Chapter 3

Infrared Emission from Interstellar Dust

For the initial detection of 60 and 100μm cirrus emission, Low et al. (1984), Draine and Anderson (1985) calculated the IR emissions from graphite/silicate grain with grains as small as 3Å and argued that 60 and 100μm emissions could be accounted for. Further processing of IRAS data revealed stronger than expected 12 and 25 μm emissions from interstellar clouds. Weiland et al. (1986) showed that this emission could be explained if very large 3-10Å grains were present. More recent observations have shown that the interstellar medium radiates strongly in emission features at 3.3, 6.2, 7.7, 8.6, 11.3, and 11.9 μm. To account for all these features, Li and Draine (2001) adopted a dust model which consists of a mixture of amorphous silicate grains and carbonaceous grains, both having a wide size distribution ranging from large grains ~ 1 μm in diameter down to molecules containing tens of atoms in which 60 x 10^-6 of C (relative to H) is locked up in PAHs. It was assumed that the carbonaceous grains have graphitic properties at radii a ≥ 50 μm and PAH-like properties at very small size ≤ 20Å that accounts for the 3.3, 6.2, 7.7, 8.6, and 11.3 μm emission features seen in wide range of objects.

The profile parameters, adjusted to closely resemble the observed profile have already been discussed by (Tielens 2010, Smith et al. 2007, Draine and Li...
It has been shown by Draine and Li (2007) that some negative features as recommended by Mattioda et al. (2005) has a negligible effect on the heating and cooling rates of PAHs except in regions illuminated by very cool stars, \( T_{eff} \leq 1500K \).

It has been established by Li and Draine (2001) that thermal equilibrium breakdowns for grains smaller than a \( \sim 250\AA \), (where \( a \) is the radius of grain), which is heated by individual photons. These small grains get much hotter than the temperature derived by equating the power absorbed with that emitted. The effect is most obvious at short wavelengths (\( \lambda < 60\mu m \)), while observed dust emissions for \( \lambda > 60\AA \) from the interstellar medium can be explained in terms of emissions from big (\( a \geq 250\AA \)) silicate and carbonaceous grains and can be obtained from thermal equilibrium brightness. However, from the Figures 12 and 13 of the Li and Draine (2001) it can be argued that for large FUV interstellar radiation field IR spectra at wavelengths (\( \lambda \geq 60\mu m \)) can be safely represented by thermal equilibrium brightness within the observed uncertainty. In the present work for most of the sample galaxies, FUV radiation field is expected to be fairly large. Therefore, temperature of spherical grains obtained from the balance of photon absorption and emission will give a representative value of dust emissions at \( \lambda \geq 60\mu m \).

### 3.1 Heating and Cooling of ‘Classical’ Dust Grains

In this section we have attempted to understand the energetics and physical conditions for the grains in the interstellar medium. We self-consistently solve for the grain temperature and consequently FIR emission by equating the power absorbed by the grain to the power emitted by it. This requires,

\[
4\pi a^2 \int_0^{\infty} G_0 F_\lambda e^{-K_\lambda A_\lambda} Q_{obs,\lambda}(a, m) d\lambda
\]
where $R_\lambda(T_0)$ is the Plank function, $T_0$ grain temperature and $Q_{\text{obs,}\lambda}(a, m)$ is the absorption efficiency for the material $m$ and spherical grain of radius $a$ at wavelength $\lambda$. $m = 1$ stands for the silicate grain and 2 for carbonaceous grains. Draine and Li (2001) have shown that balance equation (3.1) breaks down for smaller particles, ($a < 250\mu$m) which are stochastically heated. However, it has been shown by Ingalls et al. (2002) that effect is most obvious at shorter wavelengths, $\lambda < 60\mu$m and in any case it affects $<20\%$ at 60$\mu$m. It has also been shown by Draine and Anderson (1985) that lower cut off of the size of the grains does not affect appreciably $I_{60\mu m}/I_{100\mu m}$, ratio also. It is therefore, assumed that equilibrium approach does not affect significantly the conclusion drawn from FIR in the bands of 60 and 100 $\mu$m.

To calculate the energy absorbed by the dust grains, we estimate the absorption cross section per hydrogen atom as a function of wavelength following Ingalls et al. (2002).

The expression for energy absorbed may be obtained by integrating over the radiation field $G_\lambda F_\lambda$ and absorption cross section $\sigma_\lambda$ as,

$$
\Gamma = 4\pi \int_{0.0812\mu m}^{\infty} G_\lambda F_\lambda e^{-K_\lambda A_\lambda} \sigma_\lambda d\lambda
$$

(3.2)

Following Li and Draine (2001) for $Q_{\text{obs,}\lambda}(a, m)$ and albedo $\omega = \frac{Q_{\text{scatter}}}{Q_{\text{obs}}}[1 + \frac{Q_{\text{scatter}}}{Q_{\text{abs}}}]$, the expression for average energy absorbed by the grains becomes,

$$
\Gamma = G_\lambda \int_{0.0812\mu m}^{\infty} S_\lambda e^{-K_\lambda A_\lambda} d\lambda
$$

(3.3)

where for polyatomic hydrocarbons and silicate grains $S_\lambda(-F_\lambda \sigma_\lambda)$ as simplified by Shafiquallah et al. (2011), is given as follows:

For polyatomic hydrocarbons, $S_\lambda$ are,

$$
F_\lambda \sigma_\lambda = S_\lambda
$$

$4.2 \times 10^{-21} \lambda^{1.7372}$, $0.0812\mu m < \lambda < 0.11\mu m$

$2.23 \times 10^{-25} \lambda^{-1.68}$, $0.11\mu m < \lambda < 0.134\mu m$

$7.758 \times 10^{-28} \lambda^{-3.3478}$, $0.134\mu m < \lambda < 0.166\mu m$
3.1 Heating and Cooling of 'Classical' Dust Grains

\[ 1.404 \times 10^{-24} \lambda^{0.8322}, \quad 0.166 \mu m < \lambda < 0.181 \mu m \]
\[ 4.077 \times 10^{-23} \lambda^{2.8322}, \quad 0.181 \mu m < \lambda < 0.248 \mu m \]
\[ C_i(\lambda)4.63 \times 10^{-30} \lambda^{-1.33}, \quad 0.248 \mu m < \lambda < 10 \mu m \]
\[ C_i(\lambda)1.8392 \times 10^{-32} \lambda^{0.752}, \quad 10 \mu m < \lambda < 19.2 \mu m \]
\[ C_i(\lambda)1.153 \times 10^{-30} \lambda^{-0.196}, \quad 19.2 \mu m < \lambda < 50 \mu m \]
\[ C_i(\lambda)1.964 \times 10^{-21} \lambda^{-5.74}, \quad \lambda \geq 50 \mu m \]

and for silicate grains, \( S_\lambda \) are
\[ 7.095 \times 10^{-22} \lambda^{2.9172}, \quad 0.0912 \mu m < \lambda < 0.11 \mu m \]
\[ 3.76 \times 10^{-25} \lambda^{-0.5}, \quad 0.11 \mu m < \lambda < 0.125 \mu m \]
\[ 1.352 \times 10^{-25} \lambda^{-1.0}, \quad 0.125 \mu m < \lambda < 0.134 \mu m \]
\[ 4.7 \times 10^{-27} \lambda^{-2.6678}, \quad 0.134 \mu m < \lambda < 0.2803 \mu m \]
\[ C_i(\lambda)7.649 \times 10^{-30} \lambda^{-0.874}, \quad 0.2803 \mu m < \lambda < 0.6562 \mu m \]
\[ C_i(\lambda)3.126 \times 10^{-30} \lambda^{-2.61}, \quad 0.6562 \mu m < \lambda < 3.0395 \mu m \]
\[ C_i(\lambda)2.884 \times 10^{-31} \lambda^{-0.352}, \quad 3.0395 \mu m < \lambda < 10.00 \mu m \]
\[ C_i(\lambda)1.270 \times 10^{-27} \lambda^{-2.97}, \quad 10.00 \mu m < \lambda < 14.9254 \mu m \]
\[ C_i(\lambda)4.598 \times 10^{-33} \lambda^{1.63}, \quad 14.9254 \mu m < \lambda < 24.3902 \mu m \]
\[ C_i(\lambda)4.305 \times 10^{-29} \lambda^{-2.2}, \quad \lambda \geq 24.3902 \mu m \]

where \( C_i(\lambda) = w_i B_\lambda T_i \) and \( w_i \) and \( T_i \) are given in Table 2.1.

Again following the Ingalls et al. (2002), integrating over the grain distribution, the dust thermal emission is,
\[ \Lambda_{d,\lambda} = \sum_m C_m \pi \int_{a_{min}}^{a_{max}} B_\lambda(T_0)Q_{abs,\lambda}(a, m)a^{-1.5} da, \]

which may be transferred into the form,
\[ \Lambda_{d,\lambda} = \pi B_\lambda(T_0)(A_\lambda/N_h)/(1 - \omega) \]

Again following Li and Draine (2001) for \( Q_{abs}(a, m) \) and albedo \( \omega \), the expression for thermal emission is,
\[ \Lambda_{d,\lambda} = \pi B_\lambda(T_0)E_\lambda, \]
where for polyatomic hydrocarbons and silicate grains $E_\lambda$, as estimated by Shafiquallah et al. (2011) is given as follows:

For polyatomic hydrocarbons, $E_\lambda$ are

\[
\begin{align*}
2.234 \times 10^{-22} \lambda^{-0.6914}, & \quad 0.0912 \mu m < \lambda \leq 0.1167 \mu m \\
3.00 \times 10^{-25} \lambda^{-3.6914}, & \quad 0.1167 \mu m < \lambda \leq 0.1250 \mu m \\
1.05 \times 10^{-23} \lambda^{-1.9665}, & \quad 0.1250 \mu m < \lambda \leq 0.1429 \mu m \\
8.19 \times 10^{-23} \lambda^{-0.9459}, & \quad 0.1429 \mu m < \lambda \leq 0.1585 \mu m \\
6.6640 \times 10^{-21} \lambda^{-1.4488}, & \quad 0.1585 \mu m < \lambda \leq 0.1883 \mu m \\
4.5215 \times 10^{-19} \lambda^{-3.9334}, & \quad 0.1883 \mu m < \lambda \leq 0.2171 \mu m \\
1.11 \times 10^{-23} \lambda^{-2.9934}, & \quad 0.2171 \mu m < \lambda \leq 0.2480 \mu m \\
1.11 \times 10^{-22} \lambda^{-1.33}, & \quad 0.2480 \mu m < \lambda \leq 10 \mu m \\
4.40 \times 10^{-25} \lambda^{0.752}, & \quad 10 \mu m < \lambda \leq 19.2 \mu m \\
2.76 \times 10^{-23} \lambda^{-0.196}, & \quad 19.2 \mu m < \lambda \leq 50 \mu m \\
4.70 \times 10^{-14} \lambda^{-5.74}, & \quad \lambda \geq 50 \mu m \\
\end{align*}
\]

and for silicate grains, $E_\lambda$ are,

\[
\begin{align*}
3.64 \times 10^{-22} \lambda^{-0.509}, & \quad 0.0912 \mu m < \lambda \leq 0.1167 \mu m \\
5.53 \times 10^{-22} \lambda^{-0.312}, & \quad 0.1167 \mu m < \lambda \leq 0.1250 \mu m \\
3.03 \times 10^{-22} \lambda^{-0.574}, & \quad 0.1250 \mu m < \lambda \leq 0.1408 \mu m \\
2.26 \times 10^{-22} \lambda^{-0.734}, & \quad 0.1408 \mu m < \lambda \leq 0.1667 \mu m \\
1.890 \times 10^{-22} \lambda^{-0.836}, & \quad 0.1667 \mu m < \lambda \leq 0.2037 \mu m \\
2.24 \times 10^{-22} \lambda^{-0.731}, & \quad 0.2037 \mu m < \lambda \leq 0.2803 \mu m \\
1.83 \times 10^{-22} \lambda^{-0.874}, & \quad 0.2803 \mu m < \lambda \leq 0.6562 \mu m \\
7.48 \times 10^{-23} \lambda^{-2.61}, & \quad 0.6562 \mu m < \lambda \leq 3.0395 \mu m \\
6.9 \times 10^{-24} \lambda^{-0.352}, & \quad 3.0395 \mu m < \lambda \leq 10.00 \mu m \\
30.40 \times 10^{-21} \lambda^{-2.97}, & \quad 10.00 \mu m < \lambda \leq 14.9254 \mu m \\
1.1 \times 10^{-25} \lambda^{1.63}, & \quad 14.9254 \mu m < \lambda \leq 24.3902 \mu m \\
10.3 \times 10^{-21} \lambda^{-2.2}, & \quad \lambda \geq 24.3902 \mu m
\end{align*}
\]
3.1 Heating and Cooling of 'Classical' Dust Grains

The intensity of FIR emission for grains in steady state of temperature is obtained by integrating thermal emission from the surface of the cloud to $A_V$ as,

$$I_{FIR}(\lambda, G_0) = 1.87 \times 10^{21} \int_0^{A_V} \Lambda_{d,\lambda}(A_V, G_0) dA_V$$  \hspace{1cm} (3.9)

If $A_V$ is taken up to the centre of a symmetrical one dimensional cloud then the said equation is to be multiplied by a factor of 2. The value of $A_V$ is taken as 100. In order to calculate the continuum intensity from a partially ionized region illuminated by FUV field $G_0$, we follow the following steps,

(i) Attenuation of $G_0$ are obtained at various regions of PDR shielded by gas and dust.

(ii) Grain temperatures for different grain types at various positions of neutral gas/PDR are solved self-consistently. Consequently FIR emissions for time steady neutral gas region are evaluated.

(iii) Thermal emission from the surface of the cloud to $A_V$ are integrated for finding intensity.

Total flux thus obtained for various FUV field $G_0$ are fitted as a function of wavelength $\lambda$ and a parameter $T_0$ (termed here as dust brightness temperature) for obtaining Far-IR surface brightness spectra for thermal equilibrium emissions from model clouds in the following form,

$$F_{FIR}(\lambda) = C_0 / (\lambda^{4.01} \exp{(hc/\lambda k T_0)} - 1),$$  \hspace{1cm} (3.10)

where $C_0$ is a constant and its value depend upon the chosen unit of wavelength. Extensive calculations have been performed by Shafqullah et al. (2011) for a wide range of $G_0$ that gives the steady state dust brightness parameter $T_0$ as a function of $G_0$ as,

$$T_0 = 14.796 \times G_0^{0.147}$$  \hspace{1cm} (3.11)

For the carbonaceous and silicate grains taken together the infrared emission will peak at $\lambda = 195.3 G_0^{-0.147}$. This shows that for a range of $G_0 < 10^4$ steady temperature $T_0$ of grains will provide a fairly good approximation of infrared emissions for $\lambda \geq 60 \mu m$. Thus total emission for any medium of interest exposed to the FUV radiation field may be estimated using the Planck function. The dust
3.2 Heating and Cooling of Ultrasmall Dust Grains: Temperature Spikes

The IRAS and LWS discovered that wide spread emissions in the bands 12 and 25\(\mu\)m are much stronger than expected for radiatively heated dust grains. These strong emissions for \(\lambda \leq 30\mu\)m have been successfully explained by Draine and Li (2007) in terms of small, stochastically heated grains, where small grains get much hotter than the temperature obtained by equating the power absorbed with that emitted. The emissivity per H nucleon for dust mixture heated by starlight intensity \(G_0\) as given by Draine and Li (2007)

\[
\begin{align*}
  j_e(U) &= \sum_j \int da \frac{dn_j}{da} \int C_{ves}(j,a,\nu) B_\nu(T) \left( \frac{dP}{dT} \right)_{\nu,\lambda,\nu} dT \\
  B_\nu(T) &= \frac{2\pi^3}{\nu^2} \frac{1}{\exp(h\nu/kT) - 1},
\end{align*}
\]

where the sum is over composition of \(j\) and the temperature distribution function \(dP/dT\) which depends on composition \(j\), radius \(a\) and starlight intensity \(G_0\). For large grains \(dP/dT \approx \delta(T - T_0)\) where \(T_0\) is the steady state temperature at which the radiated power is equal to time averaged heating rate for grain of radius \(a\). The carbonaceous particles are assumed to have the optical properties of graphite for radii exceeding \(\sim 100\AA\) and to have physical properties of PAH for radii \(a < 50\AA\) [radius refers to the radius of equal volume sphere; for PAHs the number of carbon atoms \(N_C = 460(a/10\AA)^3\)]. We find steady state
3.2 Heating and Cooling of Ultrasmall Dust Grains: Temperature Spikes

Solution \( dP/dT \) for grains subject to stochastic heating by photon by absorption and cooling by emission of infrared photons, using the 'thermal-discrete' approximation (Draine and Li 2001), where the downward transition probabilities for a grain with vibrational energy \( E \) are estimated using a thermal approximation. For each grain size \( a \) and radiation intensity \( G_0 \), the energy range \([E_{\text{min}}, E_{\text{max}}]\) may be divided into 500 bins. \( E_{\text{min}} \) and \( E_{\text{max}} \) are found iteratively, with the requirement that the probability of grain being outside the range \([E_{\text{min}}, E_{\text{max}}]\) be negligible. The effect of PAH abundance \( q_{\text{PAH}} \) on emission is most obvious at shorter wavelengths \( \lambda < 30 \mu m \) as shown by Draine and Li (2007). In the present work we have used the same technique to find the emissions in 12 and 25 \( \mu m \) bands. The fitted form of the emissivities of 12 and 25 \( \mu m \) bands obtained by us are presented below,

\[
\text{emissivity} = \frac{10^{-27}(\coth(u) + d)(u^c + f)}{(1 + gu^b)} \text{ (ergs s}^{-1} \text{Sr}^{-1} \text{H}^{-1}) \quad (3.14)
\]

where \( u = G_0^b \) and \( xu = (0.7 - q_{\text{PAH}})/G_0^{0.1} \) and the function and constants are given the Table no 3.1.

Table 3.1: function and constants of the 12 and 25 \( \mu m \) band emissivities

<table>
<thead>
<tr>
<th>Bands</th>
<th>function</th>
<th>( f )</th>
<th>( a )</th>
<th>( b )</th>
<th>( c )</th>
<th>( d )</th>
<th>( e )</th>
<th>( g )</th>
<th>( h )</th>
</tr>
</thead>
<tbody>
<tr>
<td>12( \mu m )</td>
<td>2.1588q_{\text{PAH}}</td>
<td>0.2868</td>
<td>1.787</td>
<td>38.739</td>
<td>-0.99998</td>
<td>0.1223</td>
<td>1</td>
<td>0.1223</td>
<td></td>
</tr>
<tr>
<td>25( \mu m )</td>
<td>0.05u^{0.2} \cosh(xu)</td>
<td>0.2878</td>
<td>1.8842</td>
<td>60.829</td>
<td>-0.99986</td>
<td>0.0</td>
<td>0.025</td>
<td>0.2</td>
<td></td>
</tr>
</tbody>
</table>

Thus 12 and 25\( \mu m \) bands provide an opportunity to study the physical nature of dust and grain properties and also starlight intensities as well as the fraction \( q_{\text{PAH}} \) of the total dust mass that is in the PAH. Model infrared emission spectra for 12 and 25\( \mu m \) bands are calculated following the model of Draine and Li (2007) for a grain model that consists of carbonaceous grains and amorphous silicate grains, with size distribution that reproduce the average interstellar extinction curve. The emissivities \( \langle \nu J_\nu \rangle \) \( \text{(ergs s}^{-1} \text{Sr}^{-1} \text{H}^{-1}) \) for 12 and 25 \( \mu m \) bands
3.2 Heating and Cooling of Ultrasmall Dust Grains: Temperature Spikes

Figure 3.1: Emissivity for 12μm band
Figure 3.2: Emissivity for 25μm band
3.3 Spectral Diagnostics

We refer back to the discussion in Chapter 2 on heating, cooling and emission lines in section 3.1 and 3.2 in the current chapter on infrared and continuum emission. The environmental conditions of neutral and partially ionized gas of a galaxy are mainly governed by the steady state assumption wherein we presume (i) ionization equilibrium (ii) statistical equilibrium and (iii) thermal equilibrium. The formulation of the problems requires elaborate numerical methods needed to solve the coupled atom-radiation problem. That lead to a huge increase in level complexity and is itself to be derived self-consistently from an iterative process. The wealth of information hidden in the complexities may be derived from the diagnostics of emission line and continuum radiations from the neutral/partially ionized gas in a galaxy that yield not only radiation field and densities but also kinematical informations, elemental abundance and velocity field.

The measured fluxes of [CII] (158 \( \mu \text{m} \)) and [OI] (63 \( \mu \text{m} \) and 145 \( \mu \text{m} \)) provide an opportunity to infer the physical conditions, primarily gas density and the flux \( G_0 \) apart from abundances and velocity field. Assuming that [CII] and [OI] lines and also the continuum are emitted from common region of galaxies, attempt has been made to analyse the data in terms of [CII]/FIR and F(12 \( \mu \text{m} \))/F(25 \( \mu \text{m} \)). Correction to [CII] emission data has been discussed in section 4.3.2.

The two circumstances where we do expect [CII]/FIR ratio to change are (1) for high ratio of \( G_0/n \) (FUV flux to gas density), the grains get positively charged, raising the potential barrier for photoelectric ejection, thereby dropping the heating efficiency (Figures 2.6 and 2.7); and (2) increase in the PAH abundance which is effective in the increase of emissivity of 12 and 25 \( \mu \text{m} \) bands (Figure 3.3). Thus we expect a wide spread in the observational data when plotted against the F(12 \( \mu \text{m} \))/F(25 \( \mu \text{m} \)).

In the figure 3.3 and 3.4 the variation of ratio \( F(12\mu\text{m})/ F(25\mu\text{m}) \) calcu-
lated as a function of $q_{PAH}$ for various $G_0$ are shown. Figure 3.3 shows that emissions in the band of 12$\mu$m are stronger than that of 25$\mu$m for a wide range of $G_0$, consequently band ratio $F(12\mu m)/F(25\mu m)$ increases with increase of PAH abundance $q_{PAH}$. But the same band ratio is decreased for increasing $G_0$ as shown in Figure 3.4. The decrease in the observed emission strength of 12$\mu$m with increasing FUV radiation may be safely attributed to a gradual shift from stochastic heating to steady state temperature approximation. Also it may be interpreted that in the region where large FUV radiation field is expected the gas temperature may be sufficiently high, the impinging atoms and ions can erode the grain, one atom at a time, through the process known as sputtering. The sputtering depends upon the energy of the projectile, on the composition of target, and also on mass and charge of the impacting ion. But it is fact that temperature requirement for sputtering is very high which is not expected in normal interstellar medium Draine (2011a). From the Figure 3.3 it is also clear that band ratio is $\sim 1$ or more for PAH abundance $q_{PAH} > 1\%$. This may be treated a good basis for determination of the fraction of the total dust mass that is in the PAH.

The variation of ratio $F(60\mu m)/F(100\mu m)$ calculated for FIR emission at thermal equilibrium temperature of silicate and graphite grains exposed to FUV radiation field $G_0$ is shown in Figure 3.5. This is based on model of Li and Draine (2001) and (Weingartner and Draine 2001). Here the ratio is monotonic function of $G_0$. Thus observed ratio $F(60\mu m)/F(100\mu m)$ can be used as a tool for estimating the $G_0$. Here an ab-initio calculation is used for estimation of $G_0$ combined with the observational data.
Figure 3.3: Ratio of fluxes at 12 and 25μm are plotted against the percentage fraction of $q_{PAH}$ of total dust mass that is in the PAH for the various star light intensity $G_0$. 
Figure 3.4: Behaviour of band ratio of 12 and 25μm are plotted against FUV star field $G_0$ for various percentage fraction $q_{PAH}$ i. e. PAH index.
Figure 3.5: Ratio of continuum fluxes at 60$\mu$m and 100$\mu$m calculated at thermal equilibrium temperature of silicate and graphite grains exposed to the star light intensity $G_0$. 