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ON THE INFRARED POLARIZATION

OF THE ORION NEBULA*

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ABSTRACT

The implications of the 10 micron polarization of the Orion Nebula are re-examined, and it is concluded that the polarization is produced by preferential extinction in one of the well studied regions of the Kleinman-Low Nebula and/or its surroundings. In particular, the need for abnormally low temperatures ($\sim 6°K$) in the polarizing medium is obviated. The most likely candidate for the polarizing medium is the extended region surrounding the Kleinman-Low Nebula.

The degree of polarization produced by emission in the far infrared (~ 100 microns) is estimated to be as large as 8 percent, although other factors could reduce the observable value.

I. INTRODUCTION

Recent observations have uncovered significant linear polarization in the 3-13 micron radiation from the Orion Nebula (Dyck, et al., 1973; Dyck and Beichman, 1974). The observations of Dyck and Beichman (DB) were made throughout the Kleinman-Low Nebula (KL), including observations centered on the Becklin-Neugebauer object (BN). KL is known to consist of a number of compact objects, and a diffuse component (Rieke, et al., 1973). The observed polarization direction is roughly uniform over the angular extent of the observations ($\sim\frac{1}{2}'$). The degree of linear polarization is correlated with the 10 micron silicate absorption feature, reaching as much as 15 percent in the band. Over the observed wavelength range the polarization direction does not appear to change significantly. These features led DB to propose that this polarization is caused by preferential extinction by aligned dust particles. At these wavelengths the cooler absorbing medium does not radiate appreciably.

Application of the theory of grain alignment by paramagnetic relaxation (Davis and Greenstein, 1951; Jones and Spitzer, 1967; Cugnon, 1971; and Purcell and Spitzer, 1971) yielded grain temperatures $\sim 6°K$ (DB). In §II this is re-examined under the probable assumption that the 10 micron optical depth to BN is larger than that used by DB (Aitken and Jones, 1973; and Gillett, et al., 1975).

The 10 micron polarization has led to some observational interest regarding the polarization of the Orion Nebula at much longer wavelengths ($\sim$100 microns). Upper limits have been reported (Dennison, et al., 1977) based upon observations carried out with the NASA Lear Jet 30-cm telescope.

More detailed investigations involving larger apertures are in progress (Harwit, 1976). In §III the far infrared polarization is estimated, based upon the conclusions obtained in §II.

II. THE POLARIZING MEDIUM

DB employ a picket fence model to represent the absorbing medium with f = fraction of totally aligned grains, G = geometrical cross section of a grain, N = number density of grains, and L = path length in the medium. The optical depth in the two fundamental perpendicular directions x and y is

$$\tau_{x,y} = \frac{1}{2}[(1+f)Q_{\parallel,\perp} + (1-f)Q_{\perp,\parallel}]GNL ,$$

where $Q_{\parallel,\perp}$ are the grain extinction efficiencies parallel and perpendicular to the symmetry axis. Some simplification results if we define $\tau \equiv \frac{1}{2}(\tau_x+\tau_y)$ and $\Delta\tau \equiv \tau_x-\tau_y$. Then

$$\tau = \frac{1}{2}(Q_{\parallel}+Q_{\perp})GNL \text{ and } \Delta\tau = f(Q_{\parallel}-Q_{\perp})GNL . \qquad \text{(1a,b)}$$

The polarization produced by absorption is

$$P_a = \frac{e^{-\tau_x}-e^{-\tau_y}}{e^{-\tau_x}+e^{-\tau_y}} = -\tanh\left(\frac{\Delta\tau}{2}\right) . \qquad (2)$$

By convention P_a is negative indicating polarization by absorption. DB were able to fit their data with a model involving prolate spheroids with an axis ratio of $\sim$1/5, and f $\simeq$ 1/4. This involved the assumption that the optical depth to BN in the silicate absorption feature is $\tau_{10\mu} \simeq 1.4$. However, Aitken and Jones (1973) and Gillett et al. (1975) favor interpretations of the absorption spectra which give $\tau_{10\mu} \simeq 3.3$. The degree of polarization at 10 microns fixes the value of $\Delta\tau_{10\mu}$ (Equation 2). From

Equations (1a,b) we see that assuming $\tau_{10\mu} \approx 3.3$ implies $f \approx 1/10$, provided that we do not alter the shape of the grains.

DB argue in favor of paramagnetic relaxation (Davis and Greenstein, 1951) as the grain alignment mechanism. For this mechanism to be effective the timescale for magnetic damping of the grains' angular momentum, τ_B, must be shorter than the timescale for randomizing of the angular momentum by collisions with the gas, τ_{gas}, i.e., $\tau_{gas}/\tau_B \equiv \delta \geq 1$ (DB; Jones and Spitzer, 1967; Cugnon, 1971; and Purcell and Spitzer, 1971). DB show that the parameter δ can be related to f through the polarization reduction factor, R, (Greenberg, 1968) which is twice the fractional alignment, f. Greenberg (1968) gives $R(\xi)$, where

$$\xi^2 = \frac{1+\delta(T_{dust}/T_{gas})}{1+\delta} \quad ,$$

and T_{dust} is the dust temperature, and T_{gas} is the gas temperature. Alignment can occur only if the gas and dust temperatures are somewhat different. If $T_{dust} < T_{gas}$, then $0<\xi<1$; and since alignment requires $\delta \geq 1$, then $T_{dust} < \xi^2 T_{gas}$. For $f \simeq 1/4$ DB show that $\xi^2 \simeq 0.084$. For the 70°K average gas temperatures that are thought to exist in KL, this implies that $T_{dust} \lesssim 6$°K. As they point out this is at least several degrees cooler than the lowest temperatures that can be expected in the densest clouds (Greenberg, 1971). Since the dust in and around KL is known to be substantially hotter than this from its far infrared emission (Forrest et al., 1976; Houck et al., 1974; Ward et al., 1976; and Werner et al., 1976), DB argue that the polarizing medium lies in front of this region. However, it is likely that at this distance from the center of KL the gas is even cooler than 70°K, thus restricting further the value of T_{dust}. Also, a major fraction of the optical depth to BN must be in this polarizing medium, rather than KL and the surrounding warm dust. However, Forrest et al. (1976) found that the optical depth to the center of KL is unity at ~28 microns. When scaled to 10 microns this gives roughly the 10 micron optical depth to BN proposed by Aitken and Jones (1973) and Gillett et al. (1975) (Forrest, 1976), using Lunar silicate 12065 as a model (Perry et al., 1972). This is consistent with BN being located near the center of KL, and tends to confirm that $\tau_{10\mu} \simeq 3.3$, with virtually all of this optical depth attributable to KL, and its surroundings.

We now examine the consequences of this. As was shown, we now have $f \simeq 1/10$, then $R \simeq 2/10$, and from Greenberg (1968) $0.4 \lesssim \xi^2 \lesssim 0.5$. This then allows a much more reasonable dust temperature. For example, if $T_{gas} \simeq 70°K$, then $T_{dust} \lesssim 35°K$. The magnetic field required to produce alignment, B, varies as $T_{dust}^{1/2}\ T_{gas}^{1/4}\ \delta^{1/2}$. For $T_{dust} = 5°K$ and $\delta = 73$, DB find that $B \simeq 7$ milligauss for a reasonable choice of grain parameters. Although the larger upper limit on T_{dust} proposed here leads to a ~2.5 increase in the field strength for the same value of δ, B need not be larger since δ is by no means fixed. In fact, the larger limit on T_{dust} may even make plausible somewhat weaker magnetic fields since smaller values of δ can be obtained without depressing T_{dust} to abnormally low temperatures.

It is also possible that reverse alignment could occur if $T_{dust} > T_{gas}$ Jones and Spitzer (1967) use an alignment parameter, F, (different from f), for which

$$F = -\frac{3}{2}\, q(\xi^2-1)q(\gamma-1) \ ,$$

where γ is a shape dependent factor and q(x) is given by these authors. Observations of the degree of polarization and specification of the extinction efficiencies of the grains, and the optical depth fixes the magnitude of F

(Capps and Knacke, 1976). Thus, the magnitude but not the sign of $q(\xi^2-1)$ is fixed. From Jones and Spitzer (1967) $q(-\frac{1}{2})=.096$, which assumes normal alignment. From their tabulation we have $q(1.2)= -.096$, corresponding to reverse alignment. This gives $\xi^2=2.2$ or $3.4\ T_{gas} \gtrsim T_{dust} \gtrsim 2.2\ T_{gas}$, for $\delta \geq 1$. For reverse alignment the field would have to be at least $\sim$2.1 times greater than that for normal alignment for a fixed value of δ.

To possibly choose between normal and reverse alignment we consider several other factors. The possibly slightly stronger magnetic field required for reverse alignment does not necessarily vitiate this possibility. The gas temperature of 70°K is an average value for a 1' region centered on KL. Within the central 1/2' of this region $n_{H_2} > 10^6\ cm^{-3}$, and the gas and dust should be coupled so that $T_{dust} \simeq T_{gas}$ (Zuckerman and Palmer, 1975; Goldreich and Kwan, 1974 a, b). Indeed, far infrared spectral observations give $70°K \lesssim T_{dust} \lesssim 100°K$ (Forrest et al., 1976; Ward et al., 1976; Werner et al., 1976; Houck et al., 1974). Extending outwards from the center of KL, the dust temperature is expected to decline slowly, with $T_{dust} \propto r^{-0.4}$, and this appears to be confirmed (Werner et al., 1976; Forrest et al., 1976). The dust density gradients around KL are quite steep, perhaps varying as $r^{-1.5}$ or r^{-2} (Westerbrook et al., 1976). For constant dust to gas mass ratio, the gas density also declines rapidly with radius, and the gas should quickly decouple from the dust, such that $T_{gas} < T_{dust}$. Apparently we may have $n_{H_2} \simeq 2\times10^4\ cm^{-3}$ in this extended region (Zuckerman and Palmer, 1975). In this case the condition, $T_{dust} \gtrsim 2.2\ T_{gas}$, may be satisfied (Goldreich and Kwan, 1974a), thus allowing reverse alignment in this extended region.

To polarize effectively, this region must possess a significant fraction of the optical depth to BN. Very far infrared maps at wavelengths at which the nebula is optically thin may provide some indication. Although the data of Westerbrook et al., (1976) have an angular resolution $\sim$1', it appears that this extended region may have sufficient optical depth.

Normal alignment of the grains is a possibility that cannot be completely ruled out yet. However, the requirement that $T_{dust} \lesssim \frac{1}{2} T_{gas}$ is not consistent with the theoretical picture presented here. Normal alignment may occur well within KL where existing observations do not possess adequate resolution (<1') to rule out large values of T_{gas}, or large optical depths.

In this section we have shown that the 10 micron polarization can be accounted for in a much more plausible way, which is consistent with what is known about the Orion Nebula. The most likely candidate for the polarizing medium appears to be the extended region surrounding KL, which is reverse aligned. No recourse to unseen, abnormally cold regions is needed. The similarity of these conclusions to a discussion on somewhat different grounds by Zuckerman and Palmer (1975) is noted.

Finally it is important to mention the possibility of other alignment mechanisms being operative. Of particular interest is superparamagnetism (Jones and Spitzer, 1967) which requires considerably smaller magnetic fields to produce the alignment discussed in this section.

III. FAR INFRARED POLARIZATION

Since the polarizing medium has been tentatively identified with the regions surrounding KL, it is appropriate to estimate the degree of polarization seen in emission at longer wavelengths. The polarization by emission is

$$P_e = \frac{(1-e^{-\tau_x}) - (1-e^{-\tau_y})}{(1-e^{-\tau_x}) + (1-e^{-\tau_y})} = \frac{\sinh(\frac{\Delta\tau}{2})}{e^{\tau} - \cosh(\frac{\Delta\tau}{2})} \tag{3}$$

By definition $\frac{\Delta\tau}{2} < \tau$. P_e is positive indicating a 90° rotation with respect to the absorption polarization. $\Delta\tau$ can be related to τ through equations (1a) and (1b) giving

$$\frac{\Delta\tau}{2} = \tau\ f\ \frac{Q_{||} - Q_{\perp}}{Q_{||} + Q_{\perp}} . \tag{4}$$

For the j^{th} axis of an ellipsoidal grain it can be shown that (van de Hulst, 1957)

$$Q_j = \frac{1}{3}\frac{a}{\lambda}\left[\frac{\varepsilon''}{(L_j(\varepsilon'-1)+1)^2 + (L_j\varepsilon'')^2}\right] ,$$

where

$\varepsilon'+i\varepsilon'' = m^2$,

m = complex refractive index ,

L_j = shape factor for the j^{th} axis.

For the prolate spheroids used by DB $L_1 \doteq 0.056$ and $L_2=L_3 = 0.472$ (van de Hulst, 1957). The lunar dust studies (Perry et al., 1972) suggest that at long wavelengths ($\lambda \gtrsim 40$ microns) the optical constants may take on the simple behavior: $\varepsilon' \simeq$ constant between 4 and 7, $\varepsilon'' \simeq \frac{50\mu}{\lambda}$. Taking $f \simeq \frac{1}{10}$, we obtain $\frac{\Delta\tau}{2} \simeq .06\ \tau$ for $\varepsilon' = 4$, and $\frac{\Delta\tau}{2} \simeq .08\ \tau$ for $\varepsilon' = 7$. The optical depth in Equation (3) corresponds to a substantial fraction of the depth of the source, and the results of Forrest, et al., (1976) suggest that $\tau(40\mu) \simeq 1$. For $Q \propto \lambda^{-2}$, the resulting polarization is given in Figure 1 for $\varepsilon' = 4$ and $\varepsilon' = 7$. Several features of the curves can be readily understood. For short wavelengths the source is becoming optically thick and the polarization decreases. At long wavelengths, $\tau \to 0$, and in this limit we have

$$P_e = \frac{\Delta\tau/2}{\tau} ,$$

neglecting terms of order τ^2 or higher. For the more optimistic case ($\varepsilon'=7$)

we have P_e=.08 in the long wavelength limit. These estimates are subject to depth effects and beam size effects. If the source is optically thin at long wavelengths, then grain alignment must be maintained through the entire depth of the source, not just down to the hot 10 micron source seen by DB. The long wavelength source would appear more extended than the 1/2' studied by DB, and over a larger angular size cancellation effects may occur.

As was pointed out, the polarization by emission is orthogonal to the 10 micron absorption polarization. However, the latter was observed only over the central 1/2' of the region. For far infrared observations involving larger beam areas and small optical depths, the emission polarization arises in a more extended region in which the grain alignment may vary. Therefore, the observed emission polarization may not bear such a simple relationship (as orthogonality) to the absorption polarization.

As discussed in §II the core of KL may not be aligned, and thus the radiation emitted from this region is largely unpolarized. When seen through the surrounding cloud of aligned grains, the core will appear polarized by absorption. This may tend to cancell the polarization by emission along the same line of sight, because of the core's greater volume emissivity due to its higher density, and slightly higher temperature. The degree of polarization by absorption can be estimated from Equation (2). As we have seen $\frac{\Delta\tau}{2} \simeq (0.7\pm0.1)\tau$. From Forrest et al., (1976) the optical depth to the core is $\tau \simeq (\frac{28\mu}{\lambda})^2$, assuming $Q \propto \lambda^{-2}$. This gives $P_{a,core} \simeq (\frac{7\mu}{\lambda})^2$ for $\lambda \gtrsim 30$ microns. Thus, at long wavelengths, polarization by absorption is expected to be small. Along a ray passing through the core of KL, the total observed polarization will be small, since in this direction the flux is dominated by the denser unaligned central region. This dilution, when averaged over the entire source, should not be too severe, since about 30 percent of the total far infrared flux comes from the central 1' of the source (Werner et al., 1976).

The alternative discussed in §II, normal alignment in the core of KL, could also yield far infrared polarization. In this case the polarization would be confined to the core region, and would be of similar magnitude to that predicted by Equation (3). Depending upon the beam size, the outer regions of KL may dilute the polarized signal.

A first attempt (Dennison et al., 1977) did not detect polarization at 85 microns. The beam size used was ∿6', and the cancellation and dilution effects discussed above, may have reduced the polarization averaged over the beam. Higher resolution studies may prove to be more definitive (Harwit, 1976).

IV. CONCLUSIONS

The medium producing the infrared polarization of the Orion Nebula is tentatively identified with the extended regions surrounding KL. This identification permits dust temperatures which are consistent with both theoretical expectations and observations.

The extended regions of KL may emit polarized radiation in the far infrared (∿100 microns). In the absence of cancellation and dilution effects, up to ∿8 percent polarization is estimated.

Determining the location of the polarizing medium is important, since this also applies to the derived magnetic fields. Localizing the estimated magnetic fields is necessary for making comparisons to magnetic fields derived by other means, which are applicable to distinct regions (Zuckerman and Palmer, 1975), and for understanding the physics of regions of star formation.

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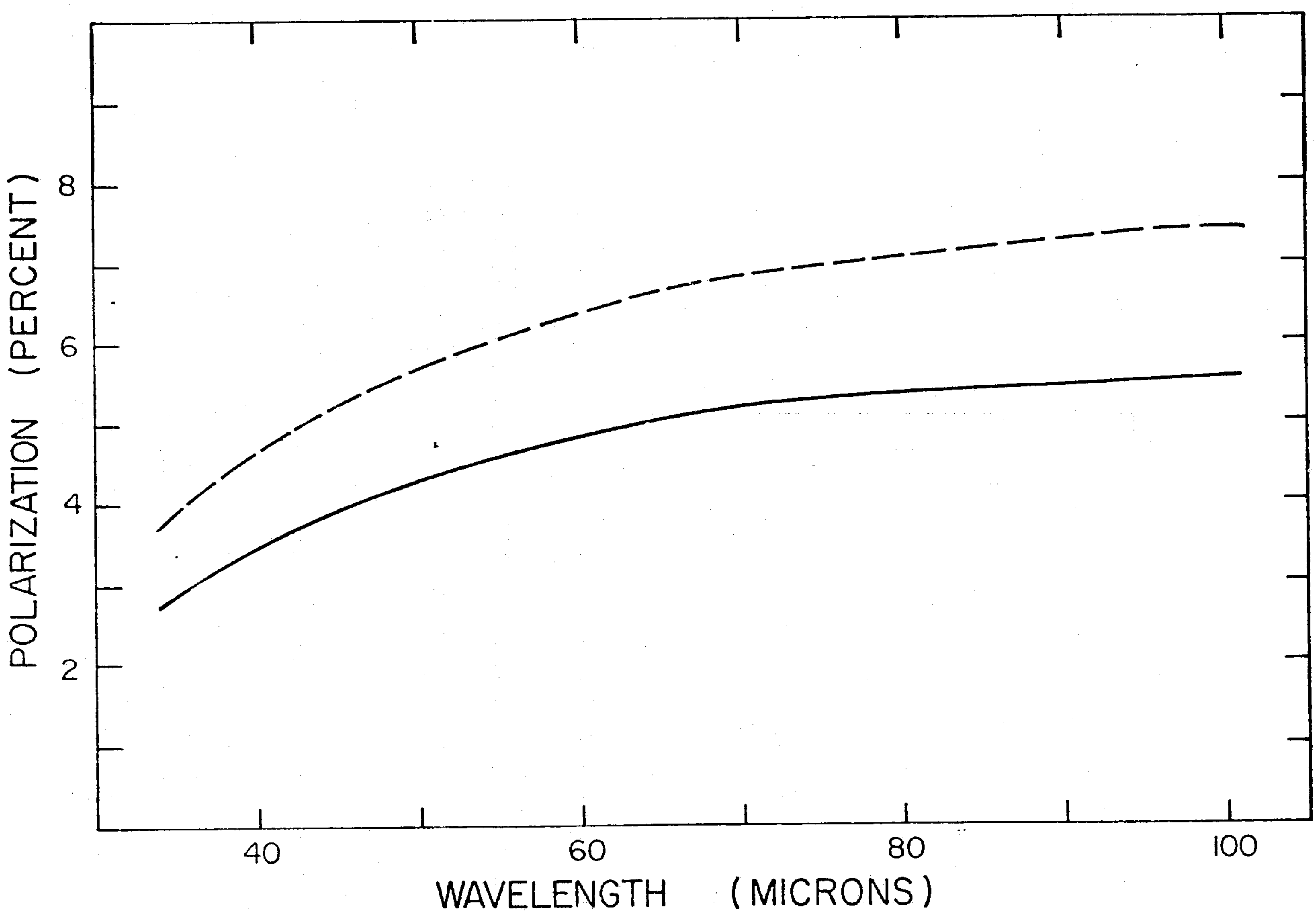
FIGURE CAPTION

Figure 1 - Theoretical polarization of aligned region in Orion. Solid curve corresponds to $\varepsilon' = 4$, and dashed curve to $\varepsilon' = 7$.


POLARIZATION (PERCENT)
8
6
4
2
40
60
80
100
WAVELENGTH (MICRONS)