THE ASTROPHYSICAL JOURNAL, 212:707–713, 1977 March 15

FAR-ULTRAVIOLET STUDIES. II. GALACTIC-LATITUDE DEPENDENCE OF THE 1530 Å INTERSTELLAR RADIATION FIELD

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Received 1976 July 26; revised 1976 August 31

ABSTRACT

A 0.62 cm^2 Geiger counter, sensitive between 1425 and 1640 Å, was used to map the far-ultraviolet brightness of about half of the sky, providing the first experimental measurement of the far-ultraviolet interstellar radiation field. At 1530 Å, the energy density is $7.4(+1.7, -1.3) \times 10^{-17}$ ergs cm^{-3} Å^{-1}. Comparison with integrations of star catalogs calibrated to the ultraviolet shows, as expected, that the bulk of the radiation comes directly from B- and A-type stars. The galactic-latitude dependence of the radiation is analyzed in an unsuccessful attempt to set limits on the absorbing and scattering properties of the interstellar grains in the far-ultraviolet. Excess radiation is observed at the galactic pole that is probably residual airglow from above rocket altitude.

Subject headings: galaxies: Milky Way — interstellar: matter — stars: stellar statistics — ultraviolet: general

I. INTRODUCTION

The far-ultraviolet radiation that is observed by a wide-angle detector scanning the sky includes starlight, starlight scattered from interstellar dust, radiation from quasars and blue halo objects, and possible radiation from a cosmic ultraviolet radiation field, related to the extragalactic X-ray radiation field. The residual terrestrial atmosphere above rocket altitude, or some solar-system source, may also make a contribution. Also, Hills (1971, 1972) has suggested that hot prewhite–dwarf stars, which he calls UV stars, may account for the excess ultraviolet radiation observed from several galactic nuclei by Code, Welch, and Page (1972). Terzian (1974) has specifically investigated the *extreme* ultraviolet (i.e., ionizing) radiation expected from the central stars of planetary nebulae, and concluded that it is of the same order as the extreme ultraviolet radiation from early-type stars (see also Salpeter 1976).

The ultraviolet brightness of the sky at 1450 Å in the direction of the north galactic pole, as viewed through a 10° full width at half-maximum (FWHM) detector from an altitude of about 160 km, was measured by Henry (1973). In the present paper, the result of a new experiment giving the distribution of ultraviolet radiation over a larger area of the sky is presented. The galactic-latitude dependence of the observed radiation field is compared with theoretical predictions, and with the observations of others. The present results have been described briefly by Shulman and Henry (1973).

II. THE EXPERIMENT

An Aerobee rocket was launched from White Sands Missile Range, New Mexico, at 0400 UT on 1970 March 1. The solar zenith angle at the time of launch was 128°, at 72° west of north. The atmosphere at the zenith was therefore illuminated above 1700 km by the Sun. The initial spin of the rocket was reduced by a despin mechanism, providing a final roll rate of 33° s^{-1}. After despin, the yaw cone of the rocket had a half-angle of about 78°. The rocket made almost one complete rotation in this precession cone during the observation time, thus providing almost complete coverage of the galactic anticenter hemisphere. Detector aspect was determined by means of photomultiplier-telescope devices, and was generally accurate to about 1°.

The major objective of the flight was to provide an X-ray map of the overhead sky. The results of this experiment were described by Davidsen *et al.* (1972). The rocket also carried two small Geiger counters sensitive to far-ultraviolet radiation. One detector had a CaF_2 window and was filled with 10 mm of NO and one atmosphere of neon, resulting in a bandpass of 1225 to 1340 Å. This detector did function, and provided a useful upper limit on the flux of redshifted Lα radiation from the Coma cluster of galaxies (Henry 1972), but it suffered from a strong isotropic background probably produced by geocoronal Lα leaking through the CaF_2 filter. This terrestrial background makes it impossible to use this detector for celestial background studies.

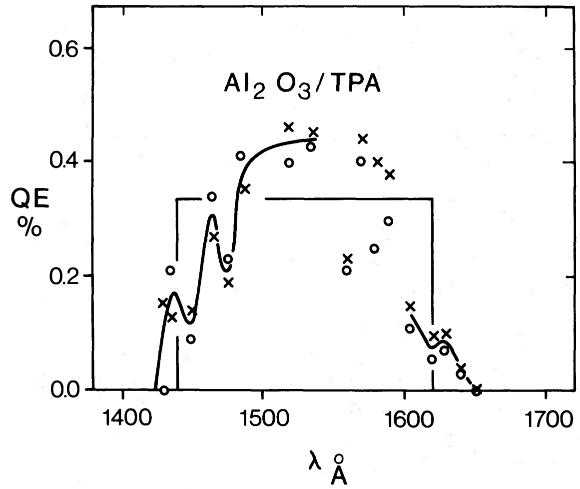

FIG. 1.—Absolute quantum efficiency of the flight Al_2O_3-windowed tripropylamine-filled Geiger counter, as measured before (*crosses*) and after (*circles*) flight. A curved solid line is fitted to part of the data. The rectangular fit was actually used in deriving intensities from the stellar data. The effective wavelength is about 1530 Å.

The other detector had a sapphire (Al_2O_3) window and was filled with 3 mm of tripropylamine, 1 mm of CO, and an atmosphere of neon. Calibration was as described by Henry (1972) and is shown in Figure 1. Previous experience leads us to expect the absolute accuracy of the calibration to be about a factor of 2 either way.

III. RESULTS

A map of the sky at 1530 Å produced from these measurements is given in Figure 2, using an Aitoff equal-area projection of the celestial sphere. The sky is shown in right ascension and declination, with 19^h(285°) at each edge of the map and north at the top. Five lines of constant galactic latitude are shown, at 30° intervals. The heavy line marks a zenith angle of 115°.

This projection has the property that equal areas on the sphere are represented by equal areas on the flat projection. The sky has been divided into sections (called squares) each roughly 10° × 10° and each having an area of *exactly* 100 square degrees (except for two polar caps). The darkening of the squares is proportional to the average count *rate* observed from the direction represented by the square. It is necessary to keep in mind that some squares were observed only very briefly; hence the proper amount of darkening is subject to considerable statistical uncertainty. Typical statistical uncertainty at high galactic latitudes is ±25%. Certain squares were not observed at all; these are shown as blank.

The average count rate observed when the counters were pointed 25° or more below the horizon has been subtracted from the plotted numbers. This, of course, results in negative "count rates" in some squares, indicated by ticks at each end of the plotted line.

A positive flux is observed over the whole sky. A portion of Gould's Belt (including Orion) shows up strongly in the figure, just south of the line indicating the galactic equator. Two isolated bright stars (η UMa in the north, Spica to the south) appear. These stars may be used for an in-flight calibration. This must be done with care. Because of the triangular collimator response function, the darkness of square in Figure 2 means very little in the case where a single bright star is the dominant source of radiation. It may be that the star was some distance off the scan path when observed, and hence was recorded as being too faint. For calibration purposes, the scans must be examined individually. Data on the usable calibration stars are given in Table 1. The uncertainty in the aspect solution (±1°) gives an uncertainty in the deduced stellar intensity which depends on the distance of the star from the scan path; this pointing error is given in the table. The dead time was not very well determined, but was about 400 μs; the dead-time correction factor for each star is also given in the table. The final column compares the observed and "true" stellar brightnesses, where "true" represents the cited adopted values. In the mean, it appears that the present experiment gives a flux a factor 1.67 ± 0.36 too high, if the laboratory calibration shown in Figure 1 is used. In all work described in this paper, including Figure 2, this factor has been taken into account, that is, the in-flight calibration has been used. The darkest squares in Figure 2 correspond to an observed counting rate of at least (the plot is saturated on the darkest squares) 1550 counts s^{-1}/(0.62 cm^2 × 0.0035 counts per photon × 1.67 × 180 Å × 0.659) = 2480 photons (cm^2 s Å)$^{-1}$, where 0.659 is the ratio of the field of view of the photometer (0.0201 sr) to the size of a square (0.0305 sr).

It is useful to compare Figure 2 with what would

TABLE 1

CALIBRATION STARS

STAR	HR	DEAD-TIME CORRECTION	SCAN CORRECTION	UNCERTAINTY IN SCAN CORRECTION (%)	FLUX Photons (cm^2 s Å)$^{-1}$ Observed	FLUX "True"	Observed / "True"
γ Cas........	264	1.28	0.68	±15	1875	727[a]	2.58
α Leo........	3982	1.02	0.49	±20	370	412[b]	0.90
α Vir........	5056	1.39	0.56	±17	4500	3200[c]	1.41
η UMa.......	5191	1.04	0.93	±10	1300	750[c]	1.73

REFERENCES.—[a]Smith 1967; [b]Evans 1972, increased by a factor of 1.55; [c]Henry *et al.* 1975.

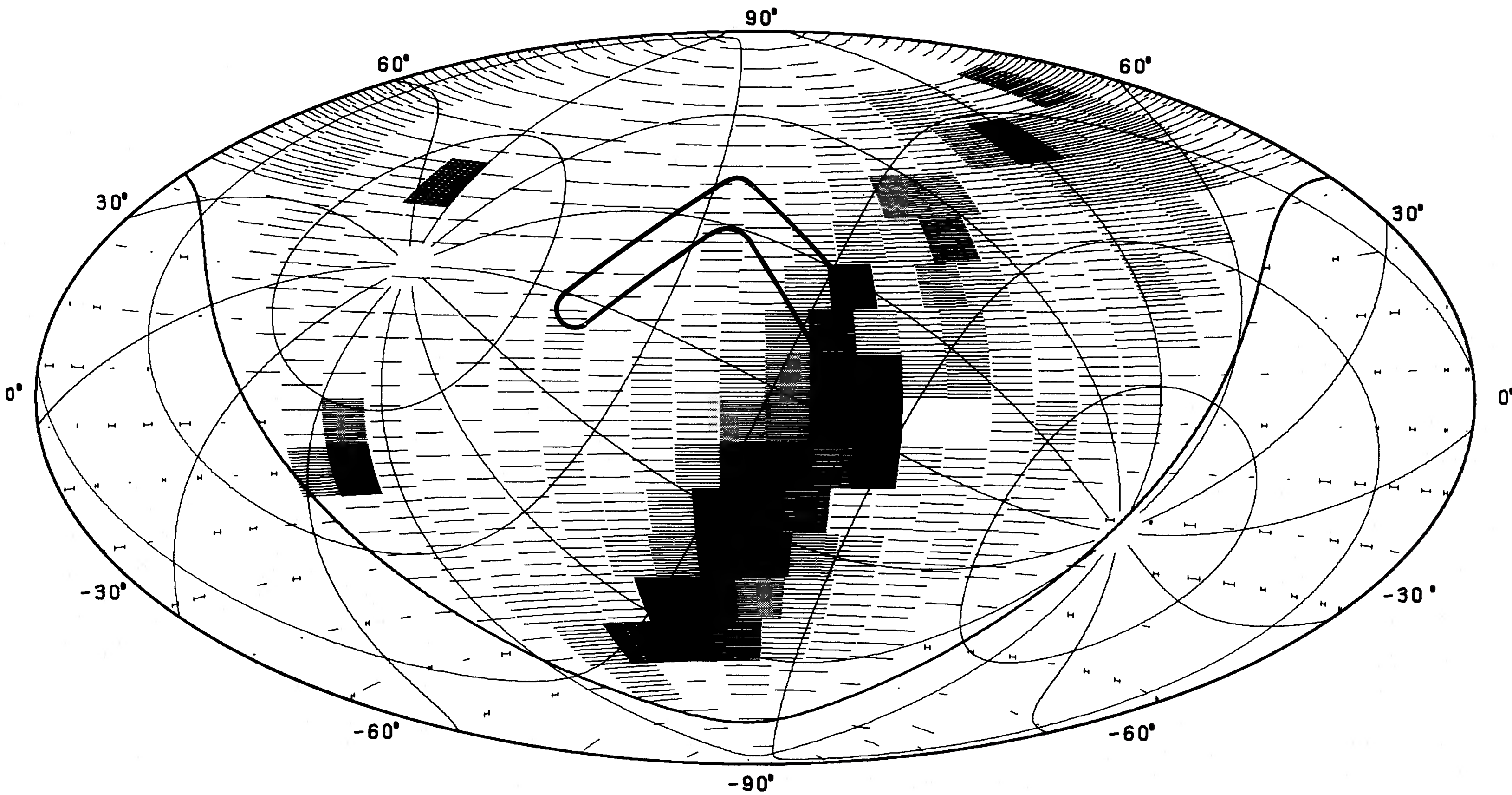

FIG. 2.—Observed brightness of the sky at 1530 Å in an Aitoff equal-area right ascension and declination map, with 19^h at each edge and north at the top. Five lines of constant galactic latitude are shown, at 30° intervals. The heavy line marks a zenith distance of 115°, the effective rocket horizon. Ultraviolet brightness is indicated by darkness of shading in the map. The average count rate looking below the horizon has been subtracted from the whole body of data, resulting in some negative values (*lines with ticks at ends*) in the nadir direction. Comparison with Fig. 3, which is a predicted map based on integration of a star catalog, shows generally excellent agreement. (The irregular enclosed area is the region observed by Hayakawa *et al.* 1969.)

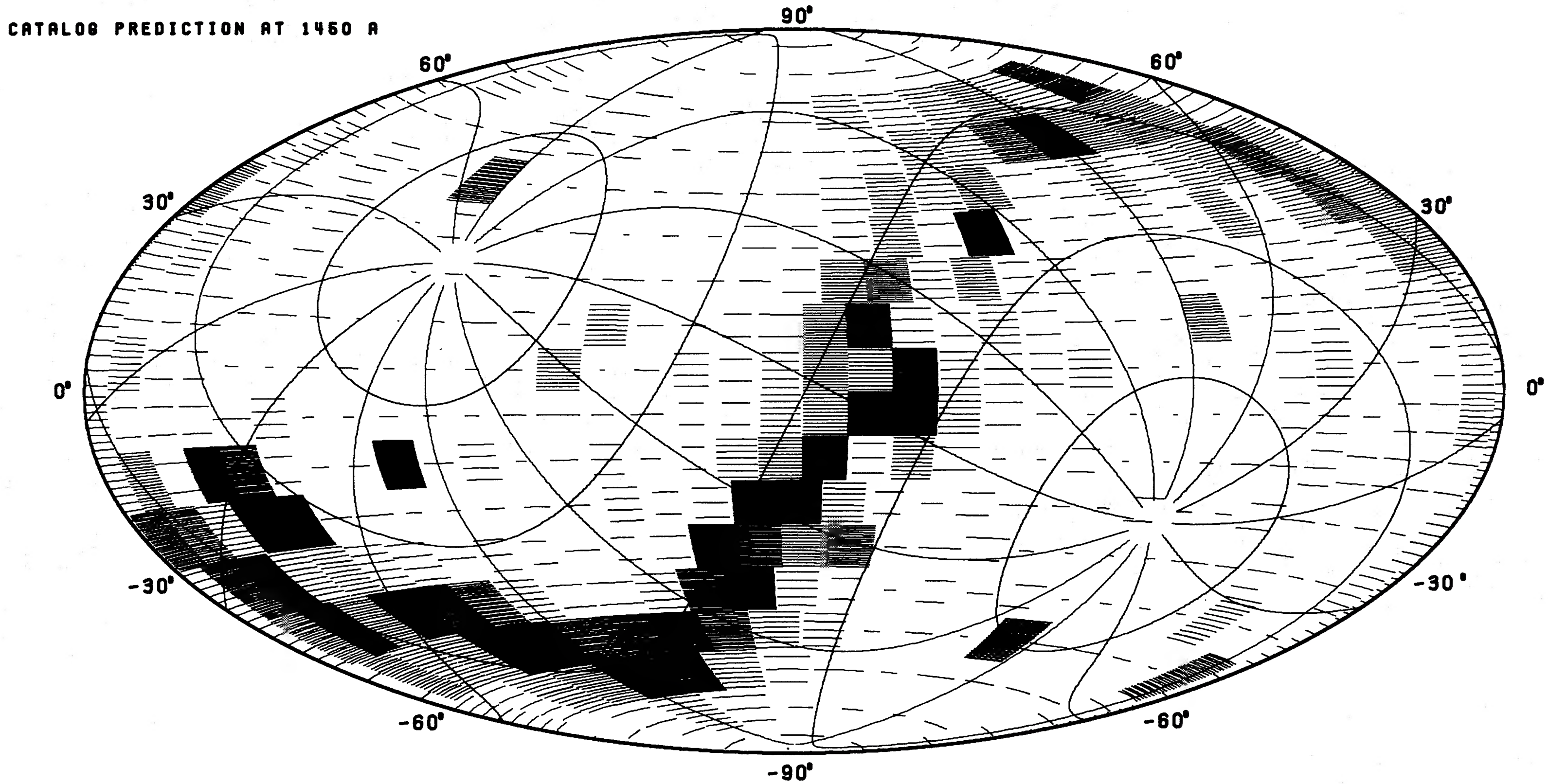

FIG. 3.—For comparison with the observed far-ultraviolet sky brightness of Fig. 2, a predicted brightness is shown here that is based on the stellar calibration of Henry *et al.* (1975) applied to the SAO star catalog.

be expected from direct stellar radiation alone. In Figure 3, we plot the result of adding up the flux expected from stars in the Smithsonian Astrophysical Observatory (SAO) Star Catalog (Whipple 1963), using the calibration $\log F = 2.54 - 5.49\,(B - V)_0$, where F is the flux at 1482 Å in photons (cm^2 s Å)$^{-1}$ for a $V = 0.0$ magnitude star. This calibration is from the *Apollo 17* ultraviolet spectrometer data of Henry *et al.* (1975). The use of star catalogs for this purpose is discussed in detail by Henry (1977). The darkest square in Figure 3 represents the same flux as the darkest square in Figure 2. The general resemblance of the portion of Figure 2 above the horizon-dip line to the corresponding portion of Figure 3 is clear. The resemblance in detail is quite good also, and the exceptions are generally explicable. For example, the stars that produce the saturated square in Figure 3 at declination +30°, galactic latitude −15°, are heavily reddened stars in Perseus; interstellar reddening is not taken fully into account in the use of the SAO catalog (see Henry 1977). This square is indeed observed in Figure 2 to be not very bright.

IV. INTERPRETATION

a) *Comparison with Others*

Hayakawa, Yamashita, and Yoshioka (1969), in a pioneering paper, presented data on the far-ultraviolet brightness of the sky as a function of galactic latitude, for northern galactic latitudes 20° to 45°. Their data are plotted in Figure 5. There is a difference of a factor of 2 to 3 between their results and the present observations, but this could be due entirely to the fact that different sections of the sky were observed. The portion of the sky which they observed is shown in

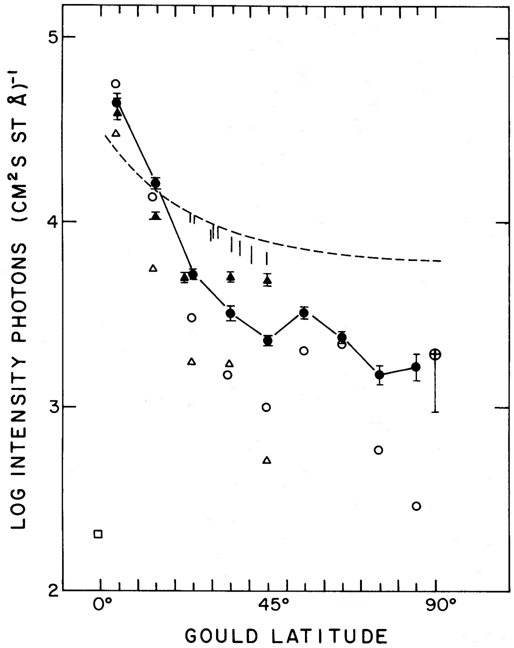

FIG. 5.—The flux of far-ultraviolet radiation as observed (*solid symbols*), and as predicted (*open symbols*) from an integration of the SAO star catalog, are plotted as a function of Gould-coordinate latitude. Circles represent the northern hemisphere, and triangles are southern hemisphere. An excess appears at high galactic latitudes that is probably due to airglow. The high-latitude observation of Henry (1973) is also shown (*circle with cross*). The prediction of Gondhalekar and Wilson (1975) is shown as a dashed line, and the data of Hayakawa *et al.* (1969) as short vertical error bars. The measurement of Kurt and Sunyaev (1968) is shown as a square; it surely represents an error.

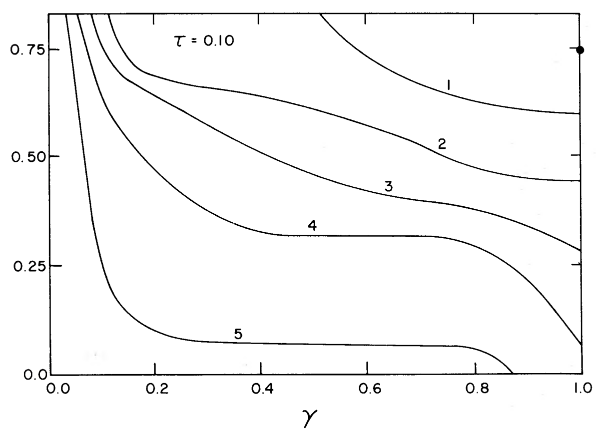

FIG. 4.—Contours of diminishing probability of fit, marked with the negative of the logarithm of the relative probability of fit, are shown for comparisons between the galactic-latitude distributions of the present data and the models of van de Hulst and de Jong 1969. The best fit (*solid circle*) is for an albedo of 1.0 and a forward-scattering phase parameter $g = 0.75$. The galactic-latitude dependence factor is $\tau = 0.10$. Although the fit is good, the assumptions underlying the models are not realistic for the far-ultraviolet, and no conclusive result is obtained.

Figure 2. Yoshioka (1972) has reanalyzed their λλ1350–1480 data, using the models of van de Hulst and de Jong (1969), in an attempt to obtain information regarding the albedo and scattering phase function of the interstellar grains, the parameter τ which characterizes the shape of the galactic-latitude distribution of the total ultraviolet starlight, and the strength of any external far-ultraviolet radiation field incident on the Galaxy. Figure 4 shows the result of applying the identical procedure to the present data. The problem of Gould's Belt is avoided by considering only data north of +25° galactic latitude. Only one van de Hulst and de Jong model fits the data well, and it is indicated by a solid circle in the figure. It corresponds to an albedo γ close to 1, a low value of $\tau \approx 0.10$, and a strongly forward-scattering phase function $g = 0.75$. Chi-square tests on the fit of other van de Hulst and de Jong models give poorer fits, some of which are indicated by contours in Figure 4 marked with the negative of the logarithm of the factor that gives the relative probability of the data fitting the model.

These conclusions regarding the albedo and scattering function agree well with those of Hayakawa, Yamashita, and Yoshioka (1969), and the value of τ is similar to that of Yoshioka (1972). But unfortunately the numbers are not meaningful, due to the nature of the van de Hulst and de Jong models, which were computed for the case of the stars and the grains having identical distributions above the galactic plane. Most of the far-ultraviolet radiation is contributed by early B stars, which are much more closely confined to the galactic plane than is the interstellar dust. Thus Henry (1977) has demonstrated this inconsistency explicitly by comparing the van de Hulst and de Jong models for direct starlight alone with integration of the SAO star catalog; this point has also been made by Lillie and Witt (1976).

b) *Gould-Latitude Dependence*

In the absence of applicable models, we can still compare (Figure 5) the Gould-latitude dependence of the complete set of data of Figure 2 (above the horizon) with the direct starlight computed from the SAO star catalog integration. The Gould system (pole of Stothers and Frogel 1974) is used because the major portion of the far-ultraviolet radiation is expected to come from stars brighter than 6.5 mag, that is, Gould Belt stars (Henry 1977). In Figure 5, the filled symbols represent observations, while open symbols represent the star catalog integrations. Circles represent northern Gould latitudes, and triangles represent southern Gould latitudes. The error bars on the data points are combined errors due to counting statistics and dead-time correction uncertainty. The absolute intensity calibration error discussed above is about $\pm 20\%$. At the lowest latitudes, agreement between the observation and the catalog integration is excellent. At moderate southern Gould latitudes, substantially more radiation is observed than the star catalogs predict; the excess is not as great at the corresponding northern latitudes. Part of this could conceivably be due to ultraviolet radiation scattered from interstellar grains. The southern hemisphere is probably richer in interstellar matter than the northern hemisphere, if only because the Earth is situated somewhat to the north of the galactic plane. However, part of the excess may be due to airglow near the horizon (see Fig. 2).

In Figure 5, the 1500 Å galactic-latitude dependence predicted by Gondhalekar and Wilson (1975) is shown as a dashed line. It agrees well with the data of Hayakawa, Yamashita, and Yoshioka (1969), but falls about a factor of 2 above the present data at moderate galactic latitudes.

At the highest northern latitudes, there is clear evidence for an excess of radiation beyond that which is attributable to starlight. The flux observed agrees with that measured previously by Henry (1972) at the north galactic pole, shown in Figure 5. This radiation could have any of the origins discussed in the opening paragraph of this paper, but it is probably due to airglow from the residual atmosphere above the rocket. Henry *et al.* (1974), observing from *Apollo 17*, halfway between the Earth and the Moon, found a level at high galactic latitudes substantially below that reported here.

c) *Ultraviolet Radiation Other than Direct Starlight*

The comparison in Figure 5, of observations with predictions based on direct starlight only, begins to place limits on any additional proposed sources of far-ultraviolet radiation in the Galaxy. The suggestion of Hills (1971, 1972) and of Terzian (1974) that a substantial neglected source of ultraviolet radiation exists in the form of "UV stars" is certainly not ruled out, for they are discussing an old population strongly concentrated toward the center of the Galaxy, and the present observations are of the galactic anticenter hemisphere. Henry *et al.* (1976) have set limits on the space density of such objects by means of negative observations in the *extreme* ultraviolet ($\sim$300 Å). Their method is limited by the very strong interstellar absorption that occurs in the extreme ultraviolet, while the present method (observation in the far-ultraviolet) is limited by the fact that most of the models for the central stars of planetary nebulae of Hummer and Mihalas (1970) predict a sharp drop in intensity longward of 912 Å. Nevertheless, Carnochan *et al.* (1975) have found a surprising number of unexpectedly bright ultraviolet objects using detectors on the TD-1 satellite, and the present method should certainly be pursued with higher-quality data.

The amount of radiation expected from scattering of far-ultraviolet starlight from interstellar grains at moderate latitudes is only about 30% of the total signal for "optimistic" (high albedo, isotropic scattering) cases of the models of van de Hulst and de Jong (1969). Thus, the quality of the present data does not permit effective discrimination among the various models. However, models more appropriate to the present case (scale height of scatters is greater than scale height of sources) would predict much greater relative contributions by scattering at moderate latitudes; when such models become available, the present data may serve to discriminate among them.

d) *The Far-Ultraviolet Radiation Field*

The far-ultraviolet radiation field in interstellar space is of great interest because of its use in determining the rate of destruction of interstellar molecules. For example, Jura (1974) used a computed radiation field (at shorter wavelengths) in a discussion of the formation and destruction of interstellar H_2. The interstellar radiation field has been computed by Habing (1968), by Witt and Johnson (1973), by Gondhalekar and Wilson (1975), and by Henry (1977), who simply integrated a calibrated star catalog. It is usual to use computed radiation fields, simply because of the difficulty of doing the present type of experiment, which requires in principle an integration over the entire sky.

The flux from Figure 2 has been summed over the entire sky above the rocket horizon. The same region was summed for Figure 3, the star catalog integration, and the result was found to be 1/2.23 of the sum of the *entire* catalog. This factor was applied to the observed

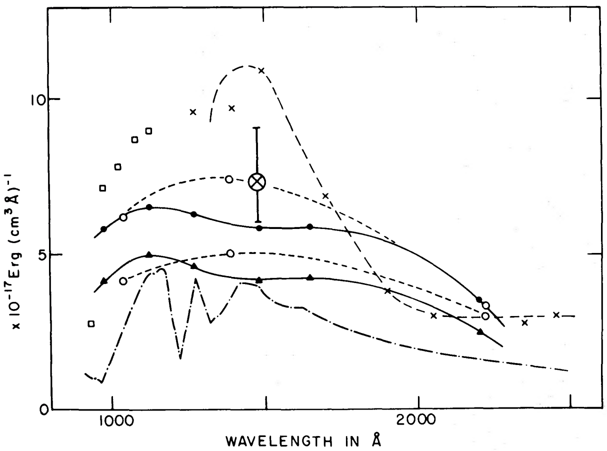

FIG. 6.—The far-ultraviolet interstellar radiation field at 1530 Å (*circle with error bar*) is compared with the calculated interstellar radiation field of Witt and Johnson 1973 (*crosses*); Habing 1968 (*open circles*), with the upper curve representing the case where the interstellar grains have an albedo of 0.9, the lower 0.0; Jura 1974 (*squares*); Gondhalekar and Wilson 1975 (*dot-dash line*); and Henry 1977 (*filled circles*) the integration of the SAO star catalog, (*filled triangles*) the integration of the Bright Star Catalog (Hoffleit 1964).

summed flux to obtain an "observed" interstellar density at 1530 Å of 7.4 (+1.7, −1.3) × 10^{-17} ergs cm^{-3} Å^{-1}. In Figure 6, this observed value is compared with the various computed interstellar radiation fields. Agreement with Habing (1968) and with Henry (1977) is good; although the error bars are large, Habing's model having a grain albedo of 0.90 appears favored over his model with albedo 0.0. It must be kept in mind, however, that Habing's models were computed with very early and uncertain ultraviolet flux distributions, and in the absence of a detailed observed ultraviolet extinction curve. Nonetheless, Lillie and Witt (1976) also find a high (~0.6) value for the albedo near 1500 Å. Agreement with the model of Witt and Johnson (1973) is quite good, but it must be emphasized that the present experiment is a difficult one, and the error bar in Figure 6 may be too small. The prediction of Gondhalekar and Wilson (1975) falls almost a factor of 2 below the observed value.

V. CONCLUSIONS

Much more extensive data regarding the general distribution of far-ultraviolet radiation over the sky than were previously available are presented and analyzed. The data are reasonably well accounted for by the expected direct radiation from hot stars, with a few exceptions which may be due to airglow above rocket altitude. The data verge on being useful in setting limits on the optical properties of the interstellar grains, and when appropriate models are available may be so used.

The far-ultraviolet interstellar radiation field has been measured for the first time, and is found to be in reasonable agreement with most computed models. The interstellar energy density at 1530 Å is 7.4 (+1.7, −1.3) × 10^{-17} ergs cm^{-3} Å^{-1}.

For the future, higher-precision data are needed. It would be particularly useful to have data on the spectral character in the far-ultraviolet of the radiation at various galactic latitudes, for radiation of hot stars in the galactic plane scattered by dust at moderate latitudes should have a spectrum quite different from the direct starlight (mostly due to early A stars) expected to be seen at moderate galactic latitudes.

The rocket aspect was computed by E. T. Byram and John F. Meekins. This work was partially supported by NASA grants to the E. O. Hulbert Center for Space Research, and NASA grant NGR 21-001-001 to the Johns Hopkins University.

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