22. INTERSTELLAR GRAINS AND SPIRAL STRUCTURE*

Introductory Report

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1. Introduction

The problem of the interstellar grains is in many ways still unsettled. The theories of the formation, growth, and destruction of the grains have undergone a number of modifications because of the very significant increase in our understanding of the dynamical processes in our Galaxy. I will emphasize here how the density wave theory of the origin of the spiral structure may lead to a new broad concept in dust formation and its generic relationship with star formation. The basic physical processes are not changed but rather the framework in which we consider them.

We should bear in mind that on all theories of dust there are key limitations based on rather 'solid' observations. There are definite optical boundary conditions imposed on the grain properties by well-established observations of the amount and the wavelength dependence of extinction and polarization. However, where possible in the following presention we will try to avoid grain characteristics whose values depend on detailed models and we will focus our attention on the most broadly-founded features as they relate to galactic structure.

The principal theme will be the question of time scales. In the earliest days of the discussion of interstellar grains, the interstellar medium was pictured as being rather amorphous and having little structure that might have significance to the physics of the grains. In such a context, the only time scale of importance was the age of the Galaxy, which was believed to be of the order of 10^9 to 10^{10} yr (thirty years ago the Galaxy was about ten times younger than it is now). When Oort and van de Hulst (1946) approached the problem, they were concerned with the fact that in such a time a grain would grow so large that its optical characteristics would be inconsistent with the observed wavelength dependence of extinction. The notion of cloud collisions was used to introduce the possibility of destroying the grains within the clouds. In this way the size of a grain had an upper limit, which depended upon the frequency of cloud collisions. Another, and important, result of this type of theory was that it gave rise to an average or steady state distribution of particle sizes with a time scale for averaging of the order of 10^7 yr. It may be seriously questioned whether the notion of clouds and of cloud collisions is any longer crucial in relation to grain destruction. Their role in limiting grain growth may be negligible, because of the existence of other grain destroying processes, such as collisions of grains and cosmic rays, sputtering by high-energy atom collisions, evaporation in the neighborhood of hot stars.

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However we will consider these processes only from a limited point of view, namely in relation to the broader problems connected with the spiral structure.

2. Basic Observations and Interpretations

Some representative observations of the wavelength dependence of extinction and polarization are shown in Figure 1. The extinction is roughly linear up to $\lambda^{-1} \approx 9\ \mu^{-1}$. The polarization is caused almost certainly by the same agency as the extinction and is due to a difference in the extinction for radiation polarized along two orthogonal directions. This implies that the particles are oriented and nonspherical. The wavelength dependence of polarization for stars whose polarization relative to extinction is greater than the median observed value ($\Delta m_p/\Delta m \gtrsim 0.025$) generally exhibits a broad maximum in the vicinity of $\lambda^{-1} \approx 2\ \mu^{-1}$. Averaged over a number of stars the values shown in the upper portion of Figure 1 are found. We can readily establish a reliable estimate of the characteristic particle size, if we assume that the particles are made of some solid material. The guideline is given by calculations of extinction by infinite dielectric cylinders. Predicted extinction cross sections are shown in Figure 2 for particles with an index of refraction $m = 1.33 - 0.05i$; this index reproduces in the visible the optical properties of 'dirty ice'. Although more refined results based on theory and measurement of extinction by other kinds of particles are available they do not modify the size estimate significantly.

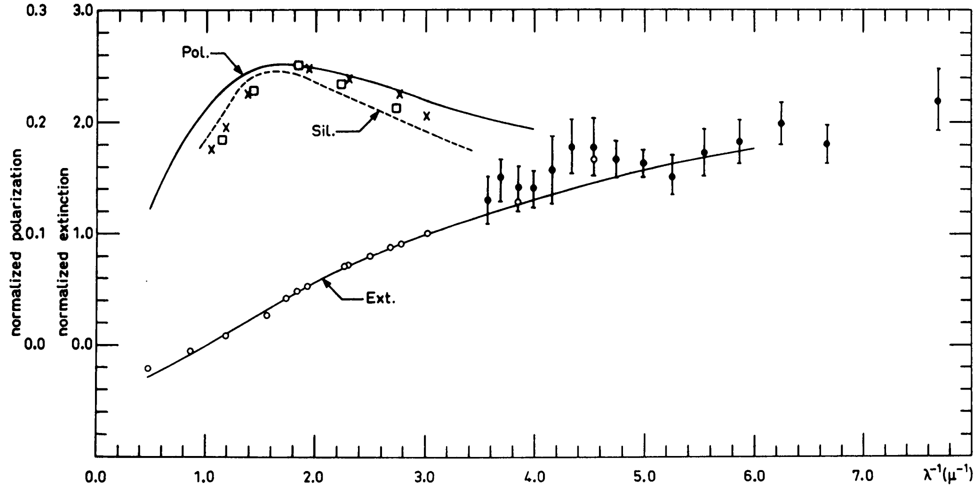

Fig. 1. Extinction observations are given by open and closed circles as specified by Stecher (1965). Polarization observations (crosses and squares) are as averaged in Greenberg (1968). Lower curve and upper solid curve labeled 'pol' are extinction and polarization by a size distribution $n(a) = 49 \times \exp[-5(a/0.2)^3] + \exp[-5(a/0.6)^3]$ of particles with index of refraction $m = 1.33 - 0.05i$. Dashed curve is polarization by a size distribution $n = \exp[-5(a/0.1)^3]$ of particles with $m = 1.66$. The theoretical polarization curves are normalized to one magnitude of extinction between $\lambda^{-1} = 1\mu^{-1}$ and $\lambda^{-1} = 3\mu^{-1}$.

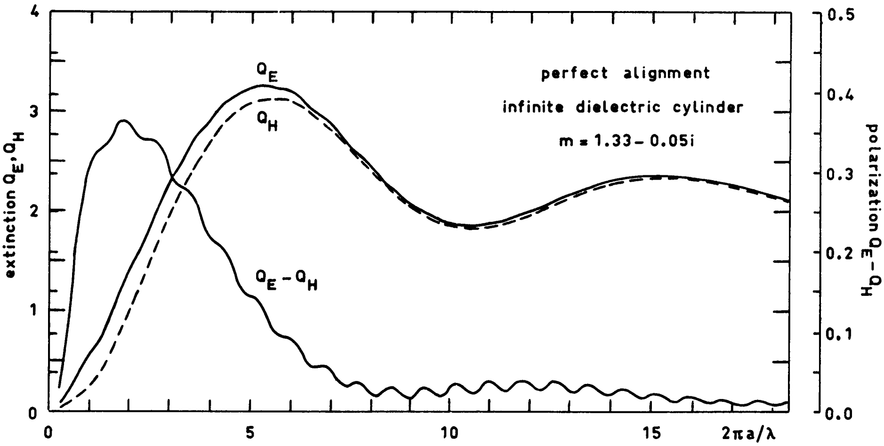

Fig. 2. Extinction efficiencies for an infinite circular cylinder with radiation perpendicular to the cylinder axis. Subscripts E and H specify respectively that the electric vector or magnetic vector of the radiation is parallel to the cylinder axis.

As the criterion for grain size we can use the wavelength of the maximum in the curve of polarization vs. wavelength (Figure 1). We then see from a comparison of Figures 1 and 2 that the $2\pi a/\lambda$ scale of the latter is roughly equivalent to the λ^{-1} scale of the former. In other words, elongated particles with a real part for the index of refraction $m' = 1.33$ should have a thickness given by $2a = 0.3\,\mu$. More detailed considerations lead to a size distribution with a range of radii from zero to about $0.2\,\mu$. For the purpose of our discussion a characteristic radius $a = 0.1\,\mu = 10^{-5}$ cm will be used. From extinction measurements we obtain as a fundamental parameter for the particle size the quantity $4\pi a\lambda^{-1}(m' - 1)$. Thus, if we consider particles with different indices of refraction, the typical size varies in such a way that $a(m' - 1)$ remains invariant. The only solid, non-dielectric particle seriously considered consists of graphite or carbon; its size spans a limited range with a maximum perhaps half that of the dirty-ice particles. Large molecules of the type suggested by Donn (1968) involve an entirely different type of scattering and are not considered here. Finally, we should point out that the interpretation of the scattered light from reflection nebulae (Greenberg and Roark, 1967) tends to reinforce our notion of solid dielectric particles whose size is of the order of $0.1\,\mu$.

The total mass of the interstellar dust is obtained from average values of the extinction. A reasonable average value would appear to be about 1 mag kpc^{-1}. The extinction in magnitudes is (ignoring polarization) given by the simple formula

$$\Delta m = 1.086 \sum \text{extinction cross section/unit area.} \tag{1}$$

Thus, for one magnitude of extinction the total extinction cross-section is about 1 cm^2 per 1 cm^2. For the particle sizes we use, the extinction cross-section is approximately given by the projected area of the particle. Using spheres, for simplicity, the number of particles N in a path length D is obtained from

$$\Delta m = 1.086\ N\pi a^2/D. \tag{2}$$

The mass density ϱ_g of grains of specific density s is

$$\varrho_g = N\tfrac{4}{3}\pi a^3 s\,D = \tfrac{4}{3}as(\Delta m/D) \times \tfrac{1}{1.086}.$$

For $D=1$ kpc, $\Delta m=1$ we obtain

$$\varrho_g \approx 0.5 \times 10^{-26}\ \mathrm{g\ cm^{-3}} \tag{3}$$

where we use $s\approx 1$, valid for dirty ice.

It turns out that ϱ_g is rather insensitive to the type of grain material. This can be understood qualitatively if $\varepsilon - 1 \propto s$, where ε is the dielectric constant of the medium. This relation, of course, holds best if for a particular material one varies the degree of porosity. The correct formula is $(\varepsilon-1)/(\varepsilon+2)\propto s$. In that case we can say that approximately

$$\varrho_g \propto as \propto a\,\frac{m'^2-1}{m'^2+2} = a(m'-1)\left(\frac{m'+1}{m'^2+2}\right). \tag{4}$$

Since we take $a\ (m'-1)=$invariant, we find that $\varrho_g\approx$constant for $m'\approx 1$. The above derivation is not valid for metallic particles.

We see from Equation (3) that the total space density of the obscuring matter is of the order of 1 percent of the density of observed interstellar atoms and molecules. This statement holds for all grain models (including the large molecule model which we have not considered here). In the solar neighborhood the hydrogen density is of the order of 20 per cent of the total of gas plus stars. Therefore, we expect that, regardless of the grain composition, of the order of 10^{-3} to 10^{-4} of the mass of our Galaxy is in the form of obscuring matter. It is interesting to note that if all planetary systems in our Galaxy have the same mass ratio to their respective stars as ours, then even if a fraction 10^{-2} of the stars (by mass) have such planetary systems, there is 10 times more mass in the form of dust than in the form of planets.

3. Distribution and Dynamics of Gas, Dust and Stars

I summarize here some simplified observational and theoretical features of spiral structure which pertain directly and critically to the interstellar grain story. The principal sources of data are the Schmidt (1965) model, the density wave theory of spiral structure (Lin and Shu, 1964; Lin *et al.*, 1969), the work of Roberts (1969) on gas motion and shock phenomena (the two-armed-spiral shock picture), and the recent studies of Lynds (1970) on the distribution of dust in Sc galaxies.

BASIC DATA AND ASSUMPTIONS

(1) The rotation period of the Milky Way is about 2.5×10^8 yr $=2\pi\times 10$ kpc/(250 km sec^{-1}).

(2) The grand design is a two-armed spiral.

(3) The density wave rotates (at the solar position) with ½ the speed of the gas and stars.

(4) Based on photos of external spiral galaxies, dust lanes increase in width with distance from the galactic center and are usually found in the inner edges of the spiral arm. Dust lanes have a width of the order of, or greater than, ¼ of the spiral arm width. In the solar neighborhood (if we are in a principal arm) we would expect the dust lane to be about 300 to 500 pc wide.

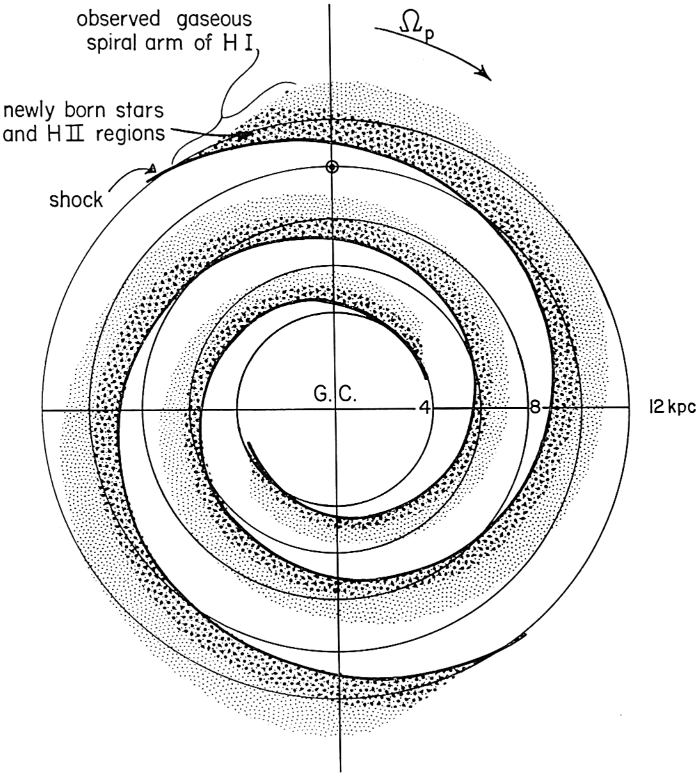

Fig. 3. Shock and background spiral pattern of the Galaxy. The shock occurs slightly on the inner edge of the background spiral arm. Dust condensation initiated just ahead of shock. (Figure from Roberts, 1969).

(5) The H II regions (presumably regions of star formation) appear to lie within and at the edge of the dust lanes.

(6) The gas follows a path as shown in Figure 3. Its velocity component normal to the spiral arm is approximately given by the projected difference in velocity between the density wave and the material circular motion. This is roughly true because of the combination of two effects: first, going through the shock, the gas speeds up; second,

behind the shock, the stream lines are closer to the tangent to the arm. The result is that the galactic material passes through the spiral arm in about the same time as it passes between the spiral arms.

4. Formation of Dust

The first question we ask is: Can grains grow out of the gas within the time available? We assume here that there exists a sufficient number of nucleation points for grain growth and that we can ignore the problem of where the nuclei come from. Several suggestions for the origin of such small nucleation particles have been made, ranging from (i) formation in stars followed by ejection to (ii) the residue of dust particles destroyed during star formation. Conceivably sufficient nuclei will be produced. We further assume that as a result of radiative equilibrium with the ambient radiation field the grains are at a sufficiently low temperature that atoms like O, C, and N readily stick to the surface if they collide with the grain. For grain temperatures of about 10 K and gas temperatures of about 100 K it is most likely that the fraction of such atoms which stick is close to unity. Although for high gas temperatures ($T_{\mathrm{gas}} \approx 1000\,\mathrm{K}$) experimental verification on the sticking fraction is lacking, it appears that some atoms (for example oxygen atoms) will stick rather well; namely those, that are bound more strongly than can be done by van der Waals forces only. This is a problem which should be studied in the laboratory. Hot H I gas, with temperatures in the range of 1000 to 10000 K may prevail in the interarm regions and also perhaps as a medium surrounding normal H I-clouds (Spitzer and Scott, 1969; Goldsmith *et al.*, 1969). We will call this hot hydrogen gas H I′.

For spherical particles the rate of growth by attachment of atoms may be shown to be

$$\frac{\mathrm{d}a}{\mathrm{d}t} = \frac{\gamma n_A}{4s} (3m_A kT)^{1/2}, \tag{5}$$

where $\gamma =$ sticking fraction, n_A and m_A are number density and mass of the condensing atoms. If we let the inner edge of a spiral arm be a 'standard' H I region with hydrogen density $n_{\mathrm{H}} = 10\ \mathrm{cm}^{-3}$ and gas temperature $T = 100\,\mathrm{K}$ we find (Greenberg, 1968) that

$$\dot{a} = f\gamma\sqrt{(TA)}\, n_{\mathrm{H}} \times 2.6 \times 10^{-20}\ \mathrm{cm\ sec}^{-1} \tag{6}$$

where $f \approx 10^{-3}$ is the standard cosmic abundance ratio of condensible atoms to H atoms, and A is the atomic weight. The high number density is achieved as a result of the compression at the inner edge of the arm. We find, under these conditions, that it takes about 3×10^7 yr for a particle to grow from a negligible radius to $a = 10^{-5}$ cm if γ is close to unity. In H I′ regions, however, the growth rate may be smaller than in H I regions. If pressure equality exists between H I and H I′ regions, i.e., $n_{\mathrm{H}}T =$ constant, then Equation (6) predicts that the growthrate in H I′ regions is smaller by a factor $(T_{\mathrm{H\,I}}/T_{\mathrm{H\,I'}})^{1/2}$.

If we use Lynds' estimate of dust-lane width of $\frac{1}{3}$ or greater of the arm width we find that in this dust lane the gas spends about $(\frac{1}{6}) \times 2.5 \times 10^8 \approx 4 \times 10^7$ yr. It thus appears that the time and conditions are not inconsistent with the idea of dust grains growing out of the gas. To complete the picture we would then have the dust participating with the gas in the formation of new stars, thus supplying the band of H II regions following the dust lanes on the inside of the spiral arms, as noted by Lynds and others.

A recent suggestion by Herbig (1969) on the formation of stars and dust appears to give, at least initially, a very similar distribution of gas, dust and stars in the spiral arms when combined with the shock picture. As a matter of fact, Herbig's suggestion may not differ in basic processes as much from the above picture as it appears at first although a quite different chemical composition of the dust results. Herbig suggests, that during the prestellar condensation the condensation of dust and the formation of complex molecules takes place under conditions of a very high density, a moderate radiation field and a moderate temperature ($T \approx 1000\,\mathrm{K}$). The resulting dust would be in the form of non-volatile solids of a type similar to the carbonaceous chondrites in our solar system. The excess volatile constituents would come off in the form of molecules consisting of the more abundant elements. Herbig estimates that the total dust output by such a process carried on over the age of the Galaxy would be sufficient to account for the total observed mass of dust. This raises the question: why isn't a sizeable fraction of the dust used up again in the subsequent formation (next generation) of new stars? If this were the case, then the total *net* production of dust would be lowered and might perhaps be insufficient to account for the present mass. But even if for this reason the 'solar nebula' hypothesis for dust formation were inadequate, it may be an important source of nucleation particles. The subsequent accretion in average interstellar conditions at the leading edge of the spiral arms will then lead to a more consistent picture with respect to the observed distribution of dust lanes and H II regions. The conclusion is that one should expect to find particles with core materials consisting of the heavier elements, Si, Fe, Al, etc., and with mantles consisting of the 'dirty ice' mixture of frozen water, methane and ammonia.

There has been some evidence in recent years for the formation of solid particles in the atmospheres of cool stars. The only direct clue is the spectroscopic identification in some stars of (possibly) olivene in emission (Knacke *et al.*, 1969). [Olivene = (Mg, Fe) SiO_3. (Ed.)]. Observations of a more indirect nature and theoretical calculations have led to the inference not only of such silicate particles but also of carbon or graphite particles. Can a sufficient amount of such materials be ejected from the stellar atmospheres to provide the observed dust mass? To answer this question let us estimate an upper limit on all material (gas as well as dust) lost by M stars.

According to Pottasch (see p. 272) all M stars together lose mass to the interstellar medium at a rate of less than $2.5 \times 10^{-13}\, M_\odot\, \mathrm{pc}^{-3}\, \mathrm{yr}^{-1}$; stars of all kinds together lose certainly less than $10 \times 10^{13}\, M_\odot\, \mathrm{pc}^{-3}\, \mathrm{yr}^{-1}$. For the M stars the amount of material supplied in 10^8 yr is $2.5 \times 10^{-5}\, M_\odot\, \mathrm{pc}^{-3}$, compared to a value of ϱ_g of 10^{-3} to $10^{-4}\, M_\odot\, \mathrm{pc}^{-3}$. The mass loss by M stars is therefore inadequate by at least an order of magnitude. Even the mass loss from all stars appears inadequate unless the ejected mass is completely in the form of dust. I should reiterate that this conclusion is based on the hypothesis of a regeneration every 10^8 yr because I have assumed the dust to be largely used up in star formation. However, even if this condition is relaxed completely, the M stars must produce dust for at least 10^9 yr with all ejected mass in the form of dust. If only one tenth of the mass loss is in the form of solid particles the time required equals the age of the Universe and would appear to be prohibitively large.

5. Magnetic Orientation and Interstellar Polarization

In this meeting, as in previous meetings in this series, one has inferred (in part at least) the existence of magnetic fields from the observation of optical interstellar polarization. Although at the moment we do not believe that these fields play an important role in the formation of the gross spiral structure, they certainly are still important in more local considerations involving gas dynamics. Magnetic field observations of a more direct nature have led to lower and lower field estimates and the entire question of associating optical polarization with magnetic orientation has been revived.

There is a rather good theoretical basis for the statement that even magnetic fields as small as 5 μG are adequate to orient 'standard' dielectric (ice or silicate) grains sufficiently for the required degree of interstellar polarization. This conclusion is based on rather detailed calculations (Greenberg, 1969) which take into account not only the scattering properties of nonspherical particles, but also the kinetics of the Davis-Greenstein (1951) orientation mechanism with physically reasonable assumptions of the gas collision processes. With a reasonable modification of the magnetic properties (Jones and Spitzer, 1967) it is possible to bring this limit down by an order of magnitude. Furthermore, the excellent correlation (Brouw, 1962) between the directions of optical and radio polarization (orthogonality) still is, to me, a convincing argument in favor of a theory in which a magnetic field is the primary agency orienting grains. Nevertheless, there are time limits in the Davis-Greenstein orienting mechanism which should be kept in mind when we consider other dynamical processes.

The relaxation time for magnetic orientation of a sphere is given by

$$\tau_0 = \frac{\omega I}{\chi'' V B^2} = \left(\frac{\omega}{\chi''}\right)\frac{2a^2 s}{5B^2}, \tag{7}$$

where ω is the angular velocity, I the moment of inertia, χ'' the imaginary part of the magnetic susceptibility, V the volume, and s the density of the grain. B is the magnetic field strength. For paramagnetic substances the value of χ'' is given by $\chi'' \approx 2.5 \times 10^{-12}$ ω/T_g where T_g is the grain temperature. For $a = 10^{-5}$ cm, $s = 1$, $B = 5$ μG and $T_g = 10$ K we get $\tau_0 = 2 \times 10^5$ yr. For other dielectric grain models the result is about the same. We see that the optical polarization can only follow gas processes with time scales of at least 10^5 yr.

6. Grain Temperature

The grain temperature is a critical parameter not only with respect to the magnetic orientation but also to such physical processes as molecule formation and the sticking of atoms on grain surfaces. For example, it has been suggested that hydrogen in solid form can accrete on grains at sufficiently low temperatures. Here it is impossible to present details of the calculations of grain temperatures. These calculations depend sensitively on the chemical constituents and the physical state of the grains since these properties determine the wavelength dependence of absorptivity and emissivity of electromagnetic radiation from the ultraviolet to the microwave regions. However, it is not difficult to present a qualitative determination of grain temperatures.

The interstellar radiation field has been estimated to have an energy density in the range 0.5 to 1.0×10^{-12} erg cm^{-3}. Since a considerable portion of this radiation comes from rather hot stars, a representation (useful for our purposes) of the interstellar radiation is by means of a radiation temperature $T_R = 10\,000$ K and a dilution factor $W = 10^{-14}$. Together these give an energy density of 0.8×10^{-12} erg cm^{-3}. If a body is placed in this radiation field it will reach an equilibrium temperature when its emission is equal to its absorption. If the body has wavelength independent absorptivity (and emissivity) the radiation law gives (disregarding proportionality constants) a black body temperature T_B according to

$$\text{Absorption} = \text{Emission}$$

or

$$W T_R{}^4 = T_B{}^4$$

with the result that $T_B = (10^{-14} \times 10^{16})^{1/4} = 3.2$ K. Very large bodies in space would reach this temperature (disregarding other processes). However, the interstellar grains are quite small and are increasingly poor emitters as the wavelength increases. For such small particles the absorptivity is proportional to the volume rather than to the area and therefore is proportional to λ^{-1}. We may then show that the equilibrium temperature is determined by $W T_R^5 = T_g^5$ which gives $T_g = 10^{6/5} = 15.8$ K. It turns out that, under normal interstellar radiation conditions, dirty ice grains and silicate grains have temperatures between these two values (generally about 10 K), whereas graphite or metallic particles tend to have temperatures between 20 to 40 K. Even in the center of very dense clouds with heavy attenuation of the ultraviolet radiation, the grain temperatures are unlikely to be less than 5 K. In the center of a cloud with 20 magnitudes of extinction dielectric grains of especially high infrared emissivity and low visible absorptivity may attain temperatures as low as 4 K. With regard to condensation of solid hydrogen (Greenberg and De Jong, 1969) this temperature is prohibitively high. However, if such very-low-temperature grains exist, they could help to bring down the gas temperature in dense clouds. For example, Heiles (1969) found OH spin temperatures as low as 4.5 K. Could such temperatures be produced by cooling of gas on grains? It may be shown that if each atom loses all of its energy on colliding with a grain the fractional change in the gas energy per unit time is given by the simple formula

$$\frac{\mathrm{d}E}{\mathrm{d}t} / E = \frac{\mathrm{d}T}{\mathrm{d}t} / T \approx \frac{\Delta m V}{R} \tag{8}$$

or $T \approx T_0 \exp(-t/\tau_T)$, where $\tau_T = R/(\Delta m V)$. Δm is the extinction through the cloud,

R is the cloud radius, V is the gas atom velocity ($\propto T^{1/2}$). For a 1 pc cloud with extinction of 5 magnitudes and $V = 1.5$ km sec^{-1} (initial gas) we get $\tau_T \approx 0.15 \times 10^6$ yr. (Here we assumed that V is constant. Actually $V \propto T^{1/2}$, but, as can be shown easily, this fact does not alter our conclusion.) In other words, to go from 50 K to 5 K would take $t \approx 10^6$ yr. This seems a bit long to be generally effective but not so long that a number of cool clouds could not be observed.

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