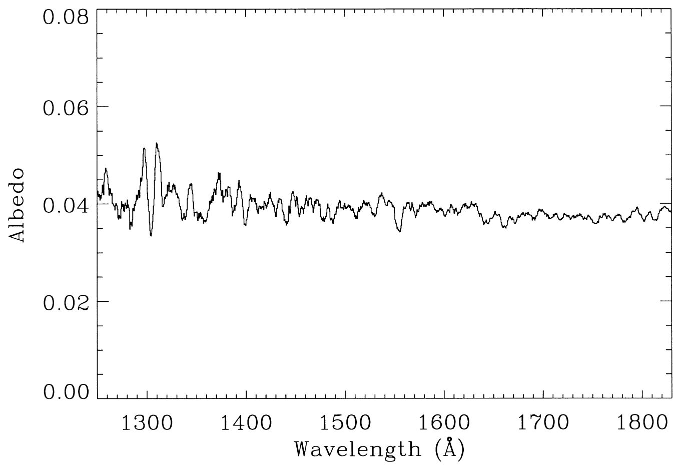

FIG. 4.—Albedo of the Moon as a function of wavelength, measured by comparing the HUT spectrum with a SOLSTICE solar spectrum from the *UARS* mission obtained contemporaneously. The albedo shows a small rise to short wavelengths, considerably weaker than that reported by Lucke et al. (1976), whose data were likely contaminated with grating-scattered Lyα radiation.

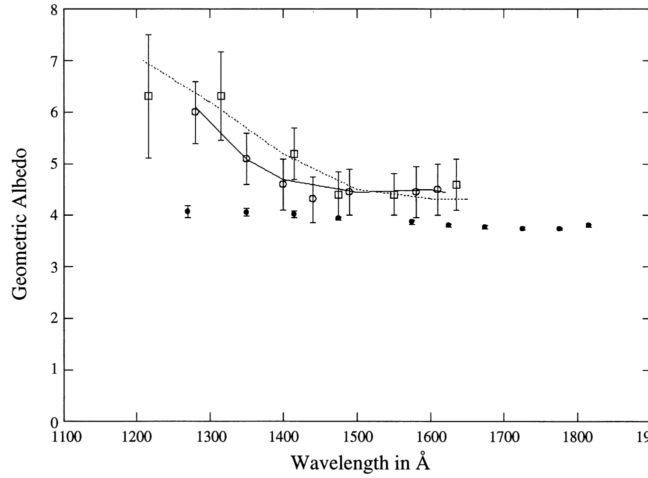

FIG. 5.—HUT albedo averaged over broad spectral bands (*filled circles*) compared with the *Apollo 17* lunar albedo (*squares*) and lunar-dust laboratory albedo (*open circles*) of Lucke et al. (1976). The solid line is the fit of Lucke et al. to their lunar-dust data, while the dashed line is their fit to their *Apollo 17* data. Apart from the question of the rise at short wavelengths, the small difference between our measurement and the *Apollo 17* result may represent real variations in the lunar albedo from place to place on the lunar surface.

17 measurement involved a simultaneous rocket measurement of the solar spectrum, so time variation of the solar flux can be ruled out as a source of this discrepancy. The rocket measurement of the solar flux however did involve an imperfectly known slit width of the spectrometer (about $\pm 10\%$) while there is an uncertainty in the HUT entrance-aperture size of 5%, which translates to 7% uncertainty in solid angle; these factors alone could account for the discrepancy. In addition, the Hapke function is imperfect, and the Hapke-function correction in the case of *Apollo 17* was 27%, compared with our 8%. Finally, there is the question of real variations in albedo from place to place on the Moon. From the *Apollo 17* data displayed by Henry et al. (1976a), there is no question that such variations exist. The Lucke et al. (1976) measurement of the direct lunar albedo that is shown in Figure 5 involves a multiplication by 0.95 to account for the fact that their direct measurement was of Mare Crisium, which Henry et al. (1976a) show to be systematically brighter than average lunar regions. The present spectrum near Flammarion-C is of a region that was not observed with the *Apollo 17* spectrometer. The region is complex and could involve mare and/or highland regions.

TABLE 1

MEASUREMENTS OF THE UV LUNAR ALBEDO

Wavelength (Å)	Astro-2	*Apollo 17*
1800–1830	0.038	...
1750–1800	0.037	...
1700–1750	0.037	...
1670–1700	0.038	...
1600–1670	0.038	0.046
1550–1600	0.039	0.044
1450–1550	0.039	0.044
1380–1450	0.040	0.052
1320–1380	0.040	...
1280–1350	...	0.063
1250–1290	0.041	...
1216	...	0.063

Wagner et al. (1987) reported that in the visible and IR, spectral features that appear in powdered samples of lunar rock are "more subdued in soils than in rock powders, and are even absent in some cases," but "the far ultraviolet spectral features are nearly as conspicuous for the soil samples as for the lunar rocks." The rise in the albedo that appears in Figure 4 from 1700 to 1300 Å is in *qualitative* agreement not only with the previous measurement of Lucke et al. (1976) but also with the laboratory measurements of Lucke et al. (1976) and Wagner et al. (1987, their Figure 14) and is probably real. However, we note that grating-scattered Lyα radiation is stronger at the shorter wavelengths and that the *Apollo 17* ruled-grating spectrometer had severe scattering (which is illustrated in Henry et al. 1978); the HUT spectrometer's holographic grating, in contrast, has excellent scattering properties (Kruk et al. 1995). Also, the SOLSTICE data are meticulously corrected for scattered Lyα (Woods et al. 1995). We therefore feel that the strength of the rise is as we report it in the present work.

During the HUT observation, the Earth-Moon-Sun angle was 3°.65 (slightly modified by the Shuttle-location parallax, but our observation was made near local midnight), which is well within the range at which enhanced backscattering ("full Moon" effect) has been reported. However, our albedo shows no significant increase over that reported by *Apollo 17*, which observed at much larger phase angles. That the so-called opposition effect is caused by coherent backscatter, rather than by shadow hiding, has recently been demonstrated by Hapke, Nelson, & Smythe (1993).

It is unfortunate that contemporaneous solar spectra are not available shortward of Lyα. Certainly, the HUT spectrum of Figure 3 remains strong below Lyα, consistent with the lunar albedo remaining near 4% all the way to 800 Å. In particular, the solar Lyman continuum short of 912 Å is prominent in Figure 3. Albedo measurements at these short wavelengths, and at still shorter wavelengths, are presented by Gladstone et al. (1994). They (and the papers they reference) show that the albedo continues at 4%–6% down to 600 Å and then drops rapidly.

5. CONCLUSION

The FUV albedo of the Moon has been measured over the spectral range 1250–1800 Å, and an albedo of 0.038 ± 0.0038 at 1700 Å obtained, with the albedo showing a gentle increase to shorter wavelengths that is in qualitative accord with previous measurements of both lunar fines and the Moon itself. The FUV albedo shows no evidence of an opposition effect. The present measurement is probably the most accurate yet made and is at a level of accuracy such that our result is dominated by place-to-place variations in lunar albedo rather than by measurement errors.

It has been a delight to participate in the Astro missions, and we thank all who made it possible. We thank in particular the Spacelab Operations Support Group at Marshall Space Flight Center for their efforts during the Astro-2 mission. We thank T. Woods and G. Rottman of the National Center for Atmospheric Research, Boulder, CO, for supplying the solar brightness data. Support for this work was provided by NASA contract NAS5-27000 to Johns Hopkins University.

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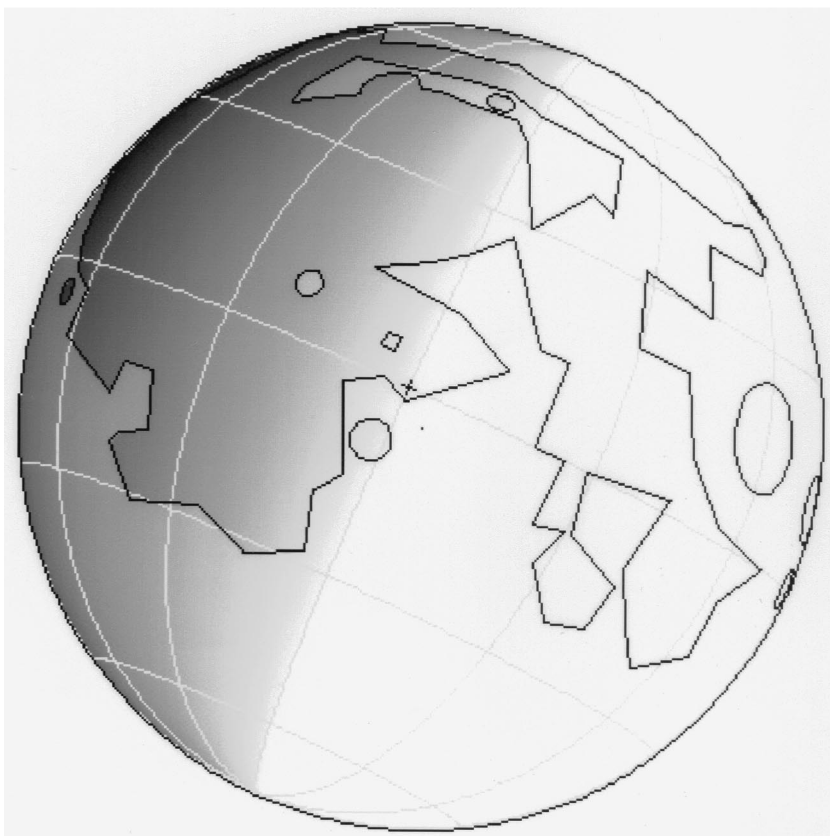

Fig. 1.—Illustration of the strong variation of the brightness of reflected UV sunlight from the Moon, according to the scattering analysis of Hapke (1963). Contours mark mare/highland boundaries and major craters. Differences with angle of illumination and observation shown are accurate, but the mare/highland difference is greatly exaggerated. An observation with HUT (*small box*) in Sinus Aestuum under these circumstances would be predicted to result in an intensity of only 2% of maximum (where maximum occurs at full Moon). North is at the top, and a dot marks the sub-Earth point.

Henry et al. (see 454, L69)

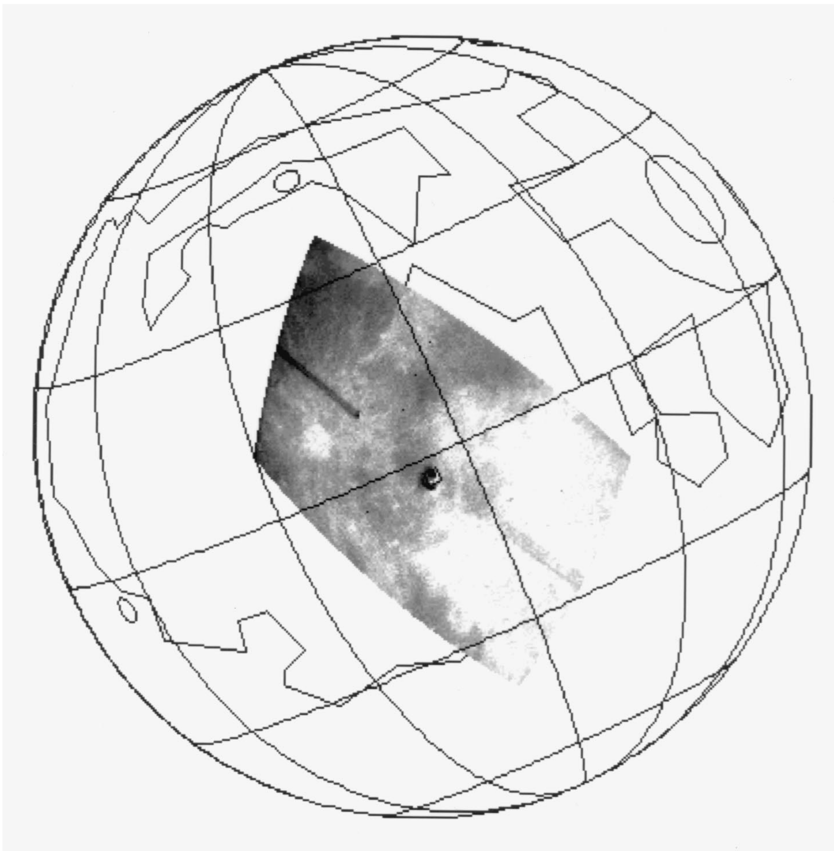

FIG. 2*a*

FIG. 2*b*

FIG. 2.—*Left*: Visible-light photograph of the Moon taken with the HUT television camera aboard the Astro-2 Space Shuttle simultaneously with the observation of the UV brightness of the Moon with the HUT spectrometer. The HUT entrance aperture is visible as a dark patch, and the dark streak is a fiducial. HUT observed close to the crater Flammarion-C. *Right*: The HUT observation was made very close to full Moon, so the Hapke-function variation with position, shown here, is minimal, resulting in minimal uncertainty in the measurement of the albedo. Differences in *actual* albedo are still present: we show here an exaggerated version of real mare/highland differences that the work of Henry et al. (1976a) suggests may be present in the UV. The small box shows the actual HUT observing location. North is at the top.