Chapter 3

Continuum Emission Mechanisms

3.1 Thermal Plasma

3.1.1 Free-Free Emissivity and Absorptivity

Also known as Bremsstrahlung or electron braking radiation, free-free emission is a type of continuum emission (e.g., emission that is not quantized into discrete allowed energies). A result of the conservation of energy, photons are emitted by electrons that scatter off of ions, in the process decelerating and losing kinetic energy. As this is emission form a thermal plasma, the energies involve range from very small changes in the overall energy (long-wavelength radio emission) up to energies on the order kT, where a typical thermal plasma temperature is 10^4 K.

We can write the free-free emissivity of a thermal plasma (the power that is radiated by this process per unit frequency per unit volume per steradian) as:

$$j_{ff,\nu} = \frac{8}{3}\left(\frac{2\pi}{3}\right)^{1/2} g_{ff}\frac{e^6}{m_e^2c^3}\left(\frac{m_e}{kT_e}\right)^{1/2} e^{-h\nu/kT_e} n_e Z_i^2 n_i$$

Some points of interest to note here: in the Rayleigh-Jeans limit (the radio regime), $h\nu << kT_e$ and $e^{-h\nu/kT_e} \sim 1$. If for some wild reason you want to evaluate this by hand, don't forget that this formulation assumes cgs units (e.g., Statcoulomb units of charge). n_e is the electron density and n_i is the ion density; for a pure-hydrogen nebula, $n_i = n_p$ or the proton density. Z_i is the ion charge number; again, for a pure-hydrogen nebula, this is just 1. Finally, g_{ff} is the Gaunt factor.

We are not going to dig too deeply into the Gaunt factor, as Draine is itself not particularly chatty on this subject, merely ascribing the Gaunt factor to "quantum effects" and giving some analytic approximations to a quantity that typically must be evaluated numerically. Classically, $g_{ff} = 1$, and we will note that if g_{ff} is a constant, then the emissivity would not vary as a function of frequency, and the spectral energy distribution of free-free emission would be essentially flat as a function of frequency.

We can evaluate two limiting conditions for estimates of the Gaunt factor: the "plasma frequency" $\nu_p = 8.98(n_e/\mathrm{cm}^{-3})^{0.5}$ kHz and the frequency corresponding to the thermal plasma energy $\nu_{th} = kT_e/h$. For a typical electron density of $n_e \sim 10^3$ cm^{-3} and electron temperature of $T = 10^4 K$, $\nu_p = 300kHz$ and $\nu_{th} = 220THz$ For $nu_p << \nu << \nu_t h$, which is well-satisfied by typical radio/mm emission with frequencies 1-100 GHz, the Gaunt factor (and thus the emissivity and the overall shape of the free-free spectrum) is proportional to $\nu^{-0.118}$.

Remembering the definition of the source function $\frac{j_\nu}{\kappa_\nu} = S_\nu$, and noting that for a thermal plasma we can say $S_\nu = B_\nu$, we can use our definition of the free-free emissivity to determine the free-free absorption coefficient. For simplicity, we will stick to the Rayleigh-Jeans or radio regime, where $B_\nu = \frac{2\nu^2 k_B T}{c^2}$ Then we can define

$$\kappa_{ff,\nu} = \frac{4}{3}\left(\frac{2\pi}{3}\right)^{1/2} g_{ff}\frac{e^6}{m_e^2 c\nu^2}\left(\frac{m_e}{kT_e}\right)^{1/2} g_{ff} n_e Z_i^2 n_i$$

3.1.2 Emission Measure

The emission measure (EM) of a thermal plasma is both a quantity that is relatively easy to determine from observations, and a quantity that describes several useful properties of the plasma.

Draine introduces the emission measure starting with the equation of radiative transfer for a uniform-temperature source:

$$I_\nu = I_{\nu,0}e^{-\tau} + \left[\frac{j_{ff,\nu}}{\kappa_{ff,\nu}}\right](1 - e^{-\tau})$$

(note that if there is no background radiation source for which are worried about the propagation of radiation through the nebula, the $I_{\nu,0}$ term can be ignored.)

We can rewrite the equation of radiative transfer by incorporating the emission measure:

$$I_\nu = I_{\nu,0}e^{-\tau} + \left[\frac{j_{ff,\nu}}{n_e n_p}\right]\frac{(1 - e^{-\tau})}{\tau}EM$$

Or, ignoring the background radiation term,

$$I_\nu = \left[\frac{j_{ff,\nu}}{n_e n_p}\right]\frac{(1 - e^{-\tau})}{\tau}EM$$

Then, by definition,

$$EM \equiv \int n_e n_p ds = \left[\frac{n_e n_p}{\kappa_{ff,\nu}}\right]\tau$$

For a pure-hydrogen nebula, $n_e = n_p$ and we can then just write

$$EM = \int n_e^2 ds$$

Since $\kappa_{ff,\nu}$ is itself proportional to $n_e n_i \sim n_e^2$ this means the emission measure is basically proportional to the optical depth of the nebula. Note that the typical units of the emission measure are *very* non-standard: they are pc cm^{-6}.

For a spherical, uniform-density HII region you can skip the integral and define the peak emission measure as

$EM_{peak} = n_e^2 D_{HII}$ where D_{HII} is the diameter of the HII region.

Example: Draine 10.4

Consider an HII region with $n(\mathrm{H}^+) = n_e = 10^3\ \mathrm{cm}^{-3}$, $T = 8000$ K, and radius R = 1 pc. Estimate the radio frequency at which the optical depth across the diameter of the HII region is $\tau = 1$. To make this estimate you may assume that the Gaunt factor $g_{ff}\sim 6$.

We will use two equations:

(1) Draine 10.14:

$$\frac{\kappa_{ff,\nu}}{n_e n_i} \approx \frac{4}{3}\left(\frac{2\pi}{3}\right)^{1/2} \frac{e^6}{(m_e k_B T)^{3/2} c \nu^2} Z_i^2 g_{ff}$$

(2) Draine 7.14

$$\tau_\nu = \int_s \kappa_\nu ds$$

For $s = D_{HII}$

$$\tau_\nu = \kappa_\nu D_{HII}$$

Putting these together (solving for τ =1)

$$\nu^2 = \frac{4}{3}\left(\frac{2\pi}{3}\right)^{1/2} \frac{e^6}{c\,(m_e k_B T)^{3/2}} Z_i^2 g_{ff} n_e\, n_i D_{HII}$$

3.2 Continuum Radiation

Draine really discusses continuum radiation mechanisms only in the context of background radiation fields. This is probably a correct and complete description of continuum radiation for a purely theoretical consideration of the ISM, however it misses some important nuances for observers. The strength and frequency-dependence of the ambient (background) radiation field is indeed extremely important to consider when considering ionization, absorption and stimulated emission processes in the ISM gas. Background radiation from starlight, dust-reprocessed starlight, X-ray emission from plasma can all be expected to be present and impacting the ISM conditions.

In general, my issue with Draine here is that it does not consider the fundamentally inhomogeneous nature of the ISM. Focusing on the solar neighborhood and defining typical intensities of the background radiation in this part of our galaxy is important, but is also not representative of many environments interesting to study (the centers of galaxies, regions in close proximity to massive stars and star clusters, and the interiors of dense clouds). In particular, inside of dense clouds the background stellar radiation field is unimportant, though you can still expect limited penetration from X-rays. Here some of the most important continuum processes to consider (apart from the CMB background) are not really discussed: thermal dust radiation, and the ionizing radiation from cosmic ray interactions.

Direct observations of the continuum radiation itself (particularly the free-free and dust thermal emission) can yield valuable insight into the properties of the ISM. However, when studying discrete sources of continuum emission one very often has to contend with the fact that these continuum emission sources are not present in isolation. The very nature of the cycle of star formation (particularly massive star formation) means that you can have dust emission from dense clouds, free-free radiation from the HII regions surrounding massive stars, and synchrotron emission from young supernova remnants, all in close proximity. Here, I supplement Draine with a brief overview of the observational properties of three main types of continuum emission that you would expect to observe at wavelengths from the radio to the infrared.

3.2.1 Synchrotron Radiation

Although it is intrinsically low-frequency radiation, synchrotron is associated with high-energy processes. In fact, if one looks at multiwavelength images of the Milky Way, one sees many more similarities between synchrotron emission and the x-ray and gamma-ray emission than with other radio/IR emission sources like ionized gas, neutral gas, and dust.

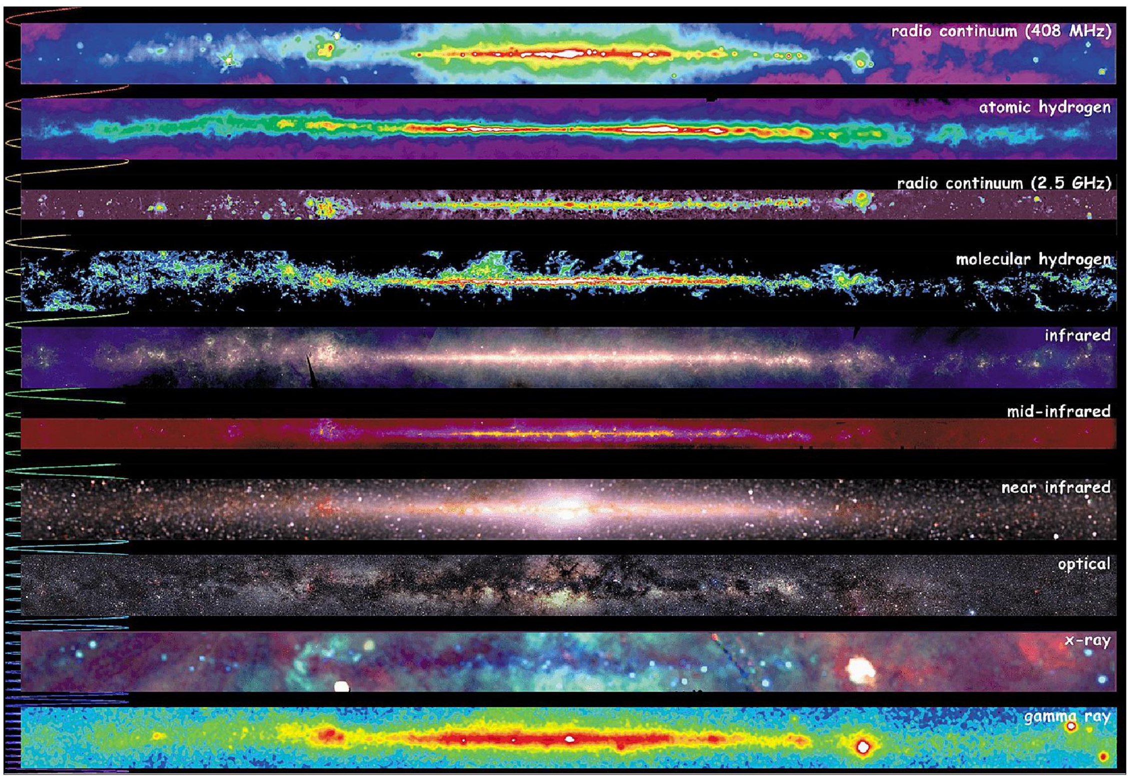

Figure 3.1: *MW_plane.jpeg*

Indeed, synchrotron and gamma-ray emission processes can be directly linked, as the same relativistic electrons that give off synchrotron photons are also responsible for inverse Compton scattering of photons to gamma-ray energies/frequencies.

The frequency-dependence of synchrotron emission, resulting in the observed spectrum of this radiation, is dependent on several variables, including the energy distribution of the radiating electrons. An important consideration is that the lower-frequency photons are more likely to undergo scattering, which hinders (or eventually prevents) these photons from leaving the plasma. This is called synchrotron self-absorption, and is analogous to the situation where a gas becomes optically-thick. Taking self-absorption into account, we get a synchtron spectrum that has 3 distinct components: an optically-thick (self-absorbed) increasing spectrum at low frequencies, a turnover where self-absorption becomes unimportant, and an optically thin decreasing spectrum at higher frequencies.(this is the most commonly-observed portion of the spectrum at radio wavelengths). The synchrotron spectrum of an idealized, homogeneous cylindrical source is shown below.

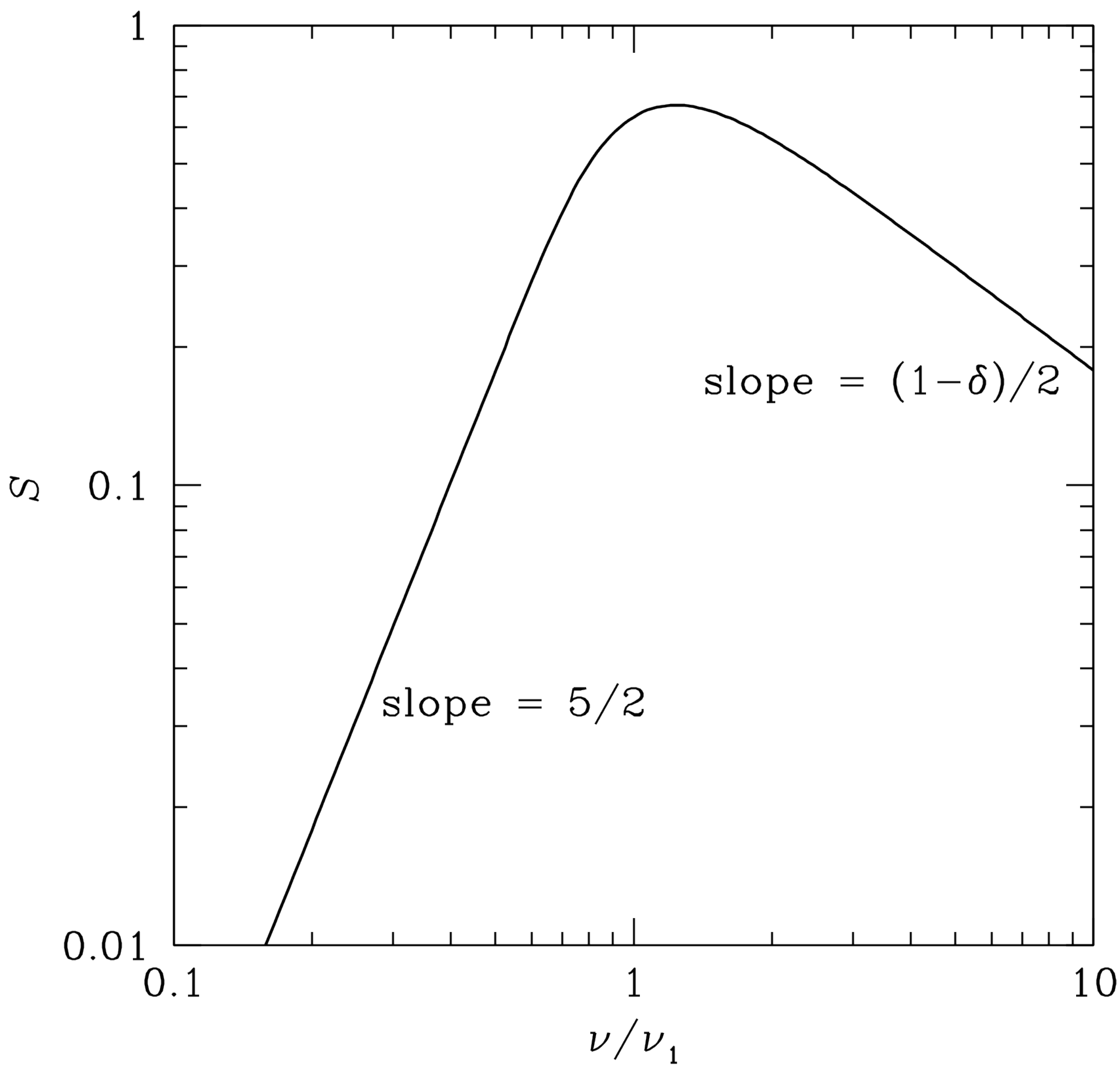

Figure 3.2: *synchrotron.png*

The two roughly linear portions of the spectrum are generally described as power laws with a spectral index $\alpha = -\dfrac{d \log S_\nu}{d \log \nu}$. The self-absorbed portion of the spectrum has an increasing power-law spectral index of $\alpha < 5/2$. The optically-thin portion of the spectrum has a decreasing power law spectral index that depends on the amount of relativistic beaming, characterized by the Doppler boosting factor δ. The power law index of this portion of the spectrum varies widely, with typically-observed values ranging from a flat spectrum ($\alpha \sim 0$) for AGN, to $\alpha \sim -0.7$ for radio galaxies and $\alpha \sim -2$ for pulsars. Typical turnover frequencies are too low to be detected, but some sources like quasars and pulsars can have turnover frequencies of a few hundred MHz - 1 GHz.

3.2.2 Free-Free Radiation

This was discussed in good detail in **Draine Ch. 10**, and we summarized the theoretical expectation for a thermal plasma already in this lecture, but I want to also highlight some of the key observational properties implied by all those equations.

Similar to what we just discussed for synchrotron radiation, a typical free-free spectrum is characterized by both an optically-thick (steeply rising) and an optically-thin (flat or slightly decreasing) component of the spectral energy distribution. For sources with large electron densities, the turnover frequency can be pushed to frequencies of tens of GHz. Below, I summarize physical and observational properties of different types of HII regions

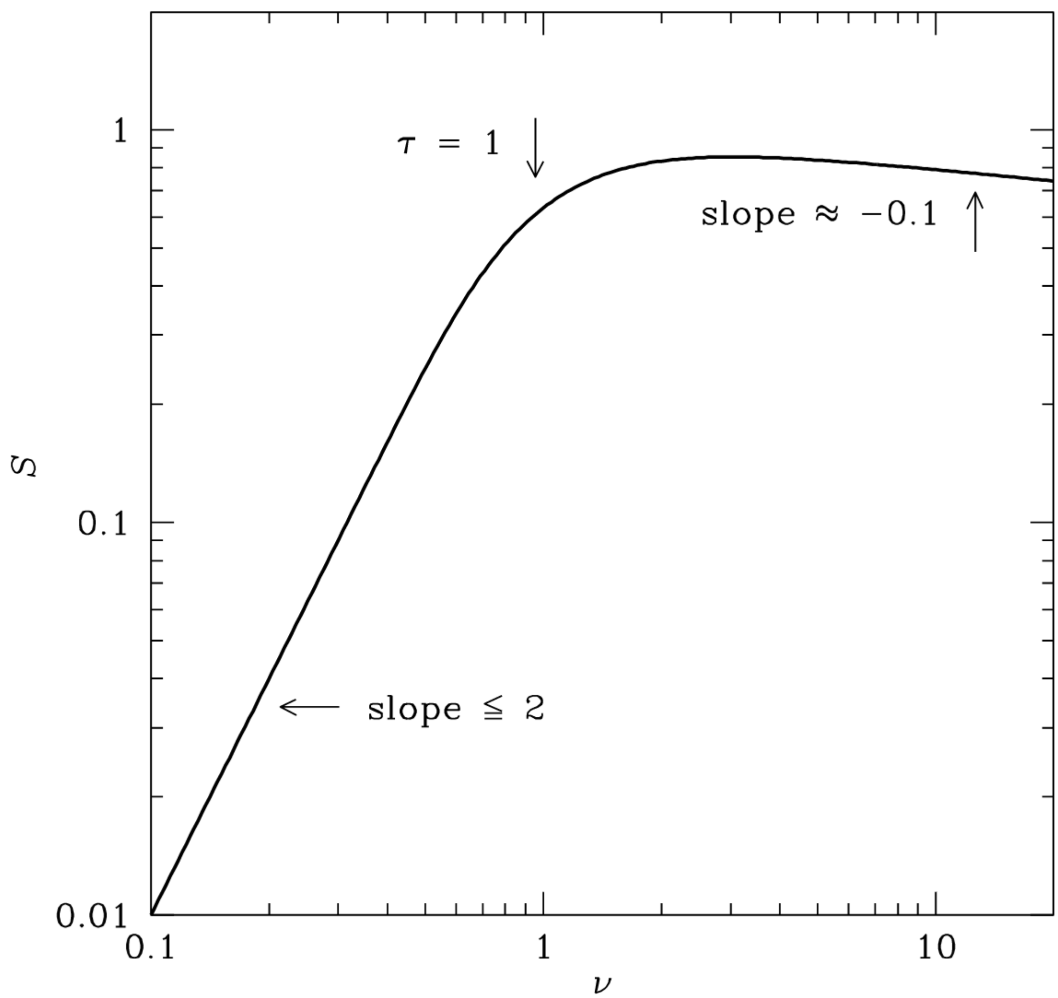

Figure 3.3: *freefree.png*

Giant HII regions Relatively short-lived nebulae (ages up to a few million years), surrounding OB associations or young massive clusters. The Orion Nebula and the Tarantula nebula (surrounding 30 Doradus) are a classic examples of giant HII regions. These are typically the HII regions that you see in optical images of other galaxies.

Diameters: 10's - 100's of parsecs

Average n_e: 1 - 100 cm^{-3}

Emission measure: 100- 10^5 pc cm^{-6}

Turnover frequency: $\lesssim$ 1 GHz

Compact HII regions Relatively short-lived nebulae (ages up to $\sim$ a million years) that can be excited by a single O-type star.

Diameters: $\sim 0.1 - 1$ pc

Average n_e: $\sim 10^3$ cm^{-3}

Emission measure: $\sim 10^6$ pc cm^{-6}

Turnover frequency: $\sim$ 10 GHz

Ultra/Hypercompact HII regions Generally the youngest sources (ages $< 10^5$ years), corresponding to very early stages of massive star formation.

Diameters: $\lesssim$ 0.05-0.1 pc

Average n_e: $\geq 10^4 - 10^5$ cm^{-3}

Emission measure: $\geq 10^7 - 10^8$ pc cm^{-6}

Turnover frequency: $\sim 15 - 50$ GHz

3.2.3 Dust Emission

In fairness, Draine devotes MANY chapters to the microphysics of dust (we'll get there), and is one of the foremost experts on this subject. Here, I just want to briefly summarize the continuum radiation properties of a cloud of dust at some temperature T. Dust emission is generally described as a 'modified blackbody', where the main modification is a result of the fact that dust grains are small, and so are inefficient radiators at wavelengths larger than their sizes. This effectively steepens the Rayleigh-Jeans portion of the Planck distribution.

As a reminder, in the Rayleigh-Jeans regime, $I_\nu \propto \nu^\alpha$ Optically-thin dust has a typical spectral index that is the Rayleigh-Jeans spectral index (2) plus the emissivity β (which depends on dust grain size and composition) and typically ranges between 1.5-2:

$\alpha = 2 + \beta \sim 3.5 - 4$

For optically-thick dust, the spectral index just approaches the Rayleigh-Jeans value of $\alpha = 2$.

The peak of the dust spectral energy distribution typically occurs around far-infrared wavelengths or THz frequencies, and the location of the peak can be used to determine the dust temperature. Dust emission generally becomes detectable at millimeter wavelengths, starting at frequencies as low as 30-40 GHz, and dominating other continuum emission processes at frequencies larger than 200 GHz.

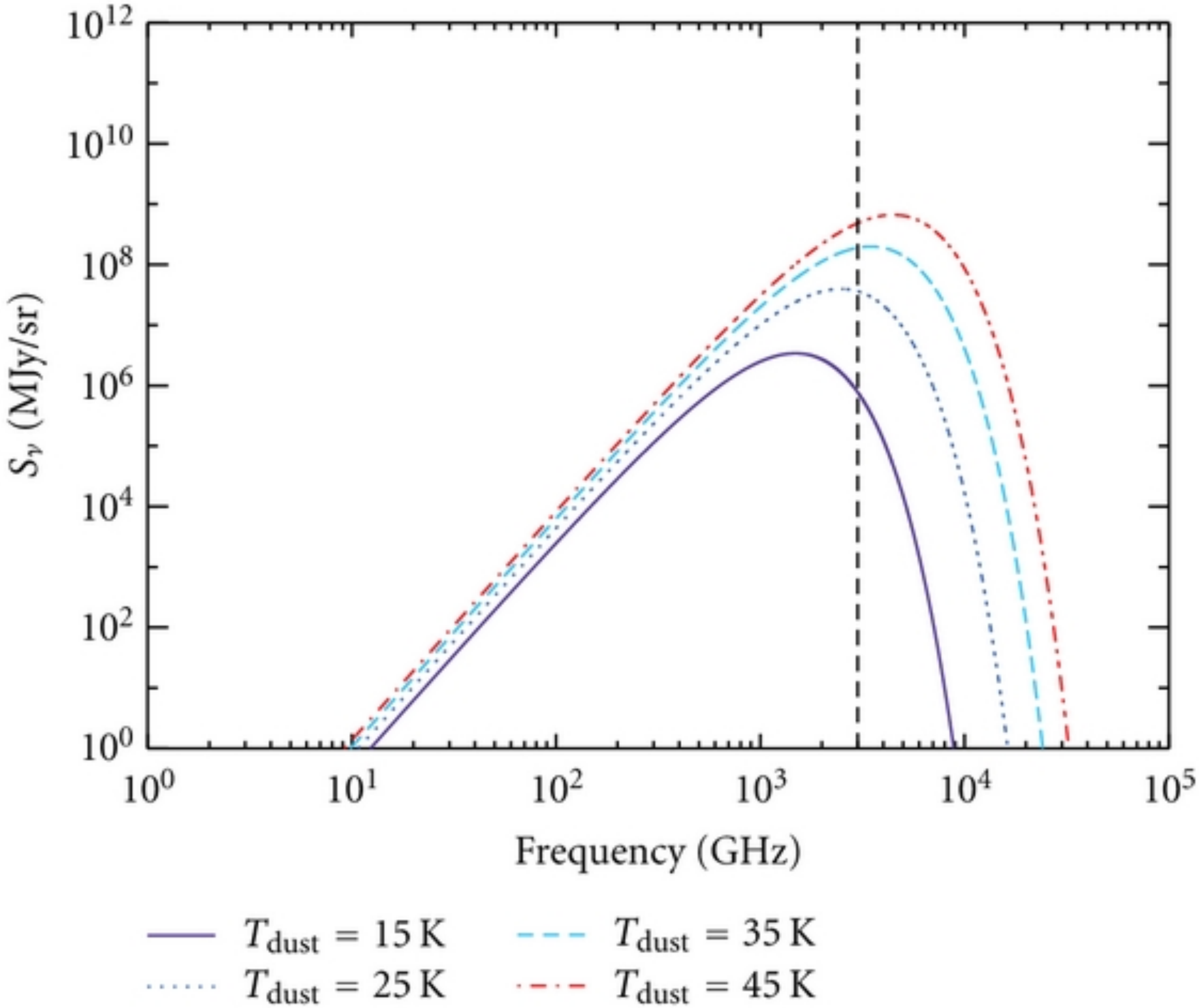

Figure 3.4: *dust.png*