Antisolar halospot

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Received 28 April 2008; revised 4 September 2008; accepted 19 September 2008; posted 22 September 2008 (Doc. ID 95574); published 15 October 2008

An isolated colorless spot of 1° diameter located at the antisolar point was observed from a plane on the clouds beneath it. The spot can be explained by light scattering on randomly oriented ice crystals via light paths similar to those responsible for the subparhelic circle. Its peculiar polarization properties potentially permit its detection in cases where the spot is embedded in a glory.

OCIS codes: 010.2940, 010.1290, 010.1350.

1. Introduction

Figure 1 shows a picture of an isolated spot located at the antisolar point. Mónika Bodó took the photograph on 27 March 2008 near the midway point of an afternoon flight from Athens to Budapest. As an air hostess, she flies several times a week, and often takes photographs of glories and subhorizon halos [1]. This was the first time, however, that she saw a phenomenon like this. The spot lasted only 1 min; its diameter of almost 1° and its appearance remained constant during the observation. Two pictures of the spot were taken. The location of the spot at the antisolar point could be confirmed by another image taken 7 min later, showing the shadow of the airplane's contrail, whose starting point was exactly at the position where the brightening had developed. Usually, at this position a glory or perhaps a subanthelion [2–4] may appear, but the spot resembles none of these. In a picture [1] from the Sun-facing side of the airplane photographed 1 min before Fig. 1, the lower part of the 22° circular halo, a subsun, and the right subparhelion are visible. In a Sun-facing picture taken about 1 min after Fig. 1, the subparhelion is gone, and the 22° halo is barely visible anymore. During the observation no other halos were apparent on either side of the plane.

We consider it unlikely that the spot is a rudimentary glory. Normally a glory has a diameter of several degrees [5], but if a glory emerges from droplets as large as 60 μm in diameter, it may result in a spot of the required size. However, simulations of this small-sized glory (see Fig. 10 in Laven's paper [5]) show that a glory-related spot would have a distinct red rim, while such a feature is absent in Fig. 1. This makes it difficult to believe that the spot stems from glory scattering. Neither does the spot appear to be a subanthelion in the classical [2–4] sense. That subanthelion is actually not a real halo, but rather an enhancement in intensity because of the superposition of two halos or two self-crossing halo branches, most often of the diffuse arcs together with the subparhelic circle. The fact that the observed spot is isolated with no trace of the subparhelic circle nor of the diffuse arcs in its environment makes it difficult to accept that this mechanism is at work. We believe that the spot is something else.

2. Antisolar Hot Spot

A process capable of producing enhanced intensity at the antisolar point with no occurrence of other halos in that region is light scattering by randomly oriented hexagonal ice crystals in which the light

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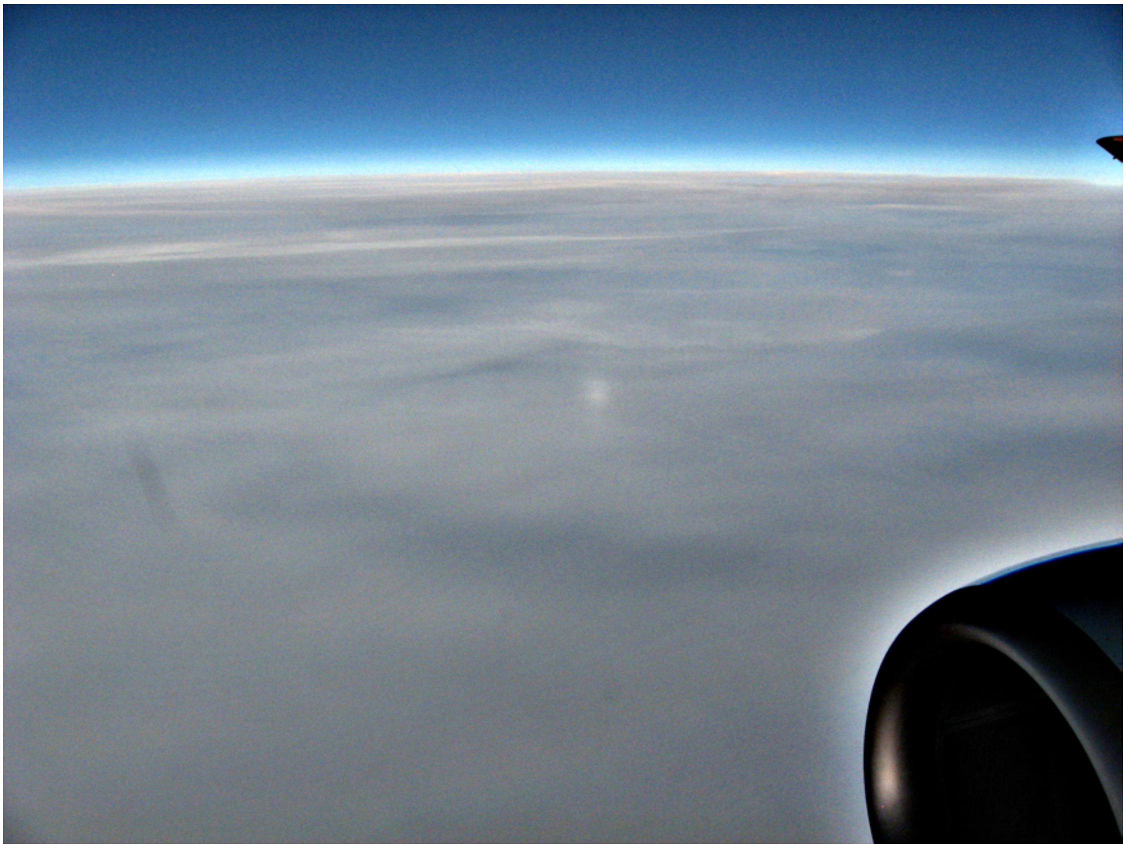

Fig. 1. (Color online) Bright spot at the antisolar point. Its diameter is 1°. The contrast is enhanced by unsharp masking. The picture was taken while flying over Serbia, between Belgrade and Szeged. Solar elevation was 12.5°. The horizontal field of view is 52°. (Photographed by Mónika Bodó on a flight from Athens to Budapest on 27 March 2008, 15:45 UTC).

travels through the crystal via the path depicted in Fig. 2. In this path (1321 in Tape's [2] notation, in which the two basal faces are numbered 1, 2 and the six prism faces 3–8) light enters and leaves the crystal via the same basal face and undergoes in its path through the crystal two internal reflections: one at a prism face and one at the other basal face. Essential in this process are the reflections at two faces that are perpendicular to each other. The mechanism at work is axial focusing.

It is easy to visualize why this light path should lead to axial focusing and hence to an enhanced intensity at the antisolar point. For this, we turn to Fig. 2 and first put—like in the diagram—the crystal *C* axis vertical, which is then the spin axis of the crystal. Oriented in this way, the light path results in the subparhelic circle [2], which is a colorless circle below the horizon having its center at the zenith (or, more general, in the direction of the spin axis) and being as deep below the horizon as the Sun is above it. A basic property of the subparhelic circle is that it always passes through the antisolar point, regardless of the value of the solar elevation; a second property is the insensitivity of its width in the antisolar region on the spin axis's tilt angle. This latter characteristic implies that in the absence of diffraction effects, the width of a subparhelic circle at the antisolar point is essentially 0.5°, which is the value of the diameter of the Sun.

Now we start to randomize the position of the crystal while keeping it spinning around its *C* axis. If this spin axis points at a certain moment to a randomly chosen spot on the celestial sphere, the crystal will create a circle centered around that spot (hence not parallel with the horizon any more) but still passing through the antisolar point. So for randomly

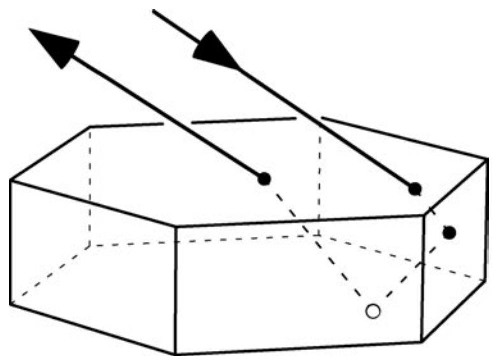

Fig. 2. If this ice crystal is in plate orientation, that is with its *C* axis vertical, the light path depicted here creates the subparhelic circle, which is a horizontal circle below the horizon passing through the antisolar point. If the crystals are randomly oriented, the light path creates a spot-shaped intensity enhancement at the antisolar point.

oriented crystals the antisolar point consists of a superposition of subparhelic circles having their center at any spot on the celestial sphere, all of them intersecting at the antisolar point. In other words, at the antisolar point the circle segments of the subparhelic circles come together from all directions like a bunch of sticks, and this superposition results in an enhanced intensity.

3. Simulations

Computer simulations show that scattering of sunlight by randomly oriented hexagonal ice crystals results in a spot 0.7° in diameter. Figure 3 depicts the simulation for equidimensional crystals (aspect ratio $c/a = 1$), but it turns out that the diameter of the spot is not affected by variations in the aspect ratio. The difference between the simulated size of the spot of 0.7° and its observed size of almost 1° may be attributed to diffraction broadening. An effective slit width of the outgoing rays of $50\,\mu$m would result in the required diffraction broadening, which puts the size of scattering crystals at the order of $100\,\mu$m.

Ray path sortings confirm that the spot is entirely due to light paths that create the subparhelic circle for oriented crystals. Three of these paths account for 80% of the spot's intensity, namely, the path shown in Fig. 2 (path 1231, for 20%), path 3163 (20%), and path 4168 (40%). Here, all paths can be passed in direct (like 1231) or reversed (like 1321) direction. However, paths 1231 and 3163 are fully equivalent, as they both represent a ray path that enters and emerges via the same face, with internal reflections at two mutually perpendicular faces, one of the latter being parallel with the entry face. Therefore only two main contributions remain, namely, 1231/3163 and 4168, each of them accounting for 40% of the spot's intensity. This percentage proves to be not very sensitive to the aspect ratio c/a of the crystals, as the decrease in contribution of path 1231 with increasing aspect ratio is counterbalanced by an increase of its equivalence 3163.

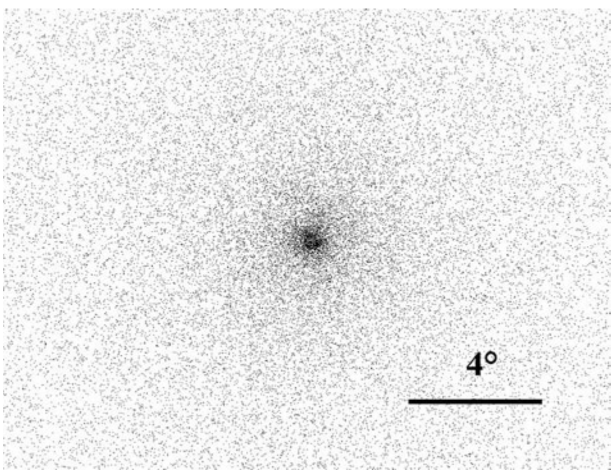

Fig. 3. Simulation of the light distribution in the antisolar region due to light scattering by randomly oriented hexagonal ice crystals with aspect ratio $(c/a) = 1$. The spot in the center of the picture appears exactly at the antisolar point; its diameter is 0.7°. The horizontal field of view of the figure is 18°. The simulation is made with the HaloSim program authored by L. Cowley and M. Schroeder [6]; the 0.5° diameter of the solar disk is taken into account.

4. Identifying the Spot in Nature

We believe that there are good arguments that support the identification of the antisolar spot in Fig. 1 as being a halo due to randomly oriented hexagonal ice crystals. Its roundness, its size, the absence of colors and of other halos in the antisolar region, and the presence of a segment of the 22° circular halo on the other side of the celestial sphere [1] are all consistent with this explanation, although one would expect the associated 22° halo to be brighter than the one in the photographs before and after the spot's appearance.

One may wonder why this antisolar hot spot is so rarely observed compared, e.g., with the 22° circular halo. A plausible explanation is that it may often be embedded in a glory and hence not recognized as such. As most of the clouds consist of a mix of water drops and ice crystals, the occurrence of a hot spot without a glory would be rather exceptional. The enhanced intensity in the glory's center may be easily overlooked as being an individual halo phenomenon.

A promising method to decisively identify the hot spot as a halo is by its polarization. As the main light paths resulting in the hot spot include two internal reflections of which at least one needs not to be total, its light should be polarized. From the Fresnel coefficients of transmission and reflection it follows straightforwardly that for the ray path shown in Fig. 2 (as well as for path 3163) the spot's polarization, just away from its center, is very high (order 70%). If one takes the other (weakly polarized) contributing paths into account, the polarization becomes 30%. The spot's polarization implies that the spot deforms from round to more or less stretched when viewed through a polarizer; this elongated structure rotates as the polarizer is rotated.

Polarization observations may also be capable of identifying a hot spot if it is embedded in a glory. The direction of polarization of the spot is parallel with the plane of scattering, and so radially directed with respect to the antisolar point. For a phenomenon whose polarization arises from reflection, this is a somewhat unexpected result [7]. It can be understood as follows. A subparhelic circle should be horizontally polarized near the antisolar point, owing to the reflections involved (Fig. 2). Thus the polarization is parallel with the circle. Regarding the spot, as before, as consisting of a bunch of intersecting subparhelic circle fragments coming from all directions implies its polarization to be in the plane of scattering. The inner part of the glory, on the other hand, is polarized in the reverse direction [5,8]. Therefore, if one views through a polarizer a glory whose central point is a hot spot, the center will become elongated and will point in the direction where the dark areas in the glory appear [5,8]. However, it should be noted that the observation is not so easy because of the polarization-disturbing properties of aircraft windows

[5], which may be somewhat suppressed but not entirely removed by putting camera or eye as close as possible to a properly selected part of the window. On the other hand, if the observation is successfully performed, polarization has demonstrated once again [9] its power as diagnostic for unraveling the nature of this kind of phenomena.

Walter Tape generously modified and ran his halo ray sorting program for this work.

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