Radar Backscattering by Melting Snowflakes[1]

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It was first noted by Ryde (1946) and by Austin and Bemis (1950) that the radar bright band results mostly from melting of snowflakes as they fall through the 0°C isotherm. As the ice is gradually transformed to liquid, the refractive index and, hence, the backscattering cross sections increase, and the radar echo intensity increases to a maximum at ~200 m below the 0°C isotherm. The decrease of echo intensity below the bright band level is mostly the result of decreases of particle concentration caused by increases of terminal velocity as the particles melt. Various authors have shown that changes in particle size and shape may also contribute to changes in echo intensity through the bright band (e.g., Lhermitte and Atlas, 1963).

To obtain the refractive index of an ice–water mixture, sometimes called *spongy ice*, Ryde (1946), Austin and Bemis (1950) and others have used the expression

$$K = fK_w + (1 - f)K_i, \qquad (1)$$

where $K = (m^2 - 1)/(m^2 + 2)$, m is the complex refractive index, subscripts w and i refer to water and ice, and f is the volume fraction of water in the mixture. This expression, attributed to Debye (1929), although used by radar meteorologists for a long time, was intended by him to be applied to homogeneous mixtures, such as aqueous solutions.

Langleben and Gunn (1952) presented curves showing the backscattering cross section of melting ice spheres calculated in two ways. In one, m was obtained from (1) after assuming that the particle was a "homogeneous mixture" of water and ice.

A second curve of backscattering cross section versus fractional mass melted was obtained by assuming that the melting particle was a solid ice sphere surrounded by a shell of water. The appropriate scattering equations for this model had been published earlier by Aden and Kerker (1951). This melting model seems appropriate to some hailstones and ice pellets, but it would seem that a melting snow aggregate would more nearly resemble a mixture of water and ice.

Recently, Bohren and Battan (1980) tested various expressions other than Debye's for calculating the refractive index of ice–water mixtures. It was concluded that an expression first derived near the turn of the century by Maxwell Garnet (1904) led to calculated backscattering cross sections of spongy-ice spherical hailstones, in reasonable agreement with measurements. In the Maxwell Garnet theory, it is necessary to specify one component of the mixture as an inclusion composed of very small (with respect to the radar wavelength) spheres in a matrix of the second component. Best results were obtained by treating the spongy ice as if it consisted of ice inclusions in a water matrix.

By means of Eq. (1) in Bohren and Battan (1980), values of backscattering were calculated for the same case considered by Langleben and Gunn; these are shown in Fig. 1. The curves are for backscattering of 3.21-cm waves by a sphere having a diameter of 0.129 cm and hence $\alpha = \pi D\lambda^{-1} = 0.126$.

In a recently completed paper (Bohren and Battan, 1982), we extended the Maxwell Garnet theory to the case where the inclusions in a two-component mixture are very small (with respect to the wavelength) randomly oriented ellipsoids. The dashed curve in Fig. 1 shows that such a model yields backscattering cross sections a few percent smaller than one in which the inclusions are spheres.

The new calculations for a mixture of water and ice yield results more closely resembling those based on the Aden–Kerker model than on the Ryde model. These results show that even when the melting sphere is treated as a mixture of water and ice, a relatively small degree of melting leads to a substantial increase in backscattering cross sections. Therefore, the rapid increase of radar reflectivity in the upper half of the

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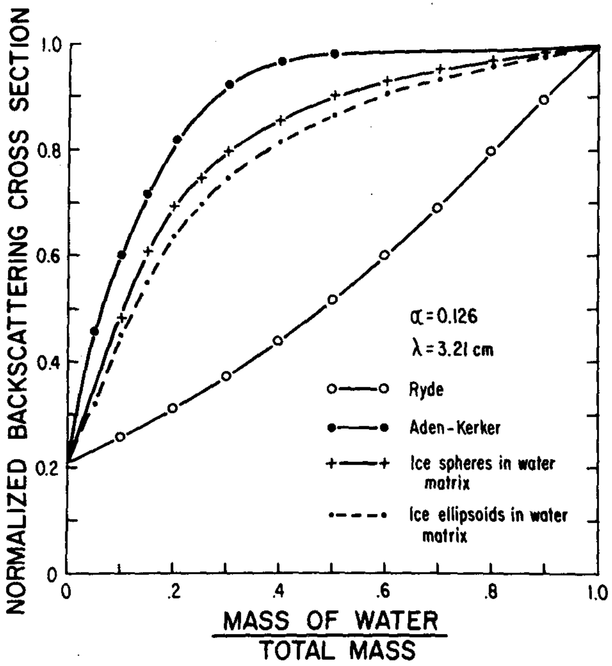

FIG. 1. Calculations of the backscattering cross sections of a melting ice sphere having a diameter of 0.129 cm as a function of the mass fraction of water to the total mass of the sphere. The ordinate is backscattering relative to that of a water drop. The Ryde and Aden–Kerker curves were reported by Langleben and Gunn (1952).

bright band can be accounted for as a result of melting, without having to make the unreasonable assumption that all the water is contained in a shell surrounding an ice core.

Since the reflectivity and attenuation of wet snowflakes depend on their refractive index, the results of this analysis have important implications beyond an improved understanding of the radar bright band.

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