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Influence of Scattering Properties Due to Complex Refractive Index of Ice

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Abstract—**The relationship between complex refractive index and complex dielectric permittivity is discussed, studied variations in pure-ice complex dielectric permittivity with wavelength and temperature using the LH model. The influence of scattering properties of hexagonal ice crystals due to the change of the complex refractive index was studied using DDA at 94GHz. The results show that the relative error of scattering efficiency, absorption efficiency, asymmetry factor and backscattering efficiency does not exceed 0.24%, 0.24%, 0.09625% and 0.83% respectively in the case of that the relative error of the real part of the complex refractive index does not exceed 0.22% while the imaginary part remain unchanged; the relative error of absorption efficiency and asymmetry factor do not exceed 1.46%, 0.2065 × 10⁻⁴ respectively while scattering efficiency and backscattering efficiency remain constant in the case of that the relative error of the imaginary part of the complex refractive index does not exceed 1.46% whereas the real part remains unchanged.**

I. INTRODUCTION

CIRRUS clouds, which are globally distributed, reflect or scatter short wave radiation of the sun on one hand, while absorbing the long wave radiation of the atmosphere and the earth's surface on the other. They thus play an important role in the climate system through their effects on the radiative balance of the Earth-atmosphere system [1]. IPCC2001 reports show that interaction of cloud - radiation and aerosol - radiation are the most uncertain factors in climatic change research; the current international atmospheric scientific community has already classified cloud - radiation interaction as one of its main areas of investigation.

The scattering properties of ice particles in the millimeter-wave band can be used to estimate the characteristics of ice clouds [2]. At present, theoretical approaches to the scattering of cirrus ice particles are mainly concentrated in FDTD [3], DDA [4] and T matrix [5] methods. Irrespective of the approach adopted, parameters of particles studied must be determined which are the shape of the particles, the distribution and the complex refractive index. Ping Yang [6] points out that the extinction and absorption efficiency in cirrus vary with wavelength due to the complex refractive index of ice crystal particles. The absorption efficiency strongly depends on the imaginary part. So, studying the influence of scattering characteristics due to complex refraction becomes very important. This paper analyzes the influence of hexagonal ice particles on scattering properties with different selection of the complex refractive index at 94GHz which provides a reference for more accurately computing scattering properties.

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II. RELATIONSHIP BETWEEN THE COMPLEX REFRACTIVE INDEX AND DIELECTRIC PERMITTIVITY OF ICE PARTICLES

The complex number of Maxwell's first equation for conductive medium is given by[7]:

$$\nabla\times\vec{H}=\sigma\vec{E}+i\omega\varepsilon\vec{E}=i\omega(\varepsilon-i\frac{\sigma}{\omega})\vec{E}=i\omega\varepsilon_c\vec{E} \quad (1)$$

where $\varepsilon_c=\varepsilon-i\frac{\sigma}{\omega}$ is the equivalent complex dielectric constant.

For dielectric medium which have electric polarization loss, the complex dielectric constant is given by

$$\varepsilon_c=\varepsilon^{'}-i\varepsilon^{"} \quad (2)$$

Where ε_c is complex dielectric constant, $\varepsilon^{"}$ stands for electric polarization loss of dielectric medium.

When the medium has both simultaneous electric polarization loss and ohmic loss, the equivalent complex dielectric constant can be expressed as follows[8]:

$$\varepsilon_c=\varepsilon^{'}-i(\varepsilon^{"}+\frac{\sigma}{\omega}) \quad (3)$$

Thus the most common form of refractive index of a medium is as follows:

$$\varepsilon=\varepsilon_r-i\varepsilon_i \quad (4)$$

The real part of the permittivity, ε_r , is a parameter describing how the electric field polarizes matter ; the imaginary part, ε_i , describes how electromagnetic waves are absorbed. The relationship between the complex dielectric permittivity and complex refractive index can be expressed as follows:

$$\varepsilon=m^2 \quad (5)$$

where $$m=n_r\text{-}in_i \quad (6)$$

According to (4)(5)(6), we can get the following formulas:

$$\begin{cases}\varepsilon_r = n_r{}^2 - n_i{}^2 \\ \varepsilon_i = 2 n_r n_i\end{cases} \quad (7)$$

The LH model [9] of imaginary of complex dielectric permittivity can be expressed as follows:

$$\varepsilon_i = \alpha(t)/f + \beta(t) f \quad (8)$$

$$\alpha(t) = (50.4 + 62\theta)\times 10^{-4} e^{-22.1\theta} GHz \quad (9)$$

$$\beta(t) = (0.445 + 0.00211t)\times 10^{-4} + 0.585\times 10^{-4}/(1 - t/29.1)^2\ GHz^{-1} \quad (10)$$

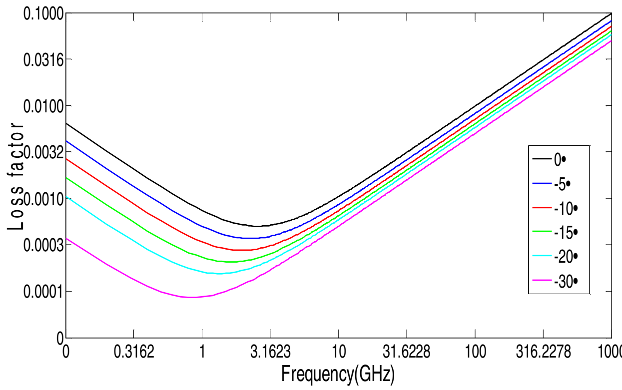

Fig.1. The loss factor ε_i of ice crystal as a function of frequency at different temperatures

As shown in Figure 1, the loss factor of the ice decreases progressively first and then increases progressively with the frequency (0.1 ~ 1000GHz) increases , the position of turning point about loss factor will migrate toward lower frequency along with the falling temperature. Actually, the loss factor of ice will decreases when temperature decreases.

Matzler C and Wegmuller U[10] made linear regression of the data obtained by resonance measuring methods and concluded that the real part of the dielectric constant of pure ice varied with temperature:

$$\varepsilon_r = 3.1884 + 0.00091T \quad (11)$$

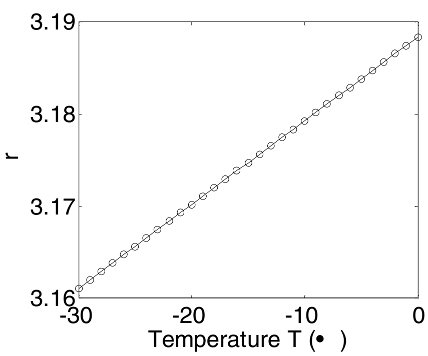

Fig. 2. The dielectric constant of ice crystal ε_r as a function of temperatures

Figure 2 shows that the real part of the complex permittivity of the hexagonal ice particles increases linearly with increasing temperature.

III. The Influence of Scattering Properties due to the Choice of Complex Refractive Index

Different authors take different values for the complex refractive index of the ice particles at 94 GHz, such as m=1.78+0.0024i[11] or m=1.782+0.0027i [12], so how much of an influence can scattering properties of hexagonal ice particles have by using different values of the complex refractive index.

First we assume the following definition of hexagonal ice particles:

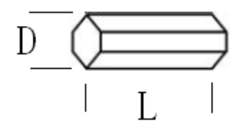

Fig 3 Dimension definition of hexagonal ice crystals

As shown in Figure 3, D is the diagonal length of the regular hexagon whose value is twice the regular hexagon side length; L is the height or length of the hexagonal prism. The dimensional relationship is as follows [13]:

$$\begin{cases} D = 0.7L & L < 100um \\ D = 6.96L^{0.5} & L \geq 100um \end{cases} \quad (12)$$

To simplify computation, the dimension of randomly oriented hexagonal ice particle is as follows: L=50um 、 D=35um.. The range of values of the real and imaginary complex refractive indices is 1.780~1.788, 0.00270~0.00278 respectively; we study the relationship between scattering properties of hexagonal ice particles(scattering efficiency, absorption efficiency, asymmetry factor, backscattering efficiency) and complex refractive index.

TABLE I
THE INFLUENCE OF SCATTERING PROPERTIES DUE TO THE CHANGE OF COMPLEX REFRACTIVE INDEX

complex refractive index	scattering efficiency	absorption efficiency	asymmetry factor	backscatterig efficiency
1.788 +0.0027i	1.5654 E-06	2.0062 E-04	5.8235 E-04	1.8645 E-07
1.786 +0.0027i	1.5590 E-06	2.0086 E-04	5.8205 E-04	1.8568 E-07
1.784 +0.0027i	1.5526 E-06	2.0110 E-04	5.8167 E-04	1.8491 E-07
1.782 +0.0027i	1.5462 E-06	2.0134 E-04	5.8165 E-04	1.8415 E-07
1.780 +0.00270i	1.5397 E-06	2.0158 E-04	5.8123 E-04	1.8338 E-07
1.780 +0.00272i	1.5397 E-06	2.0307 E-04	5.8123 E-04	1.8338 E-07
1.780 +0.00274i	1.5397 E-06	2.0457 E-04	5.8121 E-04	1.8338 E-07
1.780 +0.00276i	1.5397 E-06	2.0606 E-04	5.8121 E-04	1.8338 E-07
1.780 +0.00278i	1.5397 E-06	2.0755 E-04	5.8121 E-04	1.8338 E-07

Table 1 indicates two results of scattering properties; one is when the real part is changed while the imaginary part remains unchanged. The other is when the imaginary part is changed while the real part remains unchanged. We treat the average results as true values and then analyze the relative errors produced by variation in the real part and the imaginary part:

1) When the relative error values of the real part of the complex refractive index of the hexagonal ice particles is less than 0.22% while the imaginary part is unchanged, the relative error of the scattering efficiency is less than 0.24%, the relative error of the absorption efficiency is less than 0.24%，the relative error of the asymmetry factor is less than 0.09625%, and the relative error of the backscattering efficiency is less than 0.83%. Additionally, the scattering efficiency, the backward scattering efficiency as well as the asymmetry factor will all decrease when the real part of the complex refractive index becomes smaller. On the other hand, absorption efficiency will increase slightly when the real part of complex refractive index becomes smaller.

2) When the relative error values of the imaginary part of the complex refractive index of the hexagonal ice particles is less than 1.46%, while the real part remains unchanged, the relative error of scattering efficiency and backscattering efficiency are almost zero, the relative error of the asymmetry factor is less than 0.2065×10^{-4}. Beyond that, the absorption efficiency will increase with increases in the imaginary part of the complex refractive index of ice, the asymmetry factor is slightly decreased with increases in the imaginary part of the complex refractive index; we can think of it almost constant.

IV. CONCLUSION

This paper has analyzed, using the LH model, the variations of the complex refractive index of ice crystals due to changes in temperature and frequency. Using DDA, we have studied the influence of scattering properties due to variations in the complex refractive index at 94GHz. The results show that when the imaginary part of the complex refractive index of hexagonal ice particles is constant, while the real part becomes smaller, the scattering efficiency, the backward scattering efficiency and the asymmetry factor will all decrease, the absorption efficiency will increase slightly; when the real part of the complex refractive index is kept constant, while the imaginary part becomes larger, the absorption efficiency increases, the asymmetry factor slightly decreases; we can think of it as approximately constant.

This paper has only discussed the relationship between complex permittivity of pure ice and temperature and incident wavelength; it did not consider the case of non-pure ice (such as salt ice, ice particles with aerosol or mixed ice with air). In these cases, to more accurately select complex refractive indices, some relevant literatures [14]-[16] are recommended.

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