How big should hexagonal ice crystals be to produce halos?

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It has been hypothesized that the frequent lack of halos in observations of cirrus and contrails and laboratory measurements is caused by small ice crystal sizes that put the particles outside the geometrical optics domain of size parameters. We test this hypothesis by exploiting a strong similarity of ray tracing phase functions for finite hexagonal and circular ice cylinders and using ***T***-matrix computations of electromagnetic scattering by circular cylinders with size parameters up to 180 in the visible. We conclude that well-defined halos should be observable for ice crystal size parameters of the order of 100 and larger and discuss remote-sensing implications of this result. © 1999 Optical Society of America

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The model of hexagonal columns and plates has traditionally been used to compute the scattering and absorption properties of cirrus and contrail particles. Geometrical optics (GO) predicts that pristine hexagonal ice crystals with sizes much larger than a wavelength must produce well-defined 22° and 46° halos attributable to minimum angles of deviation for 60° and 90° ice prisms. The 22° halo is especially pronounced and represents an increase of scattered intensity by an order of magnitude relative to the background value.[1] More importantly, GO predicts strong halos not only for individual hexagonal crystals, but also for aggregates such as bullet rosettes, capped columns, and double plates.[2–4] Both the 22° and the 46° halos have been observed for natural ice clouds, thereby providing some justification for the hexagonal crystal model. However, the halos for natural ice clouds are seen less often than not,[5–7] and the lack of pronounced halos has been documented in numerous aircraft and ground-based observations and *in situ* and laboratory measurements.[8–15] Therefore, the inability of GO computations for pristine hexagonal particles to reproduce the experimentally measured phase functions may indicate a lack of understanding of dominating ice crystal habits and/or scattering mechanisms. This potential problem could have serious ramifications in remote sensing of ice clouds that often relies on accurate knowledge of ice crystal phase functions.[16,17]

If one assumes that real ice clouds consist mostly of pristine hexagonal ice crystals, then there are two possible explanations of the rare occurrence of halos at many geographic locations. The first assumes that the crystals are not randomly oriented but rather are horizontally aligned by the aerodynamic force resulting from their finite falling velocity. The second relies on the fact that the halos are GO features that are not produced unless a particle is sufficiently large relative to the wavelength. Of course, multiple scattering in optically thick clouds also tends to wash out the halo signature, but this effect is weak in optically thin cirrus and contrails.

Occasional observations of sun dogs, zenith-enhanced lidar backscatter,[18] and specular reflection of sunlight from ice clouds[19] demonstrate that nearly perfect horizontal alignment of natural ice crystals does occur. However, even if one or all these optical phenomena are observed, it does not necessarily mean that all or most cloud particles are horizontally oriented hexagonal crystals.[20] Moreover, the phase function for horizontally oriented hexagonal crystals should have many pronounced features, such as sun dogs, and strongly depend on the direction of Sun illumination.[1,21,22] This is in contrast to the observations and measurements reported in Refs. 8–15, 23, and 24. The results of experimental and theoretical studies of the process of particle orientation by aerodynamic force are also ambiguous. For example, an experimental study by Sassen[25] showed that

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only particles with diameters greater than 100–200 μm can become horizontally oriented, which rules out all contrail particles and all but the biggest cirrus crystals, whereas a theoretical study by Klett[26] predicted nearly perfect horizontal alignment for crystals with diameters as small as 20 μm. Furthermore, the degree of alignment should depend on the Reynolds number and thus on the altitude in the atmosphere. It is also obvious that frequently occurring bullet rosettes should have a much smaller degree of alignment than single columns and plates and should, therefore, produce well-defined halos if the component bullets have pristine shapes. It thus appears to be difficult at this point to estimate how often the lack of observable halos is the result of horizontal orientation of otherwise pristine hexagonal ice crystals.

The second explanation may also bear some relevance given the large number of small ice crystals in cirrus and especially in contrails.[27–29] A direct verification of this explanation requires an exact electromagnetic scattering technique that is based on a numerical solution of Maxwell's equations and is applicable to randomly oriented hexagonal crystals with size parameters exceeding several tens. Since such techniques are currently unavailable, we will use a less straightforward approach based on the recently improved ***T***-matrix method[30] and a striking similarity between ray tracing phase functions for finite hexagonal and circular ice cylinders. Figure 1 was computed using the GO code described in Ref. 31 and shows that both phase functions exhibit similar 46° halos caused by the exact same scattering mechanism (minimum deviation at 90° ice prisms), have almost identical profiles at scattering angles from 50° to 130°, and have similar backscattering peaks caused by double internal reflections from mutually perpendicular facets. (Note that the negligibly small ice absorption at visible wavelengths makes ray tracing phase functions for particles much larger than a wavelength essentially independent of size parameter.) Since the ***T***-matrix method can be applied to large circular cylinders, we can determine what minimal size parameter value is necessary to produce these GO features. By implication, this size parameter would also be sufficiently large to produce the 22° and 46° halos for hexagonal ice cylinders.

Figure 2 compares GO and ***T***-matrix phase functions computed for monodisperse, randomly oriented circular cylinders with a length-to-diameter ratio of 1 and size parameters $x = 40$, 80, 120, and 180. The small-amplitude oscillations in the ***T***-matrix curves result from interference effects typical of monodisperse particles and can be eliminated by averaging over a size distribution.[30] It is obvious that the size parameter 40 is too small to cause a pronounced 46° halo. On the other hand, the size parameter 180 results in a ***T***-matrix phase function that closely reproduces all the GO features, except perhaps the maximum at 134°. Since the 22° halo is much more pronounced than the 46° halo, we can conclude from Fig. 2 that pristine hexagonal ice crystals with size parameters exceeding 100 (or equivalent radii ex-

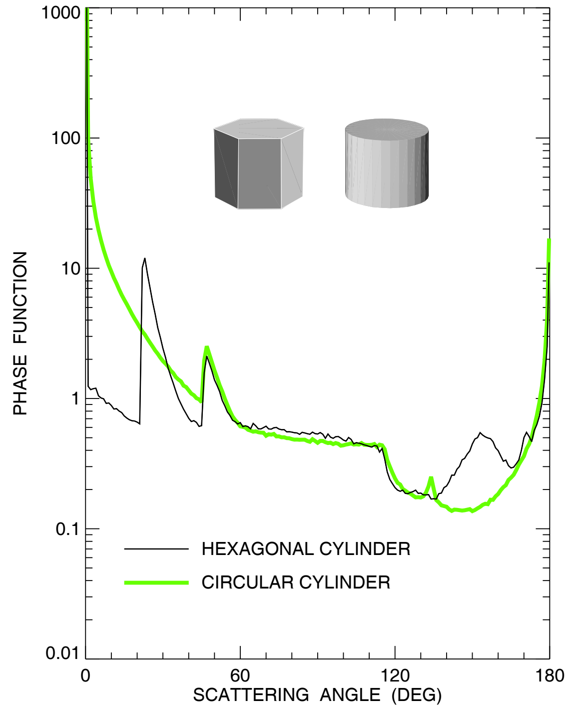

Fig. 1. Ray tracing phase functions (with diffraction not included) for randomly oriented hexagonal and circular cylinders with a length-to-diameter ratio of 1. The refractive index is $1.311 + i0.311 \times 10^{-8}$ and corresponds to water ice at a visible wavelength.[32]

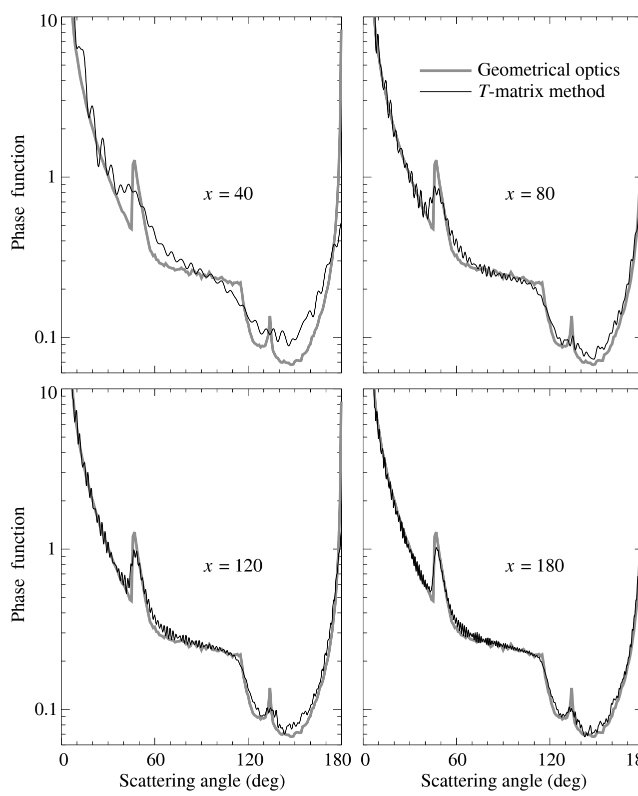

Fig. 2. Comparison of GO and ***T***-matrix phase functions for monodisperse, randomly oriented, circular ice cylinders with varying size parameters.

ceeding 10 μm at visible wavelengths) should produce well-defined, quite noticeable 22° and 46° halos.

This conclusion could be important since it rules out the second explanation of the lack of halos in most of the aforementioned observations and laboratory studies. It thus appears that alternative explanations of the absence of halos for the majority of natural and artificial ice particles should be looked for. One such possible explanation is that real ice crystals often lack an exact hexagonal shape and are highly irregular particles with rough surfaces.[17,33,34] Wavelength-sized and super-wavelength-sized surface irregularities destroy the halos and result in smooth, featureless phase functions similar to those observed in Refs. 8–15. Another possible mechanism of producing featureless phase functions is statistical averaging over a multitude of different shapes lacking the exact hexagonal symmetry.[33,35] Close examination of many microphotographs of real ice particles[6,28,29] suggests that both mechanisms could be quite plausible and should be further examined.

Finally it should be noted that the angle of minimum deviation that occurs for halos generates a cubic wave front and is largely similar to the rainbow of spherical water drops.[36] Thus the question posed in this Note is analogous to the question "how large should droplets be to produce rainbows?" In this regard, comparison of our Fig. 2 with Fig. 5 of Ref. 37 is quite revealing and supports our conclusions.

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