VOYAGER OBSERVATIONS OF THE INTERSTELLAR MEDIUM IN THE 500- TO 1700-Å SPECTRAL REGION

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Abstract. Observations of the interstellar medium have been obtained in the 500- to 1700-Å spectral region by the ultraviolet spectrometers installed on the Voyager spacecraft. A preliminary analysis of the least complex of the spectra obtained to date indicates measurable emission in spectral lines at 584, 1026, and 1216 Å. These emissions are identified with resonance scattering of solar radiation in transitions of helium and atomic hydrogen. The observations in the direction α 324°, δ -23° contain no measurable direct emission or scattering of stellar radiation by the interstellar medium to an upper limit of 5×10^{-4} R/Å at 975 Å. Spectra obtained in other directions indicate measurable sources of apparent continua having relatively broad spatial extent.

Introduction

The two Voyager spacecraft launched on August 20, 1977 (V2), and September 5, 1977 (V1), contain ultraviolet spectrometers designed for observation of planetary atmospheres, but they are also useful for observations of stellar objects and of the interplanetary and interstellar medium in the spectral region 500 to 1700 Å. We describe in this report a preliminary analysis of some observations of the interstellar medium with this experimental system. Detailed descriptions of the Voyager mission and spacecraft configuration have been given by Stone [1977] and Kohlhase and Penzo [1977].

The spectrum of primary interest in this report was chosen on the basis that it appeared to have the least complicated spectral content of the interstellar medium spectra obtained to date. In addition, the spectrum represents approximately 140 hours of integration while observing in a particular area of the celestial sphere and for this reason contains sufficient accumulated signal counts to remove statistical accuracy as a limiting factor in the dynamic range of the instrument.

We report the first measurement of the resonance scattering of the solar hydrogen Lyman β line by the interstellar medium. Other characteristics of the interstellar medium spectrum are also discussed in the following text.

Instrument

A full description of the spectrometer has been published in *Space Science Reviews* [Broadfoot *et al.*, 1977]. The instrument is an objective grating spectrometer covering the approximate wavelength range 500 to 1700 Å in 128 contiguous intervals. The instrument contains a single normal incidence grating (Hyperfine, Inc.) blazed at 800 Å in the first order, and a single array detector [Broadfoot and Sandel, 1977]. It has two observational ports. One of the ports has a small collection area of 0.78 cm^2 and is designed to observe the solar spectrum. The other port has a larger collection area of 21.2 cm^2 and is designed for airglow observations. The fields of view of the system are restricted by a mechanical collimator such that the airglow port has a field of 0.1° full width at half-maximum (FWHM) in the dispersive direction. The airglow field in the cross-dispersion direction is 0.87°, determined by the angular width of the detector anodes. The spectral resolution corresponding to the dispersive field is 33 Å FWHM, with a theoretical resolution limit of 9.26 Å.

The detector is a photon counting system which utilizes a 128-element linear self-scanned anode array. The array collects the output of a dual or chevron microchannel plate (MCP) electron multiplier. Photoelectrons are produced for detection by focusing the dispersed radiation on the bare MCP in the 500- to 1250-Å region. In the 1250- to 1700 Å region, a MgF_2 filter coated with CuI acts as a photoelectron source for the MCP input. Further details are given by Broadfoot *et al.* [1977] and Broadfoot and Sandel [1977]. Instrument sensitivity will be discussed in the following text.

Observations and Analysis

Figure 1 shows the spectrum of the interstellar medium obtained from a summation of 696 twelve-minute spectra obtained about day 263, 1977, with the V2 instrument. The spacecraft was stable during this period, and the science instrument scan platform remained in a fixed azimuth and elevation position. The mean observational direction during the 6-day integration period was α 324°, δ -23°, with a drift of about 6° in α. Limit cycle motion due to the spacecraft stability control system is about ±0.5°. The spectrum represents raw data corrected only for variation in threshold response of the individual detector array anodes.

The identifiable line features in the spectrum are HeI (584 Å, 3.8 ±0.4 R), H Lyman β (1026 Å, 2.0 ±0.16 R) and H Lyman α (1216 Å, 722 ±0.5 R). The error bars represent the statistical accuracy of the signal. The absolute intensity has an error of about ±15%. As demonstrated by Figure 1, the lines appear superposed on a measurable background signal. The 1216-Å feature is roughly 15 Å wider than the other line features in the spectrum, but according to our analysis this is due to reflection at the edge of the filter photocathode in the vicinity of channel 80.

It is clearly of interest to determine the origin and content of the remaining statistically

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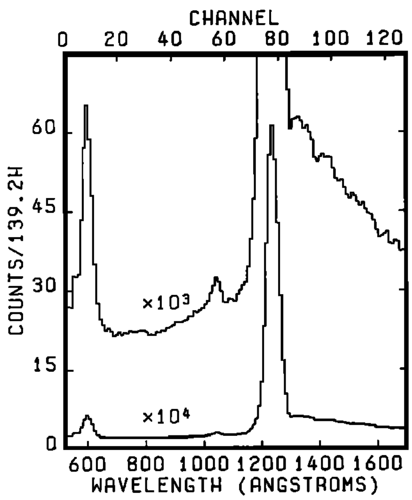

Fig. 1. Voyager 2 spectrum of the interstellar medium in the 500- to 1700-Å region. The data, corrected only for detector threshold response, are the summation of 696 twelve-minute spectra. The time intervals are not consecutive due to communication gaps and the occurrence of solar flare events. The mean observational direction was α 324°, δ -23°. The 1216 Å feature is anomalously wide due to reflection near the edge of a filter in the detector structure.

significant signal. The analysis of these data suggests that the measurable part of this signal is composed of a low-level signal generated by high-energy particles combined with internal instrumental scattering due to the observed emission lines. These conclusions are based on the following analysis.

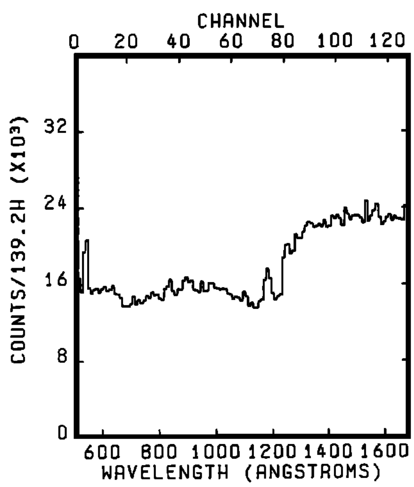

Fig. 2. Voyager 2 data obtained with the airglow port directed at the spacecraft calibration plate. A residual 1216-Å line feature has been subtracted from the spectrum. According to the discussion in the text, this signal does not represent photons entering the instrument aperture. The signal has been corrected for variation in detector threshold response. However, the correction appears not to be appropriate to this particular signal source (see text). The integration time was 10.2 hours.

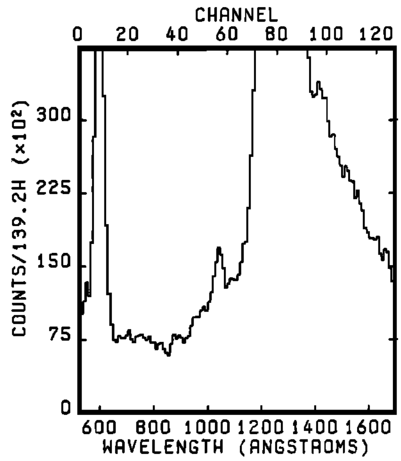

Fig. 3. The spectrum of Figure 1 after subtraction of the signal of Figure 2. According to the text these data represent the response of the instrument to photons entering the spectrometer apertures. The absolute intensities of the identifiable features in the spectrum are given in Table 1.

Dark Slide Signal

The spacecraft is mounted with a calibration plate accessible to the optical instruments on the scan platform. This allows measurement by the UV spectrometer of a signal that approaches a dark slide measurement. Figure 2 shows data taken during observation of the calibration plate, after subtraction of a weak residual Lyman α line due to an apparent finite plate albedo. We note several factors of significance in relation to the Figure 2 spectrum.

1. The count rate in the region 500 to 1250 Å is almost constant at a rate of about 3.3×10^{-2} counts s^{-1} channel^{-1} (c s^{-1} ch^{-1}). There is a step in response at 1250 Å and an approximately

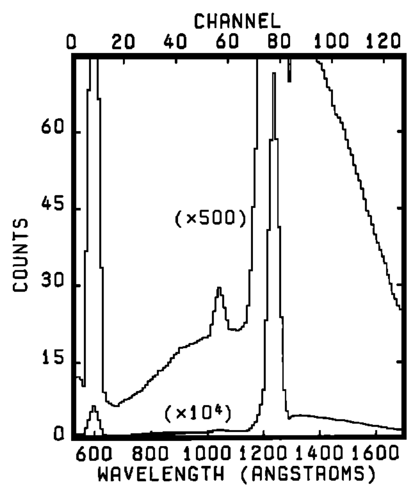

Fig. 4. Voyager 2 instrumental response, predicted from laboratory calibration data, due to the incidence of radiation at the wavelength of channels 8, 56, and 77. The intensities are appropriate to the lines in the observed spectrum of Figure 3. The underlying signal in the spectrum is due to internal instrumental scattering of the incident radiation.

TABLE 1. Measured and Predicted Line Intensities in the α 324°, δ -23° Region

Source	Measured, R	Predicted*
H Lyman α, 1216 Å	722	722
H Lyman β, 1026 Å	2.0	1.2
H Lyman γ, 972.6 Å	<0.2	0.086
H Lyman δ, 949.7 Å	<0.2	0.020
He 584.3 Å	3.8	--†

*Relative values based on the calculated scattering probabilities given in Table 2.

†The line of sight abundance ratio [H]/[He] is a model-dependent quantity. For this reason, we do not provide a predicted relative rate for the He 584.3-Å line.

constant count rate of about 4.8×10^{-2} c s^{-1} ch^{-1} in the 1250- to 1685-Å region. This response has no apparent relationship to the spectral response of the instrument, and we have concluded for this and other reasons cited below that the data are not due to photons in the 500- to 1700-Å region entering the instrument aperture. The step in response at 1250 Å corresponds to the edge of the MgF_2 filter photocathode which overlaps the 1250- to 1700-Å region of the detector.

2. The response of the instrument shown in Figure 2 is very similar to spectra obtained during a significant solar flare event that occurred about days 262 and 267, 1977. The background spectrum during that time was more intense than that of Figure 2 by as much as 2 orders of magnitude.

3. Apart from the shape of the spectral response shown in Figure 2 and correlation with the solar flare events, another aspect of the data indicates that the signal does not originate from photons impacting the detector channel plates. The threshold correction to each channel based on the calibration of the instrumental response to photons does not appear to be an accurate correction for the data in Figure 2 as well as the high background data obtained on days 262 and 267, 1977. This is most noticeable in channels 3 and 4 due to the particularly large correction required in these two cases.

The correction to the interstellar medium spectrum for this 'dark slide' signal was therefore made by subtracting the signal rates of Figure 2 from those of Figure 1 before the threshold correction was carried out. The result corrected for the threshold is shown in Figure 3. The spectrum in Figure 3 according to this analysis represents the response of the instrument to photons entering the spectrometer aperture.

Instrumental Response Function

An instrumental response matrix for the instrument has been constructed on the basis of observations of calibration line sources in the laboratory. The estimated response function includes interpolated measurements of the internal scattering characteristics of the instrument.

Figure 4 shows the predicted instrumental response obtained from the scattering matrix to spectral lines at the wavelengths corresponding to channels 8, 56, and 77 with relative intensities appropriate to the lines in the observed spectrum. The spectra in Figures 3 and 4 are normalized to the same integrated intensity. It is clear that apart from an apparent underestimation of the amount of scattering by the edge of the filter photocathode, the synthetic spectrum (Figure 4) composed of the three lines accounts for virtually all of the observed features in Figure 3.

Discussion

The α 324°, δ -23° region of the celestial sphere contains measurable emission from three spectral lines at 584, 1026, and 1216 Å. Other emissions in the 500- to 1700-Å region appear not to be detectable in 140 hours of integration time with the Voyager UV instrument. The observed signal apart from the line features can be accounted for, within measurement accuracy, by measured dark noise and internal instrumental scattering. Table 1 shows the estimated intensities of the lines, and the relative intensities of the hydrogen lines predicted from calculated resonance

TABLE 2. Calculated Resonance Scattering Probabilities for September 1977 at 1 AU

Source	λ, Å	g, s^{-1}	I, ph cm^{-2} s^{-1}	α_s, cm^{-1}
H Lyman α	1215.67	2.7 - 3	3.2 + 11[a]	41[d]
H Lyman β	1025.72	4.6 - 6	4.0 + 9[b]	57[e]
H Lyman γ	972.59	3.2 - 7	8.0 + 8[c]	60[e]
H Lyman δ	949.74	7.5 - 8	4.0 + 8[c]	62[e]
He 584 Å	584.26	1.4 - 5	2.0 + 9[b]	41[f]

I is solar flux at 1 AU. Solar line width α_s is given in energy units (cm^{-1}).

[a]Hinteregger [1977; and private communication, 1978], Rottman (private communication, 1978), Delaboudinière *et al.* [1976], and Vidal-Madjar [1975].

[b]Hinteregger [1977], see footnote *a* above.

[c]Delaboudinière *et al.* [1976].

[d]Effective width providing the correct differential intensity at line center, based on line shape measurements of White and Lemaire [1976], and Bruner and Rense [1969].

[e]Assumed widths based on footnote *d* above.

[f]Doschek *et al.* [1974].

scattering probabilities of solar radiation. The predicted Lyman α/Lyman β intensity ratio is higher than the measured value by a factor of 1.6. A discrepancy of this magnitude is not serious, since the scattering probabilities themselves are not expected to have a high degree of accuracy [cf. Sandel *et al.*, 1979]. Table 2 shows the solar line flux and calculated scattering probabilities (g) judged to be appropriate to the time of observation. The flux magnitudes in the lines were taken as 1.5 times the solar minimum values (H. E. Hinteregger, private communication, 1978). The relative flux mangitudes of the lines do not represent simultaneous measures by the same observer. We also have some uncertainty in relative line shapes.

The spectrum contains no measurable scattering of stellar radiation by the interstellar medium. Calculations by Henry [1977] predict an emission of about 4×10^{-4} R/Å or less in 975-Å stellar radiation for the spatial region of the measurements. We estimate our measurement threshold at about 5×10^{-4} R/Å. Measurements with the Voyager instruments in the α 100°, δ -11° region along with other selected regions contain measurable apparent continua above the hydrogen 912-Å absorption threshold. The measured differential rate in the α 100°, δ -11° direction is about 6×10^{-2} R/Å at 975 Å. We believe these are the first well-defined measurements of scattered stellar radiation. Preliminary analysis of these data will be presented in an upcoming report [Sandel *et al.*, 1979].

The ability to detect other emission features in the interstellar medium will depend on further refinement of the instrumental scattering matrix and on the existence of measurable variations in spectral composition.

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