Titan halos

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1 Introduction: rainbows and halos

If transparent particles are present in the air, special types of phenomena may appear in the sky. The most familiar among them is the rainbow, arising from a sunlit shower of rain. This bow can be considered as a mapping of the geometry of the drops onto the sky, and so the rainbow exhibits properties of the drops. The roundness of the rainbow is a manifestation of the roundness of the raindrops, and its radius relates to the refraction index of these drops. Figure 1 shows an application: the below-horizon part of the rainbow has a smaller radius than its above-horizon counterpart. This tells us that the seawater drops – for these generate the below-horizon rainbow – have a different index of refraction from rainwater, because seawater is salt!

Figure 1: Rainbow in fresh water and in salt water. The above-horizon rainbow arises from raindrops, hence from fresh water. The below-horizon rainbow arises from seawater drops, hence salt water. As the index of refraction of salt water is higher, its rainbow has a smaller radius. (Photograph by J. Dijkema)

If crystals are floating in the air and if they are lit by the Sun, halos may appear in the sky. In the Earth's sky, halos are well known guests and they are caused by ice. Ice often crystallises as hexagonal cylinders. The halos occur because any set of two crystal faces may act as a prism (see Figure 2). Halos differ from the rainbow in the sense that they predominantly appear at the Sun-facing part of the sky (whereas a rainbow is generated by a light path that includes a reflection, so that it appears opposite the Sun), and can exhibit exotic shapes, called arcs.

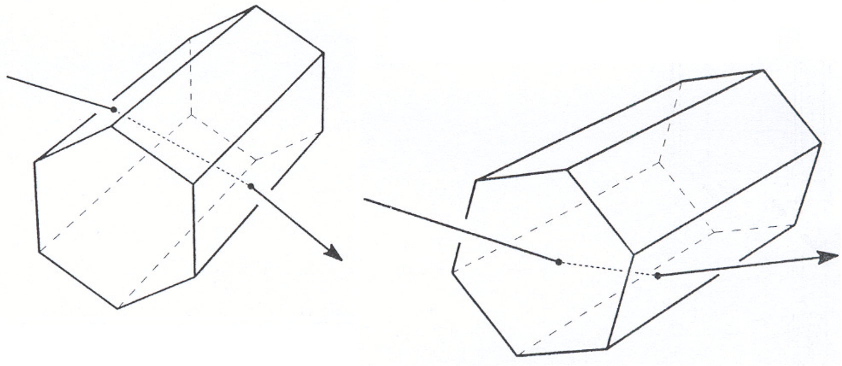

Figure 2: Halos arise because of refraction of light by the faces of atmospheric crystals. Each pair of crystal faces acts like a prism. The terrestrial 22° halos arise from pairs of faces on the hexagonal ice crystals that make an angle of 60° with each other (top); the 46° terrestrial halo from pairs of faces which make an angle of 90° (bottom).

The most familiar halos appear at an angular distance of about 22 degrees from the Sun; a second but rarer group of halos appears at 46° from the Sun.

Depending on the crystals' shapes and the orientation that the crystals assume while falling through the air, the halos may vary from rainbow-like coloured circles centred on the Sun, to coloured or white spots and arcs at various places in the sky. Truly spectacular halo displays, such as the one of Figure 3, may be observed if the ice crystals are well shaped and well oriented.

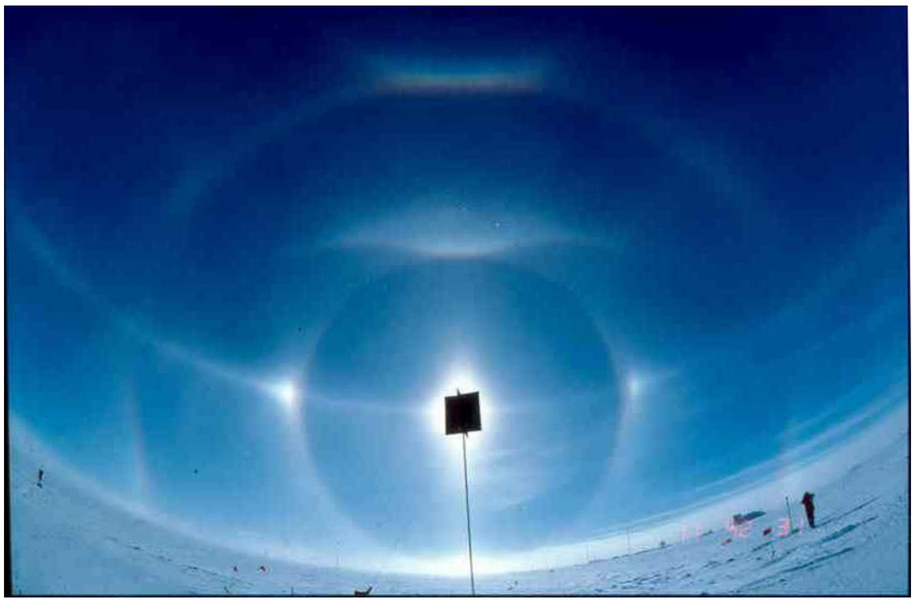

Figure 3: Wide-angle picture of a halo display; the Sun is hidden behind a nearby object. The halos arise from scattering of light by a swarm of ice crystals floating in the atmosphere. Photograph taken at US Amundsen-Scott South Pole Station on 2 January 1998.

Simpler halo displays, for instance those consisting only of a 22° circular halo around the Sun, or only of an isolated so-called parhelion at 22° left or right of the Sun (also present in Figure 3), frequently appear in the sky: in a country like the Netherlands, a halo is reported on more than 220 days a year. The reason that so many people are unaware of halos is that one usually doesn't look closely enough at the Sun.

Halo displays, especially those with many arcs, provide information about the geometrical shape of the halo-making crystals. In particular, there exists a relationship between the position of the halo arcs with respect to their associated circular halo and the orientation of the edges of the refracting prisms in the sky. The first to understand this relationship was Christiaan Huygens in 1663 (Figure 4), being ahead of his time with this by more than 150 years.

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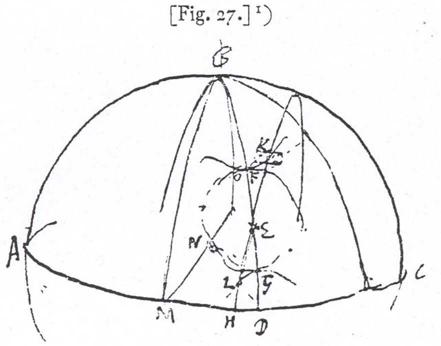
§ 40. De bogen die volgens ons onder aen de binnenſte corona moeten komen, ſouden in 2 obſervatien van Hevelius te weten die van de 30 Mart. 1660 en in die van de 7 ſonnen konnen geſien geweeſt hebben en ſijn oock eenighſins altydt in dit laetſte geſien, want hij ſeght dat in I een veſtigium van een parelium wierdt geſien. Doch door defect van materie, dewelcke raro ſoo veer ſich extendeert heeft dit maer een flaeuwe ſchijn geweeſt.

[Fig. 27.] 1)



§ 41. Porro figuras arcuum prædictas inveniendi ratio eſt hujuſmodi. In ſphæra aliqua ABC [Fig. 27] deſcribatur polo B circulus maximus ADC qui horizontem referat. deinde verticalis per ſolem tranſiens BD, poſito nempe ſolem eſſe in E, ita ut arcus DE ſit tot partium quot erat in obſervatione altitudo ſolis. Si igitur arcum inverſum qui minorem coronam tangit invenire velimus, ſoo neemt de bogen EF, EG in de verticalis BED ieder van 22½ gr. 2) ſoo zijn de puncten F en G het opperſte en onderſte deel der corona, ende te gelyck de middelſte puncten der inverſe bogen die wij ſoecken. On nu d'andere puncten daer van te vinden die

Figure 4: Christiaan Huygens' diagram on halo arc formation [1]. Huygens was the first to recognize the relationship between the position of halo arcs with respect to their associated circular halo and the orientation of the edges of the refracting prisms in the sky. This diagram from 1663 shows a quantitative calculation of the 22° halo arc straight over the Sun. This arc is visible in the halo photograph (Figure 3).

The relationship between the structures in a halo display and the geometry of the halo-making crystals is clearly apparent in Figure 3, where the arcs to the 46° halo are arranged according to a six-fold symmetry: the same symmetry that is present in the hexagonal cylindrical ice crystals depicted in Figure 2.

Within the current understanding of the Titan atmosphere, there is room for the presence of floating solid particles of methane (CH_4) and perhaps of ethane (C_2H_6). Crystals of these compounds are transparent. If the sizes of the crystals are larger than about 20 μm and if they are directly lit by the Sun, halos will appear in the Titan sky. Hence there exists a possibility that the Huygens probe will spot these halos during a certain stage of its descent.

Titan halos would differ from terrestrial ones, as the halo-making crystals are different. But as in the terrestrial case, each halo arc provides information about a pair of crystal faces, and how they are oriented in the sky. Cutting and pasting the pairs together provides a candidate shape for a Titan crystal. If Huygens is indeed lucky enough to detect halos, the shapes of the halos will provide a clue to the shapes of the Titan crystals, which is not easy to obtain by other means.

2 Halo formation on Titan

Halos may occur in the Huygens images if the following five conditions are satisfied:

- Transparent crystals are present
- Their faces are well-formed
- Their sizes are larger than ~20 μm
- They are directly lit by the Sun
- They are in the field of view of the cameras

These conditions could be loosely rephrased as "the weather should be favourable in the environment of the probe".

Titan crystals of methane are the best candidates to generate halos, because they are transparent and possibly abundant. The crystal class of methane is cubic, resulting in various possible crystal shapes. These are summarised in Table 2.

Table 2: Potential Titan crystals and their halos

	Crystal class	Refraction index	Shapes	Halo angles
Methane	Cubic	1.31	Cubes Octahedrons Square pyramids Cube octahedrons	48° 29° 20°, 29° All [20-48°]
Ethane	Hexagonal	1.44	Like ice	32º

One of the plausible orientation modes of the airborne methane crystals is random orientation; another one is having their main axis of symmetry vertical.

Ethane, the other candidate for creating Titan halos, crystallises like ice in the hexagonal class but has a higher index of refraction (Table 2). The ethane-counterparts of the 22° ice halos occur at 32° from the Sun; the counterparts of the 46° ice halos do not exist. Because of the similarity in crystal class, the 32° ethane halos are very similar to the terrestrial 22° ice halos showing up in Figure 3. For instance, ethane also allows for the formation of parhelia to the right and left of the Sun.

Figure 5 shows a marked-up simulation of a halo display from methane and ethane crystals that could occur on Titan. The simulation is obtained from a Monte Carlo ray tracing program, applied to all crystals and crystal shapes described in Table 2. The solar elevation is taken as 40°, which is the nominal value during Huygens' descent.

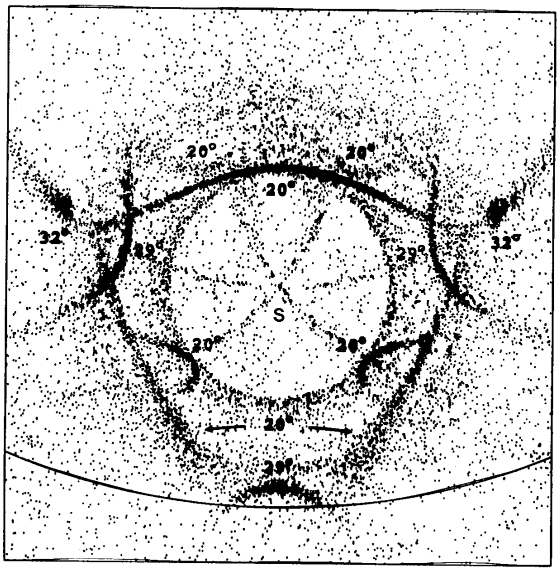


Figure 5: Halo display that may occur in the Titan atmosphere during the descent of the Huygens probe. In this Monte Carlo ray-tracing simulation, there are four populations of methane crystals: square pyramids with cubic face up and with cubic face down, randomly orientated equidimensional cube-octahedrons with all vertices truncated, and equidimensional cube-octahedrons with the 4-fold rotation symmetry axis vertical and all vertices truncated. Additionally, there are two ethane crystal populations: plate oriented and randomly oriented hexagonal crystals with basal ends. The figure is Sun-facing with a horizontal field of view of 100°. The symbol S marks the position of the Sun, which is at 40° elevation. The radius of the circular halos that are associated with the various refraction halos are indicated (compare Table 2). The regions that are in the fields of view of the Huygens's imagers consist of: a 6°-wide vertical band through the Sun extending from 15° till 65° above the horizon; a similar vertical band straight opposite to the Sun; and the entire region between the horizon and a height of 6°.

Figure 6 shows an up-looking all-sky view of the same halo display; Figure 7 a down-looking view at the display.

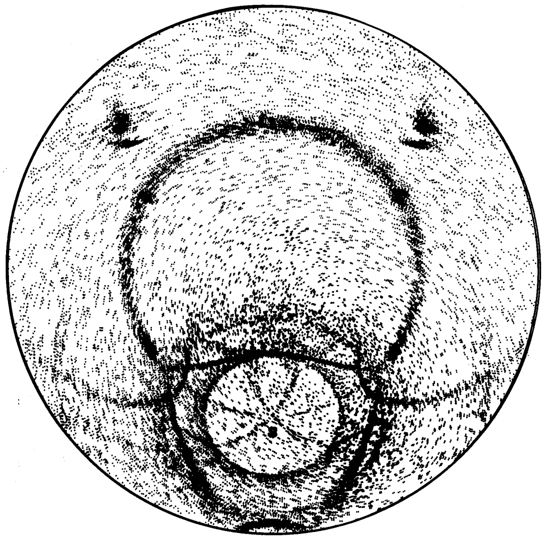


Figure 6: As Figure 5, but up-looking with a field of view of 180°: the zenith is in the centre and the circle that surrounds the simulation is the horizon. The symbol S marks the position of the Sun, which is at 40° elevation. The regions that are in the fields of view of the Huygens's imagers consist of: a 6°-wide vertical band through the Sun extending from 15° till 65° above the horizon; a similar vertical band straight opposite to the Sun; and the entire region between the horizon and a height of 6°.

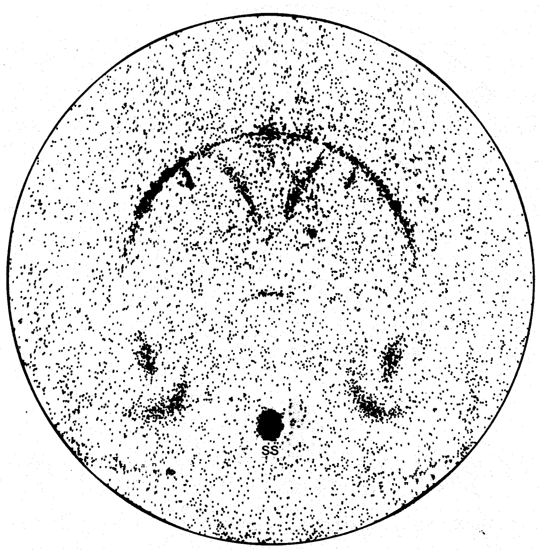


Figure 7: As Figure 6, but now down-looking: the nadir is in the centre and the circle that surrounds the simulation is the horizon. The symbol SS marks the position of subsun, which is the reflected image of the Sun at horizontal crystal faces. Hence the subsun is directly below the Sun and is as far below the horizon as the Sun is above. With exception of a circular region of 6.5° radius centred at the nadir, the entire subhorizon sky can be photographed by the Huygens probe.

The subhorizon halos in Figure 7 usually arise from more complicated ray paths through the crystal compared with those that create halos above the horizon. Some subhorizon halos look like a specular image of their above-horizon counterparts, as if we are looking at a reflected image in a lake. These halos are not secondary halos (rays passing via two crystals, one face of the second one acting as horizontal mirror), but arise from a ray path within the crystals that includes a reflection on a horizontally-oriented face.

3 Huygens instrument prospects for detecting Titan halos

Even if the five conditions for halo detection are fulfilled, and even if our simulations do represent the full truth, Huygens will not be able to detect all the halos in Figure 6 and Figure 7. Non-detection will chiefly occur in the region of the sky that is above the horizon (Figure 6), hence the region of the sky where halo displays are richest. The reason for missing the halos is that the Huygens cameras only cover small parts of the above-horizon sky: the entire band between elevations 0º and 6°, and two 6°-wide strips in the solar vertical covering heights between 15 and 65°. This rules out detection of arcs that are laterally situated with respect to the Sun, among them the 32° ethane parhelion.

On the other hand, the subhorizon halos (Figure 7), would be well within the field of view of Huygens. If they are present, the imagers will snap them. As most of these halos arise from more complicated ray paths than refraction alone, their chances for formation may depend quite critically on the precise shape of the crystals. However, if detected, they will provide more information about the crystal shape than most above-horizon halos.

A special case among the subhorizon halos is the subsun, whose appearance is like a specular reflection of the Sun on a lake (Figure 7). This halo, being the most simple of all, is a relatively likely candidate to appear, as its only requirement is one horizontally-oriented crystal face. Many crystals other than ethane or methane are capable of orienting in such a way that the subsun appears. Even transparency is not a requirement for the crystals to produce this particular halo. Of course, the other side of this coin is that its appearance would provide only very marginal information about the shapes of the halo-making crystals.

An interesting aspect of the uplooking imager is its capability of detecting polarisation. This capability enhances the possibilities for halo detection in the field of view. This holds in particular if halos should show up from some unanticipated compound crystallising in doubly refracting crystals. Then, even if the halo is weak in intensity, its polarisation could be so strong that it is still detected by the imager. Such a fortunate event might give the scientists a glimpse of the properties of crystals of low abundance.

4 Will Huygens see Titan halos?

It is still unclear how great Huygens's chances are of seeing halos. On the positive side of the balance is the global cloud-cover of Titan, minimising the probability that Huygens will descend in a region of clear sky weather. However, as Huygens descends, the sunlight will become more and more diffuse, because of the increasing thickness of the overlapping cloud deck. It remains to be seen whether or not the sunlight has become too diffuse at the moment that Huygens reaches a swarm of crystals of sufficient size. In that case no halos would show up. Then, one may perhaps still hope for other meteorological optical phenomena arising from drops to become visible, such as a rainbow from (small) ethane drops, or perhaps a so-called ‘glory’ (a rainbow-like structure around its own shadow), but the chances of halos would be gone.

In conclusion, it seems still possible that a halo or its arc may show up in the Huygens images. This would be a welcome bonus in a thoroughly planned, sophisticated mission.

5 References and further reading

[1] *Oeuvres Complètes de Christiaan Huygens*, Vol. VII (Martinus Nijhoff, The Hague, 1932)

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[3] R. Greenler, Rainbows, halos and glories (Cambridge University Press 1980) (A comprehensive and very readable account about meteorological optics and about the application of ray tracing techniques for simulating halos)

[4] G.P. Können, Polarized light in nature (Cambridge University Press 1985) (A book on the polarization of natural phenomena, including halos.)

[5] G.P. Können, “Symmetry in halos and symmetry in halo-making crystals”, Appl. Opt. **42**, 318-331 (2003) (A technical version of the present paper, which also includes a description of the technique for reconstructing crystal shapes from halos)

[6] M.G. Tomasko, L.H. Doose, P.H. Smith, R.A. West, L.A. Solderblom, M. Combes, B. Bézard, A. Coustenis, C. deBergh, E. Lellouch, J. Rosenqvist, O. Saint-Pé, B. Schmitt, H.U. Keller, N. Thomas, and F. Gliem, “The descent imager/spectral radiometer (DISR) aboard Huygens”, in “Huygens, science payload and mission”, Ed. J.-P. Lebreton, ESA SP-1177, ESA Publication Division, ESTEC, Noordwijk, The Netherlands 109-138 (1997) (A description of the Huygens imagers)