Emissivity of Ammonia Ice

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Abstract

Bodies in the outer Solar System may consist of, or be covered by, solid ammonia. Their temperature depends on its emissivity. We calculate that emissivity as a function of frequency, angle and polarization and convolve it with a Planck function to obtain its integrated emissivity.

Keywords: ammonia ice, Kuiper Belt objects, infrared, emissivity

1. Introduction

The equilibrium temperature of a Solar System object is determined by the balance between Solar heating and its infrared thermal emission. This depends on its albedo for Solar radiation and its infrared emissivity averaged over a Planck function at its surface temperature. Small bodies in the Kuiper Belt and elsewhere in the outer Solar System, such as Ultima Thule (486958; 2014 MU69) and elsewhere in the outer Solar System may be made of ices. Vapor pressures are extremely sensitive to temperature at the temperatures \( \approx 50 \text{ K} \) found there, so quantitative determination of temperature is necessary to calculate the rate of evaporative loss and vapor transport across their surfaces. This requires quantitative knowledge of the infrared emissivity.

Ammonia ice is of particular interest because in this temperature range its vapor pressure varies from values so low that it is insufficient to deposit sub-micron thick layers on colder parts of a body’s surface in the age of the Solar System to values so large that a 10 km-sized body would not survive that time \([\text{Katz}, 2019]\). In contrast, the vapor pressures of water and methanol ices are so low that evaporation is negligible, while those of methane and even carbon dioxide are so high that they would be lost entirely from a body with negligible gravity.
2. Calculation

We use the complex infrared optical constants of ammonia ice (Martonchik, Orton & Appleby, 1984) to calculate its reflectivity $R(\nu, \theta, \hat{n})$ as a function of frequency $\nu$, angle of incidence $\theta$ and polarization $\hat{n}$ from the Fresnel relations. The emissivity $\epsilon(\nu, \theta, \hat{n}) = 1 - R(\nu, \theta, \hat{n})$.

We assume a homogeneous half-space of solid ammonia; transmitted energy is eventually absorbed, either by the imaginary part of the refractive index (which is very small in most of the spectrum) or by embedded mineral matter (dirt). If this assumption were not made it would be necessary to specify the depth of the ice layer, which is not known and to match electromagnetic boundary conditions at both interfaces. In fact, the low ($\approx 0.1$) visible albedo of Ultima Thule (Stern et al., 2019) implies a deep homogeneous layer of ice in which some mineral matter is embedded; if the ice were finely divided, like snow, the visible albedo would be high because of scattering at interfaces between ice and vacuum (or air, for terrestrial snow).

Once the mean infrared reflectivity $\langle R(T) \rangle$, averaged over a Planck function, is known, the equilibrium temperature may be calculated. There are two simple cases. If sunlight is normally incident with intensity $I_\odot$ the steady state temperature is

$$T_{\text{normal}} = \left( \frac{I_\odot(1 - A)}{\sigma_{SB}(1 - \langle R \rangle)} \right)^{1/4},$$

(1)

where $A$ is the Solar albedo, averaged over its spectrum, and $\sigma_{SB}$ is the Stefan-Boltzmann constant. Averaging over a spherical body yields a mean temperature

$$T_{\text{mean}} = \left( \frac{I_\odot(1 - A)}{4\sigma_{SB}(1 - \langle R \rangle)} \right)^{1/4},$$

(2)

The Fresnel relations for interfaces between dielectric (non-magnetic) materials are

$$R_s = \frac{\sqrt{1 - \sin^2 \theta - \sqrt{n^2 - \sin^2 \theta}}^2}{\sqrt{1 - \sin^2 \theta + \sqrt{n^2 - \sin^2 \theta}}}$$

(3)

and

$$R_p = \frac{n^2 \sqrt{1 - \sin^2 \theta - \sqrt{n^2 - \sin^2 \theta}}^2}{n^2 \sqrt{1 - \sin^2 \theta + \sqrt{n^2 - \sin^2 \theta}}}.$$

(4)
where \( s \) denotes polarization in the plane of incidence, \( p \) denotes polarization perpendicular to the plane of incidence and \( n(\nu) \) is the complex relative refractive index (the index of the solid when the wave is incident from vacuum).

The mean reflectivity

\[
\langle R(T) \rangle = \frac{1}{2} \frac{\int_0^\infty d\nu \int_0^1 d\cos \theta [R_s(\nu, \theta) + R_p(\nu, \theta)]F_{\nu}(T)}{\int^\infty_0 d\nu \int_0^1 d\cos \theta F_{\nu}(T)},
\]

where \( F_{\nu} \) is the Planck function. While \( R_s \) and \( R_p \) are properties of the material, \( R(T) \) depends on its temperature through \( F_{\nu}(T) \).

3. Results

The results are shown in the Figures.

4. Discussion

The Planck-averaged emissivity at temperatures of interest for the Kuiper Belt, where solid ammonia is likely to be encountered, is \( \approx 0.75 \) and varies only slightly with temperature. Inclusion of this factor in Eqs. 1 and 2 yields a temperature about 7.5% higher than would be estimated if the body were a black body radiator. The vapor pressure is so sensitive to temperature that this can be significant.

Finely divided ammonia “snow” has higher reflectivity (lower emissivity) because light scatters at every interface between solid and vacuum. This is analogous to the high albedo of terrestrial water-snow. However, it is less extreme, because at wavelengths \( \lambda \sim 100 \mu \) near the 50 K black body peak the imaginary part of the refractive index \( n_i \sim 0.1 \) but varies rapidly with \( \lambda \) (Martonchik, Orton & Appleby, 1984), suggesting \( 1 - R \sim 0.1 \). Multiple scatterings further reduce \( R \), but a quantitative calculation would require detailed knowledge of the geometry. However, this factor is offset by the fact that the Solar albedo \( A \) of pure ammonia snow is likely to be close to unity (Martonchik, Orton & Appleby, 1984) give \( n_i = 2-4 \times 10^{-5} \) for blue and red light). Qualitatively, pure ammonia snow will be significantly cooler than solid ammonia (with or without mineral contamination), so that any vapor-deposited ice (hoarfrost) will accumulate further material if the evaporation rate is significant.
Figure 1: Emissivity $(1 - R)$ for infrared radiation with $\lambda = 50\mu$ as a function of angle of incidence.
Figure 2: Emissivity $(1 - R)$ as a function of wavelength and polarization, averaged over solid angles. The Planck function $F_\lambda$ at 50 K, with arbitrary normalization, is shown for comparison.
Figure 3: Frequency-integrated emissivity \((1 - \langle R \rangle)\) as a function of temperature, averaged over solid angles, polarization and Planck function.
References

Katz, J. I. [arXiv:1902.00997]

Martonchik, J. V., Orton, G. S. & Appleby, J. F. 1984 Appl. Optics 23, 541.

Stern, S. A. et al. 2019 [arXiv:1901.02578]

Competing Interests

The authors declare no competing interests.