Some interaction characteristics of IR radiation with ice crystals ---------New IR channel exploration

Lisheng Xu and Jilie Ding
Atmospheric Radiation and Satellite Remote Sensing Laboratory (ARSRSL)/
Institute for Space Information & Nonlinear Sciences
Chengdu University of Information Technology, Chengdu, SC 610041, China

Abstract: Some interaction characteristics, i.e., light scattering characteristics, of infrared (IR) radiation with small ice crystals are investigated systematically by using the exact T-matrix approach. Some important facts are obtained, which reveal, especially, that the combination of both the 25 and 3.979μm together has some advantages and potential applications for remote sensing of cirrus and other ice clouds. A new far-IR channel at the wavelength of 25μm is proposed.

Keywords: light scattering characteristics, T-matrix approach, ice crystal size distribution, a new far-IR channel

1. Introduction

Understanding the interaction between clouds and radiation, and thus the climate, must begin with an understanding of the scattering and absorption properties of cloud particles. Thus, a thorough study of light scattering and polarization characteristics of nonspherical ice crystals is an important scientific issue not only because of its significance in climate studies and other practical applications, but also because of the current limitations in our understanding of this complicated problem. Recent observations reveal that ice crystals in cirrus clouds have complex shapes with sizes ranging from a few micrometers to thousands of micrometers, thereby causing a basic difficulty in light scattering calculations[1]. Besides natural cirrus clouds, there has recently been increasing interest in the potential impact of *condensation trails on climate change through a* variety of radiative transfer effects[2]. Thus, the effects of small ice crystals in climate and remote sensing applications as well as in radiative transfer calculations are important and deserve further study.

In this study we specifically apply the exact T-matrix approach[3] to calculate light scattering properties, including the scattering matrix and the integral photometric characteristics, by polydisperse, randomly oriented ice crystals modeled by finite circular cylinders with different size distributions(SDs), including observed and modeled (the power law distribution), in some important IR wavelengths up to 30μm, and investigate systematically how the scattering properties depend on wavelengths, particle SDs with different effective radius r_e and different effective variance v_e and ratios of the length to diameter, L/D[4-5]. Our aim is to highlight the specific scattering nature by ice crystals that can be employed for the further study of satellite IR remote sensing of ice crystals in atmospheres.

2. Results and analyses

2.1 Scattering matrix elements

A common feature is that for the element of F_{11} the forward scattering at all wavelengths investigated increases with the size parameter x increase, but is not sensitive to the change in the particle L/D generally.

When $r_e < \lambda$ (Fig.1), F_{22} is sensitive to particle asphericity. The behavior of F_{22} for prolate cylinders differ from that for oblate cylinders. Fig.2 show the large deviation of F_{22} from 1 with different angular patterns between prolate and oblate cylinders when x increases, demonstrating stronger particle asphericity. These features indicate that deviation of F_{22} from F_{11} at λ = 3.979μm is an important indication of particle nonsphericity and can be used in polarization sounding[3] of ice crystals. Figs.1-2 indicate that the behavior of F_{33} and F_{44} not only are able to characterize sphericity of ice particles, but also are sensitive to particle sizes. Since F_{34} transforms circularly polarized incident light to linearly polarized scattering light[3], Figs. 1-2 show that the behavior of F_{34} can also provide useful information about ice crystal sizes and L/D related to scattering.

As shown in Ref. 4, the behavior of the scattering matrix elements of ice cylinders at λ = 11.02 and 10 μm, is complicated and not suitable in remote sensing of ice crystals.

At λ = 25μm, the most prominent feature is that for prolate cylinders with the x considered, F_{22} is all sensitive to L/D regularly (Fig.3). Furthermore, F_{22} is also sensitive to r_e increase. Thus, at 25μm

F_{22} is a good indicator for remote sensing of ice crystals. In addition, the behavior of both F_{33} and F_{44} depends not only on x increase, but also on L/D, demonstrating the corresponding change of the asphericity. These features indicate that at λ = 25μm elements of F_{33} and F_{44} can also be used to infer the information of ice crystals by polarization measurements.

2.2 The integral photometric characteristics

The integral photometric characteristics refer to the extinction efficiency Q_{ext}, scattering efficiency Q_{sca}, asymmetry factor g, and radiation pressure efficiency Q_{pr}[3]. As shown in Ref.5, the curve patterns of Q_{ext} at the wavelengths of 3.979, 25.0, and 6.5μm are similar. The curve patterns of g at 25.0μm are also similar to those at 3.979μm. The values of Q_{pr}

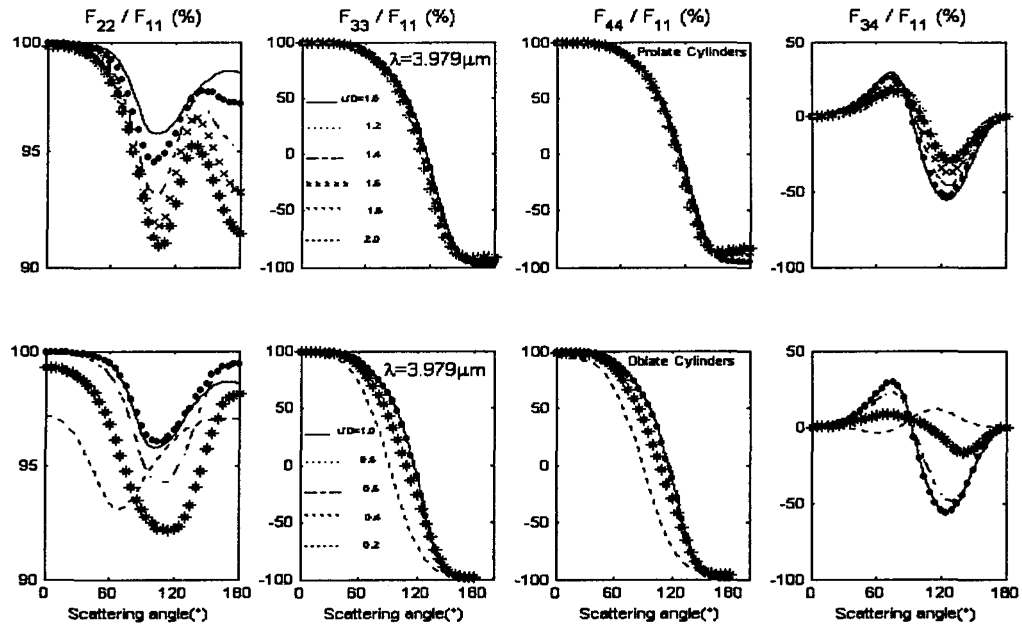

Fig.1 Angular distribution of the scattering matrix elements for ice crystals: (a) prolate cylinders (first row) with different L/D for the observed size distribution (see Ref. 4) with r_e ranging from1.5747 μm (x=2.4866, L/D=2) to 1.5859μm(x=2.5043, L/D=1) and v_e ranging from 0.0462 to 0.0442; (b) oblate cylinders (second row) with r_e ranging from 1.5766 μm (x=2.4896, L/D=0.2) to 1.5859μm (x=2.5043, L/D=1) and v_e ranging from 0.0459 to 0.0442 at λ=3.979μm.

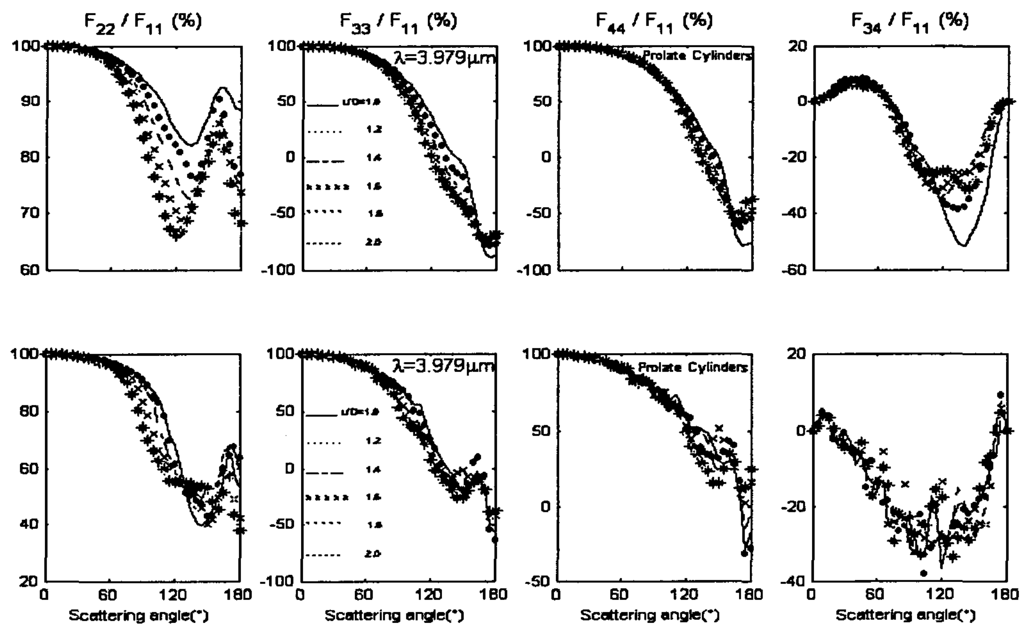

Fig.2 Angular distribution of the scattering matrix elements for ice prolate cylinders with different L/D for the modeled size distributions (see Ref. 4) with (a) r_e = 3 μm (x = 4.737) and v_e = 0.105 (first row); (b) r_e =10.17μm (x =16.059) and v_e =0.105 (second row) at λ=3.979μm.

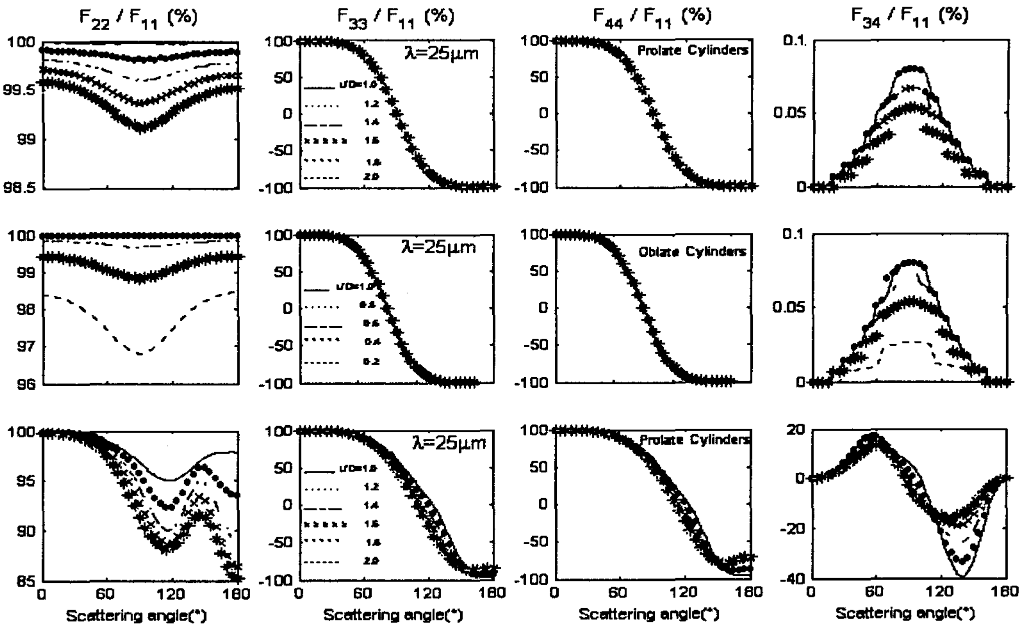

Fig.3 Same as Figs.1 and 2 but for the observed size distribution with x ranging from 0.3958 to 0.3986 (r_e: 1.5747-1.5859μm) (first row) and with x ranging from 0.3962 to 0.3986 (r_e: 1.5766-1.5859μm) (second row); and for the modeled size distributions with r_e =10.17μm (x=2.556) and v_e =0.105 (third row) at λ=25μm.

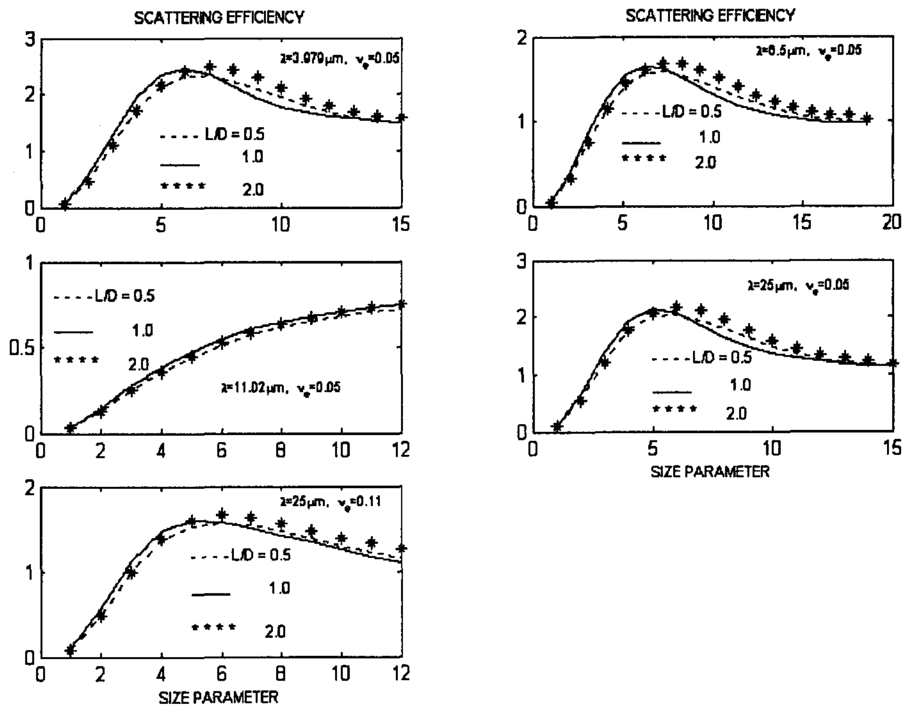

Fig.4. The Q_{sca} vs size parameter x for circular cylinders with v_e = 0.05 and different L/D at λ = 3.979, 6.5, 11.02, and 25μm. For comparison, at 25μm the curves for v_e = 0.11 are also given.

at both 3.979μm and 25.0μm are larger than those at 11.02μm and 6.5μm. Note that at λ = 11.02μm, the curve pattern of Q_{ext} and Q_{pr} exhibit remarkably different from those at other IR wavelengths. The Q_{sca} is the largest at λ = 3.979μm, and the next large at 25μm among the IR wavelengths investigated, whereas the Q_{sca} at 11.02μm is quite small (Fig.4), which indicate that both the wavelengths of 3.979 and 25.0μm exhibit scattering nature and 11.02μm exhibits strong absorption for ice particles.

3. Discussions and Conclusions

It is realized that current operational satellites have some deficiencies in accurate remote sensing of cirrus clouds, especially the ice water path (IWP), using IR wavelengths. Thus, it is important to seek new sounding channels and develop new sensors. The results in this paper show that scattering properties of small ice cylinders depend strongly on wavelengths, particle size distributions with different r_e and v_e, and shape.

One of the most remarkable finding of this study is that the behavior of scattering of small ice crystals at the 25μm far-IR water vapor absorption band and 3.979μm atmospheric IR short-wave window is similar in many aspects and exhibits important scattering nature for ice crystals. Thus, it seems promising to use a new channel at 25μm combined with 3.979μm together to enhance the ability of remote sensing of microphysical properties of cirrus clouds and other ice clouds.

The effects of particle shapes and sizes on light scattering have been more concerned and discussed in the literature. By contrast, however, less discussion has been paid to the effects of the v_e on light scattering. Another remarkable characteristic in this study is that with v_e increase, the integral photometric characteristics except g decrease regularly(for example, see Fig.4), which indicate that the effects of the v_e of size distribution on light scattering are important.

References

1. K. N. Liou, Y. Takano, and P. Yang, 1998, Light scattering and radiative transfer in ice crystal clouds: Applications to climate research, *in Preprints of the Conference on Light Scattering by Nonspherical Particles: Theory, Measurements, and Applications*, M. I. Mishchenko, L. D. Travis and J. W. Hovenier, eds., Am. Meteorol. Soc., Boston, pp. 28-31.
2. K. Sassen, 1997, Contrail-cirrus and their potential for regional climate change, *Bull. Am. Meteorol. Soc.* 78, 1885-1903.
3. M. I. Mishchenko, J. W. Hovenier and L. D. Travis, eds., 2000, *Light Scattering by Nonspherical Particles: Theory, Measurements, and Applications*, Academic, San Diego.

4. L. Xu, J. Ding, and Andrew Y. S. Cheng, 2002, Scattering matrix of infrared radiation by ice finite circular cylinders, *Appl. Opt.* 41, 2333 – .

5. J. Ding and L. Xu, 2002, Light scattering characteristics by small ice circular cylinders in visible, 1.38μm, and some infrared wavelengths, to be appeared in *Optical Engineering*, Vol.41, No.9.

Lisheng Xu graduated from Geophysics Dept. of Peking University in 1964. He worked as a visiting scholar in SSEC at University of Wisconsin-Madison from 1982 to 1985. Now he is a professor and director of ARSRSL at Chengdu University of Information Technology, and adviser of graduate students of Institute of Atmospheric Physics of Chinese Academy of Sciences. His research areas include light scattering, satellite remote sensing, cloud and radiation, scattering and lidar remote sensing, and nonlinear physics and its applications in remote sensing.

Jilie Ding graduated from Dept. of Physics of Lan Zhou University in Feb. 1982; then worked in South-Western Institute of Physics of China. Since 1996, as an assistant of Prof. Lisheng Xu, he worked in ARSRSL of Chengdu University of Information Technology. He is a vice-Research Fellow, a member of Satellite Meteorological Council /Meteorological Society of China.