ICE Particle Size and Shape Effect on Solar Energy Scattering Angular Distribution①

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ABSTRACT

The rare occurrence of te halos produced by cirrus ice crystals in nature has been investigated by modelling the incident solar (visible) light scattering angular distribution using the Monte Carlo / ray tracing method. The results show that the irregular shapes of ice crystals and large population of small ice particles in cirrus are responsible for the rare occurrence of halos.

Key words: Irregular shape, Ice crytal, Halos

I. *INTRODUCTION*

Theoretically, the existence of hexagonal structured ice crystal particles in cirrus can produce at least 22° halo. The solid column and pyramidal particles can produce weak 46° halo due to the right angle between the particle side face and its bottom face (such as column, plate and bullet *like ice crystal particle structures), and other concentric halos with unusual radii* which have been reported many times since the beginning of this century, such as Andrus (1915), Kimball (1915), Brush (1919), Leaf (1926) and Rechardson (1953). The most recent observations were from Goldie et al. (1976) and Neiman (1989), and they observed as many as six concentric halos including the common 22° halo and the weak 46° halo. The 9°, 18°, 20°, 24° and 35° halos are basically from the particles' pyramidal structure (with pyramid caped at one end or two ends of the column). Neiman (1989) explained the origination of the observed halos by calculating the halo angle values using the minimum deviation formula (Minnaert, 1954; Tricker, 1970), and the calculated results are in good agreement with the observed values.

In nature, not only are those concentric halos rare to see, it is even rare to see the 22° and 46° halos. The reason for this has attracted many investigators very recently, such as Mache (1994) and Seassen et al. (1994), owing to the available ray tracing method calculating the irregular ice crystal particle scattering properties.

The essence of ray tracing is that when the particle size parameter is large enough, the scattered light can be divided into reflection and refraction, as well as diffraction, and the diffracted energy is half of the total scattered energy. This can be seen from Mie (1908) scattering

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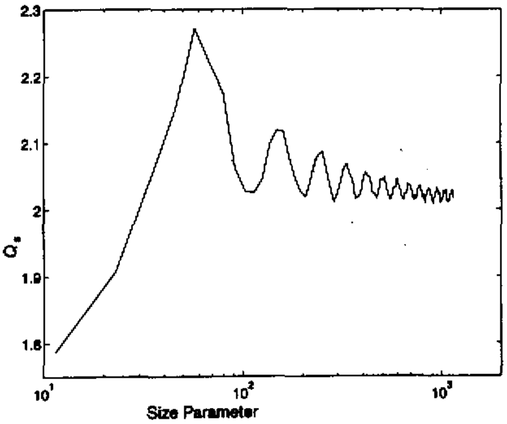

Fig. 1. Scattering efficiency variation with particle size parameter.

Q_s oscillates around 2, and asymptotically approaches 2. According to Takano and Liou (1995), the ray tracting method is valid for particle size parameter as small as 30, and for incident wavelength of 0.55 μm considered here, the corresponding minimum particle radius will be 2.5 μm, so it is reasonable to use ray tracing method to calculate cirrus ice crystal particle scattering properties.

The ray tracing method has been developed and employed for hexagonal column- and plate-like ice crystal scattering calculations by Wendling et al. (1979), Coleman and Liou (1979), Cai and Liou (1982), Takano and Jayaweera (1985), Rockwitz (1989), Muinonen et al. (1989), Takano and Liou (1989), and Yao and Liu (1996). This method has also been extended to study the scattering properties of more complicated particle structures observed by Mossop and Ono (1968), Heymsfield (1975) and Heymsfield and Platt (1984) in field measurements and by Magono and Lee's (1966) from laboratory observations, such as the hexgonal bullet- like ice crystal scattering (Iaquinta et al., 1992; Liu et al., 1995) and other structures (Macke and Tzschichholz, 1992; Macke, 1994; Liou and Takano, 1994).

In this paper, we try to study the ice particle size and shape effect on the halo appearance theoretially by modelling the hexagonal solid and hollow columns (with two pyramid cavities at two ends of the column) using rescently developed Monto Carlo / ray tracing method (Takano and Liou, 1995). In our model caculations, the incident light wavelength is assumed to be 0.55 μm, because most solar energy is concentrated around this wavelength. The incident photon number is 10^7. The ice particle refractive index at this wavelength is $1.3106-i3.11\times10^{-9}$ (Warren, 1984), and ice crystal particles are randomly oriented in space.

II. REASONS FOR RARE OCCURRENCE OF HALOS

1. *Physical Mechanism*

Macke (1994) studied the multiple scattering phase function of a homogeneous cirrus cloud with increased optical depth. For cloud geometrical thickness of 1 km, and the cloud contains columns with the size spectra derived from the experiment, it was found that even for optical thickness of 10-an extremely large value for cirrus clouds, the 22° halo is still detectable, so the rare occurrence of halos might therefore most likely be explained by the irregular nature of the particle shapes rather than by broadening due to multiple scattering.

The study by Macke for different ice crystal surface roughness indicated that high roughness will remove the peaks in the phase function, so the surface roughness is responsible for the lack of the 22° halo. Sassen et al. (1994) also pointed out that the rare occurrence of the 22° halo was mainly due to the complicated structure of the realistic particles in cirrus cloud, such as hexagonal hollow–ended column and bullet–rosette. Although his results show that the hollow column produced halos are decreased, they are still detectable. What we try to do in this section is to investigate the light scattering angular distribution after considering the particle size distribution, in order to see the small size ice crystal particle effect on the light scattering angular distribution.

In earlier studies, Heymsfield and Platt (1984) found that from 35% to 53% of the total visible extinction is due to the small ice crystals in the size ranging from 1 to 20 μm. Very recent study by Arnott et al. (1994) indicated that there can be significant number of small particles (diameter < 66 μm) and very few larger particles in cirrus. If small particles dominate the particle population, physically, the diffracted light energy will be much more widely spread in the forward direction for small particles compared with that for larger particles, so the light diffraction will dominate the shape of a single small ice crystal scattering phase function angular distribution in the forward scattering hemisphere. The scattering curve will be relatively flat around the angle less than 30°, so the halos may be smoothed out by the diffraction effect. This can be seen from the following analysis.

If too many small particles (size dimension around 10 μm) exist in the laboratory cold room or real cirrus cloud, for given ice crystal size distribution, the mixed phase function can be expressed as

$$P(\theta)=\frac{\sum n_i S_i P_i(\theta)}{\sum n_i S_i} , \tag{1}$$

where $P(\theta)$ is the mixed ice crystal phase function, n_i is the particle number concentration in the ith particle range (or channel), S_i is the ice crystal project area normal to the incident light, and $P_i(\theta)$ is the phase function of this ice crystal. Generally, S_i is proportional to the ice crystal dimension L^2, and according to Heymsfield and Platt (1984), the ice crystal distribution is

$$n_i = aL_i^{-B} , \tag{2}$$

so

$$P(\theta)\propto\sum\frac{P_i(\theta)}{L_i^{B-2}} . \tag{3}$$

If $B > 2$, the small particle phase function will dominate the mixed phase function, so the halos in the mixed phase function should be smoothed out. B is always greater than 2 in the observations of Heymsfield and Platt (1984). The problem with this explanation is that the ice crystal size (< 30 μm) spectrum is not well known, but this may be correct approach to the interpretation of the results from laboratory measurements and the field observations by aircraft.

2. *Model Results*

In order to prove above analysis quantitatively, model calculations have been carried out

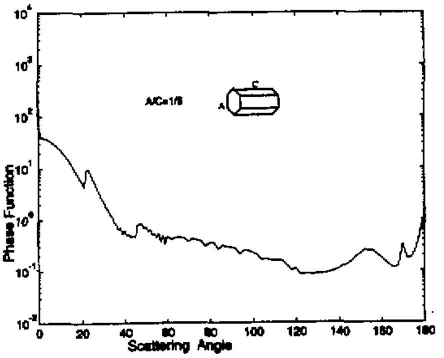

Fig. 2. Phase function angular distribution for solid column randomly oriented in space. The column length $C = 5$ μm and the radius $A = 1$ μm.

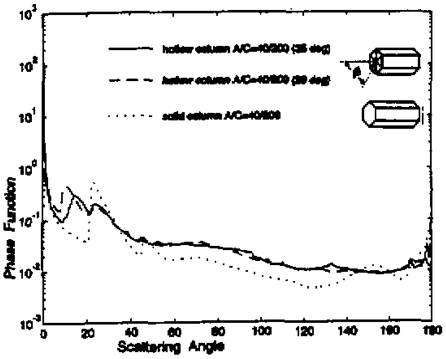

Fig. 3. As Figure 2, but for two hollow columns, together with the solid column. The column with ratio A / C = 40 μm / 200 μm, and the pyramidal angles are 28° and 35°, respectively.

for solid and hollow columns and for different particle sizes. The small solid column scattering phase function angular distribution is plotted in Figure 2. The column length $C = 5$ μm and hexagon side length $A = 1$ μm. It can be seen that the small particle phase function shows very weak 22° and 46° halos, but they are still detectable.

For hollow column, the phase functions are plotted in Figure 3 for particle size $A / C =$ 40 μm / 200 μm and pyramidal angle (defined as the angle between the hollow column long

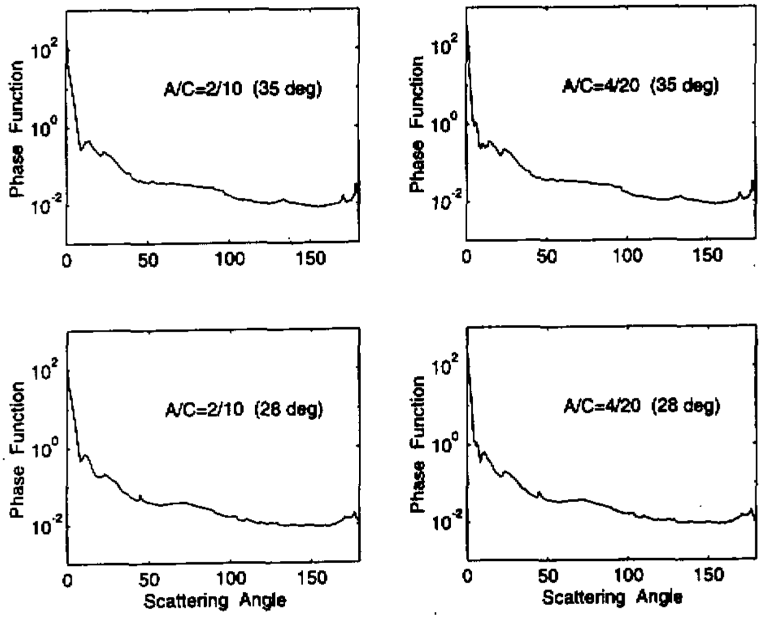

Fig. 4. As Figure 2, but for hollow columns, with ratio A / C = 2 μm / 10 μm and 4 μm / 10 μm, and the pyramidal angles are 28° and 35°, respectively.

symmetry axis and the cavity pyramid side face) $\beta = 28^\circ$ and 35°, respectively. For comparison purpose, the phase function of solid column with A / C = 40 μm / 200 μm is also plotted. The halo from hollow column is much weaker than that from solid column, and it is expected that the smaller hollow column will smooth out the halo.

The small hollow particle scattering phase functions are plotted in Figure 4 for different ice crystal particle sizes (A / C = 2 μm / 10 μm and 4 μm / 20 μm) and pyramidal angles ($\beta = 28^\circ$and 35°). The results indicate that all halos are disappeared due to the small particle diffraction effect.

So, through the combination of the small particle population and more complicated particle shapes, the rare occurrence of the halos may be explained.

III. CONCLUSIONS

The rare occurrence of the halos produced by ice crystal particles has been investigated using Monte Carlo / ray tracing method, and through our model calculations, it can be seen that the irregular particle shape plus the small particle size domination in the size spectrum, the halo can be smoothed out and the rare occurrence of the halo can be explained.

It seems that as long as the small particle dominates the volume scattering phase function, no matter what kinds of particle shapes existed in the cloud, the halos will be very difficult to be detected. Of course, this needs the further study of the small ic particle growth which depends upon the temperature, humidity and dynamics inside the cirrus cloud, and we have very limited knowledge on this subject at this moment.

The particle size of less than 50 μm has not been well studied due to the difficulty in *in situ* measurement and the limit of the employed instrument. In order to investigate the small ice crystal particle effect on halo formation, it is expected to conduct more observations of small ice crystal particle shape and size distribution in both laboratory and field experiment in future.

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