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DUST AND GAS NEAR THE PLEIADES

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ABSTRACT

Observations of molecular hydrogen show that the gas in the line of sight toward 20 Tau (Maia), a prominent star in the Pleiades, is only about 0.1 pc distant from that star. The dust which produces the observed reflection nebulosity is likely to be associated with this gas and therefore lies in front of the star. Since the foreground dust is optically thin, it should be possible to use observations of the polarization and colors to constrain models of interstellar dust, while further *Copernicus* observations may make it possible to determine the location of the other reflection nebulae in the Pleiades. Far-infrared observations of this region may enable us to measure the albedo of these grains. The nearness of the interstellar dust and gas to 20 Tau may be important in explaining why the CH^+ column density is unusually high toward this star.

Subject headings: interstellar: matter — nebulae: individual

I. INTRODUCTION

The reflection nebulae near the Pleiades are well known. One of the main hopes in studying these nebulae is to characterize the scattering properties (albedo and phase function) of interstellar dust and to constrain models for the composition and size distribution of interstellar grains (e.g., Vanysek 1967; Greenberg and Hanner 1970; Hanner 1971; Shah 1974). A major obstacle in the way of understanding reflection nebulae is that the geometric relationship between the star and the dust is usually not known. Here we use observations of H_2 to argue that the dust toward 20 Tau (B6 III) is in front of that star and that the nebula (NGC 1432) is optically thin.

Most observations of the reflection nebulae in the Pleiades (O'Dell 1965; Elvius and Hall 1966; Andriesse, Piersma, and Witt 1977) have actually been performed on NGC 1435, the nebula near 23 Tau (Merope). Although our work here does not directly pertain to this star, our procedure can be used with future observations of H_2 to determine whether the dust that produces the reflection nebulosity is in front of or behind Merope.

Another reason for studying the interstellar medium near the Pleiades is that the column density of CH^+ toward these stars has long been known to be unusually high (Adams 1949; Hobbs 1972, 1973). A better understanding of the physical conditions in these regions may provide valuable clues to the origin of interstellar CH^+, which may be the key to understanding the origin of interstellar carbon-bearing molecules (Dalgarno and Black 1976; Watson 1976).

II. GAS NEAR 20 TAURI

In the optical pumping model of Black and Dalgarno (1973, 1976), the column density of rotationally excited H_2 in levels with $J \geq 4$ is proportional to the absorption rate of ultraviolet radiation by ground-state H_2. Because 20 Tau has the highest known column density of H_2 in the $J = 5$ level, $N(5)$ (Spitzer, Cochran, and Hirshfeld 1974) yet only a moderate column density of H_2 in $J = 1$, $N(1)$ (Savage *et al.* 1977), it is clear that this cloud must be near a source of ultraviolet radiation, a source we presume to be 20 Tau itself. Compare the line of sight toward 20 Tau with the model calculated by Jura (1975) for the line of sight toward δ Per. Toward 20 Tau, $N(1)$ is observed to be about a factor of 2 greater than is predicted in the model of Jura (1975). Therefore, because the H_2 is optically thick with the result that the absorption rate varies as $N(1)^{1/2}$, we would predict that $N(5)$ would be $2^{1/2}$ greater toward 20 Tau than in the model for δ Per. Instead, it is observed that $N(5)$ is greater by a factor of 23. Therefore, the radiation field incident on the surface of the cloud toward 20 Tau is about a factor of 15 greater than the radiation field incident on the surface of the cloud toward δ Per. Equivalently, the formulation of Wright and Morton (1977) may be used to show that the H_2 pumping rate toward 20 Tau is comparable to this derived value. Because the lifetime of the $J = 5$ level is only about 3 years (Dalgarno and Wright 1972), these steady-state calculations are almost certainly applicable.

From Jura (1974) the H_2 destruction rate, $I(H_2)$, in the solar neighborhood (in the absence of shielding) which is appropriate for the cloud toward δ Per is $5.4 \times 10^{-11}\ s^{-1}$. Therefore, at the surface of the cloud toward 20 Tau, the H_2 destruction rate is about $8 \times 10^{-10}\ s^{-1}$. Using the model atmosphere of Kurucz, Peytremann, and Avrett (1974) for $T = 12{,}000$ K and $\log g = 3.0$ (for a B6 III star), we may compute the flux at a distance d from a star whose radius is r_*. From their equation (10), from the H_2 f-values listed by Morton and Dinerstein (1976 [note the error for the 0–14 Lyman transition]), and from

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the H_2 dissociation probabilities of Dalgarno and Stephens (1970), we find that

$$I(H_2) = 570 r_*^2/d^2\ \mathrm{s}^{-1}\,. \qquad (1)$$

With $I(H_2) = 8 \times 10^{-10}\ \mathrm{s}^{-1}$, we therefore find that $d = 8.4 \times 10^5 r_*$. With $r_* = 5 \times 10^{11}$ cm, then $d \approx 0.1$ pc.

Since Spitzer, Cochran, and Hirshfeld (1974) list $E(B - V) = 0.02$ toward 20 Tau, we may ignore interstellar extinction; so according to Kurucz, Peytremann, and Avrett (1974), the flux we receive from 20 Tau at V should be $8.8 \times 10^{-4} r_*^2/D^2$, where D is the distance between 20 Tau and the Sun. Since m_V(20 Tau) = 3.87 and since $V = 0.0$ corresponds to 3.65×10^{-20} ergs cm^{-2} s^{-1} Hz^{-1} (Oke and Schild 1970), then $D = 9.2 \times 10^8 r_*$. Consequently, we find that $d/D = 9.1 \times 10^{-4}$.

We may also crudely estimate the thickness of the cloud from the column density of hydrogen nuclei. Toward 20 Tau, $2N(H_2) = 1.1 \times 10^{20}$ cm^{-2} (Savage *et al.* 1977). Because 20 Tau is a late B star, the Lα absorption line cannot be used to estimate N(H) (Savage and Panek 1974). Hobbs (1971) has found from 21 cm measurements that, toward several Pleiades stars, $N(\mathrm{H}) = 3 \times 10^{20}$ cm^{-2}. If this is also true for 20 Tau (cf. Heeschen and Drake 1956), we could expect N_H, the column density of hydrogen nuclei, to equal 4×10^{20} cm^{-2}. This column density of gas would produce $E(B - V) = 0.08$ (cf. Spitzer and Jenkins 1975), which is much larger than is observed. Until 21 cm measurements with high angular resolution are performed, we cannot be certain of the amount of gas in the line of sight. Using the argument of Jura (1975) and the very uncertain assumption that the H_2 formation rate equals the H_2 destruction rate, we would estimate a density of 1000 cm^{-3} and a cloud thickness near 0.1 pc. These arguments are inconclusive; we can only note the possibility that the cloud thickness is comparable to the distance between the star and the cloud. We cannot rule out the possibility that the star is immersed within the cloud.

III. DUST NEAR 20 TAURI

Assume that we observe the reflection nebulosity at an angle ϕ from 20 Tau. Let L_ν be the luminosity per hertz of the star, so that the observed flux f_ν for 20 Tau is

$$f_\nu = L_\nu/4\pi D^2\,. \qquad (2)$$

Although the exact result depends upon the precise geometry of the star and the nebula, it is a straightforward matter to show (e.g., Rush 1975) that, if S_ν is the flux per steradian from the nebulosity and if the light is scattered through an angle θ such that $\theta \approx \tan^{-1}(\phi D/d)$,

$$S_\nu/f_\nu \approx 1/4\pi \tau_\nu a_\nu g_\nu(\theta)(\phi^2 + d^2/D^2)^{-1}\,. \qquad (3)$$

In equation (3), τ_ν, a_ν, and $g_\nu(\theta)$ are the optical depth through the dust, the albedo, and the phase function, respectively.

Because there probably is some atomic hydrogen toward 20 Tau, we may crudely estimate that $E(B - V) \approx 0.03$ instead of the observed value of 0.02. Such a small difference is well within the errors of spectral classification and photometry. With the usual ratio of total to selective extinction of $R = 3.3$ (Aannestad and Purcell 1973), we may take $\tau_v \approx 0.1$. With $a_v \approx 0.5$ and $g_v \approx 1.0$ then for observations near 20 Tau with $\phi < d/D$, we might expect that $\log S_\nu/f_\nu = 3.7$. Johnson (1960) has measured at V that $\log S_\nu/f_\nu = 3.6$ near 20 Tau (Maia) in agreement with our model.

IV. IMPLICATIONS

From equation (3), we predict that the surface brightness of the nebulosity should decrease only slowly as long as $\phi < d/D$. From our inferred value of d/D, this critical angle is about 3′; this prediction is roughly consistent with the estimates from the Palomar Sky Survey.

In our model, the dust is optically thin; it should therefore be possible to use the colors and polarization of the light to constrain models of the dust. Unfortunately, although we expect that the dust is in front of the star, we do not know the thickness of the dust sheet or how it might be oriented in space. Here we emphasize that observations in the near-infrared may be very useful for determining the geometry of the nebula; that is, our sample calculations show that, for materials usually considered for interstellar grains, at a wavelength between 1 and 2 μm the polarization approaches that predicted for Rayleigh scattering. While such observations would be difficult observationally, the percentage polarizations could be quite high. For example, at 3′ from 20 Tau, in a simple geometry, the light is scattered through 45°. Therefore, the polarization could be as high as 0.33, even greater further from the star. With a detailed understanding of the geometry, colors and polarization in the visual can be used to constrain models of the grains.

We have computed a dilution coefficient, $W = d^2/D^2$, which is $W = 10^{-12}$ for the cloud near the star. This value of W is about a factor of 100 higher than that for the average interstellar radiation field for which a diluted radiation field at $T = 12{,}000$ K is a crude representation. Since the grain temperature scales as about $W^{1/5}$, we might expect silicate grains to have a temperature about a factor of 2.5 higher than that in most interstellar clouds. Therefore, the temperature of silicate grains might approach 40 K (e.g., Spitzer 1968), while grains composed of other materials might be as hot as 100 K (e.g., Leung 1975). Since the optical depth in the visual is about 0.1, the optical depth at 100 μm is probably near 10^{-4} and the reflection nebulosity near the Pleiades could be a far-infrared source; that is, at 100 μm, with $\tau(100\ \mu\mathrm{m}) = 10^{-4}$, a 40 K blackbody produces an intensity of 10^{-18} W m^{-2} Hz^{-1} sr^{-1}. Measurement of the amount of far-infrared light compared with the amount of reflected light may enable us to measure the average albedo of the grains in the visual and ultraviolet. Measurement of the color temperature of the far-infrared radiation will be of use in constraining models for the grain composition. Also, determination of the distance between the gas and the stars may prove useful in models to describe the observed filaments (e.g., Arny 1977).

The gas toward 20 Tau is probably near that star, and the large amount of CH^+ observed toward this star could possibly result from the evaporation of methane from the heated grains (Bates and Spitzer 1951). Alternatively, the high column density of CH^+ might result from the reaction of C^+ and vibrationally excited H_2 (Stecher and Williams 1972, 1974). The high density and high ultraviolet radiation field, which prevents the hydrogen from being completely molecular, are ideal for the production of CH^+ by this mechanism. Further studies of CH^+ (cf. Jura and Smith 1977) and a search for vibrationally excited H_2 toward 20 Tau may be important.

Our results are not directly applicable to the well-studied nebulosity near Merope. (Note, however, that η Tau may be a significant source of scattered light far from Merope.) Since we suggest that the distance between the dust and 20 Tau is comparable to the distance between 20 Tau and 23 Tau, it is quite possible that the cloud observed to lie in front of 20 Tau might lie behind 23 Tau. On the other hand, the large amount of CH^+ toward 23 Tau might indicate there is interstellar matter in front of 23 Tau that is very close to this star. Observations of rotationally excited H_2 toward 23 Tau should settle this question.

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