N79-17814

MILLIMETER WAVE RADIOMETRY AS A MEANS OF DETERMINING COMETARY SURFACE AND SUBSURFACE TEMPERATURES

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Abstract

Thermal emission spectra for a variety of cometary nucleus models are evaluated by a radiative transfer technique adapted from modeling of terrestrial ice and snow fields. It appears that millimeter wave sensing from an interplanetary spacecraft is the most effective available means for distinguishing between alternate models of the nucleus and for evaluating the thermal state of the layer --which is below the instantaneous surface-- where modern theories of the nucleus indicate that sublimation of the cometary volatiles actually occurs.

Introduction

Although the cometary nucleus has never been directly resolved, its general nature has been deduced. According to the icy conglomerate model (Whipple 1950), a cometary nucleus is a solid, inhomogeneous mixture of ices and refractory material. The uppermost layer of the nucleus of a comet that has been exposed to solar heating is now thought to be a crust of refractory material, from which the volatiles have been removed by sublimation. This crust is supposedly an open structure (c.f., Mendis and Brin, 1977) through which flow the gases sublimating from the frozen volatiles below. Its thickness depends upon the comet's heliocentric distance, previous exposure in the inner solar system, and other factors. The crust must serve as an insulating layer, with its external surface in rough equilibrium with solar radiation. The interface between the crust and the region below would be at the sublimation temperature of the dominant ice component. This temperature is very important physically. It is determined by the balance among the heat input from the sun and any other source, the heat going into sublimation, and heat conducted inward to the even colder central part of the nucleus. This interface layer is the source of the gases that make up the coma and tail of the comet. To understand the nature and physical state of the nucleus it is necessary to determine the temperature gradients in the outer nucleus and the temperature at this interface.

Thermal Sensing

Millimeter wave radiometry is a demonstrated technique for remote sensing of terrestrial ice fields (c.f., Chang et al, 1976). Experimenters have been able to determine basic ice field parameters, such as temperature gradients and particle sizes. Measurements have been made from both earth-orbiting spacecraft and from aircraft, and thus much flight-proven hardware exists. It seems logical to consider this technology for application to the investigation of the icy conglomerate nucleus of a comet.

Millimeter wave radiometry should be considered in the context of other applicable technology, notably infrared radiometry. With no interference from dust in the coma, both techniques will yield data on the thermal state of the nucleus. However, infrared measurements will tell only the temperature of the external surface, and will not provide hard data on the temperature of the interface layer where sublimation occurs. They also are subject to interference from infrared radiation by superheated dust particles in the inner coma, observed in some comets, which would effectively screen the nucleus from observation. Dust comas are, however, transparent to millimeter waves. In addition, millimeter waves of different wavelengths enable observation of the radiation emerging at different depths in the nucleus. In particular, multi-channel millimeter wave radiometry will enable the determination of the interface layer temperature and the thermal gradient in the vicinity.

Nucleus Models

We have made models of the outer nucleus to establish the validity of the proposed use of millimeter wavelengths to probe the cometary surface and subsurface layers. Numerical solutions to the radiative transfer equation originally developed at Goddard Space Flight Center for the investigation of terrestrial snow and ice fields have been modified to deal with a two-component (refractory and volatile) medium. In a multi-layer, plane-parallel aproximation, the models are used to predict the brightness temperature of the hypothetical comet nucleus as a function of wavelength. The work takes into account Mie scattering and Fresnel reflection and transmission coefficients at the surface, and except for horizontal inhomogeneities, it should be realistic. Parameters that can be modeled include surface temperature, subsurface temperature gradient, relative fractions of the volatile and refractory components in the various layers, indices of the refraction of the two components, particle size and layer thickness.

In the present models, we have assumed that the two components are water ice and sand particles. The top layer of each model is composed solely of the refractory material; its thickness is varied from model to model. Internal to the crust, the layers are composed of equal fractions of water ice particles and sand particles acting as independent spheres. All of the models assume a surface temperature of 250 K, representitive of a comet slightly closer to the sun than 1 a.u. The results in Figure 1 show that the majority of the variation of brightness temperature as a function of wavelength takes place at the short millimeter wavelengths. Thus, to discriminate among a variety of models, one should choose several wavelengths in the short millimeter range. We have picked sample wavelengths of 1.7, 3.4, 6.9 mm and 3 cm as they are typical of what is already feasible in a state-of-the-art spacecraft radiometer system.

To illustrate how millimeter wave radiometry could be used to deduce physical parameters of the cometary subsurfce layers, Figure 2 shows the expected temperature variation for three models with different crust thicknesses. The temperature gradient and particle sizes for the three models in Figure 2 are the same. As can be seen, temperature measurements at the three millimeter wavelengths will discriminate between these three models.

Figure 3 is a plot of the expected brightness temperature as a function of wavelength for two models having the same particle size and same crust thickness, but with different temperature gradients. From brightness temperature measurements at the three short millimeter wavelengths it should be possible to deduce the temperature gradient. To further illustrate the effectiveness of millimeter wave radiometry to sample different depths below the comet surface we have calculated for each of these models the depth at which half the radiation at a given wavelength arises from above and one half from below. A sample of such calculations is shown in Figure 4. We conclude that millimeter wave radiometry is the most suitable way to remotely sense the cometary subsurface layers. Short of a physical landing on a comet surface, it may be the ony feasible way to investigate the energy balance, temperature structure, and physical nature of the nucleus' near-surface layers.

Instrument Concept and Spectrometry

We have developed a design for a multi-frequency millimeter wave radiometer for an interplanetary spacecraft. A schematic drawing is shown in Figure 5. This system would weigh about 10 kg exclusive of the one meter antenna and a 3 cm radiometer channel which we anticipate would be part of another spacecraft system. The choice of wavelengths was of course influenced by the existence of the 183-GHz water vapor band. Our design incorporates spectrometer channels at both 183 GHz and at 93 GHz in order to observe the emission of water and perhaps other molecular species.

The 183 GHz water vapor band is more easily excited than the typically observed 23 GHz water vapor band and of course cannot be observed from below the earth's atmosphere. Water is regarded as the principal component of comets, although direct detection of water in a comet has not been

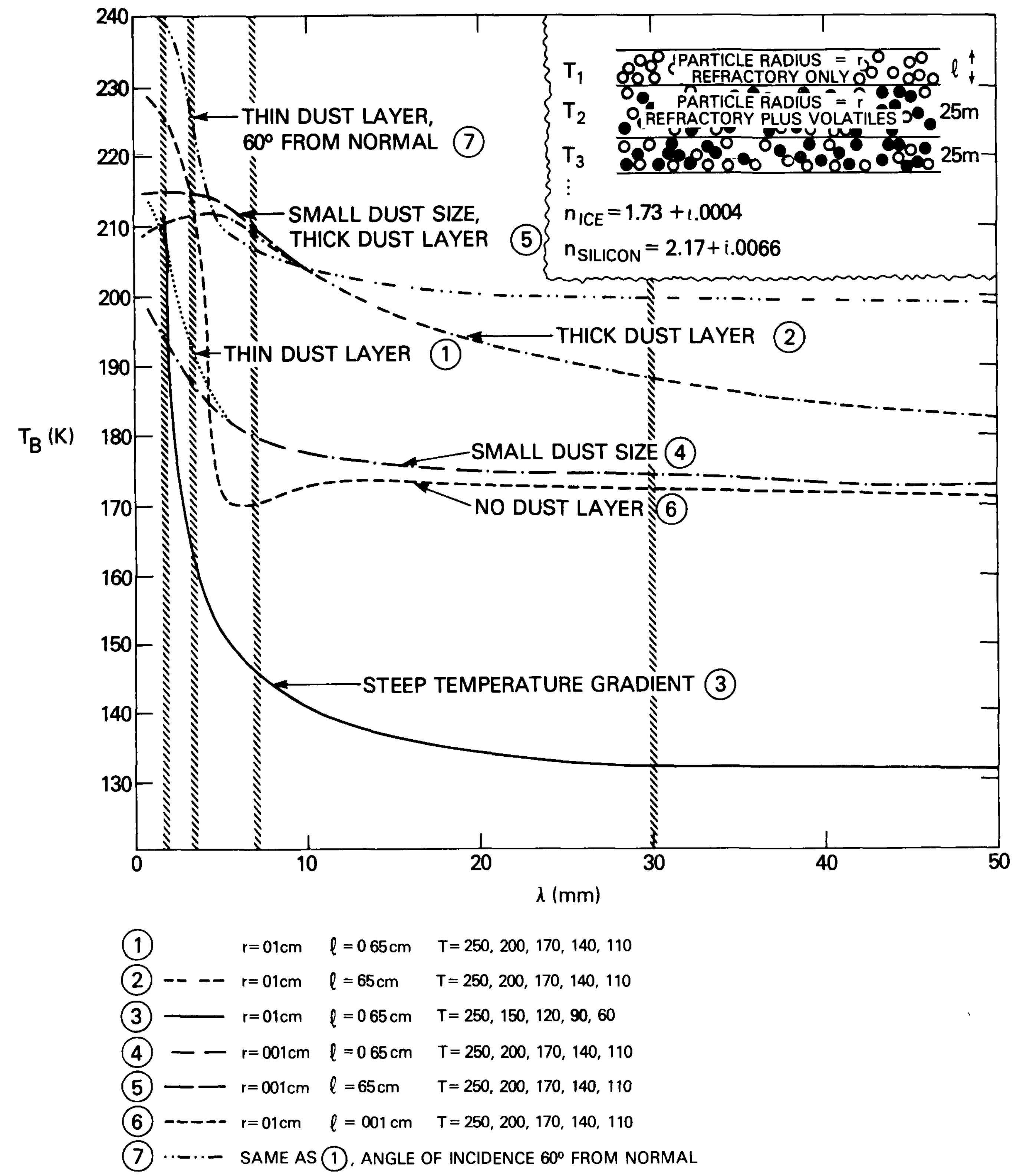

Figure 1. Brightness temperature as a function of wavelength for a variety of two component comet models. Vertical bars are typical wavelengths of observation 1.7, 3.4, 6.9 and 30 mm.

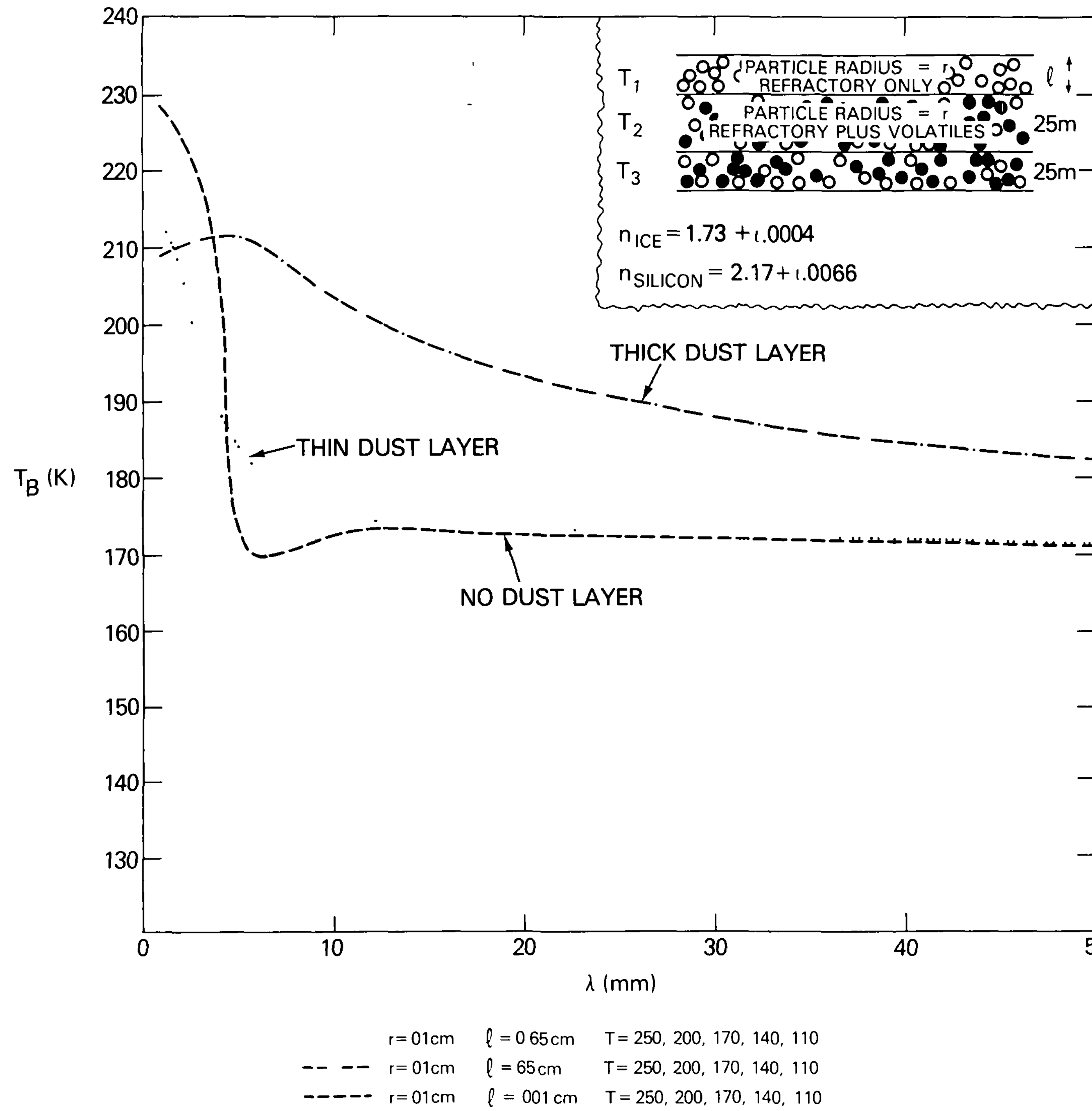

Figure 2. Brightness temperature as a function of wavelength for models with different crust thicknesses; all other parameters are the same.

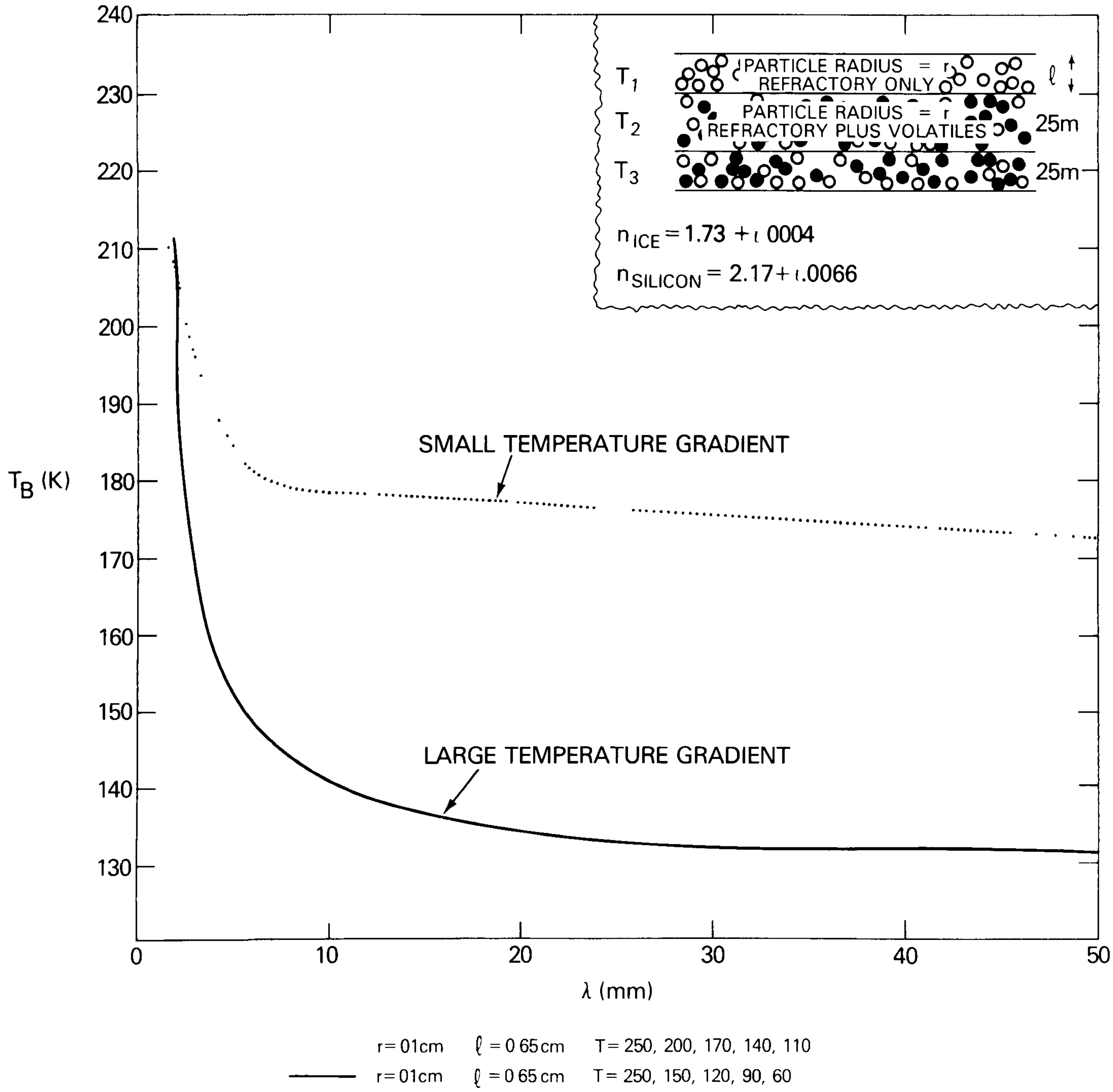

Figure 3. Brightness temperature as a function of wavelength for models with different temperature gradients through the surface crust.

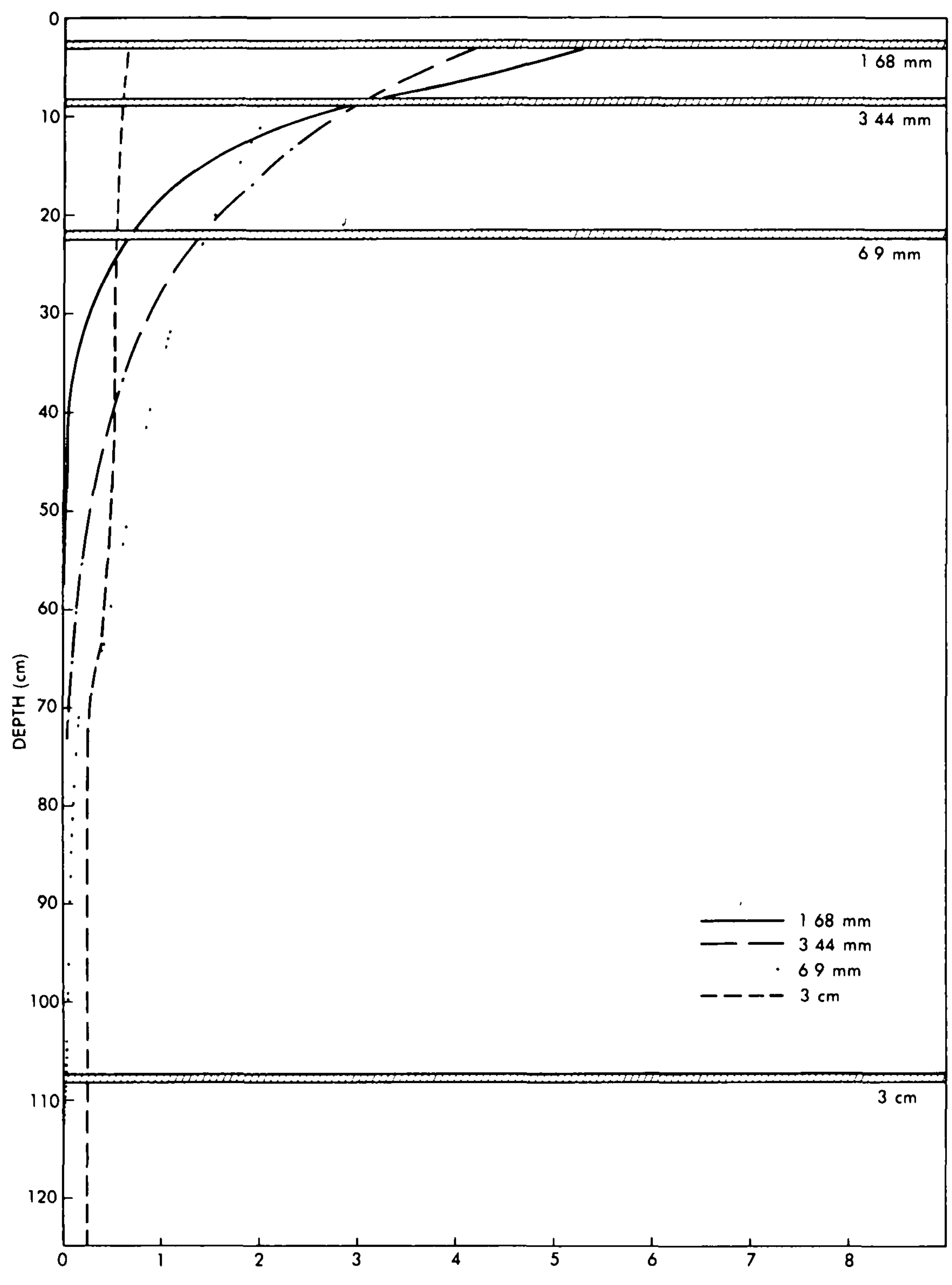

Figure 4. Weighting function as a function of depth below model comet surface. The horizontal bars indicate the depth at which the integrated weighting function becomes one-half.

MILLIMETER WAVE RADIOMETER

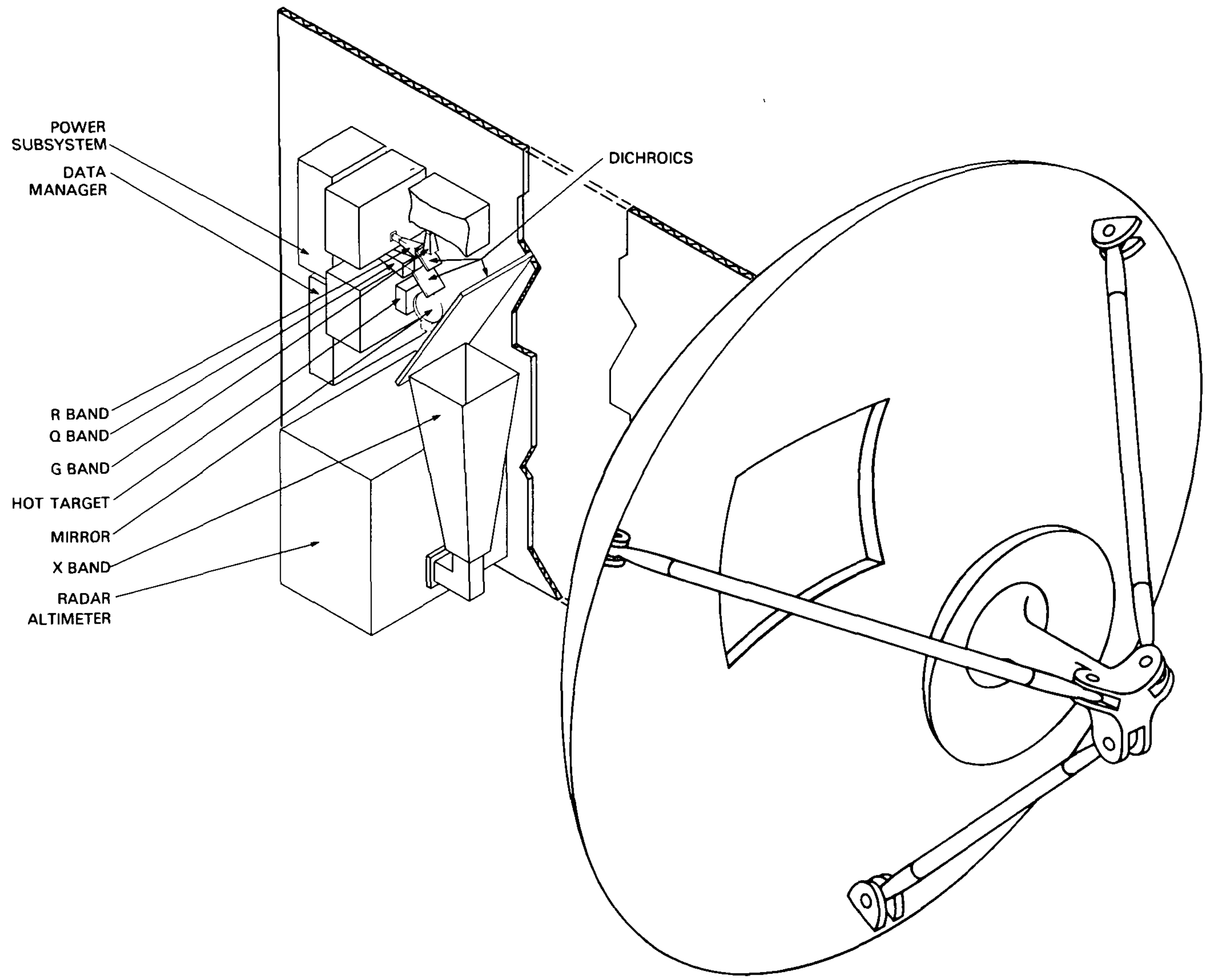

Figure 5. Conceptualized spacecraft radiometer system for 3-channel millimeter wave radiometer. The 1 meter antenna shown is assumed to be a spacecraft subsystem.

confirmed. The spectrometer channels will also permit measurements of other molecular species such as HCN and HNC from a vantage point close to the comet, eliminating the effect of beam dilution which limits the sensitivity of molecular line observations from the ground. Millimeter wave radiometry of comets cannot at the present time be carried out from the ground unless a comet were to come extremely close to the earth. Even the most sensitive millimeter wave radiometer systems used on the largest current millimeter wave telescopes are still two orders of magnitude short of making meaningful measurements of comets at distances of 1 a.u. or more from the earth.

A millimeter wave radiometer system would be a valuable component of any interplanetary spacecraft. It could probe the surface layers of icy satellites, comets and asteroids alike.

References

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