IEEE Trans. Geosci. Electron. **GE-16**, 85 (1978).
4. My program combines a computer code published by R. H. Jones [in *Applied Time Series Analysis*, D. F. Findley, Ed. (Academic Press, New York, 1978)] and additional routines written in association with O. Strand.
5. M. Waldmeier, *The Sunspot Activity in the Years 1610–1960* (Schulthess, Zurich, 1961).
6. J. A. Jacobs, *The Earth's Core* (Academic Press, New York, 1975).
7. D. G. Childers, *Modern Spectrum Analysis* (Institute of Electrical and Electronic Engineers, New York, 1978).
8. W. Y. Chen and G. R. Stegan, *J. Geophys. Res.* **79**, 3019 (1974).
9. T. J. Cohen and P. R. Lintz, *Nature (London)* **250**, 398 (1974).
10. S. Newcomb, *Astron. J.* **12**, 49 (1892).
11. W. H. Munk and G. J. F. Macdonald, *The Rotation of the Earth, a Geophysical Discussion* (Cambridge Univ. Press, Cambridge, 1960).
12. T. J. Ulrych, D. E. Smylie, O. G. Jensen, G. K. C. Clark, *J. Geophys. Res.* **78**, 4959 (1973).
13. R. G. Currie, *Geophys. J. R. Astron. Soc.* **46**, 513 (1976).
14. _____, *J. Geophys. Res.* **84**, 753 (1979).
15. *Understanding Climatic Change: A Program for Action* (National Academy of Sciences, Washington, D.C., 1975).
16. H. H. Lamb, *Climate: Present, Past and Future* (Methuen, London, 1972), vol. 1.
17. G. D. Nastrom and A. D. Belmont, *J. Geophys. Res.* **85**, 443 (1980).
18. I thank the National Academy of Sciences-National Research Council for awarding me a Senior Resident Research Associateship, NASA Goddard Space Flight Center for providing facilities, and ARCO Oil and Gas Company for granting a 1-year leave. I am indebted to L. V. Morrison for providing ΔT data through 1978 and thank A. Arking and C. Wolff for suggestions that improved this report.
* Present address: ARCO Oil and Gas Company, 3000 Plano Parkway, Plano, Texas 75075.

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Scheiner's Halo: Evidence for Ice Ic in the Atmosphere

Abstract. *Refraction of sunlight at the angle of minimum deviation between octahedral faces of crystals of ice Ic in the upper atmosphere could produce a halo around the sun or the moon at 27.46°. Crystals of hexagonal ice having low-index faces cannot produce a halo of this radius. It is therefore suggested that Scheiner's halo, which has been reported at least four times since 1629 at 28° from the sun, is due to ice Ic. If this is correct, it is apparently the first evidence that ice Ic occurs naturally and that liquid water can freeze to ice Ic.*

Scheiner's halo is a rare halo that occurs at ~ 28° from the sun or the moon. It was first reported by Scheiner more than 350 years ago (*1*) and has been confirmed several times since (*2–4*), but no convincing explanation has been proposed. Seven other halos have been reported (*5*). They are caused by light passing at the angles of minimum deviation through crystals of ordinary hexagonal ice, ice Ih, that have faces whose Miller indices are either 0 or 1. The purpose of this report is to suggest that Scheiner's halo is caused by light passing at the angle of minimum deviation through octahedral crystals of cubic ice, ice Ic.

In both ice Ih and ice Ic, each water molecule is hydrogen-bonded to four neighbors in a nearly perfect tetrahedral arrangement, and the tetrahedra are stacked differently to give the hexagonal and cubic structures, which have the same density. Several reviews (*6–9*) of their properties have been published. Ice Ih is the only form of ice that is known to occur naturally on the earth. Ice Ic is always metastable relative to ice Ih and can therefore only be made from a less stable phase of water than Ih. It seems that below ~ 180 K, all phases transform to it rather than to Ih. For example, when the vapor condenses on a substrate below ~ 180 K, ice Ic is formed if the temperature is not too low, and otherwise amorphous ice is formed. Amorphous ice and all the high-pressure phases that can be recovered in a metastable form at low temperature and pressure (*10, 11*) transform first to ice Ic on heating. Ice Ic is therefore kinetically preferred over ice Ih in transformations from a less stable phase below ~ 180 K, although Ih is the thermodynamically preferred form. Near the melting point, ice Ih is always formed. At intermediate temperatures there must therefore be intermediate probabilities of forming ice Ic.

Ice Ic has never been made from the liquid. However, the liquid can be cooled to ~ 230 K if heterogeneous nuclei are not present, and it is possible that at least sometimes the drops freeze to form ice Ic. Many droplets of water exist in the upper atmosphere at temperatures down to ~ 230 K (*12*), and naturally formed ice Ic may occur there. The question arises how to detect it if it does.

One way is by means of halos. At least eight halos occur around the sun or the moon (*5, 13–16*), of which seven are due to hexagonal ice. Scheiner's halo, however, cannot be explained by refraction by crystals of ice Ih having low-index faces. It could be explained by invoking crystals having higher index faces, but then, as Tricker (*17*) pointed out, many other halos ought to have been observed but have not been. Tricker (*17*) suggested that it is an upper arc caused by light refracted through the (10.0) and (10.1) faces (m_1p_1 in the usual halo nomenclature) of a doubly oriented crystal of ice Ih. The arc should be about 33° and 24° above the sun when the sun is at 0° and 10° elevation, respectively. If this is so, then the halo should be seen only when the sun is somewhat less than 10° above the horizon and should occur above the sun. However, the halo was observed by Whiston (*2*) at London at about 10:15 a.m. on 1 March 1727 as a short arc that appeared briefly at about 50° from the vertical, and by Greshow (*3*) at Paris at 8:40 p.m. on 20 October 1747 as a left lateral arc of the moon and at 9:32 p.m. as a right lateral arc. C. G. Andrus and H. L. Riley observed the halo at Sand Key, Florida, at 3:00 p.m. on 11 May 1915 at about 315° from the vertical (*4*). These three observations are inconsistent with Tricker's explanation. Besson (*18*) reported observing at Paris at 5:38 p.m. on 26 March 1906 a spot 28° above the sun when the sun was 6° above the horizon. It is usually identified (*19*) with Scheiner's halo, but it appears to agree approximately with Tricker's prediction and so may not be Scheiner's halo.

Andrus and Riley also reported observing simultaneously parts of the 22°, 18.5°, 17.5°, and 8.5° halos, and Andrus sketched their appearance (*4*). All but the 28° halo were approximately symmetric about a common diameter, but the 28° halo was well off the diameter and did not cut it. This is consistent with independent origins for the 28° and the other halos.

Observable single crystals of ice Ic have never been made, and so its crystalline form is unknown. If it formed cubic crystals and its refractive index were the mean refractive index of ice Ih, it would cause a halo at 46°, which coincides with the halo caused by refraction through the side and end faces of a hexagonal column of ice Ih. If it formed octahedral crystals, however, as illustrated in Fig. 1, only the (111) and ($\bar{1}\bar{1}\bar{1}$) faces, which are labeled o_1 and o_3, respectively, and the 11 related pairs of faces would form prisms having an angle of minimum deviation. The prism angle is 70.528° by symmetry,

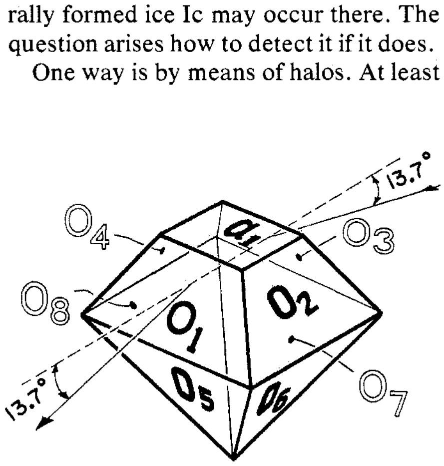

Fig. 1. Octahedron with one corner truncated to show the o_1o_3, . . . faces that cause Scheiner's halo and the a_1o_5, . . . faces that cause a halo at 19.7°.

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and the angle of minimum deviation is 27.46° if the refractive index of ice is taken as 1.307. Octahedral crystals would therefore cause only one halo, due to refraction through the octahedral faces o_1o_3, o_1o_6, o_1o_8, . . . , as labeled in Fig. 1, and it would be at the angle reported for Scheiner's halo. Scheiner's halo could therefore be caused by octahedral crystals of cubic ice.

Truncated octahedral crystals, as illustrated in Fig. 1, could form another halo due to refraction through one cubic and one octahedral face, such as a_1o_5. The prism angle is 54.736°, and it would produce a halo at 19.12°. This is very close to Burney's halo at 19.0° (*17*), which is usually attributed to refraction through the faces (01.1) and $(0\bar{1}.1)$ (p_1p_4), which should give a halo at 19.7° if the axial ratio c/a is 1.624 (*20*). The halo at 27.46° is therefore the only halo that is firmly characteristic of ice Ic crystals having low-index faces.

If a droplet of water in the upper atmosphere nucleates to form ice Ic, it will heat to the melting point in times of the magnitude of some microseconds (*12*) and will cool in times of the magnitude of some milliseconds. There is evidence from two sources that, in spite of this, single crystals of ice Ic will survive long enough for a halo to be observed. The first is an experiment in which a bulk sample of ice Ic was heated (*10*) to successive temperatures, each 10 K higher than the preceding. It was kept at each temperature for 4 minutes, cooled to 90 K, and x-ray powder photographs taken. After 208 K no Ih was present, after 218 K it was noticeable, and after 228 K the ice Ic had completely transformed to Ih. In this bulk sample, each particle that transformed could help nucleate its neighbors. If small octahedral crystals are produced in the atmosphere, they probably have a much longer life than this sample, partly because they are isolated from one another and partly because they may be only about 10 μm across, and so nucleate slowly.

The second is an experiment in which Oguro and Higashi found stacking faults by x-ray topography in ammonia-doped (*21, 22*) and pure (*23*) ice. Each fault is a thin layer of ice Ic sandwiched between ice Ih; it may be several millimeters across, and so similar in volume to a 10-μm octahedron. The faults survive for hours or days near 0°C, which suggests that a small crystal of ice Ic may survive heating to 0°C for 1 msec or so.

It therefore appears that Scheiner's halo is probably caused by ice Ic. If this is true, it shows that (i) liquid water can freeze to ice Ic at ~ 230 K and (ii) ice Ic sometimes occurs in the upper atmosphere. These points suggest that when emulsions of water are frozen at ~ 183 K at a pressure of 2 kbar (*24*) they probably form some ice Ic and that ice Ic may have some meteorological significance. It may be possible to investigate its meteorological effects by inducing it artificially because, inasmuch as hexagonal silver iodide nucleates ice Ih, cubic silver iodide may nucleate ice Ic. If this is so, controllable amounts may be generated in the upper atmosphere.

E. WHALLEY

Division of Chemistry, National Research Council, Ottawa, Ontario, Canada K1A 0R9

References and Notes

1. A. Bravais, *J. Ec. Polytech.* **18**, 1 (1847).
2. G. Whiston, *Philos. Trans. R. Soc. London* **33**, 257 (1727).
3. A. N. Greshow, *ibid.* **45**, 524 (1748).
4. C. G. Andrus, *Mon. Weather Rev.* **43**, 213 (1915).
5. R. A. R. Tricker, *Ice Crystal Haloes* (Optical Society of America, Washington, D.C., 1979).
6. B. Kamb, in *Structural Chemistry and Molecular Biology*, A. Rich and N. Davidson, Eds. (Freeman, San Francisco, 1968), p. 507.
7. N. H. Fletcher, *The Chemical Physics of Ice* (Cambridge Univ. Press, Cambridge, 1970).
8. P. V. Hobbs, *Ice Physics* (Clarendon, Oxford, 1974).
9. E. Whalley, in *The Hydrogen Bond*, P. Schuster, G. Zundel, C. Sandorfy, Eds. (North-Holland, Amsterdam, 1976), p. 1425.
10. J. E. Bertie, L. D. Calvert, E. Whalley, *J. Chem. Phys.* **38**, 840 (1963).
11. ——, *Can. J. Chem.* **42**, 1373 (1964).
12. H. R. Pruppacher and J. D. Klett, *Microphysics of Clouds and Precipitation* (Reidel, Dordrecht, 1978), chap. 16.
13. L. Besson, *C. R. Acad. Sci.* **170**, 334 (1920).
14. J. M. Pernter and F. M. Exner, *Meteorologische Optik* (Braumüller, Vienna, 1922), p. 244.
15. W. J. Humphries, *Physics of the Air* (McGraw-Hill, New York, ed. 2, 1929), p. 483.
16. E. C. W. Goldie, G. T. Meaden, R. White, *Weather* **31**, 304 (1976).
17. R. A. R. Tricker, *J. Opt. Soc. Am.* **69**, 1093 (1979).
18. L. Besson, *C. R. Acad. Sci.* **140**, 959 (1905).
19. J. M. Pernter, *ibid.*, p. 1367.
20. Chosen as a mean of the values reported by S. LaPlaca and B. Post [*Acta Crystallogr.* **13**, 503 (1960)] and R. Brill and A. Tippe [*ibid.* **23**, 343 (1967)].
21. M. Oguro and A. Higashi, in *Physics and Chemistry of Ice*, E. Whalley, S. J. Jones, L. W. Gold, Eds. (Royal Society of Canada, Ottawa, 1973), p. 338.
22. A. Higashi, *J. Cryst. Growth* **35**, 24–25, 102 (1974).
23. ——, personal communication.
24. H. Kanno, R. J. Speedy, C. A. Angell, *Science* **189**, 880 (1975).
25. This is contribution 18825 from the National Research Council of Canada.

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Natural Disturbance and the Steady State in High-Altitude Balsam Fir Forests

Abstract. *Wind-induced, cyclic waves of death, regeneration, and maturation constantly move through the high-altitude balsam fir forests in the northeastern United States. Biomass and productivity relations, species diversity, and nutrient cycling patterns are closely tied to this cycle of disturbance. Disturbance is thus an integral part of the long-term maintenance of this ecosystem. Since forests of this type normally include all phases of the disturbance-regeneration cycle, they may constitute a steady-state ecosystem in equilibrium with the surrounding environment.*

It has been an underlying assumption of much of plant ecology that, in the absence of disturbance, ecosystems eventually reach a "climax" condition in which the structure and species composition of the vegetation do not change appreciably over time (*1*). This assumption is belied by the fact that moderate- to large-scale disturbances are omnipresent in many natural ecosystems (*2, 3*). Fires, floods, windstorms, and insect outbreaks exert powerful influences that cannot be ignored in ecosystem studies (*4*). Disturbance and the responses to it must be viewed as normal aspects of the long-term maintenance of ecosystems.

Disturbance is common in the "wave-regenerated" balsam fir (*Abies balsamea*) forest of the northeastern United States (*5, 6*). The canopy of the balsam fir forest is broken by numerous crescent-shaped strips of dead trees (Fig. 1). These trees may appear to have been flattened by strong gusts. However, closer examination shows that each area is actually a band of standing dead trees, with mature forest on one side and young, vigorously regenerating forest on the other (Fig. 2).

This pattern occurs at high elevations in the Adirondack Mountains of New York, the White Mountains of New Hampshire, and the Mount Katahdin region of Maine (*5, 6*). Similar patterns are found in *Abies veitchii* and *A. mariesii* forests in the mountains of Japan—in particular on Mount Shimagare ("mountain with dead tree strips") (*7, 8*).

Each band is actually a "wave" moving slowly through the forest, with trees dying at the wave's leading edge and being replaced by seedlings (*5, 6, 9*). These waves move in the general direction of the prevailing wind (Fig. 2) at speeds of 0.75 to 3.3 m per year (*5, 6, 8–11*). Speeds are apparently related to the degree of exposure to the prevailing wind, with the highest wave speeds occurring on or near ridgetops. Trees directly exposed to the prevailing wind are sub-

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