XV.—The Fata Morgana. By Professor F. A. Forel, Morges, Switzerland.

Abstract of an Address delivered before the Society on July 14, 1911; translated by Professor C. G. Knott.

Among optical phenomena which originate over the surface of water there is one so ill-defined and ill-observed as to be still mysterious; till now it has received no valid explanation. The Italians call it the Fata Morgana. Under conditions still lacking precise description, there appear on the far side of the Straits of Messina certain fantastic visions, fortresses and castles of unknown cities, which seem to emerge from the sea, soon to vanish again. These are the "palaces" of the "fairy Morgana," which appear and disappear at the capricious stroke of the magician's wand.

Most of the accounts of the phenomenon are founded on the extravagant description and the amazing picture published in 1773 by the Dominican friar Don Antonio Minasi, professor of botany at the Roman College of Sapienzia. This drawing, with its incoherent groupings of castles and boats, reflected and refracted at random in a manner quite inconsistent with physical possibilities, was largely the creation of the distorted imagination of an artist who did not understand in the least the wonderful illusion.

To appreciate the confusion which reigns in the scientific world in regard to this phenomenon, the reader need only refer to the chapter on the Fata Morgana in Pernter's admirable work on *Meteorological Optics* (Vienna, 1910). There he will be impressed with the uncertainty of the conclusions reached by the author after a study of the insufficient and contradictory documents to which he had access.

Professor V. E. Boccara of Reggio has endeavoured to bring some little order into the question,* but with doubtful success, as a critical examination of his drawings and diagrams will probably prove.

In 1854 Charles Dufour rendered a signal service by his recognition of the phenomenon of the Fata Morgana on the Lake of Geneva;† and his

* "La Fata Morgana," *Mem. della Societa degli spettroscopisti Italiani*, xxxi., Catania, 1902; contains a full bibliography of the question, with extracts from the principal observations.

† "Mirages et réfractions anormales sur le lac Léman," *Bull. Soc. Vaud. Sc. nat.*, xxxii. 271, Lausanne, 1853–56.

descriptions and explanation were free from the exaggerations and contradictions of his predecessors. He showed the illusion to a pupil of his, a small schoolboy of thirteen; and since then, following the instructions of my beloved master, I have seen the Fata Morgana again and again every springtime, some four or five hundred times in all. I can therefore speak of it as a familiar friend.

In my monograph, *Le Léman* (Lausanne, 1895), and in my note of 1896,* I have endeavoured to lay down the determining conditions of the phenomenon. Since then I have taken a further step in the co-ordination of the facts, and I propose to give to-day the principal features of the mirage, which may perhaps serve as a better foundation for the mathematical study of the phenomenon, which I leave in the care of my mathematical and physical friends.†

The physical conditions which determine the appearance of the Fata Morgana are always the same. When, under the bright skies of spring or early summer, the lake lies calm or slightly rippled by light and intermittent puffs of air, there appears at times during the afternoon when the air is warmer than the water a phantom-like transformation of the scenery of the opposite coast. Over a horizontal stretch of twenty or thirty degrees, the familiar details of the coast-line, which may be from ten to thirty kilometres distant, become strangely transformed. Resting on the water horizon, and bounded above by another horizontal line at a height of a few minutes of arc, there comes into view a vertically striped band or striated zone (*zone striée*), seemingly composed of rectangles placed side by side, of varied tints and hues. It might be compared to the distant cliffs of Dover as seen by travellers crossing the Channel; or to a great city built on the shore, with blocks of houses ranged along the quays, a Genoa, a Naples, or a Constantinople, miraculously rearing itself in a region known to be occupied by a few

* "Réfractions et Mirages: passage d'un type à l'autre," *Bull. Soc. Vaud. Sc. nat.*, xxxii. 271, Lausanne, 1898.

† Refraction phenomena are not always presented in nature so clearly or so simply as might be desired. There may be no doubt as to the general nature of the mirage, which may nevertheless be difficult to interpret. The phenomena originate at a far distance, in air more or less saturated with water vapour, and frequently masked by a veil of fog. The observations are beset with great difficulties. Had it not been so I should not have spent more than fifty years in arriving at the present explanation. The observation of refraction phenomena over the surface of a lake demands an intimate acquaintance with all its characteristics. An occasional traveller spending a few days on its shores cannot be familiar enough with the lake scenery to enable him to know what changes, if any, may have occurred. Prolonged residence in the neighbourhood of the lake and a keen interest in the ever-shifting illusions are essential to a complete study of the phenomena.

scattered huts. Such are the palaces which the fairy Morgana creates before our wondering eyes.

The position of its first appearing varies with each occasion. It comes into view now here, now there. It does not remain steady, but moves more or less slowly in one or other direction, never lingering in the same neighbourhood for more than ten or twenty minutes. As the mirage passes on towards another part of the horizon, the coast-line recovers its ordinary aspect.

The phenomenon as a whole does not last long. Barely an hour will be consumed as it moves from one end to the other of the half circle of the opposite coast. I have never seen it before noon, and never after six o'clock in the evening.

The Fata Morgana is visible only to an observer whose eye is a few metres above the level of the lake. The best height would seem to be from two to four metres (six to twelve feet). A shift of a foot or two above or below the best position in any given case is sufficient to make the phenomenon disappear. This limited range in the position of the eye which ensures the visibility of the mirage at once explains the astonishing scarcity of good observations.

Following Dufour, we are in the habit of speaking of the Fata Morgana as being due to abnormal refraction, although we know perfectly well that there is nothing abnormal in natural phenomena. Given the conditions, the consequences necessarily follow.

"Abnormal" though we call it, the Fata Morgana comes between two phenomena which we shall call normal, because they are frequent and easily observed. It succeeds the one and precedes the other.

Under the category of optical refractions in air over the surface of a lake, I regard as "normal" phenomena those which accompany refraction in air over water whose temperature is either higher or lower than that of the superposed air. When the air is cooled by contact with cold water, the successive layers of air rise in temperature from below upwards. This might be called the *direct* thermal gradient. When, on the other hand, the lower layers are warmed by contact with warmer water, the thermal gradient is *inverse*, the temperature in the air falls as the height increases through a limited stratum of air.

The mirage phenomena which accompany *refraction over warm water* are the most frequent. This condition holds throughout the whole day during autumn and winter, and during the morning hours in springtime and part of summer. The air is then colder than the surface on which it rests; the thermal gradient is of the inverse type, and the curve of a refracted ray of light is concave above. The characteristic optical accompaniments are:

1. A depression of the plane of the apparent horizon of the lake * below its normal position; the apparent horizon is lower than the true horizon.
2. The apparent exaggeration of the rotundity of the earth, which becomes evident to the eye, although normally it is unrecognisable.
3. The approach of the circle of the horizon, much less distant than it ought to be according to the height of the observer's eye above the surface of the water.
4. The apparent exaggeration of the crests of waves, which show like crenations along the line of the horizon.
5. The phenomenon of "mirage": "the mirage of the desert." Objects lying low over the surface of the water and situated beyond the circle of the horizon are seen as inverted images below Bravais' "ligne de partage." † These images lie in the zone which separates the "ligne de partage" from the apparent horizon of the lake.

These details become more marked as the difference of temperature between the cold air and the warm water is increased.

The phenomena associated with *refraction over cold water* are rarer than the preceding. They appear only during the afternoon hours of warm days in spring and summer, and occasionally in the morning hours of very hot days in the height of summer. In this case the air is warmer than the water, and the lower layers of air cooled by contact with the water are characterised by a thermal gradient of the direct type. The curve of a refracted ray of light is concave below. The characteristic optical accompaniments are:

1. An apparent elevation of the plane of the horizon above the normal position; the apparent horizon is higher than the true horizon.
2. The apparent concavity of the surface of the lake, resembling a broad valley rising with gentle slopes towards the margin.
3. The apparent extension of the circle of the horizon; distant boats, which to the observer's eye should have been on the circle of the

* The true horizon is the tangent cone to the surface of the lake, the vertex of the cone being at the eye of the observer, and the calculation being made on the assumption of no refraction; the circle of the true horizon is the curve of contact of the cone with the surface of the lake. The cone and circle of the apparent horizon are similarly defined in terms of the rays of light as they enter the eye after having been displaced by atmospheric refraction. These cones are so flat that they may be spoken of as planes.

† This is the line which separates the erect and inverted images in the usual mirage.

horizon or beyond it, appear to be at the bottom of the illusory valley of water well within the apparent circle of the horizon.

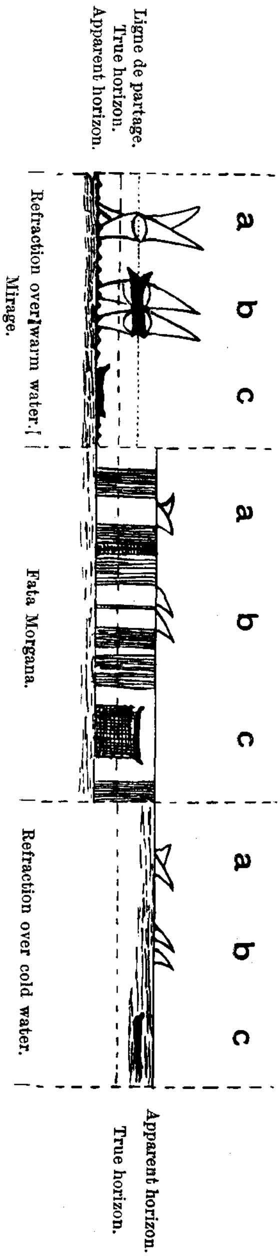
4. The visibility of the lower parts of the opposite coast, which normally should have been hidden by the rotundity of the water surface. For example, the Château de Chillon at 34 kilometres distance appeared to the spectator to be resting on the quay of Morges.
5. The reduction in relative height or dwarfing of the lower parts of the opposite coast.

These details are seen only when the phenomenon becomes established. They may be preceded by what I have called the *mirage over warm water* (*Le Léman*, p. 532, etc.). I do not dwell on it here, because it is not necessary for the purpose of this lecture.

I propose to confine my attention to the principal normal accompaniments of these refractions, namely, the depression or elevation of the apparent horizon according as the water surface is warmer or colder than the air above.

When investigating the variations of the apparent horizon,* I have carefully determined the position of the true horizon by telescopic measurement of the positions of a mountain top and its reflection in an artificial horizon. Midway between these positions, after correction for the dip of the horizon, lies the true horizon. The hill chosen was the Dent d'Oche, which is distant 24·4 kilometres from Morges, and rises beyond the opposite coast to about 2221 metres above sea-level.

Referred to this true horizon, the apparent horizon has been found to vary between the



a and *b*, vessels beyond the circle of the horizon ; *c*, boat within the circle. Fata Morgana shifts from right to left.

* *Bull. Soc. Vaud. Sc. nat.*, xxxv. 25, Lausanne, 1899 ; see also *Arch. d. Sc. phys. et nat.*, viii. 373, Geneva, 1899.

extreme positions of nearly 8 minutes of arc above and fully 4 minutes of arc below.

Let us now study the sequence of phenomena on a fine day towards the end of spring or the beginning of summer, when, as hour follows hour, the air being at first colder than the water surface becomes warmer, while the temperature of the water remains comparatively constant. The temperature of the air, lower than that of the water in the morning, becomes equal to it towards midday, and exceeds it in the afternoon. Consequently the two normal types of refraction succeed each other in time. Let us suppose, for example, that the temperature of the morning air is 15° C., that of the water 18° C. The phenomena that are associated with refraction in air over warm water are in all their perfection; the apparent horizon of the lake is depressed below the true horizon. As the day progresses, the air heats rapidly under the powerful action of the solar radiation; the water also grows warmer, but at a slower rate because of its great thermal capacity. The temperature of the air soon equals that of the water, and is not long in passing it. In the afternoon the water may have risen in temperature to 20° C., and the air to 26° or 28° C. The phenomena associated with refraction in air over cold water are developed, the apparent horizon is elevated, the surface of the lake appears concave.

But the transformation from the one type to the other does not take place slowly or progressively. The depression of the horizon due to refraction over warm water does not diminish little by little until its value is zero; and the elevation of the horizon does not grow little by little, starting from zero when the temperatures of the two media are equal, and attaining a maximum when the difference of temperature is the greatest. The transformation does not occur simultaneously over the whole lake. The change takes place suddenly at each region, and successively from point to point. At a particular instant there may appear at different parts of the lake the two types of phenomena clearly recognisable.

It is at such an instant that the Fata Morgana appears, represented, as I have already said, by a striated zone of rectangles in juxtaposition. Its features are at first quite disconcerting. When first recognised, it may appear in any azimuth. It moves slowly, in one or other direction, along the shores of the lake. It was from a study of the manner of the shifting in position that I gained the key to the explanation of the phenomenon, which may be summarised under four heads:—

I. The Fata Morgana has its origin in the region between the two regions where the opposite types of refraction rule; in the one region the morning conditions still hold, while in the other region the afternoon conditions have been established.

II. The lower limit of the striated or ribbed zone of the Fata Morgana is continuous with the depressed line of the horizon which is associated with refraction in air over warm water; the upper limit, with the elevated line of the horizon accompanying the refraction over cold water.

III. The Fata Morgana shifts always from the region where the refractions are over cold water towards that where the refractions over warm water still hold sway. The effect is due to the refraction over cold water invading the scenery point after point.

IV. On the rare occasions on which I have observed the first appearance of the Fata Morgana, I have always seen it at one of the extremities of the circle of the horizon.*

The general conclusions may be stated in these words:—

(*a*) The Fata Morgana is made manifest at the region where the morning type of refraction in air over warm water is being transformed into the afternoon type of refraction over cold water.

(*b*) At this region the eye of the observer placed at a convenient height sees simultaneously and in superposition both the depressed and the elevated horizons associated with the two types of refraction.

(*c*) Bright objects on the lower parts of the opposite coast are stretched and drawn out in height between the two momentarily coexistent false horizons of the lake, and, by forming rectangles in juxtaposition, give the appearance of the banded or ribbed structure of the striated zone. In my memoir of 1896 I showed that the transition from the one type to the other does not take place slowly and progressively; that even when towards the middle of the day the temperature of the air becomes equal to that of the water, and ere long slightly exceeds it, the depression of the apparent horizon and other mirage phenomena associated with the refraction over warm water persist for some little time. During the persistence of this mirage over the cold water there must be an unstable equilibrium due to the thermal stratification in the lower layers of air. The rapid transformation from this instability to the stability associated with the direct thermal gradient is the determining factor in the production of the Fata Morgana. The suddenness of its appearing and its brief transitory character are at once explained.

* If my hypothesis is sound, the instability which leads to the Fata Morgana may occur at the middle of the stretch round which the phenomenon is seen as well as at the extremities. In such a case we should see the Fata Morgana, at first single, splitting into two moving in opposite directions, the one to the right, the other to the left. This possible variation in the details of the illusion I have searched for in vain. Should it ever be observed, it will be an *experimentum crucis*, establishing the sufficiency of my hypothesis.

In this discussion I have limited myself to the salient features which are indispensable to the presentation of my theory. As to the identity of the phenomenon here described with that observed at the Straits of Messina I could deduce several details, such as I have given in my book *Le Léman*. For example, a ship sailing in the banded zone of the Fata Morgana, a steamer, or a house of known form, may be deformed so as to be absolutely unrecognisable. Although never bent into the impossible physical positions shown in Minasi's drawing, they may have their relative dimensions altered in an incredible manner. May we not find some excuse for the artist in the fact that, under the restrictions of his art, he attempted to draw a scene whose extraordinary distortions he could not explain? The vertical extension of objects situated in the banded zone, the flattening of objects above the upper limit of this zone, the multiplication of images of the same object, the superposition of erect and inverted images, etc., etc., are so astonishing and so irrational that we may well forgive the superstitions of early observers, amazed and perturbed by these fantastic illusions.

The accompanying figure illustrates my hypothesis; it needs no further explanation.

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