Scientific Frontiers in Research on Extrasolar Planets
ASP Conference Series, Vol. 294, 2003
D. Deming and S. Seager, eds.

The Snowline in Protostellar Disks

Morris Podolak
Dept. of Geophysics and Planetary Sciences
Tel Aviv University, Tel Aviv, Israel

Abstract. The energy balance for ice grains in a protostellar disk is computed, taking into account radiative heating and cooling as well as heating and cooling by the ambient gas. The place in the nebula where ice grains are stable is determined for particular nebular conditions, grain size and composition. I show how the position of the snowline depends upon these parameters.

1. Introduction

The *snowline* is the minimal distance from a star where ice grains are stable in the surrounding gas disk. The appearance of additional solid material in the form of ice grains may have helped to form the gas giants such as Jupiter and Saturn. The presence or absence of ice grains will also affect the opacity of the nebula and the resultant temperature distribution. The position of the snowline depends not only on the pressure and temperature of the gas in the disk, but also on the size and composition of the ice grains themselves.

2. Model

There are three major heating terms. The first is radiative heating, which is a proportional to the energy emitted by the source and the efficiency of absorption by the grain. If a is the radius of the grain, then its absorption cross section is given by $\sigma_{abs} = Q_{abs}\pi a^2$ where Q_{abs} is the efficiency factor for absorption. The rate of radiative energy absorption by the grain will be

$$E_{sol} = \frac{1}{4R^2}\int Q_{abs}S(\lambda)d\lambda \tag{1}$$

The subscript *sol* is used here to represent "solar", which is often the major source of radiative heating. In the optically thick midplane of the disk the radiation will be that of a blackbody at the ambient nebular temperature. Here R is the distance from the source (in the case of stellar radiation) and $S(\lambda)$ is the spectral energy distribution of this source as a function of wavelength, λ. In an optically thick region this must be modified appropriately.

A second heating term is due to the impact of gas molecules. The molecules strike with a kinetic energy corresponding to the temperature of the ambient gas, stick to the grain momentarily, and leave with a kinetic energy corresponding to the temperature of the grain. This is a means of exchanging energy with the surrounding gas. The nebular gas is, for the most part, molecular hydrogen. If n_{H_2} is the number density of the nebular gas, and T_{gas} is the gas temperature, then the heating/cooling rate is given by

$$E_{gas} = \frac{n_{H_2}}{4}\sqrt{\frac{8kT_{gas}}{\pi m}}\frac{jk\left(T_{gas} - T_{grain}\right)}{2} \tag{2}$$

where k is Boltzmann's constant, T_{grain} is the grain temperature, m is the mass of a gas molecule, and j is the number of degrees of freedom for the motion of the gas molecule.

In addition to collisions by ordinary gas molecules, water vapor can condense onto the grain. In such a case the molecule is assumed to stick to the grain and release a quantity of heat, q. The heating rate is given by

$$E_{cond} = \frac{n_{H_2O}}{4}\sqrt{\frac{8kT_{gas}}{\pi m}}q \tag{3}$$

Cooling is accomplished by reradiation

$$E_{rad} = \int Q_{abs}F\left(\lambda, T_{grain}\right)d\lambda \tag{4}$$

where F is the Planck function for a black body at a temperature T_{grain}. A second effect is evaporative cooling by H_2O sublimation from the grain. This is given by

$$E_{vap} = q\frac{P_{vap}(T_{grain})}{\sqrt{\pi mkT_{grain}}} \tag{5}$$

The efficiency factor Q is computed from Mie theory (e.g., van de Hulst 1981) assuming that the grains are spherical and homogeneous. The wavelength-dependent index of refraction for ice is taken from Warren (1984). The single scattering albedo of a grain depends only weakly on the real part of the refractive index, and is much more sensitive to the imaginary part. Water ice is essentially transparent for wavelengths between 0.3 and 2 μwavelength range that contains most of the radiation of a solar-type star. If any other material that does absorb at these wavelengths ("dirt") is mixed in with the ice, even in very small amounts, it will allow the grain to absorb in this range. Pure ice grains will therefore have very different albedos in this range from dirty ice grains.

A second factor in determining the efficiency of absorption and emission of radiation is the size parameter $x \equiv 2\pi a/\lambda$. For $x < 1$ (small grains) $Q_{abs} \sim x^4$, and absorbtion (or reradiation) is very inefficient. Solar radiation peaks at around 0.5 μm, so 1 μm grains can be considered large, and will absorb efficiently. In the optically thick midplane region, however, a grain will see the ambient radiation field. In the region where ice grains are stable, this might correspond to a temperature of $\sim$ 300K, and the radiation will have a wavelength of around 10 μm. A 1 μm grain in this region will be small and absorb inefficiently. Similarly, for radiative cooling of a grain at around $T \sim$ 100K the relevant wavelength is $\sim$ 30 μm.

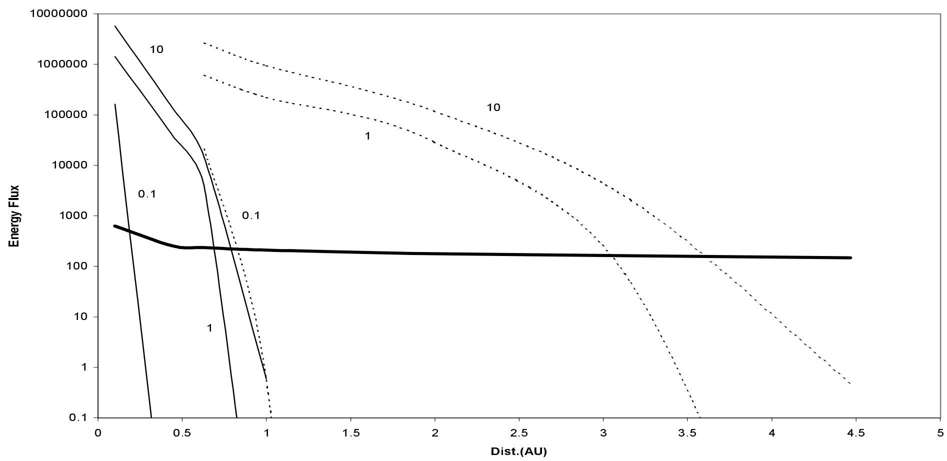

Figure 1. Energy flux of H_2O condensation (heavy solid curve) and evaporation for pure ice grains (solid curves) and dirty ice grains (dotted curves) for grains of radius 0.1, 1, and 10 μm for the photosphere of a disk with $\alpha = 10^{-4}$ and $\dot{M} = 10^{-9} M_{\odot} yr^{-1}$

The temperature of a grain can be determined by equating the heating and cooling terms and solving for T_{grain}. The resulting temperature will depend upon whether the grain is composed of pure ice or dirty ice, whether it is in the photosphere or the optically thick midplane, and upon its size.

3. Results

In addition to the grain temperture, it is possible to compare E_{cond} with E_{vap}. The point where they are equal is the position of the snowline. I have computed snowlines for models of an accretion disk computed by Bell et al (1997) to show how this position can vary as a function of the relevant parameters.

Figure 1 shows the energy flux carried by H_2O vaporization for pure ice grains (solid lines) and ice grains with 10% of generic "dirt" mixed in by mass (dotted lines) for the photosphere of a protostellar α-disk model with $\alpha = 10^{-4}$ and $\dot{M} = 10^{-9}_{\odot} yr^{-1}$. The heavy solid curve is the energy flux released by condensation heating. The snowline occurs where the vaporization curve crosses the condensation curve. This occurs at different distances for different grain sizes. Note that the smallest grains, which cannot cool effectively by re-radiation, are cooled by interaction with the gas, and by evaporation. Their snowline forms closest to the star.

Figure 2 shows the same thing for a disk with $\dot{M} = 10^{-9}_{\odot} yr^{-1}$. Here the gas densities are much lower and temperatures are much higher. This sufficiently influences the grain temperature, so that the snowline is shifted to larger distances. In addition, the dependence on grain size is reversed. The smallest grains, in addition to not re-radiating effectively, are difficult to cool by interac-

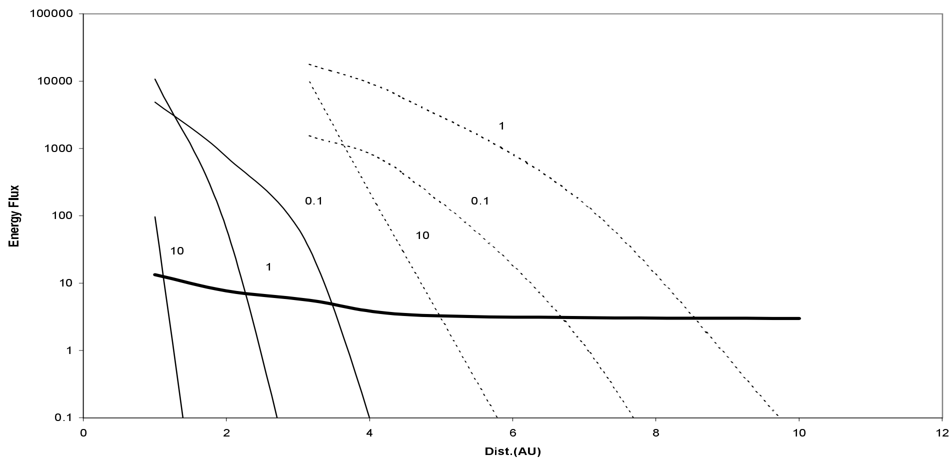

Figure 2. Same as for fig. 1, but for $\alpha = 10^{-4}$ and $\dot{M} = 10^{-5} M_{\odot} yr^{-1}$

tion with the gas because of the lower gas density and higher temperature, and their snowline is the farthest from the star.

In midplane, the radiative heating is from the ambient gas. This means that most of the radiatiation is in the several micron range, and even pure water absorbs well. All but the largest grains are "small" compared to the wavelength of the radiation, and the gas density is higher so that the gas contributes more to regulating the grain temperature. As a result, the snowline is nearly independent of grain size and composition.

4. Conclusions

The size and composition of ice grains in the photosphere affect the position of their snowline. This, in turn, affects the amount of solids in the nebular disk, and influences the rate of protoplanet growth. In addition, because the grain size distribution will be different for different compositions, the opacities will be different as well. As a result, the temperatures computed for nebular models will depend on the assumptions made for these parameters. These temperature profiles and opacities have to be computed self-consistently.

References

Bell, K. R., Cassen, P. M. Klahr, H. H. & Henning, T. 1997, ApJ, 486, 372

van de Hulst, H. C. 1981, Light Scattering by Small Particles, (New York: Dover)

Warren, S. G. 1984, Appl.Optics, 23, 1206