CHAPTER IV

SEGREGATION OF DUST GRAINS IN DARK CLOUDS

IV. 1. Introduction

Gravitational settling of dust in cosmic gas clouds has been discussed by several authors. Dust grains under the influence of the gravitation of the cloud tend to sediment towards the center of gravity of the cloud, their motion being resisted by the gas viscosity. This phenomenon was first discussed by McCrea and Williams (1965) in the context of planetary formation. Horedt (1973, 1976) and Alfven and Carlqvist (1978) have pointed out the importance of dust segregation in interstellar clouds for the formation of 'proto-cores' which may trigger gravitationally assisted accretion leading to star formation. As discussed in Chapter III we have shown that the settling of dust in Bok globules may be responsible for the observed radial variation of extinction in these objects. As the dust grains sediment towards the center of the globule, extinction in the inner regions of the globule increases at the expense of the extinction in the outer regions. A detailed model based on the gravitational settling of dust that is being driven into the globule by radiation pressure is found to be in good agreement with the observed radial variation of extinction within the globules B 361 and Globule 2 in
the Coalsack studied by Schmidt (1875) and Bok (1977) respectively.

In this Chapter we discuss another observable manifestation of the gravitational settling of dust grains in dark clouds. We start with a uniform spherical dust cloud. Initially, the dust is assumed to have a grain size distribution typical of the interstellar medium. Under the combined influence of the gravitational field and the viscous drag of the gas, dust grains sediment towards the center. As will be seen in Section IV.2 a dust grain of radius $a$, at a distance $r$ from the center of the cloud has a settling speed $|v| = \frac{c}{r}$, where $c$ is a constant. Thus the sedimentation time scale $\tau = \frac{r}{|v|} = \frac{1}{c \alpha}$. Larger grains sediment faster. Such a size dependent settling will therefore modify the grain size distribution function of the dust. In Section IV.2 for our simple model of a uniform spherical cloud we derive an expression for the modified grain size distribution function as a function of $r$ and time $t$. However, the physical quantities characterizing the dust distribution which can be directly related to the observations are: the mean grain size $\langle a \rangle$ and the extinction $A\lambda$ (at wavelength $\lambda$) along a line of sight through the dark cloud. One observes background stars through the intervening dust cloud. The dust in the cloud causes extinction and polarization of the light from the stars. The wavelength of maximum linear polarization $\lambda_{\text{max}}$ and also the ratio of total to selective extinction
\[ R = \frac{A}{(A - A V)} \] then give a measure of the mean grain size along the line of sight. An increase in mean grain size will result in an increase in \( \lambda_{\text{max}} \) and also \( R \) (Greenberg, 1968; McMillan, 1978). In Section IV.3 we therefore derive expressions for the mean grain radius \( \langle a \rangle \) and extinction \( A \) as functions of the projected radial distance \( x \) from the cloud-center and the age of the cloud \( t \). We have numerically evaluated these quantities for various values of the age of the cloud and plotted the results in Figures IV.1 and IV.2. We find that the mean grain size as well as the extinction increases towards the center of the cloud. In Section IV.4 we discuss these results with reference to the observations of anomalous reddening and polarization within dark clouds and suggest further detailed observations of dark clouds and Bok globules.

IV.2 Segregation of Dust and the Grain size distribution

IV.2.1 SEGREGATION OF DUST GRAINS

Consider a spherical cloud of radius \( R_0 \) and constant density \( \rho \). Initially the dust in the cloud is uniformly mixed with the gas. The grain size distribution for the dust is typical of the interstellar medium, and is the same everywhere in the cloud. The total dust mass is only a small fraction (\( \sim 10^{-2} \)) of the cloud mass. We therefore neglect the contribution of the dust to the gravitational field in the
cloud. Spherical symmetry is assumed. We do not take
the growth of grains into consideration.

At a radial distance \( r \) from the center of the cloud
the gravitational acceleration \( g \) directed towards the center
will be

\[
g = \frac{4}{3} \pi \rho G r
\]

where \( G \) is the gravitational constant.

A spherical dust grain of radius \( a \), density \( \rho \)
and mass \( m = \frac{4}{3} \pi \rho a^3 \) at the radial distance \( r \) will
experience the gravitational force directed towards the center

\[
F_g = mg = \left(\frac{4}{3} \pi \right)^2 \rho \Theta a^3 r
\]

If the grain moves with an inward radial velocity \( v \) through
the cloud, its motion will be resisted by the viscous drag
force

\[
F_v = \frac{4}{3} \pi a^2 \rho \nu v
\]
where \( W \) is the mean thermal velocity of the gas molecules (Williams and Crampin, 1971).

\[
W = \left( \frac{2 kT}{M} \right)^{\frac{1}{2}}, \quad \text{where } T \text{ is the temperature of the gas. } M \text{ is the mean molecular mass and } k \text{ is the Boltzmann constant.}
\]

Balancing the gravitational force by the viscous drag force \( \mathbf{F}_g = -F \mathbf{v} \) we obtain the settling velocity

\[
v = \frac{dr}{dt} = -\left( \frac{4 \pi G a r}{3 W} \right) = -ca \quad \text{IV(4)}
\]

where \( c = \left( \frac{4 \pi G a}{3 W} \right) \)

and the settling time scale

\[
\tau = \left| \frac{\Sigma}{v} \right| = \left( \frac{3 \bar{W}}{4 \pi G a} \right) = \frac{1}{ca} \quad \text{IV(5)}
\]

It is clear from Equation IV(5) that larger grains (large \( a \)) settle faster (small \( \tau \)). Therefore, if we start with a distribution of grain sizes; with the passage of time the distribution will get modified. From the outer regions of the cloud larger grains will have settled towards the
inner regions, making the grain size distribution in the
inner regions enhanced with larger grains. In the following
we make a calculation of this effect.

IV. 2:2 MODIFICATION OF THE GRAIN SIZE DISTRIBUTION
FUNCTION

Initially (t = 0) we assume the dust in the cloud to have the Oort-van de Hulst type grain size distribution

\[ n(a) = n_o \exp\left(-\sqrt[3]{a^3}\right) \quad \text{IV(6)} \]

such that \( n(a) \, da \) is the number of grains per unit volume with radii between \( a \) and \( a + da \) (Greenberg, 1968). \( n_o \) is a normalizing factor and \( \sqrt[3]{\cdot} \) is a constant related to the characteristic grain size. Here we will use \( \sqrt[3]{\cdot} = 40 \mu m^{-3} \) (Greenberg, 1968). At \( t = 0 \) the size distribution function is assumed to be the same at all points in the cloud.

From Equation IV(4) we find a relation between the position of a grain \( r(t) \) at time \( t \) and its initial position \( R_i \) as

\[ r(t) = R_i \exp(-\alpha t) \quad \text{IV(7)} \]

with the constraint \( R_i \ll R_o \).
If we consider a spherical shell of radius $r$ and thickness $dr$, then at time $t$, all the grains with radii between $a$ and $a+da$ in this shell must have settled down from another shell with radius $R_i$ and thickness $dR_i$, $r(t)$ and $R_i$ being related by Equation IV(7). If the new grain size distribution function at position $r$ and at time $t$ be $n(a, r, t)$; by conservation of dust grains we obtain

$$4\pi r^2 \, dr \, n(a, r, t) \, da = 4\pi R_i^2 \, dR_i \, n(a, R_i, 0) \, da \quad \text{IV(8)}$$

using $n(a, R_i, 0) = n_0 \exp (-\sqrt[3]{a})$ for the initial distribution function, and Equation IV(7) relating $r$ and $R_i$ we get

$$n(a, r, t) = n(a, R_i, 0) \exp (3act)$$

$$= n_0 \exp (3act - \sqrt[3]{a}) \quad \text{IV(9)}$$

The constraint $R_i \ll R_0$ in Equation IV(7) can also be written as

$$a \ll a_{rt} = \frac{1}{ct} \ln \left( \frac{R_0}{r} \right)$$

Grains with $a > a_{rt}$ will have all crossed the spherical
surface with radius \( r \) as they settle towards the center of the cloud. Therefore at time \( t \) we get for the modified grain size distribution function

\[
n(a, r, t) = \begin{cases} 
  n_0 \exp \left( 3 \frac{a^3}{ct} \right) & \text{for } a \lesssim \left( \frac{1}{ct} \right) \ln \left( \frac{R_0}{r} \right) \\
  0 & \text{for } a \gtrsim \left( \frac{1}{ct} \right) \ln \left( \frac{R_0}{r} \right)
\end{cases}
\]

We thus see that the grain size distribution function is now a function of time as well as of the position in the cloud. The factor \( \exp \left( 3 \frac{a^3}{ct} \right) \) tends to shift the distribution towards larger grains, and there is a cut-off at \( a = a_{rt} = \left( \frac{1}{ct} \right) \ln \left( \frac{R_0}{r} \right) \). Making use of the modified size distribution function derived above we can now calculate the average grain size and extinction along a line of sight through the dark cloud. These quantities are directly related to the observations of extinction and polarization produced by the cloud.

**IV. 3 MEAN GRAIN SIZE AND EXTINCTION**

**IV. 3:1 THE MEAN GRAIN SIZE**

The average grain radius \( \langle a(r, t) \rangle \) at a radial
distance \( r \) in the cloud at time \( t \) can be written as

\[
a (r, t) = \frac{\sum_{0}^{a r t} n (a, r, t) \, da}{\sum_{0}^{a r t} \exp (3 a t c - \sqrt{a^3}) \, da}
\]

where \( a_{rt} = (1/ct) \ln \left( \frac{R}{o/r} \right) \)

However, the average quantity of greater observational interest is the average grain radius \( \langle a(x, t) \rangle \) along a line of sight through the cloud passing at a projected radial distance \( x \) from the center of the cloud. For the geometry under consideration, performing the integrations along the line of sight, the average grain radius \( \langle a(x, t) \rangle \) is found to be given by

\[
a (x, t) = \frac{\sum_{0}^{a x t} a \left\{ \exp \left( -2 a t c \right) - \left( x/R_o \right)^2 \right\}^{\frac{1}{2}} \exp \left( 3 a t c - \sqrt{a^3} \right) \, da}{\sum_{0}^{a x t} \left\{ \exp \left( -2 a t c \right) - \left( x/R_o \right)^2 \right\}^{\frac{1}{2}} \exp \left( 3 a t c - \sqrt{a^3} \right) \, da}
\]

where \( a_{xt} = (1/ct) \ln \left( \frac{R}{o/x} \right) \)
IV.3:2 EXTINCTION

The extinction $A_{\lambda}$ at wavelength $\lambda$, along the line of sight can be written as

$$A_{\lambda} = \int N(a) C_{\text{ext}}(a, \lambda) \, da \quad \text{IV(13)}$$

where $N(a)$ is the column density of grains with radii between $a$ and $a+da$, along the line of sight and $C_{\text{ext}}$ is the extinction cross-section of grains. For $C_{\text{ext}}$ we use the following approximation (Greenberg, 1978).

$$C_{\text{ext}} = \pi a^2 \left\{ 2 - 4 \xi^{-1} \sin \xi + 4 \xi^{-2} (1 - \cos \xi) \right\}$$

IV(14)

where $\xi = 4 \pi (a/\lambda) (m' - 1)$

and $m' = \text{index of refraction of the grains}$.

With this approximation for the extinction cross-section and performing the line of sight integration we get for extinction
\[ A^\lambda (x, t) = 2 \int_{-\infty}^{xt} a^2 \left\{ \exp \left( -2 \frac{x}{a} \right) - \left( \frac{x}{a_o} \right)^2 \right\} \frac{1}{2} \]

* \[ \exp (3 \frac{act}{a^3}) \left\{ 2 - 4 \frac{\sin \frac{\gamma}{a}}{a} + 4 \frac{1 - \cos \frac{\gamma}{a}}{a^2} \right\} \] da

\[ \text{IV(15)} \]

where \( a_{xt} = \frac{1}{ct} \ln \left( \frac{a_o}{x} \right) \)

Equations IV(12) and IV(15) thus give the expressions for the mean grain radius \( \langle a (x, t) \rangle \) and extinction \( A^\lambda (x, t) \) respectively, along a line of sight through the cloud as functions of the projected radial distance \( x \) from the center of the cloud and the age \( t \) of the cloud.

### IV. 3:3 NUMERICAL RESULTS

Using Equations IV(12) and IV(15) we have numerically evaluated the quantities \( \langle a (x, t) \rangle \) and \( A^\nu (x, t) \) (extinction in the visual, \( \lambda \approx 0.55 \mu m \)) for various values of the cloud-age \( t \), and studied their variation with radial distance \( x \) across the cloud. The values used for the different parameters appearing in the expressions for \( \langle a (x, t) \rangle \) and \( A^\nu (x, t) \), and characterizing the dust
cloud are: $V = 40 \mu m^{-3}$, $\Theta = 1 \text{ gm cm}^{-3}$, $m' = 1.33$, $T = 10 K$, $R_o \sim 1 \text{ pc}$ and $n_o \sim 10^{-13} \text{ cm}^{-3}$. These values are typical of the interstellar dust and dark clouds (Greenberg, 1968; Martin and Barrett, 1978). $V = 40 \mu m^{-3}$ yields the mean grain radius for the normal interstellar dust $\langle a \rangle \simeq 0.15 \mu m$. $R_o = 1 \text{ pc}$ and $n_o = 10^{-13} \text{ cm}^{-3}$ would correspond to a typical Bok globule with number density of hydrogen molecules $n_{H_2} \sim 10^4 \text{ cm}^{-3}$, gas to dust ratio $\sim 10^2$ and average grain radius $\sim 0.15 \mu m$. It turns out that the constant $c \sim 10^{-11} \text{ cm}^{-1} \text{ sec}^{-1}$.

We have performed the calculations for $t = 1, 2, 4, 8, 16, 32, 64$ and $128$ million years. In Figure IV.1 we plot the average grain radius $\langle a \rangle$ against the fractional radial distance $x/R_o$ for various illustrative values of $t$ (curves corresponding to the different values of $t$ have been marked with numbers representing the cloud age $t$ in units of one million years). Similarly in Figure IV.2 $A_v$ has been plotted against $x/R_o$. Here the product $n_o R_o$ appearing in Equation IV(15) for extinction has been so chosen that $A_v (o, o) = 5$ magnitudes. There is no loss of generality in choosing $n_o R_o$ arbitrarily.

IV. 4 Discussion and Conclusions

From Figure IV.1 we find the following:
Figure IV.1: Plot of the average grain radius $\langle a \rangle$ against the fractional radial distance $X/R_0$ for various values of $t$. The curves for different values of $t$ have been marked with numbers representing the values of $t$ in million yr. The solid line corresponds to the cloud at $t = 0$ when $\langle a \rangle$ has the same value at all points in the cloud and is equal to the value for the normal interstellar medium ($\langle a \rangle = 0.15 \mu m$).
Figure IV.2: Plot of extinction $A_v$ against the fractional radial distance $X/R_o$. The curves for different values of $t$ have been marked with numbers representing values of $t$ in million yr. The solid curve is for $t = 0$. For $t = 128$ million yr, $A_v$ approaches the value $\approx 65$ as $X/R_o \rightarrow 0$. 
At any given time \( t > o \), the mean grain radius \( \langle a \rangle \) decreases monotonically with increasing radial distance \( x/R_o \).

For small values of \( t \) (\( t < 10^7 \) yr.) the mean grain radius over most of the cloud (i.e., for \( x/R_o \lesssim 0.8 \)) is the same and is close to the interstellar value \( \langle a \rangle \simeq 0.15 \) \( \mu \)m. Only in the outer most regions (\( x/R_o \gtrsim 0.8 \)) the mean grain radius begins to be appreciably smaller than the interstellar value.

With increasing age (\( t > 10^7 \) yr.) the mean grain radius in the inner regions of the cloud (\( x/R_o \lesssim 0.5 \)) increases to values appreciably larger than the interstellar value.

The average grain radius in the inner regions of the cloud increases at the expense of the outer regions where this average decreases below the interstellar value. The point which separates these two regions shifts to smaller \( x/R_o \) values with increasing cloud age \( t \).

At this stage we would like to point out a limitation of the present calculation. The lower limit of integration in Equations IV(12) and IV(15) have been taken to be zero. Thus, it has been assumed that the process of gravitational
settling occurs for even the smallest of the grains with $a \to 0$. However, grains smaller than some small radius $a_1$ will not settle. This happens when the thermal velocity of the grains becomes greater than their settling velocity. For the parameters of the typical cloud under consideration $a_1 \sim 0.01 \mu m$. Therefore even in the outermost regions of the cloud, the mean grain radius will not fall below the value $\sim 0.01 \mu m$. Inclusion of the size range $0$ to $a_1$ in the integrals in Equations IV(12) and IV(15) does not affect the results because the contribution to the integrals is very small. In any case the qualitative results of our calculations will hold. Any other different set of parameters of the dust cloud also gives the same qualitative behaviour for the dust in the cloud as presented in Figures IV.1 and IV.2.

Figure IV.2 shows that the radial gradient in extinction $A_V$ becomes steeper with increasing $t$. Gravitational settling tends to make the inner regions of the cloud darker (high $A_V$). Very old clouds ($t \sim 10^8$ yr.) have large extinction within $x/R_0 \sim 0.3$, and beyond $x/R_0 \sim 0.3$ extinction decreases to very small values. In such clouds dust has settled to form dark cores, surrounded by more transparent outer regions. Some Bok globules (B 92, B 227, B 335 for example) studied by Bok and McCarthy (1974) could be examples of clouds where this could have happened.
The variation of the grain size distribution function (and hence the mean grain size) across the cloud has very interesting implications for the observations of anomalous reddening and polarization within dark clouds. Dust in a dark cloud causes extinction and polarization of the light from background stars. For simplicity in the calculations we had taken the grains to be spherical, but in reality they would be nonspherical and thus be able to produce polarization. However, our conclusions about the grain size distribution would remain valid. The wavelength dependence of extinction and linear polarization is determined by the grain size distribution. In particular, the ratio of total to selective extinction \( R = \frac{A}{A_B - A} \) and the wavelength of maximum linear polarization \( \lambda_{\text{max}} \) are related to the mean grain size \( \langle a \rangle \) along the line of sight (Greenberg, 1968; McMillan, 1978). \( \lambda_{\text{max}} \) is proportional to the average grain radius \( \langle a \rangle \) (e.g. McMillan, 1978) and Serkowski et al. (1975) find a correlation between \( \lambda_{\text{max}} \) and \( R \) as \( R \approx 5.5 \lambda_{\text{max}} (\mu m) \). For the normal interstellar medium \( \lambda_{\text{max}} \approx 0.545 \mu m \) and \( R \approx 3 \).

It is clear from the above discussion that in dark clouds where the process of gravitational settling of dust has been at work, we may expect the following:
1. Existence of anomalous reddening because the grain size distribution has been altered.

2. Values of $R$ and $\lambda_{\text{max}}$ higher than the interstellar values, in the inner regions of the cloud, and smaller in the outer regions.

3. Radial variation of $R$ and $\lambda_{\text{max}}$ similar to the variation of the average grain radius $\langle a \rangle$ (because $R$ and $\lambda_{\text{max}}$ both are roughly proportional to $\langle a \rangle$) as shown in Figure IV.1.

4. $R$ and $\lambda_{\text{max}}$ would have a correlation with extinction $A_{\nu}$ in the cloud in the sense that $R$ and $\lambda_{\text{max}}$ both increase with $A_{\nu}$ as the radial distance from the center decreases.

It should be noted here that it would be difficult to define the outer boundary of a dark cloud by means of extinction measurements. The outermost regions where we expect the mean grain size to be smaller than the interstellar value would also have very small extinction and amount of polarization. For these regions the interstellar medium may have significant contribution to the total amount of extinction and polarization along the line of sight. To our knowledge, detailed studies of the radial
variation of $R$ and $\lambda_{\text{max}}$ in dark clouds have not been made. However, we note that Carrasco et al. (1973) found evidence for an increase in average grain radius, above the interstellar value in $\rho$ Oph dark cloud and Turnshek et al. (1980) found a similar increase in average grain radius in NGC 1333. A correlation between $\lambda_{\text{max}}$ and extinction was also found. The increase in grain size has been customarily interpreted as grain growth by condensation of heavy elements or coagulation of grains in dense clouds. Though the conditions favourable for grain growth certainly exist in dark clouds, the gravitational settling of dust grains discussed in this Chapter offers another mechanism that can give rise to an increase in the average grain size in the central regions of dark clouds, especially for the old ones ($t > 10^7$ yr).

We suggest that detailed studies of the wavelength dependence of extinction and linear polarization within dark clouds and Bok globules be undertaken. Variation of $R$ and $\lambda_{\text{max}}$ with radial distance may help us test the idea that the anomalous reddening and polarization in these objects is caused by dust that is gravitationally settling towards the center. However, the processes of grain growth and gravitational settling may both be at work in any given dark cloud.
### Table IV.1

Photopolarimetric measurements of stars in the region of B5.

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Dark Cloud B5: Polarization Map. X indicates the cloud center.

Figure IV-3
stars were measured in filter I and a few stars in filters V and R also. Figure IV. 3 is the resulting polarization map for B5. The positions of stars observed are indicated by dots and numbers. The polarization vectors passing through the dots represent the percentage polarization $P(\text{I})$ and the position angle $\Theta(\text{I})$ (measured from north and increasing eastward), the length being proportional to the percentage polarization. The polarization vectors are drawn only for those stars for which the uncertainty in position angle $\epsilon_\Theta < 10^\circ$.

IV. 5:3 Discussion

B5 is $17^\circ$ below the galactic plane and is at an estimated distance of $\sim 160$ pc (Young et al. 1982). For most of the stars therefore the observed polarization must be caused entirely by the dark cloud. Assuming that the polarization is produced by dust grains in the cloud aligned by the Davis-Greenstein mechanism, the direction of the polarization vectors will be the same as the projected magnetic field direction. Figure IV. 3 therefore represents a map of the projected magnetic field in B5. Over most of the cloud the field is more or less parallel to the rotation axis, i.e. the NE-SW direction, though there is considerable spread in the position angles. Only in the western sector the polarization vectors are clearly perpendicular to the rotation axis. We lack observations of stars in the central regions.
(the core) of the cloud. The star closest to the centre is star 16 for which the polarization vector is perpendicular to the rotation axis.

Because of the projection effects involved an unambiguous interpretation of the results on the magnetic field geometry is difficult to make. Since over most of the cloud the polarization vectors are parallel to the elongated axis of the cloud, one might suggest that there is a real parallelism between the magnetic field, the rotation axis and the major axis of the ellipsoidal cloud. In this case, however, magnetic support against gravitational collapse parallel to the rotation axis is not possible. It is possible that the magnetic field and the rotation axis are parallel only in projection. They might be mutually perpendicular, but both inclined at $45^0$ to the line of sight appropriately. In this case the magnetic field can provide polar support against gravitational collapse. The polarization vectors in the western sector of the cloud are hard to understand. That the polarization observed in this region is caused by a different cloud unrelated to the bulk of B5 cannot be excluded. Young et al. (1981) found that the core of B5 is rotating in the opposite sense to that of the outer regions and suggest that magnetic braking has occurred. It would be interesting to make polarization measurements of stars in the central regions of B5 and compare the geometry of the magnetic field in the core with that in the outer regions mapped in this work.
The wavelength dependence of polarization can provide important information regarding the size of the dust grains in the dark cloud. The wavelength $\lambda_{\text{max}}$ at which the linear polarization attains its maximum value is a measure of the average grain size (see e.g. McMillan, Astrophys. J., 225, 880, 1978). The average value of $\lambda_{\text{max}}$ for interstellar polarization is $\sim 0.55 \mu m$ and polarization on an average is maximum in the V filter. It is clear from the data in Table that for all stars for which measurements could be taken in V, R and I filters the polarization attains its maximum value in the R filter. The average value of $\lambda_{\text{max}}$ for B5 is therefore estimated to be $\sim 0.7 \mu m$ ($\lambda_{\text{eff}}$ for the R filter). The average dust grain size in B5 must be larger than the typical interstellar medium value.

The existence of grains with sizes larger than normal in the dark cloud B5 suggests that dust grains have either grown in size by means of grain-grain collision or accretion of heavier elements onto the grains, or segregation of dust grains as described in this chapter has caused the average grain size to increase.