Cosmic rays and grain alignment
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ABSTRACT

The recent detection of interstellar polarization in the solid CO feature near 4.67 µm shows that CO-mantled grains can be aligned in cold molecular clouds. These observations conflict with a theory of grain alignment which attributes the polarization in molecular clouds to the effects of cosmic rays: according to this theory, oblate spheroidal grains with H₂O- and CO₂-dominated ice mantles are spun up to suprathermal energies by molecular evaporation from cosmic ray impact sites but spin up does not occur for CO-mantled grains. Motivated by this conflict, we reexamine the effects of cosmic rays on the alignment of icy grains. We show that the systematic torques produced by cosmic rays are insufficient to cause suprathermal spin. In principle, the random torques due to cosmic rays can enhance the efficiency of Davis-Greenstein alignment by raising the grain rotational temperature. However, a significant enhancement would require cosmic ray fluxes 6–7 orders of magnitude larger than the flux in a typical cold cloud.

Subject headings: magnetic fields – polarization – dust extinction

1. Introduction

The recent detection of polarization in the 4.67 µm feature of solid CO (Chrysostomou et al. 1996) sets severe constraints on theories of interstellar grain alignment. Solid CO mantles are expected to survive only in cold, dense clouds, where the temperatures of the gas ($T_g$) and grain solid material ($T_d$) must be nearly equal due to collisional coupling. For example, the Davis-Greenstein alignment mechanism is a dissipative process which is driven by the difference between $T_g$ and $T_d$ (Jones & Spitzer 1967). Recent calculations (DeGraff, Roberge & Flaherty 1997) show that the largest polarizations observed toward molecular
clouds are inconsistent with Davis-Greenstein alignment unless \( T_g/T_d > 10 \) and that this conclusion holds even if the grains are superparamagnetic.\(^1\) Since a temperature disparity of this magnitude is inconsistent with observations, it seems certain that the grains in cold clouds— including CO-mantled grains— are aligned by some “nonthermal” process.

The first nonthermal model of grain alignment was developed by Purcell (1975, 1979, hereafter P79), who pointed out that the temperatures of the gas and dust do not limit the efficiency of alignment if the grain rotational energies are sufficiently large. P79 pointed out that spin up to suprathermal energies will occur whenever the torque on a grain, referred to axes fixed in the grain material, has a nonvanishing time average over times \( \sim \) the timescale for frictional coupling to the gas. P79 also identified three mechanisms that can produce such a “pinwheel torque”: (i) the formation of \( \text{H}_2 \) at catalytic sites on the grain surface, which requires atomic hydrogen; (ii) gas-grain collisions on a surface with spatial variations in the “accommodation coefficient,” which requires \( T_g \neq T_d \); and (iii) photoelectric emission from a surface with variations in the photoelectric yield, which requires UV photons. All of these processes are suppressed in dark clouds, where the atomic hydrogen concentration and UV flux are negligible and \( T_g \approx T_d \). If the starlight flux in the blue part of the spectrum\(^2\) is negligible, then we may also disregard the radiative torques arising from differential scattering (Dolginov & Mytrophanov 1975, Lazarian 1995a, Draine & Weingartner 1996a,b).

In view of these circumstances, it is natural to inquire whether some other process might cause suprathermal rotation. A natural possibility is related to the evaporation of molecules adsorbed on grain mantles: if a grain is not heated uniformly, then hotter places on the mantle will desorb molecules at higher rates compared to colder places. These “hotspots” can act in a manner that is similar to the catalytic sites of \( \text{H}_2 \) formation in Purcell’s model for suprathermal spin up. The required temperature nonuniformity might be caused by nonuniformities in the absorption of light. Consider, for example, a small soot inclusion on the grain surface. Such an inclusion would absorb light and have a temperature greater than the mean temperature of the grain. In other circumstances, a darker inclusion would radiate more efficiently and therefore become colder than the rest of the grain. Since variations in the grain absorption (emissivity) are likely to persist for much more than a gas damping time, the resulting torques should be long lived. If the grain dynamics are dominated by these

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\(^1\)However, helical grains may be aligned even if \( T_g \approx T_d \) (see Lazarian 1995). The process is discussed at length in Lazarian, Goodman & Myers (1996).

\(^2\)For “standard” grains of size \( \sim 10^{-5} \) cm, only short-wavelength radiation causes an appreciable torque (Draine & Weingartner 1996a). However, if the aligned grains in molecular clouds are substantially larger, then longer wavelengths will affect the alignment.
torques, rather than the torques due to gas damping, the alignment could be substantial. We plan to address this interesting possibility in a subsequent paper.

In this paper, we examine the feasibility of a related mechanism suggested by Sorrell (1995a,b). Sorrell pointed out that a cosmic ray impact heats a grain locally, and that molecular evaporation from the resulting hot spot will cause rotational acceleration via the rocket effect. According to Sorrell’s analysis, the rocket effect on an individual grain produces a nonzero time-average torque with a correlation time that is limited by changes in the mantle surface. In this view, the rocket effect spins up the grain to a suprathermal kinetic energy and the alignment occurs via Purcell’s mechanism (P79). However, the scenario considered by Sorrell (1995a) conflicts with the observations of Chrysostomou et al. (1996): Sorrell’s model predicts that grains with H₂O- and CO₂-dominated mantles will spin up to energies $\sim 100kT_g$ but that spin up of CO-mantled grains does not occur. In an effort to understand this conflict, we reexamine the effects of cosmic rays on the alignment of ice-mantled grains. In §2, we model the evaporation of molecules from a cosmic ray hotspot. In §3, we consider the conditions under which evaporating molecules may produce a pinwheel torque and hence suprathermal rotation. In §4, we describe the possible effects of the random torques due to evaporation and the resulting enhancement of Davis-Greenstein alignment. We summarise our results in §5.

2. Evaporation from a cosmic ray hot spot

The evaporation of molecules caused by cosmic ray heating has been discussed elsewhere (Watson & Salpeter 1972; de Jong & Kamiyo 1973; Aannestad & Kenyon 1979; Léger, Jura & Omont 1985, henceforth LJO85). Here we merely apply the results of LJO85 to model the evaporation of H₂ and CO molecules from H₂O-ice mantles. A cosmic ray nucleus with charge $Ze$ and energy $E$ loses energy in solid H₂O at a rate

$$Q(Z, E) = \begin{cases} 9.40 \times 10^{-4} \left( \frac{Z}{26} \right)^2 \left( \frac{E}{\text{GeV}} \right)^{-0.75} \text{erg cm}^{-1}, & 0.02 < \frac{E}{\text{GeV}} < 0.2 \\ 1.48 \times 10^{-3} \left( \frac{Z}{26} \right)^2 \left[ 1 + 0.1 \left( \frac{E}{\text{GeV}} \right)^{-1.5} \right] \text{erg cm}^{-1}, & 0.2 < \frac{E}{\text{GeV}} < 10 \end{cases}$$

(2-1)

For this purpose, the randomization of angular momentum during a spin-up interval should be small (Lazarian 1995b).
The energy is deposited initially (on a timescale $\sim 10^{-11} \text{ s}$) in a cylinder of radius $r_0 \sim 50 \, \text{Å}$ around the cosmic ray track and spreads laterally thereafter by thermal diffusion. Over the temperature range of interest here, the thermal diffusivity of H$_2$O ice depends only weakly on temperature (Zeller & Pohl 1971). Consequently, the heating of the mantle is well described by the heat diffusion equation with constant thermal diffusivity. The solution for the energy density, $U$, is

$$U(r, t) = \frac{Q}{4\pi \alpha \left(t + t_0\right)} \exp \left[-\frac{r^2}{4\alpha \left(t + t_0\right)}\right],$$  \hspace{1cm} (2-2)

where $r$ is distance perpendicular to the cosmic ray track, $t$ is time, $\alpha$ is the thermal diffusivity, and

$$t_0 \equiv \frac{\frac{r_0^2}{-4\alpha \ln (1 - f)}}{}.$$

(2-3)

Here we have adopted somewhat arbitrary initial conditions, such that $U(r, 0)$ is a Gaussian function of $r$ with a fraction $f$ of the total energy contained in $r < r_0$ at $t = 0$. In the following discussion, we will assume that $r_0 = 50 \, \text{Å}$ and set $f = 0.5$. The temperature, $T$, can be found from the relation

$$U(r, t) = \int_{T_0}^{T(r, t)} \rho \, C_V \, (T') \, dT',$$  \hspace{1cm} (2-4)

where $T_0$ is the temperature before the impact and $\rho \, C_V$ is the volume specific heat. In the calculations discussed below, we set $T_0 = 15 \, \text{K}$ and adopt the values of $\alpha$ and $\rho \, C_V$ recommended by LJO85 for H$_2$O ice.

We assume that molecules evaporate from a hotspot at the classical rate,

$$R_{\text{vap}}(r, t) = \nu_0 \exp \left[-\Delta H_s / kT(r, t)\right],$$  \hspace{1cm} (2-5)

where $\nu_0$ and $\Delta H_s$ are respectively the lattice vibration frequency and binding energy of a molecule adsorbed on the mantle surface. The probability that a molecule at radius $r$ has evaporated before time $t$ is therefore

$$P_{\text{vap}}(r, t) = 1 - \exp \left[-\int_0^t R_{\text{vap}}(r, t') \, dt'\right].$$  \hspace{1cm} (2-6)

The mean value of the total number of molecules evaporated by a single cosmic ray with charge $Z$ and energy $E$ is

$$N_{\text{vap}}(Z, E) = A_{\text{eff}}(Z, E) \theta_s,$$  \hspace{1cm} (2-7)

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4The energy loss rates in eq. (2-1) include the corrections derived by LJO85 to account for oblique cosmic ray impacts and partial escape from the grain of electrons ejected by the cosmic ray. We have taken the density of H$_2$O ice to be 1 g cm$^{-3}$.  

where \( \theta_s \) (cm\(^{-2}\)) is the surface coverage before the impact and

\[
A_{\text{eff}}(Z, E) \equiv \int_0^\infty dr \, 2\pi r \, P_{\text{vap}}(r, t_{\text{max}})
\]

(2-8)
is the effective area “cleaned off” by the cosmic ray. We assume that no evaporation occurs for times \( t > t_{\text{max}} \), where \( t_{\text{max}}(r) \) is the time when the mantle at radius \( r \) has cooled to temperature \( T_0 \); because virtually no evaporation occurs for \( T \approx T_0 \), the arbitrariness of this definition has virtually no effect on our numerical results. The value of \( A_{\text{eff}} \) depends on \( Z \) and \( E \) only through the energy loss rate, \( Q \). The dependence of \( A_{\text{eff}} \) on \( Q \) is illustrated in Figure 1 for the evaporation of H\(_2\) (\( \nu_0 = 7.5 \times 10^{12}, \Delta H_s/k = 555 \text{ K}; \) Sandford & Allamandola 1993) and CO (\( \nu_0 = 7.0 \times 10^{14}, \Delta H_s/k = 1030 \text{ K}; \) LJO85) molecules from H\(_2\)O ice.

The temperature of the vapor at a hot spot

\[
T_{\text{vap}}(Z, E) \equiv \frac{\int_0^\infty dr \, 2\pi r \int_0^\infty dt \left[ 1 - P_{\text{vap}}(r, t) \right] R_{\text{vap}}(r, t) T(r, t)}{\int_0^\infty dr \, 2\pi r \int_0^\infty dt \left[ 1 - P_{\text{vap}}(r, t) \right] R_{\text{vap}}(r, t)}
\]

(2-9)
is the mean (for all evaporating molecules) temperature of the surface at the instant of evaporation. The numerical evaluation of expression (2-9) for CO and H\(_2\) evaporation shows that, for both H\(_2\) and CO, \( T_{\text{vap}} \) increases from \( \approx 50 \text{ K} \) to \( > 200 \text{ K} \) as \( Q \) increases from \( 10^{-4} \text{ erg cm}^{-1} \) to \( 10^{-2} \text{ erg cm}^{-1} \).

### 3. Constraints on the pinwheel torque due to cosmic rays

The evaporation of a molecule from the mantle surface produces an impulsive change in the grain angular momentum, \( \mathbf{J} \), due to the rocket effect. The rotational dynamics of a grain subject to many such impulses are determined by the mean torque,

\[
\mathbf{A} \equiv \left\langle \frac{\Delta \mathbf{J}}{\Delta t} \right\rangle,
\]

(3-1)

and diffusion tensor,

\[
\mathbf{B} \equiv \left\langle \frac{\Delta \mathbf{J} \Delta \mathbf{J}}{\Delta t} \right\rangle,
\]

(3-2)

where \( \Delta \mathbf{J} \) is the cumulative change in \( \mathbf{J} \) caused by impacts during a time interval \( \Delta t \) and the angle brackets denote time averages. The mean torque due to the rocket effect has components

\[
A_k^{(\text{rck})} = \frac{1}{2} S_d \sum_Z \int_{E_{\text{min}}}^\infty dE \, \phi_Z(E) \, N_{\text{vap}}(Z, E) \, \delta J_k,
\]

(3-3)

where \( S_d \) is the grain surface area, \( \phi_Z(E) \, dE \) is the omnidirectional flux of cosmic rays with charge \( Ze \) and energies between \( E \) and \( E + dE \), and \( \delta J_k \) is the mean angular impulse due
to a single evaporating molecule. In deriving expression (3-3), we have assumed that the flux of cosmic rays is isotropic in the grain frame and that each cosmic ray impact creates 2 hotspots. The analogous expression for the diffusion tensor is

$$B_{kl}^{(rck)} = \frac{1}{2} S_d \sum_Z \int_{E_{\text{min}}}^{\infty} dE \phi_Z(E) N_{\text{vap}}(Z, E) \delta J_k \delta J_l.$$  \hspace{1cm} (3-4)

The quantities $\delta J_k$ and $\delta J_k \delta J_l$ are determined by averaging the angular impulse due to a single evaporation over the position of the evaporation site and momentum of the evaporating molecule. Consequently, $\delta J_k$ depends in general on the grain shape. In Appendix A, we show that $\delta J_k = 0$ for an oblate spheroid, the shape adopted by Sorrell (1995a,b). It follows that $A_{k}^{(rck)} = 0$, that is, there is no pinwheel torque due to cosmic ray impacts on an oblate spheroid. This statement is true for any surface of revolution.

Of course, real interstellar grains are not surfaces of revolution and it is possible to show that pinwheel torques do not vanish for less symmetric shapes (e.g. they do not vanish for square prisms). Nevertheless, we can place an upper limit on the magnitude of the pinwheel torque for any shape by assuming, unrealistically, that all of the angular impulses produced by evaporating molecules lie along the same direction in the grain frame. Since the cosmic ray hits on a real grain are uniformly distributed over its surface, this assumption is obviously extremely optimistic.

Let $\delta J = b (m_{\text{vap}} k T_{\text{vap}})^{1/2}$ be the mean magnitude of an individual impulse, where $b$ is some characteristic linear dimension of our hypothetical grain. In our optimistic scenario, the mean torque due to the rocket effect would have magnitude

$$A^{(rck)} = \frac{1}{2} S_d \theta_s \sum_Z \int_{E_{\text{min}}}^{\infty} dE \phi_Z(E) A_{\text{eff}}(Z, E) \delta J(E).$$  \hspace{1cm} (3-5)

Now suppose that all of the angular impulses lie along the $k$th principal axis of inertia. If we assume that the rotational friction is provided by gas damping, then the grain would spin up to kinetic energy $E_{\text{rot}}$, such that

$$E_{\text{rot}} = \frac{1}{2} k T_{\text{g}} \frac{[A^{(rck)} t_{\text{gas},k}]}{I_k k T_{\text{g}}}.$$  \hspace{1cm} (3-6)

where $I_k$ and $t_{\text{gas},k}$ are respectively the rotational inertia and gas damping time for rotation about axis $k$.

We have evaluated expression (3-6) using the functional form of $\phi_Z$ given by LJO85, cosmic ray abundances given in Simpson (1983) for the local ISM, and typical values for the grain properties ($b = 10^{-5}$ cm, $T_d = 15$ K, $\rho_d = 3$ g cm$^{-3}$) and physical conditions...
We find the same value, $E_{\text{rot}} \sim 10^{-5} kT_g$, whether we assume that the evaporating molecule is H$_2$ or CO. Note that this is the average excess energy for an ensemble of grains. For the cosmic ray fluxes adopted here, most of the grains in the ensemble actually experience no cosmic ray hits during the interval $t_{\text{gas},k}$, so the average energy is somewhat misleading. However, we estimate that the largest energies in the ensemble are only $\sim 10^{-3}kT_g$, so this does not alter our conclusion.

Evidently, cosmic rays cannot spin up the grains under the most optimistic scenario that one can conceive. It is easy to understand this result if one notes that only heavy cosmic rays have energy loss rates sufficiently large to produce a significant number of evaporations. For example, the cosmic ray spectrum calculated by LJO85 peaks at $E \approx 0.3$ GeV for both protons and iron nuclei. At $E = 0.3$ GeV, the energy loss rates for protons and iron nuclei are $Q_p = 4 \times 10^{-6}$ erg cm$^{-1}$ and $Q_{\text{Fe}} = 2 \times 10^{-3}$ erg cm$^{-1}$, respectively. According to Figure 1, evaporations caused by protons impacts would be completely negligible at this energy.

4. Rotational excitation by random cosmic ray torques

The stochastic torque produced by the rocket effect can enhance Davis-Greenstein alignment by increasing the grain rotational temperature (Salpeter & Wickramsinghe 1969; Purcell & Spitzer 1971). The random angular impulses produced by evaporating molecules cause the angular momentum to change in random walk fashion so that, in the absence of other processes, the $k$th component of $\mathbf{J}$ would increase without limit as $J_k \propto \left[B_{kk}^{(rck)} t\right]^{1/2}$. In reality, the rotational friction produced by gas damping and other dissipative processes limits the growth to $J_k \approx \left[B_{kk}^{(rck)} t_{\text{damp}}\right]^{1/2}$, where $t_{\text{damp}}$ is the relevant damping time. For example, suppose that the only interactions of the grains with their environment are provided by gas damping plus the rocket effect. Then one can show (see RDGF93, eq. [3.18]) that the distribution of $J_k$ is Maxwellian with an effective temperature

$$T_{\text{eff}} = \frac{\left[B_{kk}^{(g)} + B_{kk}^{(rck)}\right] t_{\text{gas},k}}{2I_k k},$$

where $B_{kk}^{(g)}$ is the diffusion tensor for gas damping. If $B_{kk}^{(rck)}$ is sufficiently large, then the rotational excitation provided by the cosmic rays can permit Davis-Greenstein alignment even in clouds with $T_d = T_g$.

It follows from equation (4-1) that the stochastic torque produced by the rocket effect increases the grain rotational temperature by a factor $1 + \Theta$, where

$$\Theta \equiv \frac{B_{kk}^{(rck)}}{B_{kk}^{(g)}}.$$
After combining expressions (2-7), (3-4), and (A2), we find that the nonzero components of the diffusion tensor for the rocket effect are

\[ B_{kk}^{(\text{rock})} = \frac{4\pi}{3} \Gamma_k m_{\text{vap}} k b^4 \theta_s \sum_Z W_Z, \]

where

\[ W_Z = \int_{E_{\text{min}}}^{\infty} dE \phi_Z(E) A_{\text{eff}}(Z, E) T_{\text{vap}}(Z, E) \]

and the \( \Gamma_k \) are weak functions of the grain eccentricity with \( 3/8 \leq \Gamma_k \leq 1 \) (see Appendix A).

The diffusion tensor for gas damping is also diagonal with components

\[ B_{kk}^{(g)} = \frac{2\sqrt{\pi}}{3} \Gamma_k n_g^2 m_g^2 v_{\text{th}} \left( 1 + \frac{T_d}{T_g} \right) \]

(RDGF93), where \( n_g \) is the number density of the gas, \( m_g \) is the mass of a gas particle, and \( v_{\text{th}} \equiv \sqrt{2kT_g/m_g} \) is the gas thermal speed. It follows that

\[ \Theta = \sqrt{\pi} (1 + T_d/T_g) \left( \frac{m_{\text{vap}}}{m_g} \right) \frac{\sum_Z W_Z}{n_g v_{\text{th}} \theta_s^{-1} T_g}. \]

Notice that \( \Theta \) is independent of the surface eccentricity.

In order to estimate \( \Theta \), we used the results of §2 to evaluate expression (4-4) by numerical integration. Due to the steep dependence of \( A_{\text{eff}} \) on \( Q \) (Fig. 1), the sum is dominated by iron, the most abundant nucleus with \( Z \gg 1 \). For example, consider the relative contributions of iron and cosmic ray protons. LJO85 found that iron and protons have approximately the same energy spectrum; according to their models, \( \phi_Z = 4\pi A_Z I \), where \( A_Z \) is the abundance of cosmic rays with charge \( Ze \) relative to the abundance of protons and

\[ I(E) = \begin{cases} 
21 \left( \frac{E}{\text{GeV}} \right) & 0.02 < \frac{E}{\text{GeV}} < 0.07 \\
1.5 & 0.07 < \frac{E}{\text{GeV}} < 0.2 \\
0.3 \left( \frac{E}{\text{GeV}} \right)^{-1} & 0.2 < \frac{E}{\text{GeV}} < 1 \\
0.3 \left( \frac{E}{\text{GeV}} \right)^{-2} & 1 < \frac{E}{\text{GeV}} 
\end{cases} \]

(cm\(^{-2}\) s\(^{-1}\) GeV\(^{-1}\)) is the mean intensity of cosmic ray protons. Taking \( A_{26} = 3 \times 10^{-5} \), the cosmic ray abundance of iron in the local interstellar medium (Simpson 1983 and references therein), we find that \( W_{26} = 5 \times 10^{-13} \text{ K s}^{-1} \) and \( W_1 = 4 \times 10^{-14} \text{ K s}^{-1} \) for the evaporation of \( \text{H}_2 \) from \( \text{H}_2\text{O} \) ice. The analogous calculations for CO evaporation yield \( W_{26} = 3 \times 10^{-13} \text{ K s}^{-1} \) and \( W_1 = 6 \times 10^{-17} \text{ K s}^{-1} \). We will assume henceforth that all of the evaporation is caused by iron cosmic rays and set \( \sum_Z W_Z = 4 \times 10^{-14} \text{ K s}^{-1} \) for \( \text{H}_2 \) evaporation and \( \sum_Z W_Z = \)
5 × 10^{−13} \text{ K s}^{-1} \text{ for } \text{H}_2 \text{ evaporation and } \sum Z W_Z = 3 \times 10^{−13} \text{ K s}^{-1} \text{ for CO evaporation}. To estimate Θ for typical cold cloud conditions, we will assume that the gas is composed of \text{H}_2, with \text{n}_g = 10^4 \text{ cm}^{-3}, T_g = T_d = 15 \text{ K}, and \theta_s = 10^{15} \text{ cm}^{-2}. With these assumptions, we find that Θ \sim 10^{-7} if the rocket effect is caused by the evaporation of \text{H}_2 and Θ \sim 10^{-6} if the evaporating molecules are CO. We conclude that the rotational excitation provided by the rocket effect is insignificant unless the flux of iron nuclei were increased by 6–7 orders of magnitude. However, an increase in \phi of this magnitude can be ruled out in general: with the flux adopted in our estimates, iron nuclei would already contribute about 10% of the total cosmic ray ionization rate, ζ, in a typical cloud with \zeta \sim 10^{-17} \text{ s}^{-1} (LJO85).

In principle, the desorption produced by low-energy electrons (Johnson 1990) could also contribute to the rotational excitation. However, the required electron flux is ruled out unambiguously by data on the interstellar ionization.

Purcell & Spitzer (1971) computed the rotational excitation which is associated with energy loss by cosmic rays in the grain solid material. Comparing our results with those of Purcell & Spitzer (1971), we conclude that energy loss is more important for enhancing the rotational temperature of grains than the desorption of molecules from hotspots. Nevertheless, even the process studied by Purcell & Spitzer has only a marginal effect on grain alignment.

5. Summary

Our study has shown that the evaporation of molecules from cosmic ray hotspots produces no pinwheel torque on an oblate spheroidal grain, regardless of its mantle composition. Although it is possible, in principle, that nonzero pinwheel torques exist for some grain shapes, we have shown that the resulting increase in the grain rotational energy is negligible for realistic fluxes of heavy cosmic rays. Our findings resolve the apparent conflict between the recent observations of Chrysostomou et al. (1996) and the grain alignment model of Sorrell (1995a), inasmuch as the alignment process postulated in Sorrell’s model does not occur. We have also shown that the random torques caused by cosmic ray hotspots produce rotational excitation that can enhance the efficiency of Davis-Greenstein alignment, even in

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5 To estimate the contributions of other nuclei, we evaluated \sum Z W_Z by setting \phi_Z = 4\pi A_Z I, assuming that I is given by expression (4-7), and adopting cosmic ray abundances appropriate for the local ISM (Simpson 1983). In this approximation, adding the effects of nuclei with Z \neq 26 increases \sum Z W_Z by less than a factor of two for \text{H}_2 and CO evaporation. An error of this magnitude in W_Z has no effect on our conclusions.
clouds where $T_d = T_g$. However, the enhancement is completely insignificant for reasonable estimates of the cosmic ray flux and less than the enhancement associated with cosmic ray energy losses in the grain material (Purcell & Spitzer 1971).

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A. The quantities $\delta J_k$ and $\delta J_k \delta J_l$ for an oblate spheroid

In order to compare our results with those of Sorrell (1995a), we assume that the mantle surface is an oblate spheroid. If the cosmic ray flux is isotropic in the grain frame, then the evaporation sites are uniformly distributed over the grain surface. The momentum distribution of the evaporating molecules is determined for thermal evaporation by the principle of detailed balancing (e.g., Roberge et al. 1993, hereafter RDGF93). Then the required coefficients are

$$\delta J_k = 0, \quad k = x, y, z, \quad (A1)$$

and

$$\delta J_k \delta J_l = m_{vap} k T_{vap} b^2 \epsilon_k \delta_{kl} \quad k = x, y, z \quad (A2)$$

(RDGF93, cf. eqs. [B8] and [B10]), where $b$ is the grain radius and the components are relative to a Cartesian basis with $\hat{z}$ parallel to the grain symmetry axis. The quantities

$$\epsilon_k(e) \equiv \frac{4 \Gamma_k(e)}{3 \left[1 + (1 - e^2) g(e)\right]}, \quad k = x, y, z, \quad (A3)$$

are weak functions of the mantle shape with $1/2 \leq \epsilon_k \leq 2/3$ and the geometrical factors

$$\Gamma_z = \frac{3}{16} \left\{ 3 + 4(1 - e^2) g(e) - e^{-2} \left[1 - (1 - e^2)^2 g(e)\right]\right\}, \quad (A4)$$

6In eqs. (A1) – (A2), we have neglected terms of order $\Omega b/v_{vap}$, where $\Omega$ is the grain angular velocity and $v_{vap}$ is a typical thermal velocity for an evaporating molecule. Here we have anticipated the result (§3) that the rotational energies of the grains are nearly thermal, so that $\Omega b/v_{vap} \sim \sqrt{m_{vap}/M_d}$, where $m_{vap}$ is the mass of an evaporating molecule and $M_d$ is the grain mass. Note that, although $\delta J_k = 0$ to zeroth order in $\Omega b/v_{vap}$, the first-order term we have neglected is always negative, so that evaporation from cosmic ray hotspots would actually spin down an oblate spheroid. We will neglect the rotational damping caused by cosmic rays, which is much smaller than gas damping for reasonable estimates of the cosmic ray flux.
and
\[
\Gamma_x = \Gamma_y = \frac{3}{32} \left\{ 7 - e^2 + (1 - e^2)^2 g(e) + (1 - 2e^2) \left[ 1 + e^{-2} \left[ 1 - (1 - e^2)^2 g(e) \right] \right] \right\},
\]
where
\[
g(e) \equiv \frac{1}{2e} \ln \left( \frac{1+e}{1-e} \right)
\]
are weak functions of \( e \) with \( 3/8 \leq \Gamma_k \leq 1 \).

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FIGURE CAPTION

Fig. 1 — The mean number of molecules evaporated by a cosmic ray with energy loss rate \( Q \) equals the number of molecules initially adsorbed in the effective area \( A_{\text{eff}}(Z, E) \) (see eq. [2-8]). Results are shown for the evaporation of \( \text{H}_2 \) (solid curves) and \( \text{CO} \) (dashed curves).
Fig. 1