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H_2 FLUORESCENCE AND THE DIFFUSE GALACTIC LIGHT IN THE VACUUM ULTRAVIOLET

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ABSTRACT

Fluorescence by molecular H_2 within the Lyman and Werner bands, as well as to continuum levels of the $X^1\Sigma_g^+$ state, occurs at wavelengths $\lambda \leq 0.18$ μm. This emission is shown to be of intensity comparable to that scattered by dust over the same wavelength range in diffuse clouds. The implied increase in dust albedo in the vacuum ultraviolet (VUV) is likely due to this effect. Thus the small particles responsible for VUV extinction are of conventional chemical composition, i.e., absorbing oxides, silicates, or carbons.

Subject headings: interstellar: matter — interstellar: molecules

I. INTRODUCTION

Observations in the vacuum ultraviolet (VUV) of the diffuse galactic light (DGL) (Lillie and Witt 1976) and of a variety of objects exhibiting nebulosity (Carruthers and Opal 1977*a*, *b*; Witt and Lillie 1978; Witt 1977) yield data that are consistent with high values for the albedo, *a*, of interstellar dust in this wavelength range. Controversy exists, however, concerning values for the phase-function asymmetry factor $g = \langle \cos \theta \rangle$ (Witt and Lillie 1978; Henry *et al.* 1978) in the region shortward of 0.2 μm. The observations of Witt and Lillie (1978) and Andriesse, Piersma, and Witt (1977) suggest that $g(\lambda = 0.15\ \mu m) \approx 0.25$, i.e., that dust scatters almost isotropically in this wavelength range. On the other hand, Henry *et al.* (1978) find from other observations that interstellar grains are *inefficient* large-angle scatterers at these wavelengths.

The requirement that g be small for wavelengths $\lambda < 0.2$ μm implies that the particles responsible for this scattering are small (particle radius $r \ll 0.2$ μm). This constraint is incompatible with a large value of a, since $a \rightarrow 0$ in the Rayleigh limit. Furthermore, most likely interstellar grain materials become increasingly absorbing at short wavelengths, so that $a = Q_{\text{scattering}}/Q_{\text{extinction}}$ should actually *decrease* in this wavelength range.

These inconsistencies would be reduced if the DGL and the light scattered in the VUV from dust clouds contained an additional diffuse component. We show here that such a component can arise from the processes involved in the formation and destruction of molecular hydrogen. We show (§ II) that fluorescence within the Lyman and Werner bands of H_2, as well as to continuum levels of the $X^1\Sigma_g^+$ state of H_2, converts short-wavelength radiation ($\lambda <$ 0.11 μm) into emission in the range $\lambda \lesssim 0.18$ μm. The relative importance of H_2 fluorescence and the scattering of light by dust in this region is compared in § III. In § IV quantitative estimates of this effect in a diffuse cloud and in the Merope Nebula are obtained. We conclude that a significant fraction of the light observed from both types of object for $\lambda \lesssim 0.18$ μm is attributable to fluorescence accompanying the formation and destruction of H_2.

II. EMISSION FROM INTERSTELLAR H_2

Absorption at wavelengths $\lambda \lesssim 0.11$ μm by interstellar H_2 in the Lyman and Werner bands is followed quickly by emission, leaving the molecule in some vibrational level v'' of the ground electronic state, X:

$$X^1\Sigma_g^+, v'' = 0 \xrightarrow[\lambda < 0.11\ \mu m]{\text{absorption}} \left\{\begin{matrix} B^1\Sigma_u^+ \\ C^1\Pi_u \end{matrix}\right. v' \xrightarrow{\text{emission}} X^1\Sigma_g^+, v'' \geq 0 \,.$$

If $v'' > 14$, then the vibrational level belongs to the vibrational continuum of X, and the molecule dissociates. A prediction that this is the main destruction route for interstellar H_2 in diffuse clouds (Stecher and Williams 1967) was confirmed by the detailed calculations of Dalgarno and Stephens (1970). The continuous emission associated with the process was subsequently observed in the laboratory and matched the theoretical spectrum (Dalgarno, Herzberg, and Stephens 1970).

The calculations of Dalgarno and Stephens (1970) showed that in the optically thin case, 23% of all excitations of the Lyman bands by a uniform radiation field ($\lambda > 0.09$ μm) lead to dissociation. The remaining excitations lead to emission in discrete Lyman bands, with $v'' \geq 0$. The calculated continuous emission (Dalgarno, Herzberg, and Stephens 1970) is shown in Figure 1. Superposed on this are some of the stronger Lyman bands, selected from the transition probabilities of Allison and Dalgarno (1969). It is clear from Figure 1 that most of the emission in this region occurs in the range 0.15 μm $< \lambda <$ 0.165 μm.

We conclude that nearly every destruction of an H_2 molecule provides a continuum photon in this wavelength range. Fluorescence to bound states yields discrete line emission between 0.09 and 0.18 μm.

III. FLUORESCENCE VERSUS SCATTERING BY DUST

To obtain an estimate of the relative importance of H_2 fluorescence and scattering by dust in the VUV, we consider a unit volume of interstellar space containing gas and dust. The space density of hydrogen nucleii is $n = n(\mathrm{H}) + 2n(\mathrm{H}_2)$, where $n(\mathrm{H})$ = density of H atoms, $n(\mathrm{H}_2)$ = density of H_2. In equilibrium, one has

$$\frac{dn}{dt}(\mathrm{H}_2) = 0 = kn \times n(\mathrm{H}) - \beta n(\mathrm{H}_2) ,$$

where β = destruction rate, k = rate constant for H_2 formation = 3×10^{-17} cm^3 s^{-1}. Then the equilibrium between the formation and destruction of H_2 will result in the volume emissivity J' (fluorescence) = $\beta n(\mathrm{H}_2)\langle h\nu\rangle = kn \times n(\mathrm{H})\langle h\nu\rangle$, where $\langle h\nu\rangle$ = average photon energy emitted. If we assume that emission occurs over a wavelength range $\Delta\lambda$(Å), then J(fluorescence) = $kn \times n(\mathrm{H})\langle h\nu\rangle/\Delta\lambda$ ergs cm^{-3} s^{-1} Å^{-1}. Since line emission is also important in this region (§ II), this expression will be multiplied by 2.

If the space density of dust = n_g, then J(scattered) = $FQ_{\mathrm{scat}}\pi r^2 n_g$, where F = mean incident intensity (ergs cm^{-2} s^{-1} Å^{-1}), Q_{scat} = efficiency factor for scattering, and r = grain radius. A measure of the relative importance of fluorescence is given by the ratio

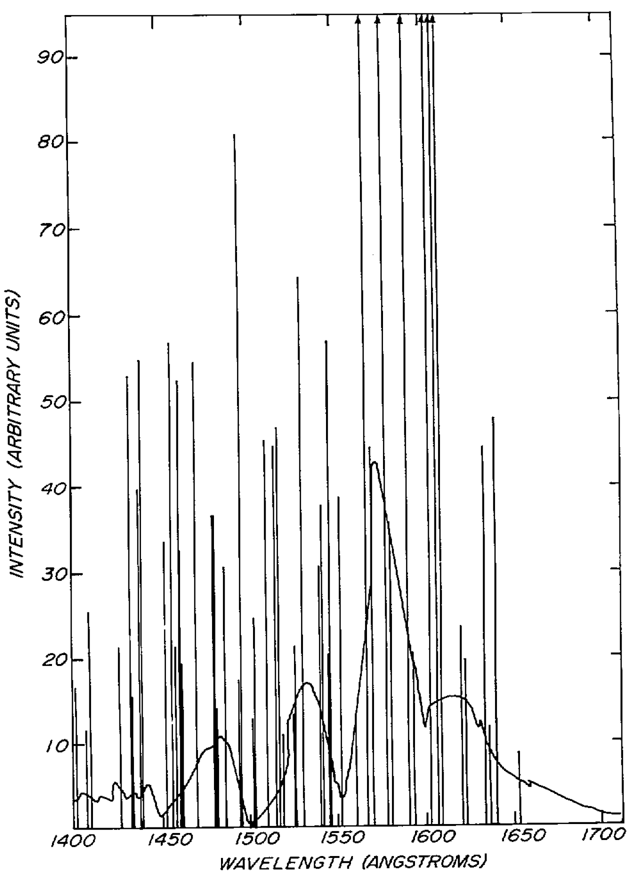

FIG. 1.—Relative emission in Lyman bands (*straight lines*) and continuum in the wavelength range 0.14 $\leq \lambda \leq$ 0.17 μm. Intensities are normalized to include the effect of absorption line strength and assume uniform, incident UV flux over the relevant spectral region to 0.0912 μm. The integrated probability for emission of a continuum photon is 0.23, while that for emission within the discrete lines between 0.14 and 0.17 μm is 0.31. The integrated probability for emission between 0.0912 and 0.14 μm is 0.46. Rotational structure has been suppressed in plotting lines of the Lyman bands.

$$\chi = \frac{J(\text{fluorescence})}{J(\text{scattered})},$$

$$= \frac{2kn \times n(\text{H}) \langle h\nu \rangle}{FQ_{\text{scat}}\pi r^2 n_g \Delta\lambda}.$$

If $n_g = fn$, where f = fractional abundance of grains, then

$$\chi = \frac{2k \times n(\text{H}) \langle h\nu \rangle}{FQ_{\text{scat}}\pi r^2 f \Delta\lambda}. \quad (1)$$

For emission in the continuum band near 1500 Å, one has $\langle h\nu \rangle = 1.3 \times 10^{-11}$ ergs, and $\Delta\lambda = 150$ Å. Then with $k = 3 \times 10^{-17}$ cm^3 s^{-1} and assuming that the scattering grains consist of 100 Å particles of mixed Si, Mg, and Fe oxides or silicates, one has $r = 100$ Å and $f = 4 \times 10^{-10}$. As a result,

$$\chi = \frac{4.2 \times 10^{-9} n(\text{H})}{FQ_{\text{scat}}}. \quad (2)$$

Since this expression is obtained from a consideration of average emissivities, it does not account for possible different angular dependences between the fluorescent and scattered terms. As such, isotropic scattering by grains is implied ($\langle \cos\theta \rangle = 0$). If the phase factor for grains is asymmetric, then χ would have to be modified to take this effect into account. As this implies a specific angular relationship between the source of radiation, the scattering volume, and the detector, generalizations are not possible. However, even in an extreme situation in which the dust is strongly forward scattering, while observation is made in the forward direction, the effect on χ is unlikely to exceed a factor 2–3.

The result (eq. [2]) is relatively insensitive to dust size and composition. It can be rewritten $\chi = 4.2 \times 10^{-3} rn(\text{H})/FQ_{\text{scat}}$ for particles of mixed Si, Fe, and Mg oxide composition. For small carbon particles, one obtains $\chi = 2 \times 10^{-3} rn(\text{H})/FQ_{\text{scat}}x$, where x = fraction of available carbon in dust. Since Q_{scat} increases with increasing r, this tends in part to minimize the effect of grain size on χ, although in the Rayleigh limit $Q_{\text{scat}} \propto r^4$.

While we have assumed equilibrium between formation and destruction of H_2 molecules to arrive at an estimate of the fluorescent intensity from H_2, significant emission may also be obtained in nonequilibrium situations. The destruction of H_2 in interstellar shocks and in boundary layers adjacent to H II regions will also lead to enhanced emission in the VUV.

IV. DISCUSSION

To compare the result of equation (2) with observations, we will consider two representative cloud types. The first is a normal diffuse cloud exposed to the ambient background-radiation field in the VUV. It will be assumed that in such a cloud $n(\text{H}) = 35$ cm^{-3} (Myers 1978). The radiative flux F at 1500 Å is taken to be 1.2×10^{-6} ergs cm^{-2} s^{-1} Å^{-1} attenuated by 0.7 mag of extinction (Habing 1968). Then

$$\chi_{\text{diffuse cloud}} = \frac{0.24}{Q_{\text{scat}}}.$$

For our second type of cloud, we adopt the model of the diffuse cloud in the Merope (NGC 1435) Nebula proposed by Jura (1979). This has $n(\text{H}) = 300$ cm^{-3}. Using the flux measured at 1550 Å for 23 Tau by Andriesse, Piersma, and Witt (1977), together with an average star-cloud distance of 1.15×10^{18} cm, $F = 8 \times 10^{-5}$ ergs cm^{-2} s^{-1} Å^{-1}. Then

$$\chi_{\text{nebula}} = \frac{1.6 \times 10^{-2}}{Q_{\text{scat}}}.$$

For typical oxide or silicate materials in the 1500–1600 Å region, Q_{scat} for 100 Å particles lies in the range 0.01–0.1. Thus it is evident that fluorescence from H_2 may contribute significantly to diffuse UV fluxes in both diffuse clouds and nebulae. The relative importance of fluorescence as given by the ratio, χ, is seen to depend directly on the ratio $n(\text{H})/F$. Since $n(\text{H})$ will also depend on F, one expects that a variety of different objects will show this effect. It should be noted that radiative-transfer effects may also cause the value of χ to vary along a particular line of sight. Thus anything other than a general comparison between theory and observation would require a detailed calculation of such effects along the complete line of sight.

The existence of an additional radiative term in diffuse clouds at wavelengths $\lambda < 1800$ Å whose magnitude is comparable to that produced by starlight scattered by dust suggests that the derived increase in the albedo of dust in this region may not be real. This would have the effect of reducing the somewhat contradictory constraints placed on dust by available observations (Witt 1977). For example, observational data now require that the grains responsible for scattering in the VUV are both small (to scatter isotropically) and yet have high albedo. Furthermore the derived albedo actually *increases* with decreasing wavelength for $\lambda < 2000$ Å, implying that the particles are nonabsorbing over this range. Unless one is willing to invoke exotic materials (e.g., solid Ne, LiF) such a constraint is physically unreasonable.

It now appears likely that the small particles responsible for an increase in extinction in the VUV are of conventional chemical composition (oxides, silicates, carbons) and that this increase in extinction arises primarily as a result of absorption. Thus, for these particles, $Q_{\rm extinction} \approx Q_{\rm absorption}$ and $a = Q_{\rm scat}/Q_{\rm ext}$ is small. Such particles would have a small asymmetry factor for scattering.

The present analysis leads to the prediction that the DGL should exhibit spectral features due to emission by H_2. These features, which would be present as excess emission against the scattered light background, would be most noticeable in the range 1400–1700 Å. In this regard, it is interesting that the calculations of Joshi and Tarafdar (1977) on ionization equilibria in diffuse clouds conclude that the interstellar radiation field should exhibit a maximum at 1600 Å.

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