Meteorology. — *Contribution to the Explanation of Complex Halos.* By M. PINKHOF. (Communicated by Prof. E. VAN EVERDINGEN)

(Communicated at the meeting of June 26, 1926)

1. *Introduction.*

Though at present most of the separate halo phenomena have been explained in a satisfactory way, i. e. have been brought in connection with ice crystals of acceptable shape and orientation, it must be admitted that as yet comparatively little attention has been given to the theory of complex halos. The second edition of PERNTER's *Meteorologische Optik* revised by EXNER, does not yet deal with it. Nevertheless it is necessary also for the theory of the simple halo phenomena, to study the complex halos more closely. By the simultaneous appearance of different phenomena an explanation of one of them, based on the occurrence of very specially formed crystals, can be rendered less probable. It is beyond doubt that, in the case of complicated halos, there is very often a greater number of the component parts mutually related than could be contributed to by one and the same crystal at a fixed moment. In the latter case WEGENER (**20**) — who was the first to occupy himself with the complex halos — speaks of "verschwisterte Halos". All the other phenomena that make their appearance simultaneously, he calls "vergesellschaftet". I myself have pointed out afterwards (**17**, p. 66) that WEGENER's "vergesellschaftete Halos" should be divided in their turn into two groups:

1. phenomena arising in the same cloud;
2. phenomena that find their origin in different Ci or Ci-St clouds present at the same time.

As a classification into two, I should therefore prefer a group A of phenomena in one cloud ("verschwistert" in a wider sense) and a group B of phenomena in different clouds ("vergesellschaftet" in a narrower sense). In what follows here, an attempt is made to account for the way in which the phenomena of group A can be connected together.

On an earlier occasion I made an attempt to find a solution of this problem of the complex halos (**16**, p. 72; **17**, p. 65). I started from the supposition that in one ice-cloud, arising as it does under very definite circumstances, a wide diversity is not possible either in the shape of the crystals, which is dependent on the temperature, or in their size, which is related with the vapour tension. From this there ensues amongst others that the simultaneous presence of the two fundamental shapes of ice crystals — the *plates* falling with vertical principal axes, and the *rods* falling with horizontal principal axes — is not probable. Basing myself on DOBROWOLSKI's experiences (**6**), I drew, however, attention to the fact that, in consequence of the difference in size of their central cavity, some of the rods of the most prevalent form, i.e. the hemimorphous form, will fall with vertical, others with horizontal principal axes, (Fig. 1). Accordingly, if a cloud consists merely of hemimorphous prisms, a pretty complex halo can already appear in this way:

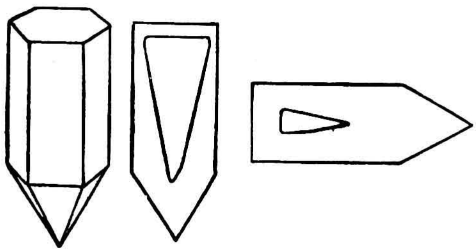

Fig. 1. Hemimorphous ice prisms.

1. Ordinary ring caused by the practically never lacking not specially directed crystals;

2. A. Parhelia } caused by crystals with vertical principal axes.
B. Circumzenithal arc

3. Upper and lower tangent arc, due to crystals with horizontal principal axes.

Theoretically the following phenomena might be added to this:

large ring ("verschwistert" with 1);
arcs of Lowitz ("verschwistert" with 2);
parhelic ring ("verschwistert" with 2 or 3);
light column ("verschwistert" with 2 or 3);
lateral tangent arcs to the large ring ("verschwistert" with 3).

From the fact, however, that these phenomena are much rarer than the first mentioned, there follows that they evidently require still other circumstances than those under which the general form of a complex halo so often occurs.

In my earlier publications (**16, 17**) I have not occupied myself with the very rare halo forms; HASTINGS, however, has tried to draw up a theory (**11**), in which also the possibility of their presence was taken into consideration. I do not, however, consider his attempt as successful:

1. because he uses for his explanation at the same time the two fundamental forms: plates and rods;

2. because for some of the phenomena he does not only require an orientation in a definite plane of the crystallographic principal axis, but also a fixed position for definite lateral faces.

However this may be, it remains necessary, in an explanation of complex halos, to take the less usual phenomena into account as well. The question then arises: under what circumstances can hemimorphous iceprisms cause, besides the more common phenomena, the rarer ones also? To these belong not only the above-mentioned phenomena, but also the *anthelion* and the *paranthelia*, of which it is not even certain with what other halo forms they are "verschwistert". Before proceeding to the discussion of this question, it is desirable to give a summary of the explanations of the anthelion c. a. published so far.

2. *The Anthelion and the Paranthelia.*

BRAVAIS (**5**, p. 189, cf. also **14**, p. 424), who imagined the crystals, when falling, to orientate themselves in such a way that they meet with the least resistance, explained the anthelion by the aid of double interior total reflection against planes making an angle of 90° with each other (Fig. 2) and which are in a vertical position. This theory is untenable since it has become known that ice plates fall with their bases *horizontal*, and ice rods — supposing they do not rotate about their principal axes in falling — will not have an edge downward, but a side face, in consequence of which the side face corresponding with A of Fig. 2 will not be vertical.

Of the explanations of the paranthelia before BESSON's, that of SORET (cf. **14**, p. 428) was considered as the least artificial (Fig. 3). Several

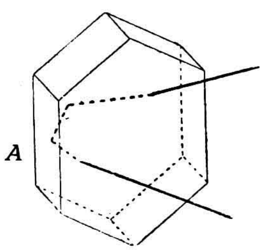

Fig. 2. BRAVAIS' explanation of the anthelion. (According to BESSON).

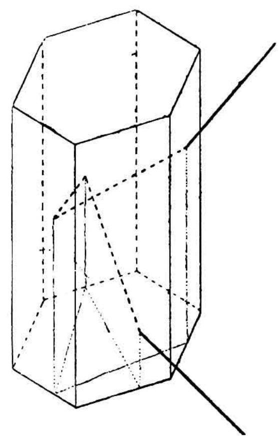

Fig. 3. SORET's explanation of the paranthelia. (According to BESSON).

objections, however, were advanced against it by BESSON (**2**, p. 77), and EXNER (**14**, p. 428).

As a substitute for the earlier theories BESSON (**1**; **2** p. 80) has given an explanation, according to which the anthelion and the paranthelia are due to aggregates of crystals. To the figures 4 and 5 nothing need be added to make it understood that the crystal faces which act as "double mirrors", [1]) at an angle of 90° always change the direction of the horizontal projection of the rays 180°, and at an angle of 120° give it a deviation of 120°.

By the aid of the aggregates of figures 4 and 5 the phenomena in question are therefore, "easily" explained.

[1]) Mirrors including an angle α, reflect the light in a direction deviating $360°-2\alpha$ from the original, independent from the angle of incidence. *German*: Winkelspiegel.

Now the question is: 1. do the postulated aggregations occur in reality, and even in large quantities? 2. do they bear their reflecting side faces really vertically?

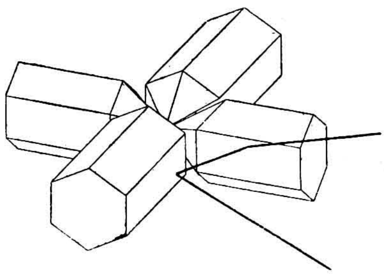

Fig. 4. BESSON's explanation of the anthelion. (According to BESSON).

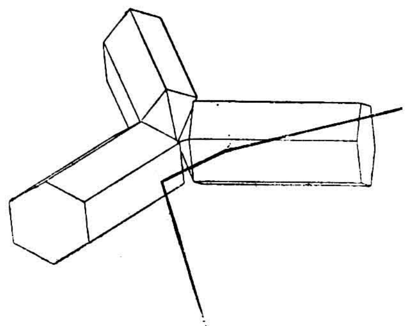

Fig. 5. BESSON's explanation of the paranthelia. (According to BESSON).

In answer to the first question it may be said that the very basis on which BESSON founds his theory is DOBROWOLSKI's experience (**6**) that the hemimorphous ice rods very often form radiary aggregates by uniting their tips. In 1903 already, DOBROWOLSKI gave a number of drawings of such aggregates in his extensive publication, both of completed ones and of those in statu nascendi (**6**, p. 32—37).

Not only these aggregates of 3 and 4 arise by union of hemimorphous ice rods. DOBROWOLSKI showed that also the so-called holohedric prisms have, after all, been formed by two joined hemimorphous ones. In 1916 DOBROWOLSKI (**7**) was able to publish micro-photographs of all these forms, made by F. HALLBERG. Four of these photos are reproduced in the figures 6—9 [1]).

The answer to the second question cannot be given as yet with certainty. As may be seen from the photo, it is not to be avoided that the edges of the crystals soon melt off during the observation, so that the exact position of the faces cannot be ascertained. BESSON (**4**, p. 379), however, points out that from the fact that in the combinations of 2 the faces always lie exactly in each other's prolongation (twisted specimens have never been observed), it may be concluded that also with combinations of 3 or 4, the mutual position of the component crystals shows great regularity. In this case they would both turn either a face or an edge towards each other. If it is a face, they act as "double mirrors" with vertical planes.

In his treatise of 1923 BESSON complains that his theory of the anthelion c.a., published as early as 1907, has not been favourably received. "It has been thought improbable that shapes so complicated

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[1]) I am greatly indebted to the Société Astronomique de France for the loan of the clichés and I gladly express my thanks to Dr. BESSON for his kind assistance.

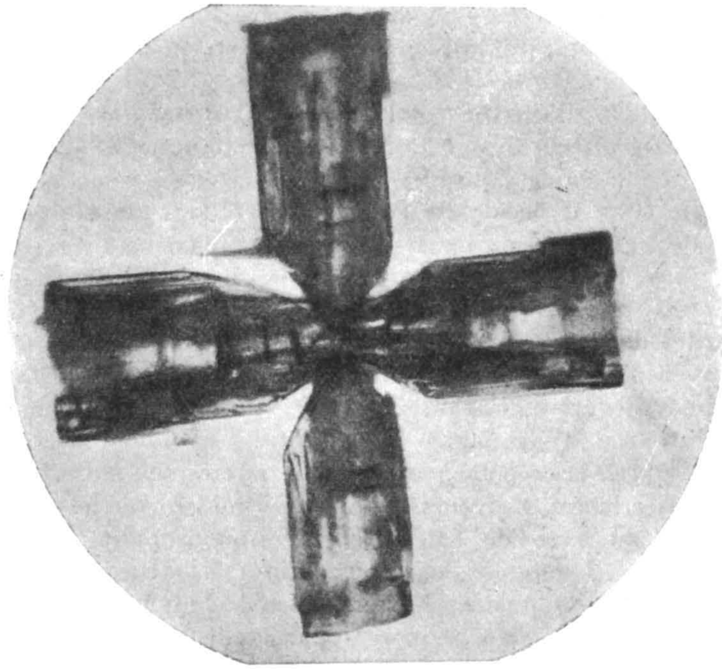

Fig. 6. Aggregate of 4 hemimorphous ice prisms (Photo F. HALLBERG). *(Cliché of the Société Astronomique de France).*

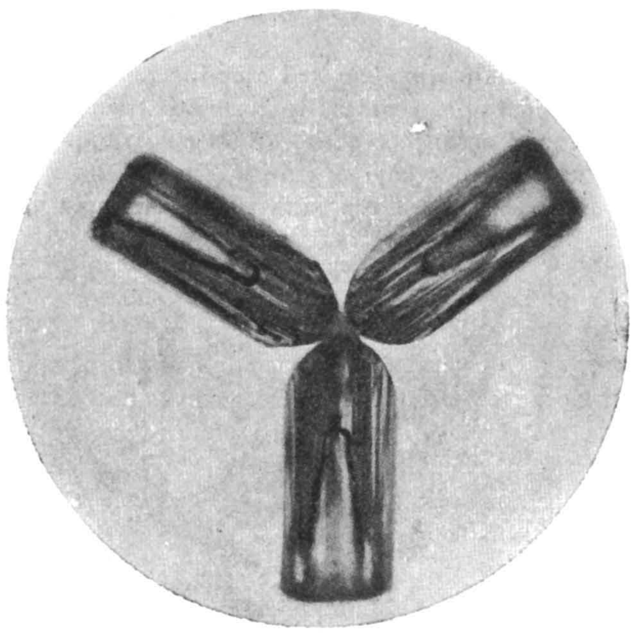

Fig. 7. Aggregate of 3 hemimorphous ice prisms (Photo F. HALLBERG). *(Cliché of the Société Astronomique de France).*

could exist in the atmosphere in quantities large enough to give rise to a luminous phenomenon". The microphotos of HALLBERG reproduced

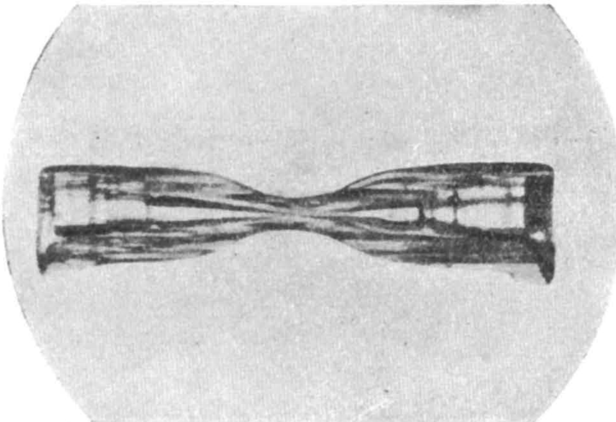

Fig. 8. Aggregate of 2 hemimorphous ice prisms in statu nascendi (Photo F. HALLBERG) *(Cliché of the Société Astronomique de France).*

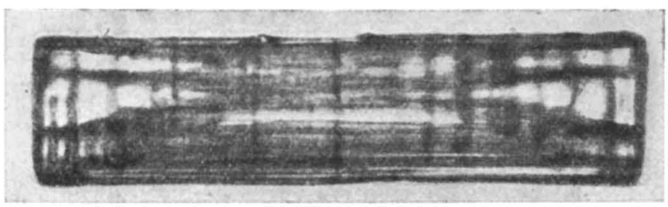

Fig. 9. Aggregate of 2 hemimorphous ice prisms (holohedric prism). (Photo F. HALLBERG). *(Cliché of the Société Astronomique de France).*

here show irrefutably that radiary aggregates of ice crystals exist and are well defined crystalline forms.

It seems to me that the complex halo, observed by me at Amsterdam on December 23^{rd} 1925, and described in the March number 1926 of "Hemel en Dampkring" (**19**), supplies an important support to BESSON's theory. At the same time the explanation of complex halos can get nearer to a satisfactory solution.

3. *The Halo of Dec. 23, 1925.*

A. The following phenomena were observed:

1. ordinary ring	faint
2. upper tangent arc to same	exceedingly bright and extensive
3. parhelia with arcs of LOWITZ	bright
4. large ring	relatively very bright and extensive
5. upper tangent arc to same	relatively faint
6. anthelion	faint uncoloured little column.

N⁰. 1—5 are represented diagrammatically in Fig. 10, which has been borrowed from the above-mentioned article in "Hemel en Dampkring", to which we refer for the description of the course of the phenomenon. [1])

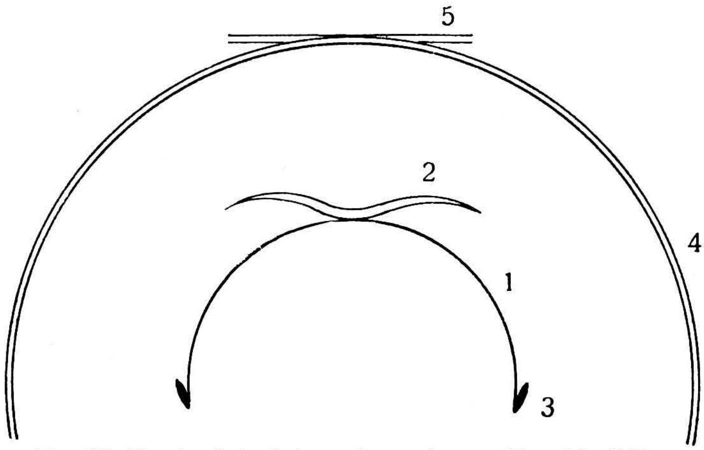

Fig. 10. Sketch of the halo at Amsterdam on Dec. 23, 1925.
1 = ordinary ring; 2 = upper tangent arc; 3 = parhelion; 4 = large ring; 5 = circumzenithal arc. The anthelion cannot be shown in this way of representation. *(Cliché "Hemel en Dampkring").*

Two things were particularly noteworthy in this halo: the strong development of the large ring and the presence of the anthelion in the absence of a parhelic ring. It should further be pointed out that of the other phenomena the upper tangent arc was the most intense, the small ring remaining faint.

B. The explanation of the large ring has only recently been made a point of closer investigation. After it had already been recognised as the equivalent of the ordinary ring for optical prisms of 90° by CAVENDISH (cf. **5**, p. 79), little attention was further devoted to it, since the prisms in question were not to have any definite orientation. In my preceding publication I, accordingly, considered the large ring only from this point of view.

HASTINGS (**11**, p. 326), however, has pointed out that the possibility exists of an optical phenomenon which, whilst practically not to be distinguished from the large ring, yet arises in a different way, viz. in ice-prisms which lie almost or entirely horizontally. His explanation is very closely allied to that which BRAVAIS (**5**, p. 121, compare also **2**, p. 72 and **13**, p. 359; it is greatly to be regretted that EXNER in the second edition of PERNTER's handbook has omitted BRAVAIS' explanation) has given for the lateral tangent arcs to the large ring. HASTINGS points out that prisms in a horizontal plane have already refracting edges of 90° in all possible directions, so that with comparatively small

[1]) See also "Zur Erklärung der komplizierten Halos", published afterwards in the Meteorologische Zeitschrift, Nov. 1926, p. 411.

deviations from the strictly horizontal position of the principal axis, many of the optical prisms can already get a position of minimum deviation.

BRAVAIS' theory of the lateral tangent arcs to the large ring is in conformity with his explanation of the circumzenithal arc: to the latter all the prisms with an upturned basal surface contribute, thus giving a circle with the zenith as its centre. In the same way all the horizontal prisms with basal surfaces turned in one direction give a circle with its centre in this direction. There are, however, in the horizontal plane an infinite number of directions in which the prisms may be directed. Of the infinite number of circles which would theoretically be formed in this way, a certain number lie so close to each other that together and under favourable circumstances they produce a visible arc. Thus the lower lateral tangent arcs are formed by rays of light entering through a basal surface and leaving the crystal through a side face, and the upper lateral tangent arcs (sun's altitude below 30°) when the rays of light pass the faces in inverse order. These latter must turn their convex side towards the sun, and for this very reason already they coincide mainly with the large ring. In BRAVAIS' time they had not yet been observed. In his dissertation BESSON (**2**, p. 72) mentions two cases observed by himself and his colleague DUTHEIL. Afterwards he has recorded another very positive observation of these arcs (**3**, p. 5). I myself had for a long time already, considered the possibility that a number of cases, in which mention was made of the large ring, would really refer to the arcs in question. In my publication of 1919 (**16**, p. 31) I already alluded to this with reference to the halo of Dec. 29, 1914 (Fig. 11; taken from **8**). In a publication in "Hemel en

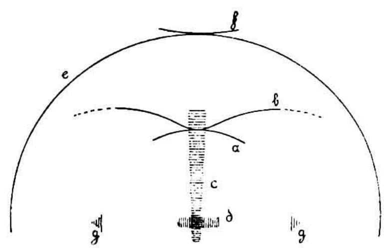

Fig. 11. Halo of Dec. 29, 1914.
a = ordinary ring; b = upper tangent arc; c = light column; d = parhelic ring; e = large ring; f = circumzenithal arc; g = parhelion. (The parhelia and the ordinary ring were only seen by some of the observers). *(Cliché K. N. M. I.)*

Dampkring" (**15**, p. 37) I ascribed the large ring on Jan. 8 1919 (cf. **10**, p. 51) to intensification caused by the upper lateral tangent arc. On Febr. 21, 1918 (cf. **9**, p. 155), and on March 28, 1920 (cf. **18**, p. 55) intensified portions of the large ring were clearly observed by me; in the latter case the height of the most intense part was estimated, and found to correspond to the height required by BRAVAIS' theory. In most of these cases (with the exception of Jan. 8, 1919) the upper tangent arc to the ordinary ring was particularly strongly developed, both as regards intensity and extension. This suggests the great prevalence of *horizontal ice rods*, which, as said before, would have to be held responsible for the upper (and lower) lateral tangent arcs to the large ring.

Hence the conclusion should be drawn in my opinion that in a number of cases in which (with solar altitudes $< 20^{\circ}$) the large ring was observed in complex halos — accompanied by an intense tangent arc to the ordinary ring, this ring itself being faint — this large ring was caused by almost horizontal ice rods, and has to be explained by the theory of BRAVAIS for the upper lateral tangent arcs, or by that of HASTINGS. I cannot, however, agree with HASTINGS that this explanation of the large ring can replace the earlier one. The observations of the large ring at the same time with an intensive ordinary ring which I published before (**16**, p. 31, 36) can only be explained in the old way.

These considerations may elucidate to some extent, how, given the practical impossibility of seeing the large ring detached from the tangent arcs under consideration, these tangent arcs, which were predicted by the ingenious BRAVAIS, could remain considered as non-existent for so long a time.

Now recurring to the halo of Dec. 23 1925, we arrive at the conclusion that both the very intensive and extensive upper tangent arc to the ordinary ring and the intensive large ring point to a particular development of the horizontal ice rods.

C. Besides the striking brightness of the large ring and upper tangent arc, it was the presence of the anthelion *without parhelic ring* that made the halo of Dec. 23, 1925 so remarkable. We might also give the following account of this phenomenon: Among the infinite number of possible directions of reflection, the one with an angular difference of 180° was the privileged one. As we have seen, according to BESSON's theory there is question of such a privilege of the direction of 180° in the occurrence of combinations of 4 ice prisms fused together with their points and falling with vertical side faces: The "double mirrors" can be turned over a considerable angle in the horizontal plane, and all the same reflect the light from the direction of the anthelion. Every other reflecting vertical face will at the turning, send out the light every time in another direction.

These aggregates may, further, be the crystals that fall most undisturbedly in horizontal position: The air having an opportunity of escaping between the arms, the "Schaukeln" to which the ice plates are liable, need not occur here. By this circumstance it is rendered possible that the anthelion appears exactly at the sun's altitude.

If we now accept BESSON's theory, we must assume that with the halos under consideration the particular circumstance presents itself, that the ice prisms have combined in large numbers to + shaped aggregates. When the circumstances of temperature etc. in that cloud had to give rise to the occurrence of aggregates, the chance was still greater that also the combination of 2 would occur, i.e. the so called holohedric prisms. That these were actually present in great numbers, is rendered probable by the strong development of upper tangent arc and large ring; in consequence of the greater stability in the horizontal orientation which the holohedric prisms show compared with the hemimorphous ones, the more common phenomenon (in casu the upper tangent arc) becomes exceedingly intense and extensive, the necessarily less intense and consequently rarer phenomenon (in this case the upper lateral tangent arcs to the large ring) coming in the region of visibility. Another factor that can contribute to the greater intensity is the double length of the holohedric prisms. If once such a crystal has the right position to give a definite point of the halo, twice as much light passes as a hemimorphous prism would have given in this position.

4. *The Very Complex Halos.*

A. It seems to me that from the above a far-reaching conclusion may be drawn with reference to the explanation of complex halos:

Under rare circumstances the hemimorphous ice prisms — which already under ordinary circumstances are able to produce several halo-phenomena at the same time (cf. p. 173) — begin to join to combinations of 2, 3, and 4. If this is the case "the" rare halo-phenomena may be added to a halo. These are: the upper and lower lateral tangent arcs to the large ring, the paranthelia and the anthelion.

B. Besides in the observation of Dec. 23, 1925 and the other halos already mentioned, this hypothesis finds a firm support in the statistical data published by MEYER in 1925 (**12**, p. 13, cf. also **21**, p. 191).

The part of the "Table of Relationship" referring to the 3 rare phenomena in question, is reprinted here. Every value has been calculated by MEYER according to the formula $\frac{G^2}{N_1 N_2}$, in which G is the number

	Ordinary ring	Large ring	Upper and lower tangent arcs to the large ring	Lower lateral tangent arcs to the large ring	Parhelia	Circumzenithal arc	Light column	Parhelic ring	Paranthelia	Anthelion	Arcs through anthelion
Lower lateral tangent arcs to the large ring	1	2	2	—	3	0	0	7	24	8	13
Paranthelia	3	4	3	24	4	2	0	14	—	4	4
Anthelion	1	4	2	8	2	1	0	9	4	—	40

of observations in which the two phenomena the relationship of which is to be determined, occurred simultaneously, and N_1 and N_2 the total number of observations of each separately. The values thus obtained have been multiplied by 100.

Very recently in his discussion of MEYER's work in the *Meteor. Zeitschrift* (**21**) WEGENER pointed out that the anthelion according to MEYER's table shows close relationship to the lateral tangent arcs to the large ring. To this may be added that it is also much more closely allied to the large ring itself than to the ordinary ring. In the light of our hypothesis these relationships become very comprehensible. The relation to the large ring suggests that, among the circles observed simultaneously with the anthelion, there will probably be some not well distinguished upper lateral tangent arcs. That also the paranthelia (3-aggregates) present a very close relationship to the lower lateral tangent arcs is a surprising result. In contrast with WEGENER, who questions the validity of the theory of the paranthelia — because they are so closely allied to the halo-phenomena caused by refracting edges of 90° — I arrive at the conclusion that the theory (but then that of BESSON) is certainly valid. The relationship is, however, not to be looked for in the angles of the crystals, *but in the appearance of the phenomenon of "aggregation"*.

And this again makes it clear how the study of the halo-phenomena might lead to conclusions about the state of the atmosphere.

Postcript during the correction of the Dutch edition. After this communication had been presented to the Academy there appeared a publication by WEGENER (**22**), in which inter alia, a new theory is given of the arcs through the anthelion not discussed here by me. The anthelion itself is, then, considered as the luminous nodal point of the arcs. Though WEGENER's theory seems plausible for the explanation of the arcs in question, it cannot be accepted as the only correct one for the anthelion. This appears already directly from the fact that the anthelion of Dec. 23 1925 was observed with a solar altitude $< 14°$ [i.e. between 12°15′ (10.40 a.m.) and 13°21′ (11.07 a.m.)], whereas the lowest limit of visibility according to WEGENER lies at a solar altitude of 14°.1. Hence the explanation of BESSON, ignored by WEGENER, will have to be maintained at least by the side of the new theory.

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