Optical properties of contrail-induced cirrus: discussion of unusual halo phenomena

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Photographs of a 120° parhelion and a 22° parhelion within persistent contrails are presented. These phenomena result from hexagonal plate-shaped ice crystals oriented horizontally with diameters between 300 μm and 2 mm. From our observations and reinvestigation of previous reports, we conclude that a subset of the population in persistent contrails can consist of highly regular, oriented, hexagonal plates or columns comparable to the most regular crystals in natural cirrus clouds. This is explained by measured ambient humidities below the formation conditions of natural cirrus. The resulting strong azimuthal variability of the scattering phase function impacts the radiative transfer through persistent contrails. © 1997 Optical Society of America

Key words: Aircraft, contrail, climatic impact, crystal growth, halo phenomena, ice crystals, optical properties, relative humidity, remote sensing, scattering phase function.

1. Introduction

Natural cirrus clouds that on average cover approximately 20% of the globe are known to play a major role in the radiation balance of the earth.[1] In past years because of increased air traffic, research activities were extended strongly toward anthropogenically induced cirrus (contrails) and the possible impact on climate[2,3] resulting from an additional surface coverage of at most 2% on long-term average.[4,5] (By anthropogenically induced cirrus we refer to primary induced cirrus, which results from a rapid formation of ice particles, not to a possible secondary formation of ice particles late after the aircraft emission of aerosols.) This human-made enhance of cloud coverage has to be judged bearing in mind the highly nonlinear dependence of solar backscattering and infrared absorption from cloud coverage and optical thickness.[6] Remote-sensing approaches for studies of ice clouds were adapted to contrail research; e.g., in our group a backscatter-depolarization lidar is implemented with a fast-scanning capability.[7] With this the evolution of geometry and optical thickness can be monitored.[8] An airborne lidar was applied for this purpose,[9] as well as advanced satellite multichannel imagery.[5,10] In investigating the climatic effect of contrails, one of the important questions we address is whether in persistent contrails there is any significant difference in radiative impact compared with natural cirrus, i.e., whether there are differences in optical properties as ruled by particle compositions, crystal shapes and orientations, and size distributions.

Direct imaging of the crystal shape and orientation within contrails is sparse. Weickmann took microphotographs from airborne particle sampling in a young contrail (aged 3–4 min) at an altitude between 8 and 9 km and a temperature between −49 °C and −53 °C.[11,12] He found small (1-μm) primary particles difficult to resolve and few large (100-μm) hollow prisms typical for highly ice-supersaturated conditions; however, as stated by Weickmann, the hollow prisms are "under no circumstances to be considered as typical for contrails." An ice replicator measurement on a young contrail (2 ± 1 min) was reported recently by Strauss showing nearly but not exactly spherical particles (droxtals) with sizes ranging from 1 to 5 μm.[13] Using a one-dimensional optical-array particle spectrometer, Knollenberg found mean particle diameters of the order of 0.5 mm in old (persistent) contrails.[14] Similar measurements with enhanced resolution give an indication of a comparably large fraction of small particles in young contrails.[9]

Remote-sensing with halo phenomena, i.e., the photographing of halos and comparison with simula-

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tions through ray-tracing methods of ice crystal refraction and reflection phenomena, can give detailed information on ice crystal shapes and orientations.[15,16] However, there are only a few early notes on halo observations within contrails, all without photographs and most with no unique scientific analysis.[12,17–22] To our knowledge, hitherto only one unique photograph of a halo (refraction and reflection) phenomenon in contrails was reported: Sassen presented the photograph of an old and persistent contrail that clearly shows an upper 22° tangent-arc halo component together with a weak 22° halo.[23] Related to halo phenomena are optical phenomena caused by diffraction effects that point to small crystals. Such a diffraction (iridescence) phenomenon is also observed in the photograph of Ref. 23. From this the author derived a growth of the spherical and monodispersed particles from 2 μm (200 m behind the aircraft) to 3 μm (400 m behind the aircraft). Furthermore, Sassen observed corona (diffraction) effects within contrails that point to a considerable fraction of relatively small (~10-μm) ice particles in medium-aged (~10-min) contrails.[24]

In this paper we present first photographs of two different further halo phenomena within persistent (aged >0.5 h) contrails, including one halo component rarely observed even in natural cirrus. With this we derive an unambiguous characterization of the ice crystal shape, size range, and orientation within the contrails responsible for the observed phenomena. Together with the discussion of the previous observations, we draw some conclusions on typical ice crystal properties in persistent contrails.

2. Photographic Observations

The video image of our first contrail halo observation (Fig. 1) was performed with a commercial CCD camera (Sony XC-77CE) with a video processor (AEG) and a frame-grabber (Matrox). The camera is characterized by focal lengths of $f = 12.5$–75 mm, a maximum field of view of 40°, and a resolution of 756 × 581 picture elements. The observation direction is computer controlled with a two axis scanning mount.

On 18 January 1996 all of Europe was under the influence of an extended high-pressure system with weak northerly winds, free from significant synoptic disturbances. Persistent contrails were formed at approximately noon above the IFU [47.7 °N, 11.1 °E, 730 m above sea level (asl)] at 8700 m asl (height measured by lidar). From the Munich radiosonde data [100 km to the north, 12 Coordinated Universal Time (UTC)] we find a temperature of $T = -46.5$ °C at this height and calculate a relative humidity above ice of $RH_i = 79\%$. These conditions are close to the Appleman–Schmidt threshold for initial contrail formation (for kerosene and overall propulsion efficiency of 0.3).[25,26] Note that the radiosonde humidity measurements display large errors (above 10%) at this temperature; thus we have just an indication that ambient humidities were below or close to ice saturation.

In addition to two young contrails (~1 min) in its upper left-hand side, Fig. 1 shows the aged contrail (lower part) that was advected by the northerly wind. We briefly observed a white, brightly illuminated spot-halo phenomenon seen in Fig. 1. The center of the halo was observed at a zenith angle of 71.1° and an azimuth angle of 315° at 12:25:18 UTC on 18 January 1996. The apparent angles of the sun at this time are calculated by a ray-tracing computer program (Sun-zenith angle of 69.39°, Sun-azimuth angle of 194.82°).

The observed halo phenomenon is unambiguously identified to be a 120° parhelion according to the following threefold criteria: (1) white color, (2) appearance at the same zenith angle as the Sun, and (3) appearance at an azimuth angle difference of 120° relative to the Sun. All three criteria are matched for our observation of Fig. 1. The white color was uniquely recognized from our visual observation, and the angle criteria were matched within the accuracy of our angle determination (±1°) from the video picture. For completeness, note that our observation also might have been attributed initially to the phenomenon of a parhelic circle[15] resulting from less specific crystal properties; we exclude this possibility. The only criterion for this circle-type halo is a zenith angle equal to the actual Sun-zenith angle. Our observed bright spot would then be caused by a crossing point between the contrail and the circle given by the parhelic circle criterion. We exclude this possibility because in this case the halo spot should have been observable for a longer time. Additionally, during this time it should have moved along the contrail while the contrail was drifting; this was not the case. Finally, note again that the 120° parhelion appeared only for the short time when the contrail passed the twofold angle criterion (see above). This proved that the observed halo was indeed caused by the contrail; i.e., it was not caused by a possible weak or subvisible natural cirrus. Typical ray paths responsible for the occurrence of the 120° parhelia are discussed, e.g., in Ref. 16. Our observation of a 120° parhelion within the persistent contrail results unambiguously from ice crystals of the shape of hexagonal plates that are oriented horizontally (oriented plates, c-axis vertical, one rotational degree of freedom).[15,16]

Another halo phenomenon caused by persistent contrails was photographed close to sunset on 17 June 1996 with a 35-mm format camera ($f = 35$–70 mm) (Fig. 2). The observation was in a main air corridor 30 km west of Augsburg, Germany. We have no lidar information on the contrail height. However, the typical flight levels in this corridor are in the range of 9300–10,500 m asl. Because of the northerly winds at this height we observe the nearest radio soundings to the north of the observation (Stuttgart 12 UTC radio soundings, 100 km to the northwest). From the 300-hPa (9390-m asl) measurements we find a temperature of $T = -44$ °C and a relative humidity with respect to ice of $RH_i = 69\%$. For these data the Appleman–Schmidt threshold for contrail formation is not fulfilled. From the 250-hPa (10,590-m asl) measurements we find a temperature

Fig. 1. CCD camera image of a 120° parhelion within a persistent (aged >0.5 h) contrail at 8700 m asl. The center of the halo (marked with a +) was observed from the IFU, Garmisch–Partenkirchen (47.7 °N, 11.1 °E, 730 m asl) at a zenith angle of 71.1° and an azimuth angle of +315° at 12:25:18 UTC on 18 January 1996. From nearby radio soundings a relative humidity with respect to ice of $RH_i = 79\%$ is calculated.

of $T = -54$ °C and a relative humidity with respect to ice of $RH_i = 62\%$. For the latter data the Appleman–Schmidt threshold for contrail formation is fulfilled; however, the relative humidity with respect to ice is even further below ice saturation. Thus we conclude that the conditions during halo observation were probably close to the Appleman–Schmidt threshold and the relative humidity was certainly not much above ice saturation and probably even below it. The phenomenon is caused by several contrails observed over a longer time period (aged >0.5 h). It is uniquely designated as a left 22° parhelion. This phenomenon results from a cumulation of rays that are refracted with minimum deviation by passing the 60° prisms within oriented hexagonal plate crystals.

3. Discussion

A. Orientation and Size

From our photographs (Figs. 1 and 2) we obtained proof that the persistent contrails in both cases consisted of hexagonal plates oriented horizontally. This can be concluded from a comparison with computer simulations of halo phenomena by ray-tracing techniques (geometrical optics). Such modeling of the scattering by oriented hexagonal plates or columns was completed in a series of subsequent studies[27–31]; a special area of research focuses on the intensity and polarization distribution around local scattering maxima of halos.[15,16] The vertical extension of the 22° parhelion in our observation (Fig. 2) is somewhat larger than the minimum extension but

Fig. 2. Photograph of a left 22° parhelion within a group of persistent (aged >0.5 h) contrails observed close to sunset on 17 June 1996. From nearby radio soundings a relative humidity with respect to ice in the range of $RH_i = 62–69\%$ is estimated.

within the typical range. Computer simulations show that this results from oscillations of the plate crystals of a few degrees of standard deviation from equilibrium. This was also found from halo observations[32,33] as well as lidar measurements[34,35] to be typical for natural ice clouds.

Plate-shaped particles tend to fall oriented[36] only for Reynolds numbers between 1 and 100.[37] (The Reynolds number depends on particle diameter, terminal velocity,[38,39] and viscosity of the medium.) For ice plates falling oriented in air, diameters between 300 μm and 2 mm were found.[37] The persistent contrails in our observations (Figs. 1 and 2) are obviously composed to a considerable degree of oriented plates of this size.

B. Previous Halo Observations in Contrails

Table 1 gives an overview of the halo observations in contrails found in the literature. There are reports on the 22° halo, 22° parhelia, parhelic circle, circumzenithal arc, upper 22° tangent arc, and 120° parhelion, in part according to our interpretation of the early notes (see footnotes of Table 1). In particular the attribution to either the 22° halo or the 22° parhelion is not clear in some cases. This distinction, however, is essential for the conclusion on particle shapes and orientations: Whereas the 22° halo appears almost always when ice particles are present (see footnote *d* of Table 1), the 22° parhelia is the typical halo component resulting from oriented plates. From Table 1 we learn that most of the halo observations are caused by oriented plates with diameters between 300 μm and 2 mm (see above). At least in one case there is unique proof for the additional existence of singly oriented columns,[23] i.e., hexagonal columns with their long axis oriented horizontally (two rotational degrees of freedom). As a typical result columns with diameter-to-length ratios of 1:10 and lengths between 200 μm and 1 mm are expected to be singly oriented.[35] Note that we find plates at least as likely to be formed as columns at the temperatures typical for contrail occurrence (below −40 °C); this is in contrast to laboratory experiments that found column-type crystals to be strongly favored below −22 °C.[40] However, as noted in Ref. 41, at low relative humidities with respect to ice in combination with low temperatures, the occurrence of plates is possible. Deviations from the laboratory results[40] were also reported in Ref. 16.

C. Why do Contrails Display Bright Halos?

Generally, the occurrence of halo phenomena results from the simplest crystals (hexagonal plates and columns) and the most regular crystal shapes. We can observe halos in contrails that are probably even more pronounced than those in natural cirrus. In one of the first contrails ever produced (on 11 May 1919 above Munich[17,18]) a halo was observed. Furthermore, in his early flight observations, Weickmann[12] stated that "We remember several contrails where the most wonderful halo phenomena developed we ever saw." In addition, the statements by Boerner[20] and aufm Kampe[21] point to the observation of unusual bright halo phenomena in contrails (see Table 1). This also might be confirmed by our observation of the 120° parhelion within a contrail (Fig. 1), a component that has been observed rather rarely even in natural cirrus.

Persistent contrails obviously often consist of unusual regular crystals. For an explanation we first consider the state-of-the-art knowledge of the initial growth phase of contrails.[26] Visible particles form within a distance of 10–30 m after the engine. There is a rapid freezing, with particles formed at least partly by condensation on soot particles. The subsequent early growth of these sublimation nuclei in the young contrail can then be determined by a high water supersaturation caused by the en-

Table 1. Halo Observations in Contrails

Ref.	Date	Report (*Verbally, Manual Drawing, Photograph*)	Halo Component	Crystal Type and Orientation
17, 18	May 1919	*Verbally*: "part of sun ring," "northern and southern part of ring at distance of 22°"[a]	Not unique:[a] 22° halo (or possibly 22° parhelia)	No distinct type[b] (or possibly oriented plates)
22	April 1942	*Verbally*: "horizontal circle, in any case circumzenithal circle, whose extrapolation does approximately pass the sun"[c] *Manual drawing*: northern 30% part of a ring whose extrapolation passes the sun[c]	Not unique:[c] parhelic circle	Oriented plates and/or singly oriented columns
19	Dec. 1942	*Verbally*: "mock sun of faint red color"[d]	Not unique:[d] 22° parhelion (or possibly 22° halo)	Oriented plates (or possibly no distinct type)[b]
20	1943	*Verbally*: "side suns (of small ring) and circumzenithal arc (upper tangent arc of large ring) very bright colored, weak parts of 22° ring"	22° parhelia, circumzenithal arc, weak 22° halo	Oriented plates and further crystals with no distinct type[b]
21	1943	*Photograph*: no additional information *Verbally*: "most beautiful and manifold halos"	Not unique: circumzenithal arc or upper tangent arc?	Oriented plates (or possibly singly oriented columns)
12	1949	*Verbally* (flight report): "we remember several contrails where the most wonderful halo phenomena developed we ever saw"	No statement	
23	Oct. 1974	*Photograph* *Verbally*: "parhelia of 22° halo"	Upper 22° tangent arc, Weak 22° halo, 22° parhelia	Singly oriented columns and oriented plates and further crystals with no distinct type[b]
This paper	Jan. 1996	*Photograph* with angle measurement	120° parhelion	Oriented plates
This paper	June 1996	*Photograph*	22° parhelion	Oriented plates

[a]The second statement could be taken as an indication of the occurrence of the 22° parhelia rather than parts of the 22° halo.
[b]Nearly all randomly oriented crystals show the 22° halo; however, circular halos do not necessarily require random orientation.[16]
[c]The manual drawing points to a parhelic circle, which forms in the north opposite the Sun. Contrary to the verbal note, we exclude circumzenithal arc and circumhorizontal arc, which would be centered around the Sun-azimuth angle (we calculate $azi_{\mathrm{Sun}} = 215°$ from the observation time of 13:00 UTC on 3 April 1942, Augsburg, Germany) and extend at most a third around the horizon; furthermore, the latter are restricted to elevation angles above 58° and below 32°, respectively. This does not fit the Sun elevation of 47.5° that we calculate from the observation time.
[d]The 22° parhelia (mock Suns) usually contain all colors, whereas the 22° halo is just red inside the ring.

gines. For the highly regular crystals responsible for halo phenomena in persistent contrails to be explained, there must be a subsequent main phase of extremely regular crystal growth: As already pointed out by Weickmann[12] this late growth of contrails depends on the ambient humidity just as in the case of natural cirrus. Let us assume a region with low relative humidities near (below or slightly above) 100% with respect to ice, as found in our two observations. In such a region natural cirrus is not favored to form because investigations of natural cirrus formation[42,43] yielded a minimum relative humidity significantly above 100% with respect to ice.[44–46] However, a visible contrail can form in this region,[25,26] growing fast until all water vapor from the airplane in excess of the ambient relative humidity is deposited on the ice particles. It can then become persistent for hours even at ambient humidities below ice saturation or grow extremely slowly (in cases of low ice supersaturation) according to the low relative humidity of the entrained ambient air. Low ice supersaturations are known to favor regular crystal growth.[40,47] So a contrail is more likely than natural cirrus to find ideal conditions for formation of the more pristine crystal shapes that are capable of producing halos. The resulting crystals might be more perfect than the ones in cirrostratus.

4. Conclusions

From the video observation of a 120° parhelion and a 22° parhelion halo phenomenon within persistent (aged >0.5 h) contrails, we obtained proof that these contrails consisted to a considerable degree of hexagonal plates oriented horizontally with diameters between 300 μm and 2 mm. We reinvestigated previous halo observations within persistent contrails reported in the literature. This confirms our conclusion that a subset of the population in persistent contrails can consist of oriented plates and singly oriented columns that grew at least as regularly as the most regular crystals found in natural cirrus (cirrostratus). This can be understood considering an extremely slow crystal growth (after the fast initial growth process) of aged contrails that were formed and can become persistent in ambient conditions close to ice saturation, in which natural cirrus could not originate. Note that our findings, i.e., the contrail persistence (order of hours) at ambient humidities close to or below ice saturation and the occurrence of halo phenomena in persistent contrails that might be brighter than those in natural cirrus, are based on the current experimental data available as discussed in this paper; for further confirmation we point to the need for a long-term statistical analysis of optical phenomenon frequencies of occurrence together with accurate humidity measurements.

The results of our research may add a piece of information to the current debate about whether the optical properties of contrails can be parameterized identically to natural cirrus in general circulation models: It is essentially the old (persistent) contrails that are to be discussed for an impact on the radiative balance; the highly specific optical properties found in this study are attributed to a subset of the population in persistent contrails. The observed halo phenomena are examples of the azimuthal variability of the scattering behavior as induced by highly regular oriented crystals. This emphasizes the need for a three-dimensional (including azimuthal variability) radiative transfer model for the description of natural cirrus and, even more importantly, of persistent contrails.

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