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Schiaparelli's Shooting Stars

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Translated by

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PREFACE

The fundamental work on this translation was done by Miss Francis M. Svaldi, a student working on National Youth Administration funds. After Miss Svaldi's graduation, her work was revised and corrected by James R. Naiden, Special Research Assistant in Astronomy (now 1st Lieutenant Army Air Corps), working under the direction of C. C. Wylie, Professor of Astronomy.

The pressure of war work, and the enlistment of Mr. Naiden in the Armed Forces, have made it impossible to smooth out the translation as planned. However, it has been thought best to publish it in its present form, since it is not known when further work will be possible. The language of Schiaparelli is unusually full, and very precise. In this translation, such a precision would have appeared exaggerated, and an occasional word or phrase has been omitted to enhance clarity.

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University of Iowa
May 25, 1943

NOTES AND REFLECTIONS ABOUT THE ASTRONOMICAL THEORY OF SHOOTING STARS

G. V. Schiaparelli

Florence, Italy
1867

CONTENTS*

*The contents so indicated by the translators was considered the index by Schiaparelli and was published in the back of his book.

22. Direction variation according to Schmidt and Coulvier-Gravier.

23. Annual diurnal variations of the resultant according to Coulvier-Gravier.

24. One assumed by him as the basis of the meteorologic theory and of the prediction of weather.

25, 26. Brandes has given the key to the explanation of all these phenomena, in the cosmic theory.

27. Calculations established on the periodic variation, according to the principles of Brandes, by Bompas, A. Herschel, Newton, etc.

28, 29, 30, 31. Relation of the shooting stars to the apex of the earth's movement.

32. Annual motion of the apex.

33. Diurnal motion of the apex.

34. Directional motion of the apex.

35. These movements give complete reasons for all the periodic varitions of the shooting stars.

IV. Absolute motion of meteors in space, Paragraphs 36-41.

36. All the absolute velocities can be regarded as the earth's velocity times $\sqrt{2}$.

37. Directions of the absolute movements, radiants; their catalogue.

38. Radiants.

39. Shooting stars are divided into a definite number of streams.

40. Distribution of these streams in space; examination based on the analogy with cometary orbits.

41. It does not appear that the meteoric streams follow one prevailing direction.

V. Motion of meteors relative to the earth. Paragraphs 42-58.

42. Direction of the relative motions.

43. Coordinates of the radiant points of Greg with reference to the apex.

44. Some of the meteoric streams concealed by the sun.

45. The streams hidden by the sun are chiefly streams of direct motion.

46. The positions of radiants do not reveal any particular condensation of the meteoric streams on the plane of the ecliptic.

47, 48. Obstacles confronting the careful study of the periodic variations.

49. Velocity of the relative motions.

50. Real velocity of the fall of the meteors.

51. Great difference in this velocity from maximum to minimum.

52, 53. Different effects which arise according to the direction in which the fall occurs.

54, 55. The proportion of meteorites to the shooting stars ought to be less from the area around the apex, than from the area about the anti-apex.

56. Why are meteorites more numerous in evening than in morning?

57. Why do meteorites not fall in greater numbers in the regular epochs of August and November?

58. There is no reason to assume meteorites have different origin than shooting stars.

VI. Effects of the earth's attraction on the fall of meteors Paragraphs 59-70.

59. Encounter of a meteoric stream with the earth.

60. Volume of the cylinder representing the hole made by the earth in the meteoric stream.

61, 62. Effect of the earth's attraction on the fall of a meteor.

63. Calculation of the elements of the paths of meteors relative to the center of the earth.

64. Examples for the stream of November, 1866.

65. Calculation of the zenith attraction on the radiants.

66. Limiting values of zenith attraction, and need to allow for it.

67. Up to what height of the apex we can omit the zenith attraction.

68. The earth's attraction augments the number of shooting stars on the earth, in different proportions in various directions.

69. Diurnal aberration of radiants.

70. Effect of the atmosphere on the diurnal aberration.

VII. Perturbations exercised by the earth or by other planets on the course of meteors. Paragraphs 71-94.

71. Effect produced by the earth on meteors that pass by at small distances.

72. Deviation of meteors from their direction.

73. The relative velocity is not changed by perturbations.

74, 75. Changes in the direction and in the absolute velocity.

76, 77. The earth disperses the meteoric streams in directions limited by an oblique cone.

78. Maximum perturbations that the earth can exercise on the Leonids.

79. Successive displacing of the radiants of perturbed meteors.

80, 81. Greater or less stability of the radiant points.

82. Maximum effect which the earth can produce on the parabolic orbit of any meteor.

83. Perturbations exercised on the Leonids by Uranus, according to Leverrier.

84, 85. Difficulty about this hypothesis.

86, 87. Calculation of the circumstances in which such perturbations are admissable.

88, 89. Limits of the perigee distance.

90, 91. Maximum limit of the diameter of the meteoric cloud before the perturbations in the hypothesis discussed.

92. The same calculation in the hypothesis that Jupiter and Saturn are the perturbing planets.

93, 94. The present form of the orbit of the Leonids is due to one of these latter two planets.

VIII. On the transformation of celestial material into meteoric streams. Paragraphs 95-134.

95. Value of the cosmological considerations in this argument.

96. Various ways to explain the connection between the meteoric stars and the comets.

97. Nature and origin of the comets according to Laplace.

98, - 104. Phenomena which the attraction of the sun produces on a very rare mass describing a very elongated orbit.

105. Necessary result is the transformation of the mass into a parabolic, or almost parabolic, stream.

106. Limit of the density that a homogeneous, spherical mass of material can have and not be broken up into streams.

107. Causes which aid in dissolution.

108. Generation of annular periodic streams.

109. Not more numerous than the non-periodic streams.

110, 111. The different condensation of the celestial material in stellar space is sufficient to account for the existence of simple comets, of comets accompanied by streams, of streams without comets.

112. Why the masses transformed into streams become invisible.

113, 114. Very dense masses observed on various occasions.

115. Observations of the great comet of 1618 made by P. Cysat.

116. Observations of Wendelin.

117. Diameter of this comet or of the mass at the head.

118. Another example given by the comet of 1652.

119. First observations of Konigk and of David Christians.

120. Observations of Hevelius.

121. Of Malvasia.

122. Of Wendelin.

123. Reflections on the nature of this heavenly body.

124. On the size and presumable limit of its mass.

125. Different nature of the second comet of 1811.

126. The meteoric stream is composed of separate particles.

127. Hypothesis of Father Serpieri.

128. The material of the universe is probably continuous in its original state.

129 - 132. In spite of this, streams of separate particles can arise.

133, 134. Functions of these streams in the order of the universe.

IX. Different opinions about the relation which exists between the comets and the meteoric streams. Paragraphs 135-159.

135, 136. What we mean by "dissolution of comet into streams."

137, 138. Emissions from nucleus and tail are different phenomena.

139.Phenomena of the luminous jets.

140. We cannot explain with a repulsive force.

141. Fundamental problem of the formation of the cometary tail.

142. The conclusions of Bessel about the existence of a repulsive

force on the tail is not a hypothesis, but the mathematical result of observations.

143. Example of the comets of 1835, 1858, 1680.

144. The phenomena of the tail attest the existence of a repulsive or "elective" attraction.

145. On the contrary the material of the shooting star obeys the laws of Kepler, as does that of the planets.

146, 147. Hypothesis of Erman of the generation of meteors.

148. Generation of the streams by the effect of a moderate resistance.

149, 150. Why it is not probable.

151. The short-period orbit described by non-planetary bodies is due to the perturbations of large planets.

152. Connection of the shooting stars with the zodiacal light.

153 - 155. Exact description of the appearance which we see.

156 - 158. The zodiacal light is not composed of luminous and phosphorescent bodies, nor of opaque bodies with a surface of low albedo.

159. Neither is the zodiacal light the reflection of a cloud of meteorites.

X. Some historical notes. Paragraphs 160-165.

160. Relation between the comets and the meteors already indicated by Cardano and by Kepler.

161. Opinion of Halley and of Maskelyne.

162. Theory of Chladni.

163. Speculations of Reichenbach.

164. Opinions of Boguslawski, Erman, Newton.

165. The form of the meteoric orbits cannot be deduced with certainty from the diurnal variation.

I

BASIS OF THE NEW THEORY

1. In the last months of the past year, 1866, I published a new theory on the paths and probable origin of shooting stars, in which I attempted to explain the remarkable relations that exist between these falling stars and the comets. It seemed difficult to reconcile the retrograde motion and the great inclinations of their paths with the hypothesis of circular (or almost circular) orbits, then applied by Newton to the November meteors, and favorably accepted by the most active investigators of this question, especially in England. In the hope of obtaining some decisive facts on the origin and paths of these meteors, I weighed the evidence for planetary origin of meteors against the evidence for an origin in the region of space from which the comets came. The probability in favor of the second hypothesis seemed to me so great that I did not hesitate to set about investigating how these systems or swarms of little bodies could be transported from the regions of the fixed stars to the most central parts of the solar system.

I was pleasantly surprised to find that a cloud of rare material (whether continuous or discontinuous), when moving about the sun, according to the law of gravity, is necessarily transformed into a long thin stream. This stream follows a curve which differs very little from a parabola in the space nearest to us, and in general approximates a very elongated conic section. In this way I have explained the meteoric radiant without recourse to any artificial hypothesis. The perturbations exercised at small distances by the great planets upon masses of rare material, not yet changed into this thin and long current by the attraction of the sun, are sufficient to explain the formation of the rings of meteoric material, i. e., the continuous streams, which produce the periodic appearances similar to the one in November.

2. This theory, whether it be true or false, was advanced by a celebrated French astronomer (Leverrier). He did not disdain to add this little feather to the glorious crown already won by him in scientific research. However, to speak truthfully, he could support the hypothesis only by a clever combination of various probabilities. It lacked that certainty of a conclusion based on facts of physical researches. These are always necessary to win universal acceptance, and without doubt this hypothesis would have been discarded as a hundred other theories if a most unexpected coincidence had not given strong support to it. The orbit of the periodic meteors of August, calculated according to the new theory, was found identical with that of the great comet that appeared in the summer of 1862, Tuttle's Comet. The tens of thousands of meteors that made the nights of August 9, 10, and 11 so splendid and interesting form the escort of that noble heavenly body, and occupy the entire ellipse of a hundred years which it describes in space. Not much later came the discovery that the ellipse of 33 years, calculated for the Leonids on the same principle, was identical in size, position, and form to the orbit described by the only comet that appeared in 1866. Later, it was found that the shooting stars of December 10 describe in space an ellipse which may be the same as that of the puzzling comet of Biela. A few days ago it was announced that a similar relation is probable for the shooting stars of April 20 and the first comet of 1861.

3. These singular discoveries unquestionably show that a close relation exists between the shooting stars and the comets. My hypothesis is splendidly confirmed by what has occurred, and the kindness of nature has surpassed the most indiscreet expectations. The shooting stars certainly have originated with the comets or from the comets. They do not go about in almost circular rings in the principal plane of the planetary system, neither did they have a common origin with the planets.

The native land of the meteors is that immense space which lies between the stars and which seems empty to us.[1] The periods of their revolution are either very lengthy or nonexistent. They arrive from all points of the sky without distinction, filling up the planetary spaces

1. Schiaparelli believed that the comets came from the region of the stars, a belief not now accepted. *Translator.*

with a large number of paths that intermingle and intersect in every possible manner. We are in constant exchange of communication with the infinite stellar systems which surround them, while in the past from time to time a rare visitor has come to us from there. Who is to say how much matter fills the space we believed empty, and what are the perturbations which the attraction of this matter introduces in the movements of larger bodies?

4. Turning our glance to the things that are still unknown, and to the numerous questions that confront us, we have a rather long list. There exists a connection between comets and shooting stars; but of what nature? Will the same hypothesis that has led to this discovery be a pure and complete expression of the truth, or can other equally probable methods be imagined to explain the reciprocal relation of heavenly bodies so different in appearance? Ought we to regard every shooting star as a comet, or as a body of different order? Is it possible to suppose that shooting stars arise from the dissolution of comets? And in what manner are we to imagine such a dissolution? Or, finally, ought we to regard every comet as a cloud of shooting stars? What relation can the tail of the comet and the zodiacal light have with these little bodies? Is the relation of the shooting stars and the comets necessary or accidental? Do there exist meteor paths without comets? And, may we imagine a comet not accompanied by shooting stars? Are the meteor streams formed exclusively of separate solid particles, or do they contain also some elements of continuity? Are they perpetual and indestructable? What influence can the attraction of the planets which cross meteor streams have on them? Is it possible for meteor streams to fall into the sun? Is it possible that the same laws govern the shooting stars, the bolides, and the meteorites? And finally, can we hope that from new findings silence may be forever imposed on the partisans of the atmospheric theory?

5. In the present state of knowledge, it would be vain to undertake a discussion of all these interesting queries; many of them must wait for their solution from long and diligent observations; for others a satisfactory reply can only be found in time. There are however, a few upon which it is already possible to shed some light. For others, one can limit the indeterminacy by reasoning. In this article I propose to discuss some points, on which my investigations should be useful for later studies. Much material has appeared within the last few months, including amplifications and modifications of the theory I published, and substitute theories. I wish to amend and modify, when needful, that which I have written, profiting from these opinions. That will give me opportunity to propose some new thoughts, and at the same time, I will fulfill the pleasant task of rendering justice to those who before now have held correct ideas on the relation between comets and meteors. This treatise can be regarded as a continuation of the five letters written by me to Father Secchi on the paths and the probable origin of meteors, and published by him in the *Meteorology Bulletin of the Roman College.*[1]

[1] Volume V, p. 81, and volume VI, p. 9.

II

EXAMINATION OF THE LATEST OBJECTIONS TO THE COSMIC THEORY

6. *Atmospheric Theory.* I shall commence by examining the latest arguments which the advocates of the atmospheric origin of the shooting stars, bolides, and meteorites propose in its defense. The facts and arguments supporting the cosmic theory have not silenced the small but obstinate group of those who do not understand how material can fall from the sky to the earth. Among these are famous chemists and naturalists. Six years have passed since the publication of a rather large book by Kesselmeyer,[1] in which the author reveals learning and genius worthy of a better cause. He attempts to demonstrate that the meteorites are the product of condensed vapor emitted from a volcano. The atmospheric theory, somewhat transformed and corrected, forms the basis of all the meteorology of Coulvier-Gravier and his students. It seems one of our party has accepted this theory in recent years. According to this school, whose faith is not yet shaken by the tempests which the comets have raised against it, the importance of shooting stars is entirely meteorological.[2] The supporters and followers of the modified atmospheric theory are not concerned with the origin of the shooting stars, and especially since November, 1866, they are forced to admit that they come to us from celestial space;[3] but they insist that once having entered the atmosphere of the earth, these bodies become subject to all its changes and that their final motion depends upon the varying aerial currents crossed by these bodies. They utterly deny the phenomenon of radiation, (the existence of the radiant), and they have invented a very ingenious scheme to avoid seeing it. The scheme is to turn the shoulders to that region of the sky from which the largest number of meteors comes. "You do not see," they say, "the part of the path that belongs to the celestial space and on which truly astronomical research might be founded. The shooting stars do not become luminous until contact with the atmosphere, when their first motion has been modified in a thousand ways. Therefore, the study of the curves described by them belongs to meteorology, not astronomy." This conclusion would be true were the premises correct. We admit that the part of the train traced in the celestial vacuum is invisible, and admit that the visibility of the shooting stars depends upon their contact with the atmosphere. Further, the movements of the atmosphere must, according to the principles of elementary mechanics, influence the paths that we see. But the importance of this last effect has been extraordinarily exaggerated by the adversaries of the cosmic theory.

7. *Influence of the rotation of the atmosphere on the paths of the*

1. *Ueber den Ursprung der Meteoriten,* Frankfurt, 1861, quarto.
2. In the *Comptes Rendus* of the Academy of Paris, vol. 64, p. 595 (March 18, 1866); see also under the section "Meteorologia" a note of Coulvier-Gravier on the shooting stars.
3. Coulvier-Gravier and Saigey: *Introduction historique* pp. 165-166. Coulvier-Gravier: *Recherches sur les meteores,* p. 229. See also the journal of Abbe Moigno entitled *Les Mondes,* vol. 12, p. 650.

shooting stars. The first and most general movement of the atmosphere is the diurnal rotation, which it has in common with the rest of our earth. Its direction for every place on the earth is from west to east and its velocity is 15 Italian miles per minute (465 meters per second) for the equatorial regions, and 10.61 miles, or 329 meters, per second for latitude 45°. The velocity of shooting stars has been measured directly many times, and it is known, independently of every speculation connected with the cosmic theory, that such velocity is frequently greater than that of the earth in its orbit. The supposition that the shooting stars reach us with a relative velocity of 1000 miles per minute is not an exaggeration.[1] Let us suppose that at the 45th parallel a meteor arrives with the aforesaid velocity falling in an exactly vertical direction; entering the rotating atmosphere of the earth, it will receive a horizontal impulse, the effect of which is gradual at first and then increases, and will finally impart to the meteor a horizontal velocity equal to that of the atmosphere. That will happen gradually; however, for greater simplicity, and in order to give the influence of the rotating atmosphere all the imaginable strength, let us suppose that the meteor acquired the horizontal velocity of the atmosphere from the first moment at which it penetrated. Then the meteor will no longer fall in the direction of the radius of the earth, but it will describe a line obliquely inclined from west to east and making with the vertical an angle of 36′28″, which has for its tangent the ratio 10.61/1000—the ratio of the velocity of the atmosphere to the velocity of the shooting star. This deviation, very small in itself, would, however, remain unnoticed by the spectator, who, since he shares in the rotary movement of the atmosphere, would still see the star falling exactly in the vertical direction.[2] On the contrary, if the meteor had fallen without any effect from the atmosphere and followed exactly the direction of the radius of the earth, the spectator would have seen the meteor in a slightly oblique direction, and the center of radiation (the radiant would be found 36′28″ to the west of this point,[3] instead of at the zenith.

8. Thus we are able to say that the resistance of the atmosphere serves to modify the position of the radiant, which, were it not for the air, would be subject to an aberration analogous to that of light. In reality, we always have a phenonemon somewhat different: on entering the atmosphere the shooting star does not deviate quickly, but gradually. For this reason, the path in the air, which was tangent to the direction in space, becomes curved. Only after some time will its direction be that which we have just described. In the case we are considering, the angle of deviation between the first direction and the last or deviated direction cannot exceed 36′28″. The spectator will see the shooting star fall along a slightly curved line, of which the upper part

1. This is almost the exact orbital velocity of the earth.

2. We do not take account of the curvature of the earth and of the atmospheric layers, the effect of which is not noticeable in this calculation.

3. We define the center (or the point) of radiation as that place where the parallel to the meteor path, through the eye of the spectator, meets the celestial globe. This is termed, more briefly, the *radiant*.

will have for its radiant a point not more than 36′28″ from the zenith, while the tangent to the lower part will verge to the zenith.[1] The effect, then, for a shooting star falling vertically is very small. For the inclined paths the effect will be less in proportion to the sine of the angle made with the east-west line, that is, with the direction of the rotation of the earth. In no case will it be noticeable in observations.

9. *Influence of the Winds.* We are able, with far greater emphasis, to state the same about the influence of the winds, to which Coulvier-Gravier attributes much importance. Without doubt, they deflect the paths somewhat; but this curvature will be almost unnoticeable for a wind of velocity equal to that of the rotation of the earth, which below the parallel of 45° is also the velocity of sound. To obtain the effect of the deviation and of the curvature which Coulvier-Gravier mentions, it would be necessary for the supposed wind to have a velocity of 30, 40, and 50 times the velocity of the earth's rotation, completing the entire rotation of the globe in an hour or in a half hour. The centrifugal force of that velocity would hurl our atmosphere out to inter-planetary space, and we would be left in a vacuum more perfect than that in a barometer. We are able to see exactly how much the wind curves the path of a shooting star by observing those streamers of luminous vapor, which shooting stars sometimes leave behind, often continuing for several minutes like a comet's tail. If anything would have to obey the impulse of the atmospheric motion, certainly this nebulous mass would, in which the pre-existing velocity is rapidly diminshed by the resistance of the air. Now observations show, for the most part, such luminous tails remain for long intervals almost motionless, and even the trained eye is rarely able to detect a trace of even a very slow motion. It is impossible to suppose there are in those high regions winds capable of noticeably deviating meteors from their course. Probably with the intention of avoiding arguments, the atmospheric party has recently substituted for the direct action of the wind a mysterious but very strong and rapidly acting force, situated in the most elevated regions of the atmosphere, capable of regulating by its influence in a very short time all the movements of inferior strata from one pole of the earth to the other.[2] To this force is attributed the curving and the deviation of the path described by the shooting star. But what is the nature of this *Deus ex machina*, invested especially for the circumstances, and with what category of forces could one say this new force had any analogy? And what other indications do we have for its existence?

10. *Curved Path.* I now come to another strong bastion of the atmospheric theory, a curvature sometimes observed in meteoric paths, sometimes very noticeable. This curious phenomenon appears in different guises. Many times one can observe in the course of shooting stars (especially the less swift) an oscillation, or an uncertainty of direction, made by the meteor turning slightly to the right or left,

1. We suppose that at the end of its course through the atmosphere the meteor will receive the total horizontal impulse imparted from the rotating atmosphere.

2. *Recherches sur les meteores*, pp. 254-269.

describing instead of a circle a somewhat broken curve. More rarely the train is greatly curved so as to change its direction 90°, or even 180°, returning to that place from where it came. From long and persistent observations Coulvier-Gravier has discovered the trains so curved can be estimated as 0.3 of one percent of the whole number. I have chanced to observe this singular phenomenon two times, although I have more frequently seen stars proceeding with irregular courses or badly imitating a gr t circle. Finally, there is the very rare phenomenon of winding, in which the star describes a strongly sinuous line. Observations of this kind were made by Coulvier-Gravier only three or four times in many years and spiral and winding lines were noticed recently by some observers of the last November fall. For example, we find these sinuous lines already cited by Chladni and by Brandes.

11. All these strange phenomena do not require the help of the wind or of multiple atmospheric currents agitating the shooting star in various directions. When a meteor penetrates the atmosphere, the certainly known forces of nature, on which its movements depend, are two: gravity, and resistance of the medium. During the short time between the appearance and the disappearance of the shooting star, the effect of gravity can be considered negligible. We have nothing to consider other than the resistance of the air. When the shooting star is simply a material point, or a homogeneous sphere, deprived of noticeable rotation, such resistance, acting always against the motion, cannot change that direction. If the motion was rectilinear in the vacuum, it will still be rectilinear when it undergoes the influence of the surrounding medium. If, on the other hand, the projectile has a rotating movement, or is not a spheroid, or if these circumstances are combined, at any one moment the resultant of all the resistances will have a different direction from that of the motion, and produce a lateral component capable of curving the path in a noticeable way. One sees then, that the movement of the shooting stars in the atmosphere belongs to the most complicated problems of ballistics.

12. *Movements of projectiles of rifled cannons.* The projectiles of artillery rifles are not spherical, but for the most part of an oblong shape with an ogival cross-section. They have a rotating motion about the axis, which comes from the grooves of the piece. Their course in the resisting air gives us some explanation for the path described by certain shooting stars. The determination of the movement of these projectiles is a problem of great difficulty, which was treated in Italy by Count Paolo di San Roberto and in Russia by General Mayewski. Not having at my disposal the results of the first, I shall give those of the second, described in vol. 8 of the *Bulletin* of the Academy of Petersburg. While the center of gravity of the oblong projectile describes its path in the air, the axis of the same figure turns about the tangent, describing a conical surface. The number of turns will be two or three, and it is much greater when the initial velocity of the movement is greater. This conical motion of the projectile produces a corresponding winding in the path described. This, however, is not

large enough to alter the general direction, and the wavy motion induced is barely a few decimeters measured obliquely. But the most singular phenomenon is the lateral deviation of a projectile, in virtue of which its motion is not in a vertical plane, but is constantly deviating toward the right or toward the left, according to which direction the spiral of the cannon turns. The projection of the path upon a horizontal plane is not the straight line which the axis of the piece determines, but a curve tangent to that line at its inception at the muzzle, a curve only slightly different from an arc of a circle (for the cases treated by Mayewski), which deviates from the initial direction more and more rapidly, as it departs farther from the cannon. By calculation and by experiment Mayewski has found that an oblong projectile of 14 pounds weight shot at inclination of 10°, with initial velocity of 1004 feet per second, deviates to the right not less than 40 feet after a course of 8400 feet; and the condition of motion is such that if the projectile were able to get away from the effect of gravity, such deviation would finally bend the path backward, reconducting it to the point of departure after a great horizontal circular path. If the conditions would remain nearly constant, this circle would have a radius of 882,000 feet or 270 kilometers. A howitzer of four pounds firing a distance of 1316 feet at an angle of 45° deviated in this distance not less than 27 feet. The horizontal projection of the path is very little different from an arc of a circle with radius of 64,000 feet or 20 kilometers. The singular effects described here are not developed fully during the short trajectory of the projectile; but this is enough to make us comprehend what it would be if the trajectory could be prolonged indefinitely.

13. *Effect of the Boomerang.* From related principles we can seek the explanation of the extraordinary curve described in the air by the terrible boomerang of the aborigines of Australia. It is a piece of hard wood, 50 centimeters long, one part plane and the other convex, curved to form a half moon. Hurled with great force, it deviates to the right, to the left, or above, according to the intention of the thrower, and frequently makes many unforseen changes in the direction of its course. Sometimes the thrower is compelled to prostrate himself to avoid being hit.[1] The invention of this projectile and the art of flinging it have seemed to some so subtle that they would have us see therein the traces of a decadent civilization.[2] This weapon was known to the savages of western Europe, and the ancient Celts used it with dexterity equal to that of the Australians. Bishop Isidorus of Seville wrote in book XVIII of the *Origins*: "There is a kind of Gallic weapon, made of very tough material, which does not go a great distance on being thrown. Where it goes, it hits with terrific force. If it is hurled away by its maker, it returns back to him."[3]

1. James Brown: *Die Eingeborenen Australiens* in the journal of Petermann, 1856, p. 453.

2. Burnet Tylor: *Researches on the Early History of Mankind.* London, 1865, pp. 176-186.

3. Burnet Tylor: *ibid.*
Ferguson: *Transactions of the R. Irish Academy,* Vol. 19, 1843, which I have been unable to consult.

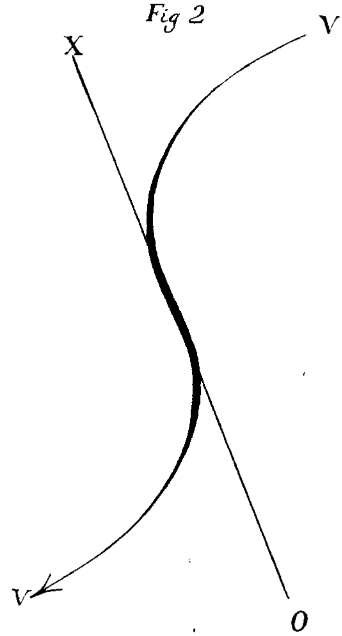
14. *Spiral motion produced by the resistance of the air.* When the rotation of a projectile is such that after a certain period the circumstances that determine the motion reoccur, the movement will continue under similar laws to the preceeding movement, and the projectile will describe a curve all the parts of which are similar and identical. This curve in space will be a spiral, or in special cases, a straight line or a circle. A good example of such a movement is seen in the following simple experiment. Cut a piece of paper in the form of a trapezoid with parallel bases, of which the altitude is five or six centimeters, with the bases somewhat unequal, but only by a few millimeters. Let it be dropped from an elevated balcony. and carried down by its own weight. In the first moments the movement is somewhat uncertain, but soon it will establish a permanent axis of rotation parallel to the long side of the trapezoid, and turning over and over swiftly it traces in its slow fall a regular spiral, whose dimensions can be somewhat greater towards the end of the motion than in the beginning. Varying the dimensions and the form of the trapezoid, we are able to obtain many different spirals.

15. *Application to the shooting stars.* These three examples of the curving of the path produced by the resistance of the air in cases of different velocity (those of the artillery gun, of the boomerang, and a piece of paper falling because of its own weight) permit us to argue how the shooting stars should move. This motion could be 100 times swifter than that of the shells from rifled cannons. If it is true that the resistance of the medium increases as V^2 or even in a more rapid proportion, we can easily comprehend in what manner even in the most rarefied layers of atmosphere there can be produced a resistance capable of all the singular effects we have described. We now have the explanation of many rare phenomena which the observers have mentioned. We are able to comprehend how a shooting star can seem to be suddenly detained, or to go backward over the path already pursued or over a slightly different way. For this effect the spectator O (Fig 1) must be upon a tangent to the visible part of the curve.[1] If, however, the point of contact is at the same time a point of inflection (Fig. 2) we will see the shooting star detained in its course for a moment, then continuing in the first direction.[2] A spiral motion, with spirals of great length, will produce this oscillating path that often occurs in these meteors. If the twists are slow and short, the path will appear winding and will manifest a series of points of regression or even nodes according to the obliquity of the axis of the helix with respect to the line of sight.[3] Finally, since the curvature of the path can even be from bottom to the top, we have a simple and natural explanation of the ascending meteors, provided that their existence is substantiated.

1. A phenomenon I saw in August, 1856.
2. Phenomenon observed by Coulvier-Gravier, February 26, 1853.
3. It is probable that in this last type we ought to class the spiral paths, to which Father Serpieri referred (*Bullettino Meteorologico d'Urbino*, Nov. 1866.) Faye gave another explanation of the winding paths in the *Comptes Rendus*, v. 63, p. 1100, which seems less natural.

Fig 1

Fig 2



16. We are not only able to explain the curving of the path without introducing the action of the wind or some unknown force, but if we wonder at any thing, it is this, that the number of curved paths and irregularities is small in comparison to the others. On viewing the difficulty in judging with accuracy whether a given curve described in the sky is or is not an arc of a great circle (a difficulty augmented by the rapid disappearance of the meteor and by the apparent figure of celestial bowl, much different from a hemisphere), it is conceivable that rapid deviation from the rectilinear course, not obvious to the unaided eye, is rather frequent, when we further consider that the path described by the meteor in the atmosphere is visible often for only a small part.[1] Otherwise, one must conclude that most shooting stars are formed of many small homogeneous spherical pieces, or are composed of homogeneous spherical layers, and have no rotating motion; and that only few have a form irregular enough for deviations in their course. Since such a distinction would create two different classes of shooting stars, a thing neither probable nor plausible, we prefer to admit a gradation of form, from almost exact sphericity to those most rare and singular meteors that describe spiral curves. That will necessarily establish a graduation in the figures of the path.[2] The irregularity of these paths makes us also comprehend why the

1. We are led to this opinion by the fact that the height of luminosity of the shooting star is very variab'e. In other words, many meteors, which in the beginning of their courses are not visible because of great distance, can become visible with increasing nearness to the observer; others, visible at first, disappear because of remoteness.

2. Speaking of the forms attributed to shooting stars, we do not exclude the possibility that they are divided into parts, and also in a pulverized state.

phenomenon of the radiation does not appear as an exact geometric fact (many stars follow lines which, prolonged backward, do not fall exactly at the radiant). That precise kind of radiation cannot be observed except when the visible path commences where the meteor abandons celestial space and enters into our atmosphere. But we have good reason to believe that the luminosity appears only after the meteor has crossed a layer of air of considerable thickness, and the path has undergone some modification. Nevertheless, it would be folly to deny the existence of radiants solely because some paths deviate a good deal from them. Instructive in this regard are the maps of the phenomenon of November, 1866, given us by A. Herschel and Glaisher.[1]

17. The resistance of the air completely accounts for all the apparently complicated phenomena of curvature of the paths, to explain which, all the complicated and arbitrary combinations of moving atmosphere have been found insufficient. After 1837 Olbers imagined the possibility that the curved and ascending paths are derived from the resistance of the air to a body which is very different in form to a sphere. This is what he wrote in Schumacher's Jahrbuch.[2] "Certainly the resistance of condensed air, especially when the bolides have a form that is irregular, crushed, and much different from a sphere, can produce a wavy curve, winding, curved upward, downward, and also laterally. Children often see similar changes in the motions of flat stones and oyster shells which they throw vigorously." These few words, which we have presented with comments in paragraphs 10 to 16, are enough to blast the last argument of any weight that the sponsors of the atmospheric theory can still invoke. I say the last because recently they have also lost (though they do not wish ever to admit themselves beaten by our side) the formidable support of some periodic laws of frequency of shooting stars, known under the names of *diurnal, annual, and direction variation.* The research on these laws is an extremely interesting study, and was carried on particularly by the followers of the atmospheric hypothesis, and especially by Coulvier-Gravier. At first glance they seem irreconcilable with the cosmic theory and consideration of them for a long time put in doubt the most authoritative investigators of this material. We must consider these laws now.

III

PERIODIC VARIATIONS OF THE SHOOTING STARS AND THE EXPLANATION

18. *Annual Variation.* By 1823, Brandes had recognized that the number of shooting stars is greater in autumn than in spring. This was the first recognition of the annual variation which was later observed with greater exactness by Coulvier-Gravier, and still later by

1. *Monthly Notices of the Astronomical Society,* v. 27, pp. 55-56.
2. *Schumacher's Jahrbuch* 1837, pp. 51-52.

Schmidt and Wolf. The following table gives the average number of shooting stars counted in an hour in the various months of the year according to these observers:

Month	Coulvier-G. 1841-1845)	Schmidt (8 years)	R. Wolf (10 years)	Resulting Average
January	3.6	3.4	5.5	4.2
February	3.6	....	5.4	4.5
March	2.7	4.9	5.2	4.3
April	3.7	2.4	4.6	3.6
May	3.8	3.9	4.1	3.9
June	3.2	5.3	5.4	4.6
July	7.0	4.5	9.8	7.1
August	8.5	5.3	12.9	8.9
September	6.8	4.7	7.4	6.3
October	9.1	4.5	6.4	6.7
November	9.5	5.3	5.0	6.9
December	7.2	4.0	4.1	5.1

In spite of the noticeable difference in the results of the three observers, we see that the minimum number of shooting stars takes place near the vernal equinox, and the maximum near the autumnal equinox, the average number corresponding closely with the solstice.[1] The difference between maximum and minimum is very obvious, and has about the ratio of 2:1. This interesting fact is further verified for the bolides, which is a probable indication of their identity of origin with the shooting stars. We may compare in this regard the information and figures given at the end of my first letter to Father Secchi. Coulvier-Gravier, followed by Arago and Edward Biot, has announced the law of the annual variation of the shooting stars and of analogous meteors: the earth encounters far fewer meteors going from perihelion to aphelion than it encounters from aphelion to perihelion. We will see that this method of considering the subject is not exact; the annual variation does not depend upon the position of the earth with regard to the apses of its orbit, but solely upon the equinoxes and the solstices.

19. The daily variation (or as others say improperly, "hourly"), observed by Herrick in 1838, became better known through the tireless labors of Coulvier-Gravier. According to his first research published in 1847, the number of shooting stars (all other circumstances being equal) was at a minimum in the evening, a maximum in the morning, and toward midnight reaches its average value.[2] Still later he published a second series of hourly values, in which the maximum of the morning takes place at three hours after midnight, a point which Coulvier-Gravier first stated to be at 6 A. M.[3] Here are the two series

1. The series of Coulvier-Gravier is copied from the *Introduction Historique* already mentioned, p. 172; that of Schmidt is given in the *Cosmos* of Humboldt, vol. 3, p. 471, of the Milan edition; that of Wolf is taken from *Les Mondes* of the Abbe Moigno, vol. 13, 1867, p. 24.

2. *Introduction Historique*, p. 171.

3. *Recherches sur les meteores*, p. 219.

of average frequency during the year, corresponding to the hours of the night.

Astronomical time	1st series (1841-1845)	2nd series (12 years)
5 hr.— 6 hr.	....	7.2
6 hr.— 7 hr.	3.3	6.5
7 hr.— 8 hr.	3.5	7.0
8 hr.— 9 hr.	3.7	6.3
9 hr.—10 hr.	4.0	7.9
10 hr.—11 hr.	4.5	8.0
11 hr.—12 hr.	5.0	9.5
12 hr.—13 hr.	5.8	10.7
13 hr.—14 hr.	6.4	13.1
14 hr.—15 hr.	7.1	16.8
15 hr.—16 hr.	7.6	15.6
16 hr.—17 hr.	8.0	13.8
17 hr.—18 hr.	8.2	13.7
18 hr.—19 hr.	....	13.0

The numbers in the third column are all almost exactly equal to double the corresponding values of the second column, which seems without much doubt to derive from a much different method used by Coulvier-Gravier to caluculate the hourly frequency in the two cases. But if we make an abstraction from the absolute values and consider the law of progression in any one series we find a noticeable parallelism. Secchi has observed the fact that the greater frequency of shooting stars in the hours after midnight is commonly[1] known. Herrick had already concluded from his observations that the morning meteors are three times as numerous as the evening meteors.[2]

20. This singular phenomenon was for some time the corner stone of the hypothesis which connected the shooting star with the atmospheric movement. It is at first difficult to comprehend how a cosmic phenomenon can depend upon the local hour of any one observer, while nothing is more natural than relating the daily variation of the shooting stars to that of the barometer and thermometer. The explanation of this fact embarrassed not a little the advocates of the cosmic theory and some of them nearly returned to the contrary party. I will quote here, from the third volume of the *Cosmos*, the reflections which the phenomenon of diurnal variations had suggested to Humboldt.[3] "It is difficult to imagine what influence the hour of the night has on this phenomenon. If it were established that shooting stars show their maximum frequency at a determined hour, we would be constrained if we wish to maintain the cosmic hypothesis, to admit this guess, otherwise very improbable, that certain hours of the night or the morning are more favorable to the lighting up of the shooting stars, and in the

1. Bullettino, Meteorologico, vol. 5, 1866, p. 88.
2. Newton, *"On Shooting Stars,"* in the American Journal of Science, vol. 39, p. 206.
3. *Cosmos*, vol. 3, p. 480, of the Milan edition.

Proceedings of the Iowa Academy of Science, Vol. 50 [1943], No. 1, Art. 6

earlier hours a part of them are invisible." These words were written in 1851. Let us listen now to what Quetelet says in his famous work *The Physics of the Globe* published in 1861: "The phenomenon of the shooting stars is very well known, for an hour does not pass without one for the attentive observer, regardless of the season of the year. However, the last six months evidently produce more meteors than the first; the same is true of the second half of the night, more fertile in meteors than the first half. Finally, North America encounters more during a given time than the countries of Europe and Asia. This result, of great importance for the theory of shooting stars, has not been studied with the attention it deserves. In fact, it can help us learn whether the shooting stars originated in our atmosphere, or whether they came from the outside."[1] Later on, after noting the difficulty of assigning the bolides and meteorites other origins than the cosmic, he adds, "The shooting stars present another entirely different spectacle. We see that these meteors belong to the stable part of our atmosphere, where they originate and where they are extinguished.[2] They are not able to exist in the medium in which we live. Our eyes reveal the length of their existence, but it is impossible for us to touch them and submit them to direct observation however great their number is in their most splendid appearances. They are phenomena of another medium than that in which we live, and they cannot be extraneous to our earth, being subjected both to a diurnal period and to an annual period. They are more frequent toward dawn than toward sunset, and they have a greater frequency in certain regions of the earth than in others."[3]

21. Finally, we see how the famous director of the Observatory of Athens, Juilus Schmidt, reasons on this argument, in a letter to Professor Heis, written January 12, 1867. "Coulvier-Gravier in Paris was the first to demonstrate, many years ago, that the hourly frequency of the meteors is subjected to variation in the course of every night: that in general, the maximum occurs after midnight, and that for such phenomena the difference of longitude has little or no effect. Apparently that ought to shake from the foundation the hypothesis of the cosmic origin of meteors. In reality, this fact shows a still unknown influence of the nearness of the earth, from which we ought to derive the luminosity and the combustion of the meteors and their variable frequency every night. In 1851, I stated this point to Alexander Humboldt in a letter, at his request. I attempted to avail myself of Ampere's theory about the electro-magnetic fluid that circles the earth, in combination with the distribution of the sun's heat on the surface of the earth, to explain such variation. I asked him not to publish these things, but I shall return to them later. The day will come when this knot will be untied, but as yet we do not have enough

1. *Quetelet, Physique du globe,* 1861, pp. 317-318.

2. Quetelet considers the atmosphere as divided into two parts, the superior or stable (very rare), not subject to the irradiation of the sun nor upset by the wind; the inferior or unstable (more dense), in perpetual agitation, where the seat of all meteorological phenomena is.

3. *Physique du globe,* p. 322.

observations. We shall find that in the face of this and other phenomena it will be impossible to explain everything by gravity alone; and that our physical cognizance is too imperfect for us to flatter ourselves that we find quickly the explanation of every new phenomenon that presents itself to us. In order to keep ourselves to the cosmic hypothesis, it is enough to know that many points of "prospective divergence" exist in the sky, and that meteors have a planetary velocity. The phenomena still not explained are the light, the motion of the tail, the variations of frequency, etc. We ought to find their explanation in the influence of the earth, and in part, derive them from forces[1] which have never been mentioned in our books yet." To reason in this way is to give up victory to the atmospheric party, because to invent a new force for use in a particular hypothesis, is a thing permitted at most once a century, and only to a Newton.

22. *Direction variation* presented difficulties not less dangerous to the cosmic origin of the shooting stars. This is a distribution, already considered by Brandes in 1823, of the direction of the shooting stars with reference to the point of the horizon from which they seem to come. The phenomenon was first investigated by Schmidt (1842-1844) and by Coulvier-Gravier, who determined it with greater precision than any of the others, examining minutely the details. The following table gives the results of Schmidt's observations:[2]

Number of shooting stars	1842	1843	1844
From north	21	30	78
From east	108	151	247
From south	20	34	72
From west	30	79	76

In the table to follow we have the more complete and detailed results of Coulvier-Gravier, based upon his observations of some 4400 meteors.[3]

Number of stars (direction)	1842	1843	1844	Average
N.—N.E.N.	106	54	160	107
N.E.N.—N.E.	99.5	63	222.5	128
N.E.—E.N.E.	65	67	223.5	118
E.N.E.—E.	120.5	90	180.5	130
E.—E.S.E.	179	102	209	163
E.S.E.—S.E.	143.5	65	163.5	124
S.E.—S.E.S.	127.5	61	223.5	134
S.E.S.—S.	140.5	66.5	133.5	113
S.—S.W.S.	97.5	47.5	123.5	89
S.W.S.—S.W.	50	27	68.5	48
S.W.—W.S.W.	32.5	25.5	63.5	40
W.S.W.—W.	41.5	22	56.5	40

1. Heis: *Wochenschrift fur Astronomie*, etc. 1867, no. 5.
2. *Introduction Historique*, p. 159.
3. *Ibid.*, p. 174.

W.—W.N.W.	51.5	36.5	53	47
W.N.W.—N.W.	40	21.5	59	40
N.W.—N.W.N.	48.5	12	89	50
N.W.N.—N.	72	40.5	161	91

Both series show a remarkable agreement in their progression despite the difference in frequency of the observations in the various years. The prevailing direction is from east to west; the direction from west to east is seldom observed; the two directions north and south give almost a median frequency.

23. Later Coulvier-Gravier believed he discovered that the law of direction variation is not constant in the different seasons, for the direction of greatest frequency, or what he calls the resultant, oscillates over a considerable angle around the east point, now deviating towards south, which occurs more frequently in winter and spring; now towards the north, which occurs more frequently in summer and autumn. And finally, this direction variation depends upon the hour of night in which we make the observations. So the directions from the north are more numerous toward midnight than in the morning; from the east, meteors arrive in greater numbers in the morning than in the evening; from the south, there are more in the morning; from the west, there are more in the evening. The author confesses these last conclusions are still not supported by a sufficient number of observations.[1]

24. Since these laws are the result of pure statistics, one ought to reject those hypothesis that do not take sufficient account of them in accounting for the origin of shooting stars. We see that the frequency of the meteors has an obvious relation with the direction of the principal points of the horizon of every observer; and this relation varies with the hour of night and the time of year exactly like the winds, considered in their average direction and frequency for a certain number of years. Here was the place where the cosmic theory ought necessarily to be discarded! Precisely here was the origin of the meteorological theory developed by Coulvier-Gravier in his two books and in different writings successively presented to the Academy of Science at Paris. Cum hoc, ergo propter. The shooting stars were considered announcers of all the great movements of the atmosphere and their resultant becomes the foundation of the prediction of the weather. The whole theory, with all the indeterminacies and contradictions (whereby those works of fantasy that pretend to truth are customarily distinguished) may be found in the writings I cited, but especially in the *Research on Meteors*,[2] which is a dissertation on meteorology founded in part on these principles, and in the book published by G. Bresson in the past year under the title *La Prediction du temps*.

25. If the instinct for truth, which sometimes makes us resist the most sophisticated arguments and the deception of false appearances, had not kept most astronomers and physicists on the right path, the

1. ***Introduction Historique***, p. 175.
2. *Recherches sur les meteors et sur les lois qui les requissent*, Coulvier-Gravier, Paris, 1859. *La prediction du temps*, G. Bresson, Paris, 1866.

cosmic hypothesis would have ended by disappearing from the scientific scene. The words of Humboldt, Quetelet, and Schmidt, to which we have referred, show us where we might have ended. And yet the explanation of all these strange difficulties had been found many years before by Brandes. Brandes, whose work on shooting stars few have equaled, and none surpassed, wrote in 1827 as follows: "Besides the proof deduced from attraction, we are able to cite two phenomena as direct demonstrations of the motion of the earth in space. One is the aberration of light . . . . the other, which we still need to establish by more exact observation, is the apparent motion of the shooting stars. Since this phenomena is known through few observations, and deduced by me from them, we can not give it much weight, as yet, but I do not doubt that future observations will confirm it. When observations of shooting stars are made from different places, and the points over which they appear and disappear are determined, we find that amid the variety of directions, the direction opposed to the orbital motion of the earth prevails. Now if these luminous objects remained motionless in space, they ought to appear to people on the earth as endowed with movement equal and contrary to that of the planet Earth. The shooting stars are not motionless, and are endowed with the most various movements, but it is clear that, in general, for such movements, the effect described above ought to be sensible. Conversely, the observations, which show that the greatest part of these bodies show such a motion contrary to the orbital motion of the earth, furnish a new and unexpected demonstration of the true movement of the earth."[1] Thus the great Brandes reasoned in his *Lectures on Astronomy*, unjustly forgotten today.

26. However varying and different the motions of the meteoroids in space are, it is clear that the motion of the earth combines with them to produce the relative motions and gives to them a certain character and a certain relation with the direction along which our planet is advancing. It follows that the meteor swarm will observe certain laws of position and of frequency with respect to the apex of the terrestrial movement, i. e., with respect to that point of the stellar sphere toward which the earth is moving at the instant of observation. This apex takes part in the diurnal motion of the celestial sphere and hence has a diurnal variation everyday in altitude and azimuth. It moves along the ecliptic, running through the twelve signs in a year. There is, then, an dannual variation in altitude and in direction for any given hour of the day. We believe that the diurnal and annual movements in altitude and azimuth of the apex give rise to just such periodic variations in the frequency and direction of the meteors, and further study has splendidly confirmed this opinion.

27. In 1838 Herrick observed at New Haven, Connecticut, that the prevailing direction of the meteors was from northeast to southwest, and that the number was much greater in the morning hours than in

1. H. W. Brandes: *Vorlesungen ueber die Astronomie*, Leipzig 1827, vol. 1, pp. 158-159. The same idea is already found in his *Observations on Meteors*, published in Leipzig, 1825.

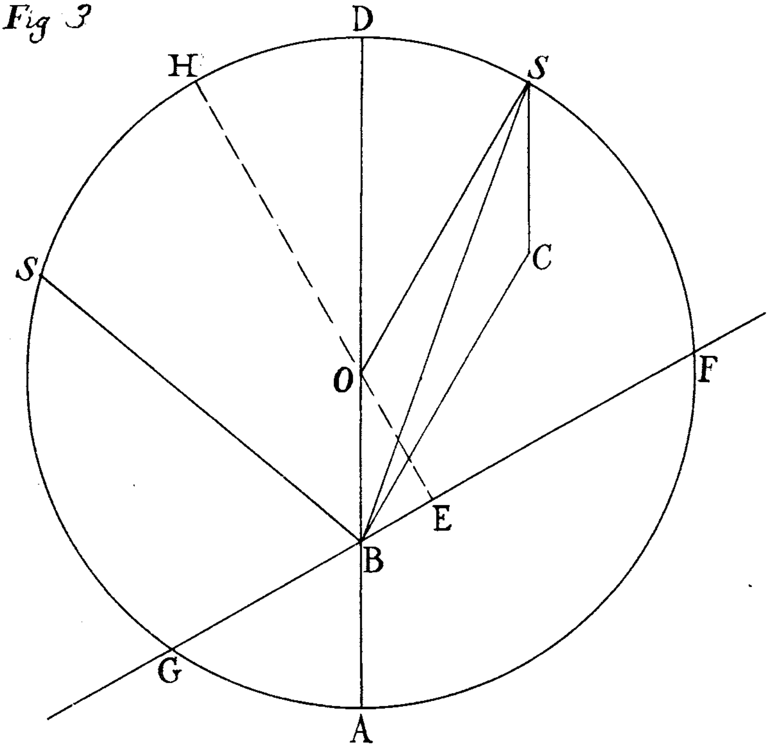
the evening, and explained both phenomena by the principles of Brandes. We wish then, to regard this illustrious American as the first to have offered an explanation of the diurnal variation of number and of direction. The diurnal variation was, however, considered theoretically by Bompas in 1857, who also tried to deduce numerical proportions, supposing that the velocity of the meteor is double the orbital velocity of the earth.[1] In 1864 Alexander Herschel published a complete mathematical theory of the annual variation, the proportions of which, he found, approached the observed result, when he supposed the average velocity of the meteor equal to the velocity of the earth.[2] In 1865 Professor Newton derived formulas for the hourly variation based on the average velocity of meteors in space, and was led to conclude that this velocity ought to be greater than that of the earth, approaching that of the comets.[3] The following year, 1866, I published in my first letter to Father Secchi a caluculation for the hourly variation, differing in form, but identical in result: the average absolute velocty of the meteor ii space I found to be almost exactly equal to the parabolic velocity. I did not then know of the somewhat earlier work of Newton. It would not be amiss to record here that Greg has shown it possible to have for the hourly and direction variation a different explanation from that derived from the principles of Brandes.[4]

28. *Relationship of the shooting stars with the apex of the annual terrestrial movement.* I propose to examine in the following paragraphs the theory of the periodic variation of the shooting stars; and I will show that from the effects of the rotation and revolution of the earth, and from laws which actually arise from observations, it is possible to derive that variation. We wish to begin with the hypotheses more or less explicitly admitted by Bompas, by Newton, and by Herschel, that in any one instant shooting stars reach the earth with equal absolute velocity and with equal frequency from all directions of space. A simple construction shows the fundamental relation between the apex of the terrestrial movement and the frequency of the meteors and the directions from which they seem to come.

29. Let us imagine that an observer is motionless in space, and consider the meteors that come toward him. According to the hypothesis just stated, in a given time, e. g., in a second, he will receive an equal number of meteors from all directions. He might imagine himself as at the center of a large sphere of radius equal to the absolute velocity common to all meteors (a velocity designated by v). Then from all points on the surface of the sphere in a given unit of time a certain number of meteors will appear. ASS' is this sphere, (Fig. 3) O is the center, radius=OS=v. If now the observer moves somewhat toward the direction OD with velocity V, the resulting appearance will de-

1. *Monthly Notices of the Astronomical Society,* vol. 17, pp. 147-148. *Report of the British Association,* for the year 1857, p. 143.
2. *Monthly Notices of the Astronomical Society,* vol. 24, pp. 133, 135, 189.
3. American Journal of Science, vol. 39, pp. 205-206.
4. *Report of the British Association for the year* 1861, pp. 38-39.

Fig 3



pend upon the relative motion of the meteors that fall toward O with velocity v, and of the observer who arrives at O with the velocity V. We can further suppose that the observer is fixed, and attribute instead to the meteors an equal and contrary velocity to V. So the meteors that should have fallen at O with velocity OS=v will fall instead in the direction SB, whose components are OS or v and SC or V, the last being taken in a direction opposite to the observer's motion. Since OB=SC =V, the point B will always be the same, regardless of the position of S on the surface of the sphere. The meteor S′ will fall in the direction S′B, and so will all the others. If the observer is supposed at B, one can express the laws according to which the shooting stars fall toward him, by saying that from all parts of the surface of the sphere in numbers proportional to the areas of these parts, meteors fall not upon O, but upon B in the direction SB, S′B, etc. From that, the meteor showers should have the maximum density in the direction BD, that is, of the apex toward which the observer moves; the minimum is in the direction BA, opposite to the apex. And it is easy to see that the two densities, maximum and minimum, will be as the squares of the lines BD, BA, or as $(v+V)^2:(v-V)^2$. As a matter of fact, $v = V\sqrt{2}$, nearly, and the relative density of the meteors coming from the apex to the density of the meteors coming from the opposite point is about 34:1. The lines SB, S′B, etc., express the relative velocities, with which the meteors SS′ meet the observer.

30. Let this observer be no longer isolated in space but his visibility limited by the plane GF of a horizon. Let ϕ be = the angle DBF, which is the apparent altitude of the apex. It is plain that the meteors that arrive from the portion GHF of the sphere always remain visible, and the number of visible meteors is to all the meteors as the segment GHF is to the whole sphere, or as HE is to the total diameter. This diameter is 2v and HE = OH + OE = v + Vsin ϕ; then the frequency of the meteors seen above the horizon by the observer at B is proportional to $\frac{v + V\sin\phi}{2v}$. Calling F this frequency and taking for unity the number of meteors that come from the half of the sphere in the unit of time, we have simply

$$F = 1 + \frac{V}{v}\ \mathrm{Sin}\ \phi \quad \text{.........} \quad (1)$$

The formula was used for the first time by Alexander Herschel. It shows us how the quantity of meteors increases with the apparent altitude of the apex above the horizon. Considering the two extreme values that occur when the apex is at the zenith and when at the nadir, we find the relation of the maximum frequency to the minimum frequency of the visible meteors above the horizon, by the expression $\frac{V + v}{V - v}$. In the case of $v = V\sqrt{2}$, this relation is greater than 5:1.

31. The directions from which the shooting stars come, are found so very densely about the apex, that the frequency of their appearance depends for the most part on the position of this with respect to the horizon. We see more meteors in that hour of the day when the apex is at a superior culmination; they are more numerous in those seasons of the year where the apex rises on the meridian, to a greater height, and finally we see a greater number of shooting stars arrive from that region of the horizon which is nearest, at that instant, to the apex. As the quantity of heat radiated by the sun depends upon its diurnal and annual variation, the number of meteors observed follows the annual and diurnal movement of the apex. We can now consider this point as a sort of *meteoric sun*, a principal center of the radiation of shooting stars. We may term its time of rising *meteoric morning*, the time of superior culmination *meteoric noon*, etc. In this way we can describe all the movements of the apex in the sky with brevity and clarity.

32. *Annual motion of the Apex.* The tangent to the curvilinear motion of the earth is constantly in the plane of the ecliptic, except for very small deviations which arise from the forces perturbing that motion, which it is useless to consider here. The angle of this tangent with the radius vector does not ever differ from a right angle more than 58′. In the course of a year the apex runs through the celestial ecliptic with an almost uniform motion, remaining behind the sun in longitude by an arc varying from 89° 2′ to 90° 58′. Without great error we are able to regard this distance as constant and equal to 90°. The maximum northern declination of this meteoric sun takes place

at the time of the autumnal equinox, and the maximum southern declination coincides with the vernal equinox. Its declination is zero at the two solstices. From the summer solstice to the winter solstice we find it in the northern parallels and culminating at greater heights than the points of the equator, and the contrary takes place in the months from the winter solstice to the summer solstice. In the first case more meteors ought to fall than in the second; this constitutes the law of the annual variation. (See paragraph 18)

33. *Diurnal motion of the apex.* The difference of the right ascension of the sun, and of the meteoric sun varies during the year, and can differ almost 6° from a right angle. Neglecting these circumstances, we say, that in general the superior culmination, or the meteoric noon, precedes sun noon by six hours, and always takes place a little before or after 6 A. M. The inferior culmination occurs in the evening, near 6 P. M. Six A. M. will make a maximum and 6 P. M. will mark a minimum in the diurnal variation of the meteors; that is precisely the law expressed in paragraph 19. Sun noon and sun midnight ought to have a mean frequency of meteors. It is obvious that the diurnal period extends throughout the twenty-four hours, and of this twenty-four hour period, the only observable part is at night, the shooting stars being little visible in the twilight, and rarely in the daytime. In the summer we are not able to observe either of the two culminations of the apex, but in the winter, we are able to observe both. The rising of the meteoric sun (the meteoric morning) corresponds always to the hours near midnight, and is observable all year, while the sunset of the meteoric sun always occurs in the daytime in our latitudes.

34. *Direction motion of the apex.* The meteoric sun is at superior culmination near 6 A. M. and at inferior culmination near 6 P. M. From the first to the second of these times during the day it remains constantly in the western hemisphere of the sky; the region of the horizon corresponding to the maximum frequency of shooting stars is in the half of the horizon that contains the western winds. In daytime, the prevailing direction of the shooting stars is from the west, and from that region of the *compass.* But at this time the meteors are not observable. During the night, from 6 P. M. to 6 A. M., the meteoric sun is always in the eastern hemisphere; the shooting stars will come toward the observer most abundantly from the east and adjoining directions. This is the general reason for the direction variation that the law referred to in paragraph 22 fully confirms. During the last half of the night, which is incomparably more abundant in shooting stars than the first, the apex is found in the east and northeast in the summer and in autumn, and in the southeast and south in winter and in spring. This is exactly the annual oscillation of the "resultant" of Coulvier-Gravier (23), which in summer seems attracted toward the north, in winter toward the south. Finally it is obvious that in the period of twenty-four hours, the apex describes in our latitudes an entire circuit about the vertical, and is found successively in all the possible directions, whatever, the season of the year. Hence it will be true

that in the same period the resultant makes a complete trip on the horizon. At 6 P. M. we find the apex in inferior culmination, and the resultant will be directed to the north; it will pass successively to the east during the night, and in the hours of the morning it will arrive at south. We have then a periodic diurnal motion of this resultant, which agrees sufficiently well with the laws (still somewhat uncertain) derived from the observations of Coulvier-Gravier.

35. The theory of Brandes, and his successors, thus explains all the particulars of the periodic variation, at least as regards the laws of their increase and decrease. Let us note that all the things we have just developed may hold even if we do not admit the perfect uniformity of the falling of the shooting stars from all directions of space, a premise assumed in paragraph 29. If, for example, we suppose all the meteors move near the plane of the ecliptic, in place of considering ASS′ (Fig. 3) See paragraph 29 as a sphere, we must consider it as a circle situated in that plane. If we admit the uniformity of the directions and of the absolute velocities in this plane, we evidently have here too a point, D, of maximum frequency in the direction of the apex; in this case the line GF no longer represents the plane of the horizon, but the line in which this plane intersects the plane of the ecliptic. The reasoning is here similar to that of the preceding case. The same can be said of other intermediate cases, as if, for example, the shooting stars did not all move in the plane of the ecliptic, but their orbits were more dense in the direction in this plane than in the direction perpendicular to the ecliptic. But if the paths of the shooting stars in space did not preserve uniformity according to all the directions in a plane, but tended instead to follow a single fixed direction (for example, if their motions about the sun were all direct, or all retrograde, or all convergent toward the sun), the explanation given above is not, in any way, applicable. In addition to the visual apex determined by the motion of the earth, there would then exist a physical apex, around which the paths would be clustered truly and not merely apparently; the phenomenon would become much more complex. The same would happen if the absolute velocities of the shooting stars in space were not uniform, but tended to be greater in certain directions, and less in others. Let us examine with some care all these particulars.

IV

ABSOLUTE MOTION OF SHOOTING STARS IN SPACE

36. *Uniformity of the absolute velocities.* If at one time there existed some doubt about the almost perfect uniformity of the absolute velocities of the shooting stars in the space adjoining the earth, now this doubt has disappeared. We are able with confidence to pronounce that such velocity can be regarded in every case as very nearly equal to parabolic velocity. As a matter of fact, we may here reason about meteors as we do about comets. Letting the semi-major axis of the

terrestrial orbit be unity, the radius vector of the earth may be put in the form $r = 1 + \omega$, ω being a small variable quantity, that is not greater than 1/30. Calling U the average velocity of the earth,[1] the velocity V corresponding to the radius vector r will be expressed by the formula,

$$V = U \sqrt{\frac{2}{r} - 1} = U \sqrt{\frac{2}{1 + \omega} - 1}$$

When we neglect the square of W, we have the more simple form

$$V = U \ (1 - \omega \ \dots\dots\dots \ (2)$$

For a comet describing an orbit with very large semi-axis *a* the velocity corresponding to the radius vector *r* is:

$$v = U \sqrt{\frac{2}{r} - \frac{1}{a}} = U\sqrt{2} \sqrt{\frac{1}{1 + \omega} - \frac{1}{2a}}$$

which, neglecting the square of ω and of 1/2a becomes

$$v = U \sqrt{2} \left\{ 1 - \frac{\omega}{2} - \frac{1}{4a} \right\} \dots\dots\dots (3)$$

The ratio of these two velocities is

$$\frac{v}{V} = \sqrt{2} \left\{ 1 \pm \frac{\omega}{2} - \frac{1}{4a} \right\} \dots\dots\dots (4)$$

and we see that the term $(1/2)\omega$ can not alter the relation v/V more than + 1/60. The term 1/4a is sensible only for a comet or for a shooting star of short period. It amounts to 1/14 for the comet of Biela, and to 1/41 for the periodic meteors of November. But for the great majority of meteors, it is negligible; for this reason we are able to suppose without great error $v/V = \sqrt{2}$ in all the cases.

37. *Direction of the absolute movement.* Until recent years, we believed that most meteors wandered confusedly in space, falling upon the earth with different velocities, and from different directions. Some particular systems of meteors as those of August and November ,for which we had found radiants, we supposed assembled in clouds or cosmic currents, and we called them periodic, or shower meteors, to distinguish from the great number of the first type, to which we gave the name *sporadic. Heis,* in Munster, has been the first to attempt the classification of all the shooting stars into the shower, or fixed systems, fixing for every time of the year a sufficient number of radiants to permit the radiation of almost all observed meteors. A first series of radiant points was published by him in 1849,[2] but a complete catalog of all the principal radiants observed throughout the year was not published until 1864, after eleven years of observation.[3] The same catalog corrected and enlarged has been reproduced by Faye in the Comptes Rendus, Vol. LXIV, page 549. The catalog of Heis is divided into fortnights, that is, every month is divided into two halves, and to every half month there are assigned the radiant points of the stars observed in that interval; hence when a shower of meteors extends over days in

1. That is, the velocity that corresponds to the circular orbit of unit **radius.**
2. Heis: *Die periodische Sternschuppen, Cologne,* 1849; a work that we are very sorry we were not able to consult.
3. ***Monthly Notices of the Astronomical Society,*** Vol. 24, p. 212.

two different fortnights, the radiant point is repeated, sometimes with slight variation in its coordinates.

Shortly after, Robert Phillips Greg, having constructed on maps drawn for this purpose the apparent meteor paths of 1746 meteors, deduced the positions of 56 distinct radiant points, corresponding to that many meteoric showers, whose duration varied from a few hours to seven or eight weeks.[1] His results agree perfectly with those of Heis on essential points. Both these catalogs contain only radiant points made manifest from a reasonable number of observations. Further, they do not extend to the southern hemisphere of the sky. One may assume that the total number of radiant points considerably surpasses 100, and there have already been announced 39 other radiant points, determined in the southern hemisphere from observations made at Melbourne, Australia, by Dr. Neumayer (Comptes Rendus, in the place cited). The observations of Heis and of Greg have given on an average four to five radiants for every night of the year, whence it is easy to argue that for the whole celestial sphere the number rises to 10 or 12 each night.

38. The interpretation of the radiants considered as an effect of perspective is too well known to be recorded here. Every radiant point corresponds to a meteoric shower, and indicates at that moment the earth encounters a stream of bodies travelling together through space in parallel orbits and in orbits slightly different from ours. The visual line from the eye of the observer to the radiant point indicates the direction of the relative motion of the earth and of the meteor. In any one instant then the earth is striking a certain number of these meteoric streams, whose directions can be very different. They are so sparse that they can intersect one another without disturbance or change. Some are more abundant, some less; some are continuous, others are intermittent or periodic. The August meteors are the most noteworthy example of continuous streams; the November meteors are now the best known in the periodic group. I say *now*, because these phenomena are subject to a radical variation with the passage of centuries. The stream of November is not found mentioned in the chronicles before 902, while the splendid meteor shower which was observed September 26 in 288, September 23 in 585, and from September 10 to 18 of the year 881, seems to have ceased to appear.[2]

39. It is not true that the shooting stars arrive upon the earth from all possible directions; in every night the number of these directions is quite limited, though the number of shooting stars that arrive from any one direction can be very great. However, if one considers the periodic variation of the meteors during a single night, the phenomena are far from the regularity of the hypothesis used as a basis of our reasoning in paragraph 29. Because not only can ten or twelve points of radiance of that night (granted that there are that many) be un-

1. *Proceedings of the British Meteorological Society*, Vol. 2, p. 305; and *Report of the British Association*, 1864, p. 98.

2. See Biot: *Catalogue des etoites filantes*, etc. under the years indicated.

equally distributed, but if among the meteoric showers is one of an extraordinary abundance, the laws of frequency or direction are determined essentially by that alone. Fortunately we are not seeking the laws that suit any one night in particular, but those that suit the resulting average of all the nights of the year, or a majority of the same. There one can assume an averaging-out of circumstances, which would take place if all the radiant points of the year, which number more than 100, were to occur simultaneously in one night. The results thereof would be the same as the averaged results of the showers throughout the year. A careful examination will show that such a superposition of all the nights is permissable, and will not cause an error of importance in the result. Hence, the problem can be treated as if at each instant the radiant points occurred in infinite numbers, and produced showers equally abundant; which is equivalent in substance to the hypothesis of the sporadic meteors, where for every meteor we substitute a meteoric current falling from all possible directions.

40. It follows that the distribution of the meteors in streams is not the origin of any great difficulty for the explanation of the periodic variation; only, there may result a less perfect cancelling of the accidental variations. Much more perplexing is the question, whether the meteoric material can arrive upon the earth in equal abundance from all the directions in space at every time of the year; and whether the plane of the ecliptic and the direction of the radius vector do not produce an appreciable effect on the distribution of the motions of the meteors. Then we should be able, relying upon the connection of the shooting stars and comets, to find some explanation from the examination of the distribution of the orbits of the comets about the sun. But the true law of such distribution can not be derived from the catalog of comets observed, for different reasons. First of all, our place of observation moves in the plane of the ecliptic, and that augments the facility of discovery and observation of the comets that come closest to the orbit of the earth, and which have a small inclination with that plane. In the second place those comets, the axis of whose orbit is almost perpendicular to the plane of the ecliptic, pass perihelion in points of space that often are visible only to the observers of the southern hemisphere; this is another cause of apparent grouping together of the orbits of the comets with respect to the plane of the ecliptic. Finally the comets of short periods, the greater number of which have orbits inclined very little with respect to the plane of the ecliptic,[1] are, because of their frequent appearance, much more likely to be discovered than others; hence their number, although to judge from the probabilities it ought to be extremely small in comparison to the multitude of other comets, forms a rather considerable fraction of the total number of comets observed.[2] For all these reasons the orbits of the comets should seem more dense toward the plane of the ecliptic than about the

1. Because the comets of small inclination can approach the great planets much oftener and undergo noticeable modifications in their orbits.

2. Of 222 comets, observed from 1456 to 1866, fourteen have periods less than 100 years.

poles of this plane. That this is true we see from the following table, which gives the distribution of the inclinations as we actually observe them, and those which ought to exist according to the hypothesis of the uniform distribution about the sun.

Interval of the Inclination	Number of comets observed	Number calculated according to uniform distribution
0° - 10°	16	3.4
10 - 20	16	10.0
20 - 30	19	16.3
30 - 40	23	22.2
40 - 50	35	27.4
50 - 60	32	31.7
60 - 70	26	35.1
70 - 80	28	37.4
80 - 90	27	38.5

The comets here considered are 222 in number, observed from 1456 to 1866 inclusive; the computation is made from the catalog of Galle, reproduced recently by Littrow.[1] Having in mind all the circumstances just indicated, we see that the comparison of these numbers leaves small doubt of the perfect indifference of the comets with respect to the plane of the ecliptic. That is even a natural consequence of the origin of the comets, which everything leads us to regard as foreign to that of the planetary system.

41. I shall not prolong this digression on the arrangement of the orbits of comets, which are those described by the shooting stars. Those who concerned themselves therewith were not able to find any obvious law, or if some norm was proposed, it was not accepted by the universal consensus of the astronomers. This is enough to persuade us that, if some vagary exists from a casual distribution of the orbits, this is not so great or so plain as to modify in an essential manner the conclusions drawn from the hypothesis that the orbits of the comets (and consequently also of the meteors) follow indifferently all the possible directions about the sun without regard to any circle or any particular point of the celestial sphere.

V
MOTION OF THE METEORS RELATIVE TO THE EARTH

42. *Directions of the relative movement.* We have another way of throwing some light upon the thorny question that confronts us. Let us admit for a moment that from the surface of the sphere ASS′ (Fig. 3) See paragraph 29, meteoric currents depart in great number and with uniform distribution, and, with equal velocity, fall on O. When the observer is in movement, the direction of the relative motion is

1. *Die Wunder des Himmels*, 5th edition.

such that they fall, not upon O, but upon B (paragraph 29). It is easy to see in this case that the number of radiants seen from B, above the horizon GF, is to the total number of radiants as the segment GDF is to all the sphere. In other words, we have for the number of visible radiants the proportion expressed by the formula $F = 1 + (V/v) \sin \phi$, ϕ being the altitude of the apex above the horizon.

When $\phi + 90°$, we see above the horizon many more than half the radiants. The points are abundant about the apex, and rare in the point opposite in the sky; and this holds for every night in the same way. If, however, we observe all the radiants of the two hemispheres throughout all the seasons, the number of those whose distance from the apex is less than 90° ought to exceed by far half of the total number.[1] But we are very far from knowing all the radiants. The southern hemisphere of the sky is practically unexplored. Besides, the catalog of the radiants of the northern hemisphere is itself almost entirely based upon observations in the evening, since observations in the morning hours have not been made diligently. Now the culmination of the point opposite to the apex occurs in the evening, the apex itself culminates in the morning. From this combination of circumstances arises the fact that the radiant points closest to the anti-apex have been more completely determined than the radiant points near the apex. We must add to this the absolute impossibility of examining those radiants that are near to the sun, or set during the evening twilight, or rise during the dawn. From all these inconveniences we can be sure that the study of the radiants in the two hemispheres demands the cooperation of many observers determined not to spare labor; we will never have a complete catalog of these radiants, because the sun hinders the determination over a region that is not less than a quarter of the sky, as we shall now see.

43. Nevertheless, it seems to me worth while to examine the position of the radiant points already known, referring to the apex considered as the fundamental point. For such, I have chosen as a base the catalog of Greg. In the first column of the accompanying table is given the ordinal number of the fifty-six meteoric showers contained in this catalog. In the second is given the duration of each shower; and in the third the longitude of the apex for the median epoch of each meteoric shower. In the fourth and in the fifth the right ascension and the declination of each radiant is given; and in the sixth and the seventh, the corresponding longitude and the latitude.[2] Finally, in the eighth the longitude of each radiant, not counted from the equinoxes, but from the position of the apex considered as fixed is given. The numbers of the eighth column are the differences between the numbers of the sixth and third. The seventh and the eighth, then, contain the coordinates of the radiants referred to the ecliptic, and to the apex as the origin of the longitudes.

1. Ought to be more than 4/5 of the total number.

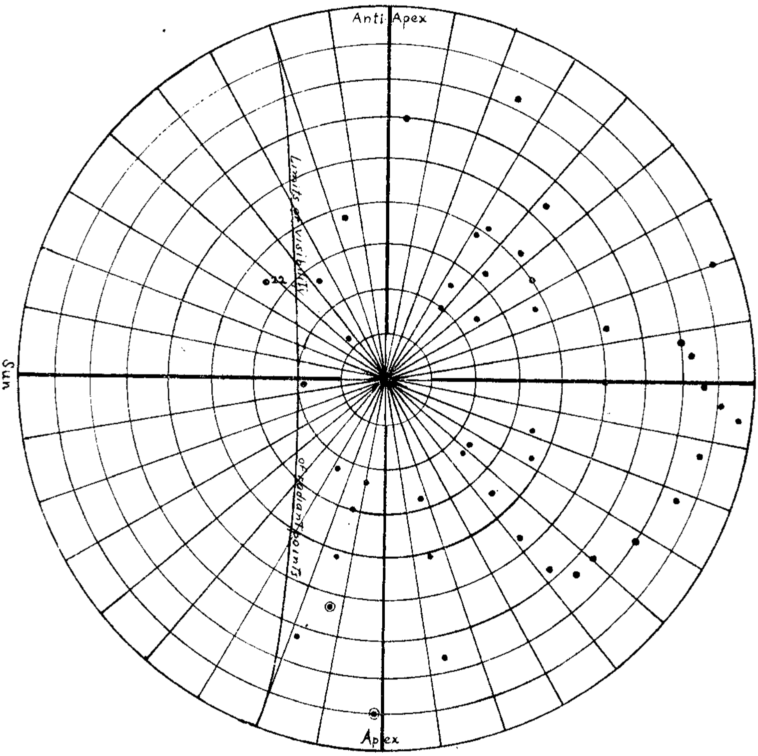
2. For this conversion of coordinates I have used the doubly reticulated star charts of Flamsteed, which are sufficiently exact for our purpose.

	Duration and date of meteoric shower		Long. of apex = a	Coordinates of radiant point		Longi. L	Lat. B	Long. of Apex L — a
				R. A.	Decl.			
1	Dec. 20......	Jan. 30.........	200°	22°	75°	63°	57°	—137°
2	Dec. 20......	Jan. 30.........	200°	5°	85°	78°	65°	—122°
3	Dec. 21......	Feb. 4.........	203°	68°	17°	68°	—5°	—135°
4	Jan. 2........	Jan. 3..........	193°	234°	51°	203°	67°	+ 10°
5	Jan. 2........	Feb. 4.........	209°	133°	40°	124°	22°	—85°
6	Jan. 5........	Jan. 25.........	205°	173°	32°	160°	27°	—45°
7	Feb. 4.......	Feb. 26.........	236°	147°	34°	138°	20°	—98°
8	Feb. 7.......	Feb. 26.........	238°	136°	70°	113°	50°	—125°
9	Feb. 9.......	Feb. 17.........	234°	76°	40°	79°	17°	—155°
10	Feb. 10......	March 17.......	249°	168°	9°	165°	4°	—84°
11	Feb. 11......	March 16.......	249°	37°	1°	35°	—13°	+146°
12	Feb. 19......	Feb. 26.........	244°	220°	84°	103°	70°	—141°
13	March 3......	March 27.......	264°	44°	72°	69°	52°	+165°
14	March 3......	March 31.......	266°	145°	67°	119°	49°	—147°
15	March 3......	March 31.......	266°	186°	58°	151°	53°	—115°
16	March 12.....	March 20.......	265°	223°	39°	202°	52°	—63°
17	April 1.......	June 2.........	312°	194°	52°	163°	51°	—149°
18	April 2.......	May 1..........	297°	189°	4°	187°	7°	—110°
19	April 8.......	May 28.........	313°	227°	—8°	227°	9°	—86°
20	April 12......	April 13.........	293°	276°	26°	278°	49°	—15°
21	April 16......	May 3..........	305°	96°	87°	91°	64°	+146°
22	April 19......	April 20.........	300°	282°	33°	287°	56°	+129°
23	April 25......	June 4.........	324°	255°	48°	240°	70°	—84°
24	April 30......	June 4.........	327°	243°	20°	237°	40°	—90°
25	May 9.......	June 3.........	331°	277°	42°	282°	66°	—49°
26	May 9.......	June 4.........	331°	286°	21°	290°	43°	—41°
27	May 29......	June 17.........	347°	336°	45°	2°	49°	+15°
28	June 1.......	June 30.........	355°	236°	30°	223°	48°	—132°
29	June 1.......	June 30.........	355°	300°	85°	82°	71°	+87°
30	July 2........	July 24.........	21°	302°	48°	328°	66°	—53°
31	July 10.......	Aug. 6.........	31°	257°	13°	254°	36°	—137°
32	July 20.......	Aug. 4.........	35°	359°	70°	48°	60°	+13°
33	July 22.......	Aug. 10........	39°	335.5°	11°	341°	20°	—58°
34	July 29.......	Aug. 22........	47°	296°	48°	318°	68°	—89°
35	Aug. 6.......	Sept. 10........	61°	0°	90°	90°	67°	+29°

	Duration and date of meteoric shower		Long. of apex = α	Coordinates of radiant point: R. A.	Decl.	Longi. L	Lat. B	Long. of Apex L — α
36	Aug. 7........	Aug. 16........	47°	44°	56°	60°	37°	+13°
37	Aug. 17......	Sept. 12........	67°	253.5°	8.5°	251°	30°	—176°
38	Aug. 17......	Sept. 30........	75°	282°	42°	290°	65°	—145°
39	Aug. 17......	Sept. 30........	75°	332°	50°	4°	55°	—71°
40	Aug. 18......	Sept. 29........	75°	13°	34°	25°	26°	—50°
41	Aug. 22......	Nov. 5..........	96°	1°	15°	7°	13°	—89°
42	Sept. 6.......	Nov. 23........	112°	22°	—9°	17°	—16°	—95°
43	Sept. 20......	Oct. 11.........	98°	83°	48°	85°	24°	—13°
44	Sept. 25......	Oct. 10.........	100°	51°	84°	82°	62°	—18°
45	Sept. 27......	Nov. 2..........	112°	14°	58°	42°	47°	—70°
46	Oct. 3...	Oct. 20.........	109°	140°	45°	128°	28°	+19°
47	Oct. 4........	Nov. 10........	120°	45°	33°	52°	15°	—68°
48	Oct. 18.......	Nov. 3..........	123°	83°	12°	83°	—11°	—50°
49	Oct. 20.......	Nov. 21........	133°	91°	56°	91°	32°	—42°
50	Oct. 31.......	Dec. 9..........	148°	139°	7°	139°	—8°	—9°
51	Nov. 1.......	Nov. 23........	140°	16°	49°	37°	38°	—103°
52	Nov. 7.......	Nov. 15........	142°	149°	23°	143°	10°	+1°
53	Nov. 23......	Dec. 9.........	159°	279°	56°	297°	78°	+138°
54	Nov. 24......	Dec. 10........	160°	59°	38°	65°	17°	—95°
55	Nov. 26......	Dec. 30........	171°	96°	36°	94°	12°	—77°
56	Nov. 27......	Dec. 19........	166°	157°	71°	122°	55°	—44°

44. Taking for coordinates of the radiants the numbers of the last two columns I have drawn those north of the ecliptic on the planisphere that forms Plate 1. The central point is the north pole of the ecliptic; on the external circle that represents the ecliptic itself is represented at the bottom the apex, which is origin of the longtitudes. At the top is the opposite point, the anti-apex; at longitude +90° to the left is the sun (whose elongation from the apex is assumed constant and equal to a right angle); in longitude of –90° to the right is the point opposite the sun. The projection adopted is that of right is the point opposite the sun. The projection adopted is that of Lorgna, which representing correctly the ratio of the areas, permits us to judge where the radiants are most dense, and where most rare; which is not possible in the stereographic projection. A glance at this paper reveals a great void near the sun, a result of the impossibility of determining the radiants that are near the sun, or too near to the twilight. Tracing on the projection the curve which represents the circle of points distant 70° from the sun, we see that in the space or segment of that circle including the sun, there falls only one radiant,

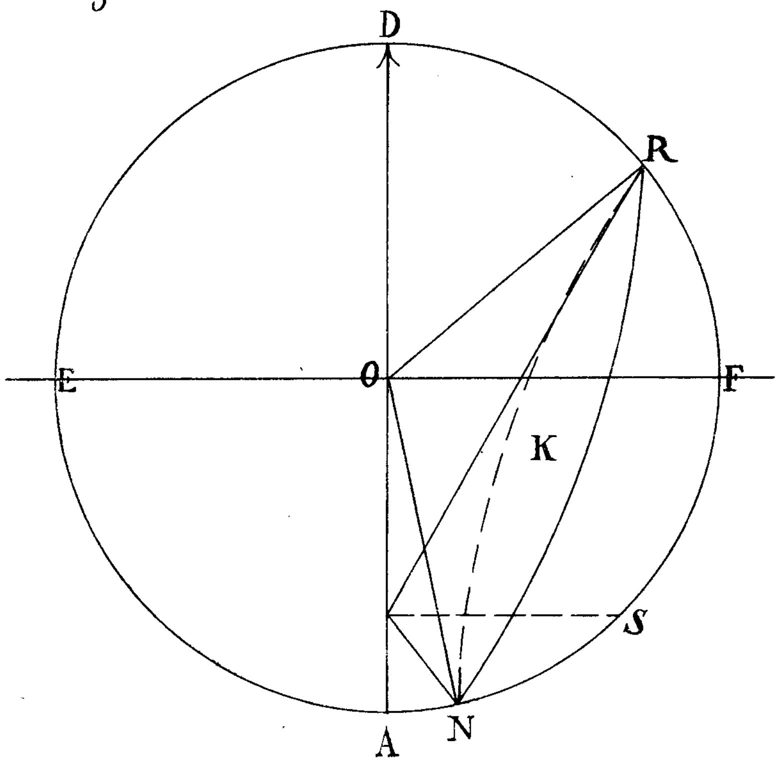
PLATE I



No. 22, which corresponds to the well known shower of August 19 and 20. Therefore, we have designated on the map the afore-mentioned circle as the limit of visibility of the radiants. In the circle whose points are distant from the sun 60°, there does not fall any radiant; hence we see that in our latitudes the sun occults 1/4 of the sky for this type of observation. All the meteoric showers, then, which have a relative motion inclined less than 60° to the radius vector, are to be regarded as not observable by us, although it is not impossible that some may be observed in the equatorial regions where the twilight is shorter, so that in time we may decrease the area of that empty space that surrounds the sun in our drawing.

45. A singular consequence of this fact is indicated in the following. In figure 4, AED is the sphere indicated in figure 3, see paragraph 29, OB the velocity of the earth, and $OA = OB\sqrt{2}$, that of the meteor streams supposed to fall in all directions from the surface of the sphere on O. The relative motion of all meteors is represented by the fall of the same streams from the surface of the sphere on B (para-

Fig 4



graph 29); BD designates the direction of the apex; BS the direction of the radius vector of the earth perpendicular (or almost so) to BD. Imagine that the line BR making an angle of 60° with BS, turns about BS, describing a cone RBN. This cone cuts the surface of the sphere along a curve RN, that intercepts on the sphere an oval space RSNK. It is obvious that all the meteoric streams, of which the relative motion lies on a line within the cone RBN, are concealed by the solar twilight (see paragraph 44). If now we describe another conic surface, which has its vertex at O, and for its directrix the curve RN, it is obvious that the meteoric streams whose motion is within the cone RON will be hidden by the twilight. And if the streams do not follow any particular law in their path about O, it will follow that the number of the streams hidden is to the total number of streams as the surface of the oval curve RNSK is to the surface of the sphere. But if this sphere is divided by the plane EF perpendicular to DA, into two hemispheres EDF and EAF, the first contains the directions of the retrograde streams, the second those of the direct streams. We see that the area of the said oval falls rather more in the second hemisphere than in the first. Hence we have this proposition, that the solar twilight hides

from us almost exclusively meteoric showers endowed with direct motion. And other things being equal, among visible meteoric showers, those which are produced by retrograde streams ought to prevail in number.

46. Returning to our map of the radiants, the hemisphere there represented is divided in two parts by a circle of latitude passing through the sun and prolonged toward the point opposite the sun. Of these two parts, or spherical quadrants, that which contains the apex ought to be (referring to the reasoning of paragraph 42) at least 5 or 6 times more abundant in radiants than the other quadrant. Actual enumeration gives for the first quadrant 31 points of radiance, for the second 20. We see that the preponderance of the first quadrant is far from that which theory demands in the hypothesis of uniform distribution of absolute movements. The principal cause of this is the circumstance that the radiants of the second quadrant culminate in the evening, and thus in the best observed part of the night. There is some condensation about the pole of the ecliptic due to the fact that the radiants of great declination are observable all the year, while those that are near to the equator and to the ecliptic are conveniently observed only during a part of the year. Finally, the greater rarity of the radiants about the ecliptic can be partly caused by the obliquity of the ecliptic itself, of which the southern half culminates rather low, where the shooting stars are not easily seen. No aspect of our map confirms the opinion of Faye, that the orbits of the shooting stars are most abundant about the ecliptic, and give origin to the well known phenomenon of the zodiacal light.[1]

47. We do not have any reason to suppose that the absolute motion of the shooting stars is more in one direction than another; nor does any trace appear of the greater abundance of their orbits about one plane than about another. Hence, it is permissable to develope more rigorously with calculations the theoretical explanation of the diurnal, annual, and direction variation given by us in the rough form in paragraphs 31, 36. A. Herschel, Newton, and I have done this, taking as fundamental the hypothesis of uniform distribution of directions.[2] Examining the problem more minutely, however, we find that, for such a calculation to represent satisfactorily the workings of nature, one must keep count of various circumstances, some of which are very difficult to reduce to numerical proportions. Besides the variable position of the apex along the ecliptic, an effect which can be expressed without difficulty in formulas, one needs to consider: (1) The varying visibility of the shooting stars according to the inclination of the path to the line of sight; (2) the different abundance with which the meteors radiate according to the zenith distance of a point of the celestial sphere; (3) the curving which the attraction of the earth produces in the path de-

1. *Comptes Rendus*, Vol. LXIV, p. 549 and following.

2. I was led to the cometary hypothesis of meteors by such a calculation (see my first *Letter to Father Secchi*). Faye has, however, rightly observed that there are too many difficulties to obtain in these calculations the rigor that is necessary for making them a basis for further research.

scribed by the meteor,[1] by virtue of which their radiant can be noticeably displaced in the sky; (4) the difference in relative velocities with which the meteors fall upon the earth, differences that can greatly change the abundance of their fall; (5) the greater or less inclination of the meteor orbits with respect to the direction of the apex, which causes the earth to take a longer or shorter time to traverse streams of equal density and size; (6) finally, the different conditions of visibility that arise from more or less rapid combustion of the meteors entering the atmosphere with different relative velocities.

48. Since the distribution according to their diurnal and annual variation and according to the direction on the horizon can be considered as fundamental laws for the study of meteors, it is very important to attempt to derive some results by calculation, as did the authors cited in the preceeding paragraph. We know now where the shooting stars come from; and the nature of their paths in space is not unknown to us. The progress of this investigation depends upon diligent observations of meteoric showers and of their radiants. The periodic variation (especially the direction) becomes a secondary object. We shall be satisfied if these variations do not contradict other facts obtained in this investigation, and that in the cosmic theory we have a very simple and natural explanation. We shall not, then, waste our effort in reducing to exact calculations a class of phenomena, the effect of which we shall never be able to estimate except with much approximation. The time of referring meteors to the zenith and to the cardinal points is past; they are astronomical bodies, and we must record the observations by coordinates of the moving celestial sphere. But the examination of some of the circumstances, mentioned in paragraph 47, accompanying the fall of meteors upon the earth, is of great importance, and full of consequences, for the present study. We do not hesitate to undertake the examination, even without the preciseness that tion.

49. *Falling velocity.* In figure 3, (see paragraph 29) v = OS, the absolute velocity of a meteor; OB = V the velocity with which the earth moves from A toward D; the relative velocity of the two bodies is SB; and the angle of apparent direction of the fall, with the line prolonged to the apex, is DBS. We then see the radiant in the direction BS; hence the angle DBS is designated as "elongation of the radiant from the apex." We can regard V and v as constant, and since generally the ratio $v/V = \sqrt{2}$ very nearly, (paragraph 36), the relative velocity BS designated by u is simply a function of the elongation DBS. The maximum relative velocity is to the minimum as $(\sqrt{2} + 1) : (\sqrt{2} - 1)$, or as 5.82:1. It is easy from the solution of the triangle OSB, to calculate the relative velocity corresponding to any given elongation, when we know the value of the average terrestrial velocity OB. Now can be obtained from a more exact consideration of the periodic varia-

1. This is a curvature which ought not to be confounded with that which takes place in the atmosphere and which we have discussed in paragraphs 10-16.

this, if we adopt 8″.95[1] for the value of the equatorial solar parallax, it is given by

$$V = 29261 \text{ meters}$$
$$\log V = 4.466287$$

If we neglect the small inequality of the terrestrial velocity and the radius vector, and also the slight divergence of a meteoric orbit from a parabola, there results for the greatest relative velocity 29261 $(1 + \sqrt{2})$ meters = 70642 meters, and for the minimum 29261 $(\sqrt{2} - 1)$ meters = 12120 meters.

50. This relation is very simple when the observer B is isolated in space. But the attraction of the earth accelerates the afll of the meteor. If we consider now only the central falls, that is, those which are directly toward the center of the earth (considered as spherical) the relative motion can still be considered as rectilinear. Indicating by u′ the meteor's velocity at infinity (before the attraction of the earth is appreciable), by g the gravity at the distance r from the center, so that attraction at the distance ρ is gr^2/ρ^2; with W the accelerated velocity at the distance r from the earth's center, we have by the well-known law of kinetic energies the relation

$$W^2 = u'^2 + 2\int_r^{\propto} g \frac{r^2}{\rho^2} . dp = u'^2 + 2gr$$

When the shooting star falls upon the surface of the earth, we can, without sensible error, suppose r equal to the average radius of the earh, or to 6364550 meters;[2] at this distance from the center we have g = 9.80 meters;[3] hence the preceeding relation becomes, when the velocities W and and u′ are expressed in meters:

$$W^2 = u'^2 + 124{,}745{,}180.$$

The number 124,745,180 here expresses how much the square of the relative velocity u′ increases from the earth's attraction. It is obvious that for u′ it is convenient to take the relative velocity of the earth and the meteor at their point of contact, as it would be without the attraction of the earth, and as it would be calculated with the rule designated in the preceding paragraph. That is equivalent to supposing that the acceleration produced by the earth takes place as if the relative motion in the two orbits were rectilinear and uniform; this hypothesis is not far from true, because of the smallness of the sphere in which the effect of the earth's attraction is felt. Letting u be the relative velocity SB, not perturbed, the relative accelerated velocity W can be calculated by

$$W^2 = u^2 + 124{,}745{,}180 \qquad (5)$$

1. The modern value is 8″.80. This makes V=29760, log V=4.473633, V $(1+v^2)$ = 79847; V $(\sqrt{2}$-1) = 12,322. *Translator.*

2. The modern value is r = 6,371,230 meters,
whence $W^2 = u'^2 + 2.(9.80)\ 6{,}371{,}230$
$W^2 = u'^2 + 124{,}876{,}108$
Translator.

3. *H. Resal*: *Traite elementaire de Mecanique Celeste.* Paris, 1865. Let us here assume that the height of the shooting star is negligible in comparison to the earth's radius.

From this formula it is easy to see that the earth's attraction augments all the relative velocities, but the smaller velocities proportionally more than the larger. Thus, the greater relative velocity in the direction of the apex, that was just found to be 70,642 meters becomes 71,520 meters, increasing no more than 878 meters. On the contrary, the minimum velocity that corresponds to the point opposite to the apex, increases from 12,120 meters to 16,482 meters, an increase of 4,362 meters. One effect of the earth's attraction then, is, to diminish the proportion between the maximum and minimum relative velocity. Their ratio of 5.82:1 is reduced in this way to 4.34:1.

51. The velocity with which the meteors fall into the atmosphere can then vary from 16½ to 71½ kilometers per second. This limit is still larger for special cases, if one corrects for the variable velocity of the earth, and for the eccentricity of the orbits of the meteors (that eccentricity in some cases can be noticeably different from unity). This great difference in the velocity of the fall must produce an effect on the appearance of the shooting stars. For equal masses, the kinetic energy of a meteor in the direction of the apex is to the kinetic energy of a meteor in the opposite direction as $(71\frac{1}{2})^2:(16\frac{1}{2})^2$, or as 19:1. Now this energy, which causes the meteoric material in the atmosphere to vanish, is completely destroyed by transformation into heat and into light. We deduce from this that, for equal masses, the first shooting star ought to develop 19 more times more heat than the second, and give rise to a greater production of light. From this fact, then, in general, the meteors that fall from the direction near to the apex ought to be visible in greater numbers and be more brilliant than the meteors falling upon the earth in the opposite direction. We see these circumstances tend to modify the numerical expression of the diurnal variation.

52. But the different speeds of the movements produce a difference in the duration of the luminous phase. Whether the light of the meteor arises from simple friction or in part from chemical combustion, it is certain that its splendor ought to increase with greater intensity and rapidity when the course is more swift, all the other circumstances remaining identical. Let v and v′ be the velocities with which two meteors of identical mass, m, enter the atmosphere; R, R′ the resistance that is encountered in any one instant, in which they cover the element ds of their path in the air. If we suppose the annihilation of their velocity at the end of their course, we ought to have the relation:

$$mv^2 = 2\int R\,ds, \quad mv'^2 = 2\int R'\,ds,$$

The integral being extended from the beginning to end of the path described in the atmosphere. Let us suppose for the moment that the movement is uniform from the beginning to the end of the space s, and that it ceases entirely when the resistances R and R′ (which we suppose constant) have entirely destroyed the force. We have

$$mv^2 = 2Rs, \quad mv'^2 = 2R's.$$

If the resistances R and R′ are proportional to the squares of the velocities v and v′, these two relations give

$$s = s';$$

that is, the two paths comprised between the entry of the meteors into the air and the point of their total destruction have equal lengths, and the duration of the luminous phases is in inverse ratio to the velocity. If the resistances R and R′ increase more rapidly than the square of the velocity (which seems probable), the space described by the more rapid and more luminous meteor is shorter.

53. The result of this tedious calculation is perfectly confirmed by facts. A mass, such as one of the Leonids, entering into the atmosphere at a speed of 70 kilometers per second, is in a short time reduced to vapor by the heat produced by the resistance of the much rarified air of the outer layers. A second mass equal to the first, that enters in the atmosphere with a velocity of 300 meters per second (that is not unusual in artillery projectiles), merely falls untouched to the earth, perhaps somewhat heated, but without any noticeable loss of material during its course. No development of light accompanies the journey. So great is the diversity of phenomena that arises from the various velocities. Between these two extreme cases, we are able to imagine a series of other intermediate cases, since the velocity of the second mass may be augmented to the point that it commences to become red-hot at the end of its course. If the velocity increases to some degree, we have a luminous path in the inferior portion; simultaneously, it passes from a red color to a white color. A greater velocity than the preceding produces a beginning of volatilization; the falling mass would diminish more or less noticeably in weight. As we advance in the scale of velocity, there exists a step at which the mass, exactly at reaching the ground, will be dissipated into vapor. It is then obvious that for velocities still higher, the mass will be completely volatilized at heights more or less great, and this is the case for shooting stars. There is no doubt, then, that the shooting stars describe in the air, before being totally destroyed, a longer path when their velocity is low. And if this velocity could be reduced to a few hundred meters, all the shooting stars would strike the ground.[1]

54. Probably the minimum velocity of the falls, fixed by us at 16½ kilometers, is so high that it produces the complete dissolution of all the shooting stars, meteors, whose weight is below a certain limit. Others are dissipated only on entering into the more dense and more resisting layers of the lower atmosphere; still others are only partially destroyed, and fall to the ground as meteorites. But this limit of size or weight, to exceed which causes the shooting star to become a bolide or a meteorite, is different for velocities greater than 16½ kilometers. Let us suppose two equal masses, one falling with the velocity just given, the other falling with the maximum velocity

1. Except for the case when chemical action takes place even at a low temperature.

of 71½ kilometers. The first can reach the ground slightly changed, although the second may be entirely destroyed by the heat developed by a force 19 times greater (paragraph 51). Then, circumstances being alike, the proportion of meteorites and bolides to shooting stars ought to be greater for meteoric streams that encounter the earth with a lesser relative velocity, and that have radiants very near the anti-apex. The atmosphere takes the rôle of a kind of shield that protects the earth from striking meteors; but this defense is incomparably more effective on the anterior part (turned toward the apex), than the posterior part (turned toward the anti-apex).

55. We have seen (paragraph 19) that the shooting stars are much more numerous in the hours of the night towards morning, and it has been proved that this depends upon the combination of the orbital motion of the earth with the diurnal motion (paragraph 33). We do not have any reason to believe that the same is not true for meteorites, but the presence of the atmosphere ought to render us cautious in drawing conclusions. The region of the sky surrounding the apex, or the meteoric sun, is the most abundant in shooting stars, but at the same time it is there we find very great velocity of fall because of the small elongations from the apex. Conversely, the part of the sky that surrounds the anti-apex has few shooting stars, but the elongation from the apex is near 180°, and the velocity of fall is near the minimum value. Although the frequency of the meteors is greater near the apex, the circumstances that permit them to fall to the earth as meteorites operate most effectively near the opposite point. According to variation of these two influences the diurnal variation of the meteorites can follow that of shooting stars, or not follow, or even degenerate into an opposite law; this last is exactly what has been found true.

56. In the report of the Committee on Meteors of the British Association of 1860,[1] Greg has examined the hourly distribution of the falls of 135 meteorites, and of 62 detonating meteors, of which the last can be considered as demonstrably related to the meteorites. In spite of the paucity of the observations the daily variation is manifested in a clear way, as can be seen from the following table, transcribed from page 117 of the report just cited:

Hour of astronomical time (measured from noon)	Fall of meteorites	Detonating meteors	Sum
0 hr.— 1 hr.	7	1	8
1 hr.— 2 hr.	6	1	7
2 hr.— 3 hr.	11	5	16
3 hr.— 4 hr.	20	2	22
4 hr.— 5 hr.	14	4	18
5 hr.— 6 hr.	14	3	17
6 hr.— 7 hr.	8	4	12
7 hr.— 8 hr.	6	3	9
8 hr.— 9 hr.	10	6	16

1. *A Catalogue of Meteorites and Fireballs*, by R. P. Greg. *Report of the British Association*, 1860, p. 48-120.

9 hr.—10 hr.	4	12	16
10 hr.—11 hr.	0	2	2
11 hr.—12 hr.	2	1	3
12 hr.—13 hr.	0	0	0
13 hr.—14 hr.	0	2	2
14 hr.—15 hr.	2	1	3
15 hr.—16 hr.	0	2	2
16 hr.—17 hr.	0	1	1
17 hr.—18 hr.	1	0	1
18 hr.—19 hr.	3	1	4
19 hr.—20 hr.	3	2	5
20 hr.—21 hr.	7	2	9
21 hr.—22 hr.	7	1	8
22 hr.—23 hr.	4	2	6
23 hr.— 0 hr.	6	4	10

The result, shown in the numbers of the last column, is that the maximum frequency of the meteorites corresponds to 6 P. M., which for the shooting stars is the minimum frequency (paragraph 19); conversely, the minimum number of meteorites corresponds to 5 A. M., which is very close to the hour of maximum for the shooting stars. The law of hourly variation is then exactly reversed; and the difference between maximum and minimum is truly enormous. It seems to prove that of 100 meteorites which the air will let pass when they are falling with the velocity of 16½ kilometers, perhaps not one will finally penetrate to us if it falls from the opposite part of the sky with the velocity of 71½ kilometers. This inversion is seen, but less obviously, in the annual variation of the meteorites, for which Greg has prepared the following table:[1]

Month of the year	Meteorites
January	12
February	13
March	20½
April	20
May	28
June	25
July	28
August	18½
September	17½
October	20
November	21½
December	16

The irregularity of these numbers is due to lack of observations; at any rate the minimum is noticeable in August and September, when the number of shooting stars is a maximum. Besides, we cannot forget that the frequency of the meteorites depends not only on the relative velocity with which the streams encounter the earth, but also on the degree of pulverization of the material in the streams themselves. Perhaps some streams are so finely pulverized as not to produce any meteorites; while other streams might include many bodies

1. Ibid.

so great as to produce a veritable deluge of meteorites. The presence of such exceptional streams can modify in a very essential way the diurnal variation and the annual variation of the meteorites, but the latter much more than the first.

57. After considering the preceding paragraph, no one will wonder that from the very numerous shooting stars of August and November, not even one has reached us; and that the classical reports on these meteoric showers include no references to meteorites. The elongation from the apex of the radiant of the stream of the Perseids is only 38°, and the relative velocity of its fall is 60 km. The radiant of the Leonids is only 10° from the apex; and the relative velocity is 70 km., only slightly below the maximum possible. In such circumstances it is natural to believe that the atmosphere offers an insuperable obstacle to particles in this stream. Only abnormally large pieces could reach us. Thus fall, never to rise again, all the arguments for the assumption that meteorites (and consequently also the bolides) are in a different class from shooting stars. Those brilliant meteors that during the showers of August and of November plough the sky as rapidly as thunderbolts, and develop much light in a short time so as to produce the effect of lamps, are masses of the same order of size, and of composition similar to those slow bolides whose irregular motion lets them fall in flames from low heights. When meteors enter into the atmosphere with a velocity more than double the orbital velocity of the earth, the resistance of the highest layers of the atmosphere is enough to kindle and consume them rapidly. If from that height (which seems to vary from 80 to 120 km.) they still display much splendor and illuminate that rare and feebly reflecting mass of air surrounding them with such vivid light, it is easy to comprehend that their lighting effect can be at least equal to that of the most brilliant bolides. And finally we see what a beneficial function is exercised by our atmosphere as a shield against the masses that the heavens send on us; without it we would be continually exposed to frequent blows far more fatal than those of fire arms.

58. I shall now note a rather important consequence of the things discussed up to this point, that provides a means of checking their truth by direct observation. Since the meteors of higher speed kindle more quickly, and are more rapidly consumed, clearly the average height of their path ought to be greater than for the meteors of slower fall. Hence, the higher paths ought to belong in general to those meteoric streams whose radiant is very near to the apex.[1] One group of observations supports this proposition: the average height of 78 meteors observed in America, November 13, 1863, exceeds by 15 or 20 miles the ordinary height of the meteors. Further, Newton has concluded that the meteoric showers of November are composed of material more easily destructable, or more easily inflamable, than the bodies of the meteorites.[2] Newton's hypothesis is not really necessary, in

1. We observe that this fact influences the visibility of the meteor and its diurnal variation.

2. American Journal of Science, Vol. XL, p. 252.

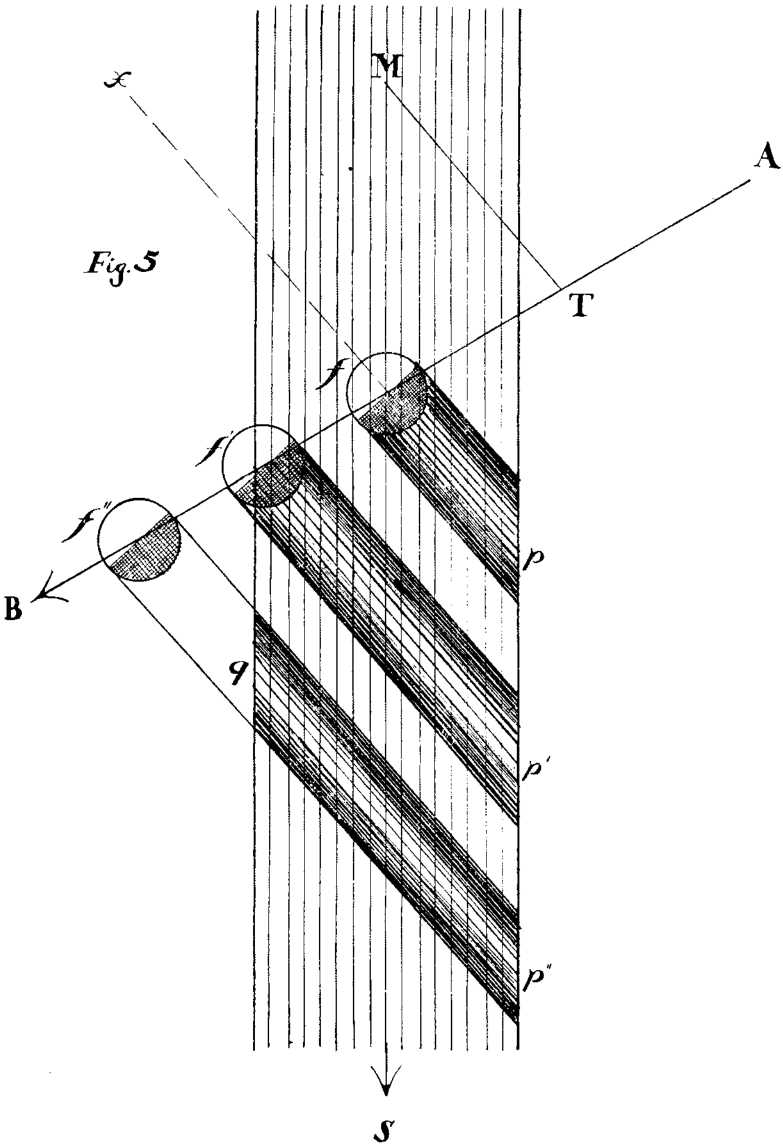
our opinion, to explain the fact. Among all known showers the Leonids are those which fall with the greatest velocity, and those whose radiant is nearest to the apex. It is no wonder then, that the combustion and dissolution of those meteors occurs more rapidly, and in the more rarified layers of the air. It is possible that from meteor to meteor, and from stream to stream, there are chemical differences whose influence should not be neglected in the study of the phenomena that accompany the conflagration; but what we know up to now on this point can be termed nothing.

VI

EFFECT OF THE EARTH'S ATTRACTION ON THE FALL OF METEORS

59. *Encounter of a meteoric stream by the earth.* In figure 5, let us represent by the dotted lines a meteoric stream moving directly along the arrow MS. AB is the path of the earth, whose movement is indicated by an arrow. The velocity of the earth is tT, the velocity of the meteors is Mt, the direction of the relative motion and the radiant is TM. When the earth is at t, it receives the meteor shower as if it had come from the direction tx, and in the opposite direction tp, there remains an empty cylinder, with diameter equal to that of the earth. When the earth arrives at t′, the empty cylinder will be extended to t′p′. When the earth leaves the stream, the empty cylinder travels with the meteor stream, and when the earth reaches t″, it is qp″. It will continue to advance until the small differences in the velocities of the meteors and other circumstances have deformed it and broken it up. The terrestrial observer sees the greatest number of meteors fall, when the radiant point, or the direction tx, is found at his zenith. When the radiant point is far from the zenith, it is easy to see that the number of the meteors is proportional to the cosine of the distance of the radiant from the zenith. From this we conclude: that every meteoric shower is subject (for an observer) to a daily variation, the maximum frequency taking place when the radiant point culminates on the upper meridian. When the radiant point is below the horizon, the meteoric shower ceases entirely. For the great showers of August and of November the radiants culminate in the hours of the morning; hence, there is an increase in these showers from midnight to morning, a circumstance that frequently has been confused with the increase produced by the diurnal variation, of which the cause is entirely different. The diurnal variation reaches its maximum when the apex culminates, since then the greatest possible number of radiants is above the horizon. But for a given radiant the maximum occurs at the time of its culmination, which can be at any hour of the twenty-four.

60. Let a be the diameter of the stream; the length of the empty cylinder qp″ is equal to a multiplied by the cosecant of the angle, tMT, that the axis of the cylinder makes with the direction MS of the



stream. If the diameter of the cylinder remains the same, the volume of the empty cylinder, or the number of shooting stars received by the earth will be greater when the angle tMT is very small. Because of this, one sees that the streams arriving in the direction of the apex and those that arrive in the opposite direction will be damaged most by the earth. The minimum damage will be that done to a stream that has its radiant 90° from the apex. This circumstance is one of many that influence the diurnal variation of the shooting stars, producing greater numbers of meteors near the apex and the anti-apex than in the intermediate points.

61. *The effect of the earth's attraction on the fall meteoric showers.* The earth's attraction changes the course of the meteors in the last hours of their cosmic existence, curving their orbits diversely and modifying somewhat the preceding conclusions, which suppose rectilinear and parallel the lines described by the elements of the stream at the instant of their fall. Since the effect of the earth's attraction beyond the sphere of the moon does not produce on the course of the meteors any noticeable change, and since for distances equal to that of the moon the course of the earth and the meteors in space can be regarded as rectilinear, we refer the movement of the meteor to the center of the earth, totally neglecting the perturbations due to the sun, which everyone will allow us to do. Let us suppose, then, the earth stationary, and attribute the relative motion to the meteor; this motion will be a conic section having the center of the earth at the focus; the plane of this orbit will pass through the center just mentioned, and through the line that represents the direction and the position of the relative motion that would take place if the earth did not exercise any attraction. It is evident that if the meteor comes to us from celestial space, the orbit is necessarily a hyperbola, and not a closed curve. The asymptote that approaches the anterior branch of the hyperbola,[1] is the direction of the relative motion at infinity; it can be thought of as the line that the meteor would have passed along relative to the earth, if the attraction of our planet did not exist.

62. Since the plane of the hyperbola passes through the center of the earth, considered as spherical, that plane is vertical for an observer located at the point where the shooting star terminates its course. The curving of the path due to the earth's attraction then must take place in a vertical plane through this observer.[2] Since the path is necessarily concave toward the center of the earth, the tangent observed by the observer, which determines the radiant for him, makes with the vertical an angle less than the parts of the meteor path described outside the atmosphere. If O is the center of the earth (figure 6), AB, the direction of the stream before being perturbed, indicates the true position of the radiant in the sky. A meteor that falls along AB directly toward the center of the earth, will not suffer any change in direction, but only in velocity. On the contrary, a meteor that describes the line QD parallel to AB, is, instead, deviated so as to follow the hyperbola SMF, of which O is the focus, and QD the asymptote to the anterior branch. It will meet the earth at M; the observer sees it come in the direction MV, while in reality the true direction was MN parallel to AB. The radiant is then seen nearer the vertical MZ by the angle NMV, that we shall now try to determine.

1. This is the branch of the hyperbola that is described by the meteor before its perigee.
2. We suppose that the place of the observer coincides with the groundpoint. The error in this supposition is always negligible.

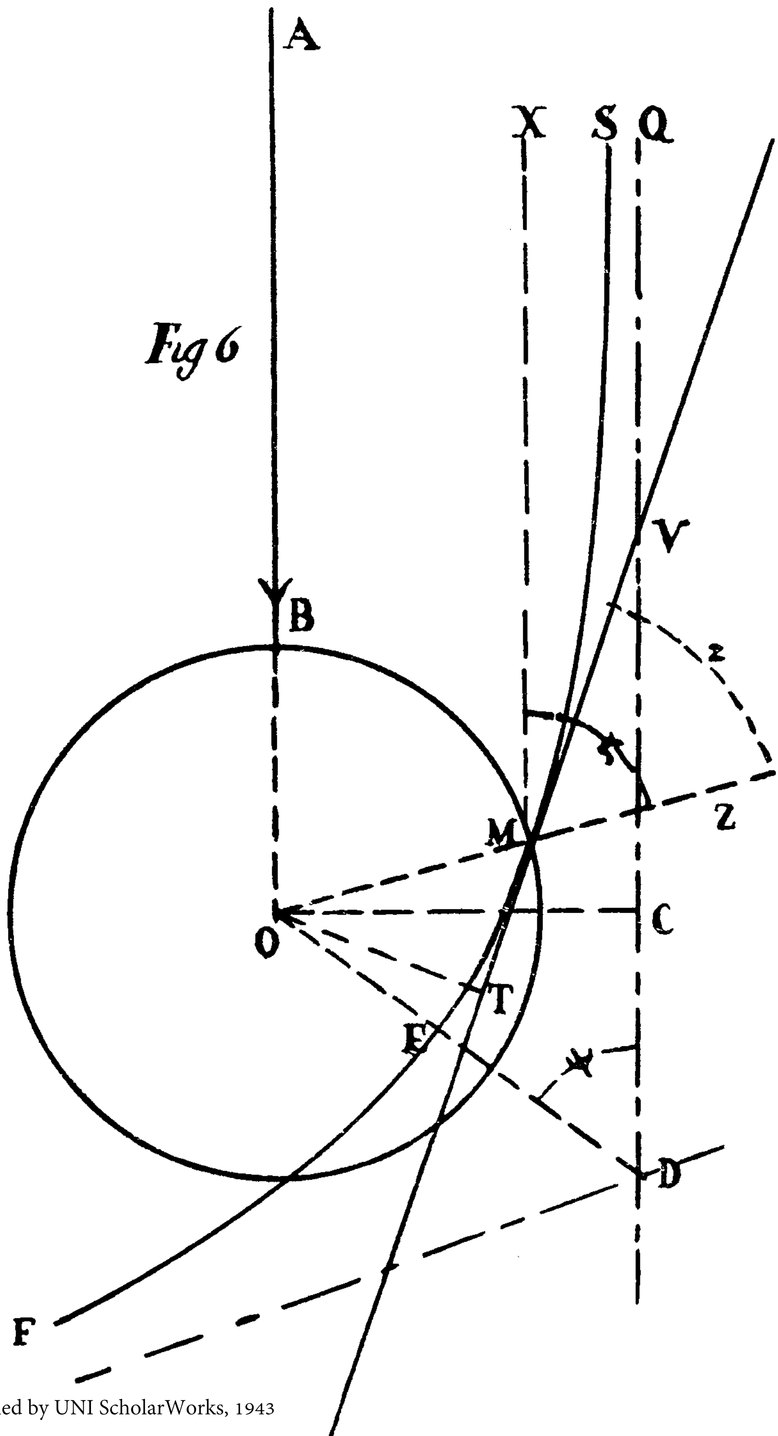


Fig 6
A
X
S
Q
V
B
z
M
Z
O
C
T
E
D
F

Proceedings of the Iowa Academy of Science, Vol. 50 [1943], No. 1, Art. 6

63. Let r be the distance of the point M from the center of the earth, g the gravity corresponding to this distance, u the relative undisturbed velocity, and w the velocity accelerated at M; we have here as in paragraph 50:

$$w^2 = u^2 + 2gr \qquad (6)$$

where $2gr = 124{,}745{,}180$, if the assumed units are the meter, and the second of time. The area described in a second by the meteor about O, when falling, is equal to $\frac{w \,.\, OT}{2}$, where OT is the perpendicular from O upon the tangent TV. Let z be the apparent distance of the radiant point, then $VMZ = OMT = z$, and thus $OT = OM \sin z = r \sin z$. Thus the area described in a second, by a body arriving at M will be $\frac{wr \sin z.}{2}$ With this area it is easy, using known theorems, to deduce the elements of the hyperbola.

The semi-axis DO is given by

$$a = g.r^2 \,/\, u^2 \,. \qquad (7)$$

The parameter is:

$$a\ (e^2 - 1) = \frac{w^2}{g} .\sin^2 z, \qquad (8)$$

ψ = angle ODQ, between the asymptote and the real axis, is given by

$$\tan \psi = \frac{uw}{gr} \sin z, \qquad (9)$$

and we have also

$$\cos \psi = 1/e \quad ; \qquad (10)$$

The distance $CO = s$, of the asymptote from the center of the earth, is

$$s = r \frac{w}{u} \sin z. \qquad (11)$$

The true zenith distance of the radiant point, that we now desire, is NMZ, indictaed by ζ. We have from the figure

$$MOB = \zeta,\ DOB = \zeta + MOD = 180^\circ - \psi,$$

then

$$\zeta = 180^\circ - \psi - MOD. \qquad (12)$$

We know ψ, let us denote by π the amount MOD is deviated from the point M on the hyperbola, and we have:

$$r = \frac{a\ (e^2\ -\ 1)}{1 + e \cos \pi} \;;$$

substituting for e and $a(e^2 - 1)$ their value taken from (8) and (10) we obtain:

$$\cos \pi = \cos \psi \left\{ \frac{w^2 \sin^2 z}{gr} - 1 \right\} . \qquad (13)$$

So from (12) we calculate $\zeta = 180^\circ - \psi - \pi$, where ψ and π are obtained from (9) and (13). More simple is the system of the equations when substituting for ψ and π their complements $\psi' = 90^\circ - \psi$, and $\pi' = 90^\circ - \pi$. We then determine ψ' and π' from the formulas

$$\cot \psi' = \frac{uw}{gr} \sin z\ ,$$

$$\sin \pi' = \sin \psi' \frac{w^2 \sin^2 z}{gr} - 1 \qquad (14)$$

we have $\zeta = \psi' + \pi'$

Such is the calculation through which, from the observed position of the radiant points of the meteors of November, 1866. For Greenwich the earth's attraction. In the theoretical calculations that concern the orbit of the shooting stars it is evidently necessary to use this last position, and not the first. But to be able to reach this corrected value of the zenith distance of the radiant, it is necessary to know beforehand the relative undisturbed velocity u, and hence the orbit of the meteoric stream in space. However, an approximate knowledge of this orbit is sufficient.

64. For example, let us select the observation made in England of the radiant points of the stars of November, 1866. For Greenwich the maximum of the appearance, which we suppose to correspond to the instant of determination of the radiant, took place November 14 at 13^h12 of mean time[1]; in that moment the zenith distance of the radiant point determined was 64° 45′.3, and this is the value of z. From the orbit of the meteors, which is already known,[2] I deduced the relative undisturbed velocity $u = 69{,}363$ meters per second; whence from formula (6), the real velocity of the fall $w = 70{,}257$ meters. Using for gr the value 62,372,590 (see preceding paragraph), there results from the calculation of (14)

$$\psi' = 0°\ 48'.6,\ \pi' = 64°\ 8',\ \zeta = 64°\ 56'.8\ ;$$

where the value of ζ exceeds z by only 11′.5. That is the amount by which the earth's attraction has caused the radiant point to approach the zenith at the time of observation. Hence it results that the observed coordinates of the said point need to carry the correction +8′.4 in R.A. and –8.′5 in declination. Such a small quantity is much below the limit of accuracy which one can hope to obtain in the determination of the radiant. Similarly, making the calculation for the August meteors, we find that the effect of the earth's attraction upon their radiant point is not noticeable. But the same conclusion does not hold for all the cases, as we shall now see.

65. The angle NMV, which is the difference between the observed zenith distance z of the radiant point and the corrected distance ζ, is the quantity by which the earth's attraction causes the radiant to approach the zenith, and for brevity is designated by *zenith attraction.* If then we consider a definite meteor shower, the quantities u and w are equal for all its elements, whatever be the obliquity with which they encounter the surface of the earth; that obviously results from formula (6). After consideration of (14) it is easy to see that the zenith attraction, for different elements of the same meteoric stream, is a function of z only. This attraction is nothing when $z = 0$, when the meteor falls along the vertical as AB (figure 7); but it increases for the paths A′B′, A″B″, etc., that encounter the earth with greater obliquity, and it reaches the maximum value for the meteor that just touches the surface of the earth, as it describes the curve SMF; in that case evidently $z = 90°$. The zenith attraction operates then on the

1. Mean time denotes astronomical mean time. *Translator.*
2. *Astronomische Nachrichten, No.* 1629.
3. *Bulletino Meteorologico* of Father Secchi, Vol. 6, p. 9.

radiants of the meteoric stream about as refraction on the places of the stars; it is zero at the zenith, it increases from that point to the horizon, where it reaches its maximum value. It is easy to derive from formula (14) or from direct consideration of fig. 7 that, if we let ϕ denote this maximum value, then $\phi = 90° - \psi$. From (9), and using $z = 90°$, one obtains readily

$$\tan \psi = \frac{uw}{gr} , \qquad (15)$$

or, in view of the relation (6) between u, w, and gr, also

$$\tan (1/2)\ \psi = \frac{u}{w} . \qquad (16)$$

66. This shows that the phenomenon of zenith attraction of the radiant points is not identical for all meteoric streams; it operates with maximum intensity on the streams that come from the radiants near the anti- apex; the intensity is a minimum for the streams that come from radiants at the apex itself. In the first case we have seen that (paragraph 49-50); $u = 12{,}120$ meters, $w = 16{,}482$ meters, hence $\phi = 17°20'$; that is, the radiant point seems to rise from the horizon, when it is still to be 17°20′ below. When this radiant point comes to the zenith, the zenith attraction is nothing; we see then that by this effect alone, the radiant, or the center of radiation, while being carried from the horizon to the zenith by the diurnal motion, will seem to move 17°20′ among the stars. This circumstance complicates greatly the already complex appearances that the meteoric showers present. The movement of the radiant can be greater still, if one compares the positions before and after culmination. So, for an observer situated upon the equator, a radiant point of declination zero will describe, in its diurnal motion, the prime vertical; along this, in the interval between the rising and setting, it will pass over an arc of 34°40′ in the stars. Such an effect may be further increased in special circumstances, if, for example, there were streams with orbits of short periods where the motion is direct and parallel to that of the earth.[1]

67. The zenith attraction decreases rapidly, however, with tne removal of the radiant points from the anti-apex. For radiants 90° away from the apex, we have $\phi = 3°58'$; and finally, for those that coincide with the apex, $\phi = 0°\ 42'$. The shifting of the radiant points during the observations is in general much less than the maximum value of ϕ, because the determination of the radiants is not easy, except when the points are elevated considerably above the horizon. Considering these circumstances and remembering the degree of exactness usual for observations of this kind, we believe that, as a general rule, we ought to take account of the displacements due to the zenith attraction for all radiants, whose distance from the apex is more than 90°. Now we

1. Let us assume that we have a direct stream which describes an orbit similar to that of Biela's comet, moving parallel to the earth; if $a = 3.5$ the velocity relative to the earth is only 9,042 meters, and the accelerated velocity with which we see it fall from the point opposite to the apex is $w = 14{,}370$ meters; from this we find the maximum value of the zenith attraction $\phi = 25°38'$. If we imagine as above, that the radiant point is in the celestial equator, and that the observer is on the earth's equator, the displacement of the radiant point between the stars can reach, from rising to setting, 51° 16′, a quantity truly enormous.

understand how important it is to note the hour when the apparent paths of the meteors are represented on the planisphere for use in the determination of the radiants.

68. *Effect of the earth's attraction on the number of shooting stars in the atmosphere.* Considering figure 7, we see that many shooting stars which the earth would not have encountered if they had continued in their rectilinear course are attracted into our atmosphere by gravity. If we imagine that the hyperbola SMF, tangent to the earth, turns about the line OA, it will describe a conoid of revolution. At an infinite distance this coincides with the cylinder that the asmptote QD generates turning about OA. The paths described by the meteors that penetrate into the atmosphere are all contained in the aforesaid conoid, and the radius of the empty cylinder is OC, and it is easy to see that

$$OC = r\ w/u\ ; \qquad (17)$$

Let a be the diameter of the stream, ξ the angle TMt (fig. 5) and V the volume of the empty cylinder. The volume is

$$V = \pi r^2\ (w^2/u^2)\ a \operatorname{cosec} \xi\ ;$$

and since $w^2 = u^2 + 2gr$,

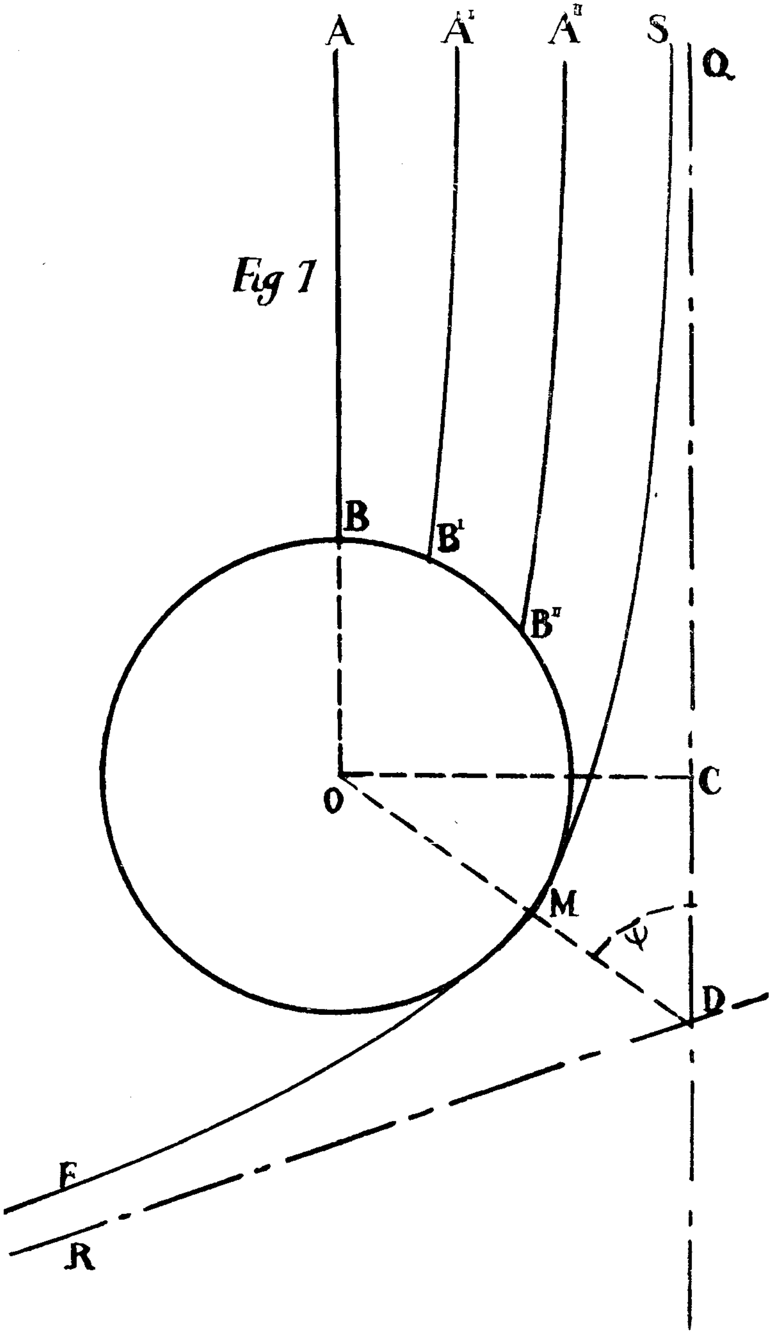
$$V = \pi r^2 a \operatorname{cosec} \xi \left\{ 1 + \frac{2gr}{u^2} \right\} \qquad (18)$$

This formula describes a fact noted for the first time by Newton,[1] that because of the earth's attraction the number of shooting stars is increased in the ratio of $\left\{ 1 + \frac{2gr}{u^2} \right\}$ to 1. This increase is relatively much more noticeable for the streams with a low velocity, than for others. For the streams of maximum velocity, the increase is in the ratio of $\frac{(71520)^2}{(70642)}$: 1, or as 1.025 : 1 ; the number of meteors increases about 1/40 over what it would have been without the attraction of the earth. On the contrary, for the streams that fall with minimum velocity, the increase is in the ration of $\frac{(16482)^2}{(12120)}$; 1 or as 1.849 : 1; the number of shooting stars becomes almost doubled. Moreover, under similar circumstances the number of shooting stars in the direction of the apex is to the number of shooting stars in the direction of the anti-apex as 1.025 : 1.849; that is, as 1 : 1.804, or simply as 5 : 9. This noticeable fact tends to compensate in great part for the effect of the diurnal variation of the meteors, diminishing the disproportion between the frequency of shooting stars in the morning and in the evening.

69. *Diurnal aberration of the radiants.* To complete our consideration of the apparent motion of the radiants, I will give the formula for their diurnal aberration, originating from the rotary motion of the observer about the axis of the earth. This formula is the same as that for the diurnal aberration of the light for the fixed stars.

Let w be the velocity of the fall of a meteoric stream, Omega ω the velocity of the rotary motion of the observer along the parallel of lati-

[1] American Journal of Science, Vol. 39, p. 199.


A
A'
A''
S
Q
Fig 7
B
B'
B''
O
C
M
Ψ
D
F
R

tude, θ the hour angle, and δ the declination of the radiant point at the moment of observation. To correct its apparent position for the diurnal aberration, one adds to its right ascension α and to its declination δ the corrections

$$\left.\begin{aligned} \Delta\alpha &= -\frac{\omega}{w}\,\frac{\cos\theta}{\cos\delta}\,; \\ \Delta\alpha &= -\frac{\omega}{w}\sin\theta\sin\delta\,. \end{aligned}\right\} \qquad (19)$$

The maximum numerical value for $\Delta\alpha \cos\delta$ and for $\Delta\delta$ is ω/w, a quantity that for an observer situated on the equator, and for the minimum value of w ($w = 16{,}482$ meters), is equivalent to 1°37′. For the radiant of the meteors of November 14, 1866, upon the parallel of Greenwich at 13^h12^m of mean time, $\Delta\alpha = -3'.2$ and $\Delta\delta = +5'.4$. It is clear that only in rare cases is it necessary to take account of the diurnal aberration of the radiant points.

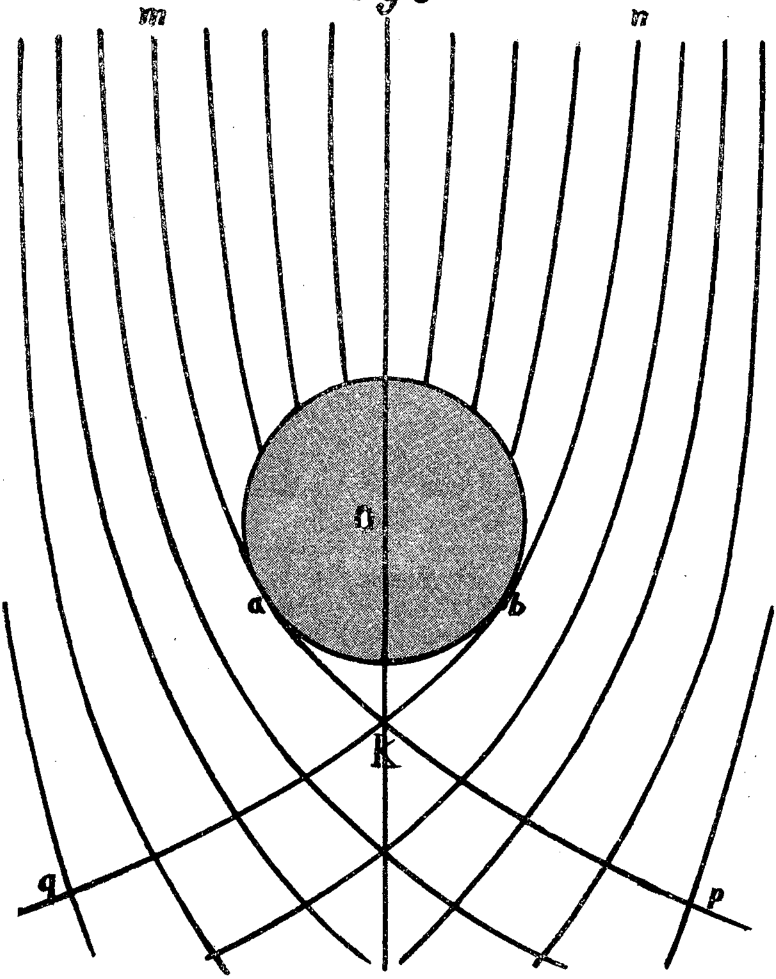
70. The diurnal aberration in question seems weakened, and even almost completely destroyed by the resistance of the atmosphere, when the journey of the meteor lasts a sufficient time, as has been observed (paragraphs 7-8); but considering the brief period that the shooting stars customarily take to run through the atmospheric part of their paths, we are inclined to believe that the effect of the resistance of the air on the diurnal aberration is appreciable and that the application of formula (19) is justified in all cases. Further research on this matter is desirable.

VII

PERTURBATIONS EXERCISED BY THE EARTH OR OTHER PLANETS ON THE COURSE OF METEORS

71. When the earth cuts through a meteor stream, it produces in it an empty space, whose axis lies along the direction opposite to the relative motion (fig. 5). This space is not always empty, because of the attractive force of the earth; it contains shooting stars, but in a smaller quantity than the rest of the stream, and it has a diameter greater than that of the earth. Figure 8 gives an exact idea of what happens. The meteors contained in the conoid mkn, already noted in paragraph 68, are stopped by the earth, and all fall with velocity w; those whose paths form the surface of the conoid, will continue hteir paths along the posterior branch of the hyperbola ap, bq; finally, the meteors that pass close to the earth but remain outside the conoid, describe relative to the earth other hyperbolas with focus at O, and they are more or less deviated from their course. At a distance of several diameters of the earth, that deviation is almost unnoticeable. The earth then, without making a completely empty space in the stream, distributes the meteors along a line which lies in a direction opposite to that of the relative motion (or from the radiant point corrected for zenith attraction and diurnal aberration).

Fig 8



72. A planet at O (fig. 9), of which the mass (taking that of the earth as unity) is μ, exercises at the distance ρ the attraction $\mu gr^2/\rho^2$, where as usual g indicates the earth's gravitational force corresponding to the distance r from the center. If U is the undisturbed relative velocity of a meteor, W the corresponding velocity at the point M, for which OM $= \rho$, we have a relation analogous to (6) in paragraph 63,

$$W^2 = U^2 + 2\mu gr^2/\rho^2 \qquad (20)$$

when M is any point on the hyperbolic orbit. Let us indicate by M the perigee of the meteor,[1] and by ρ the perigee distance, or the closest

1. To avoid neologisms, we call the point of closest approach of the meteor and **the planet** ***perigee;*** **it ought to be the** ***periplaneta.***

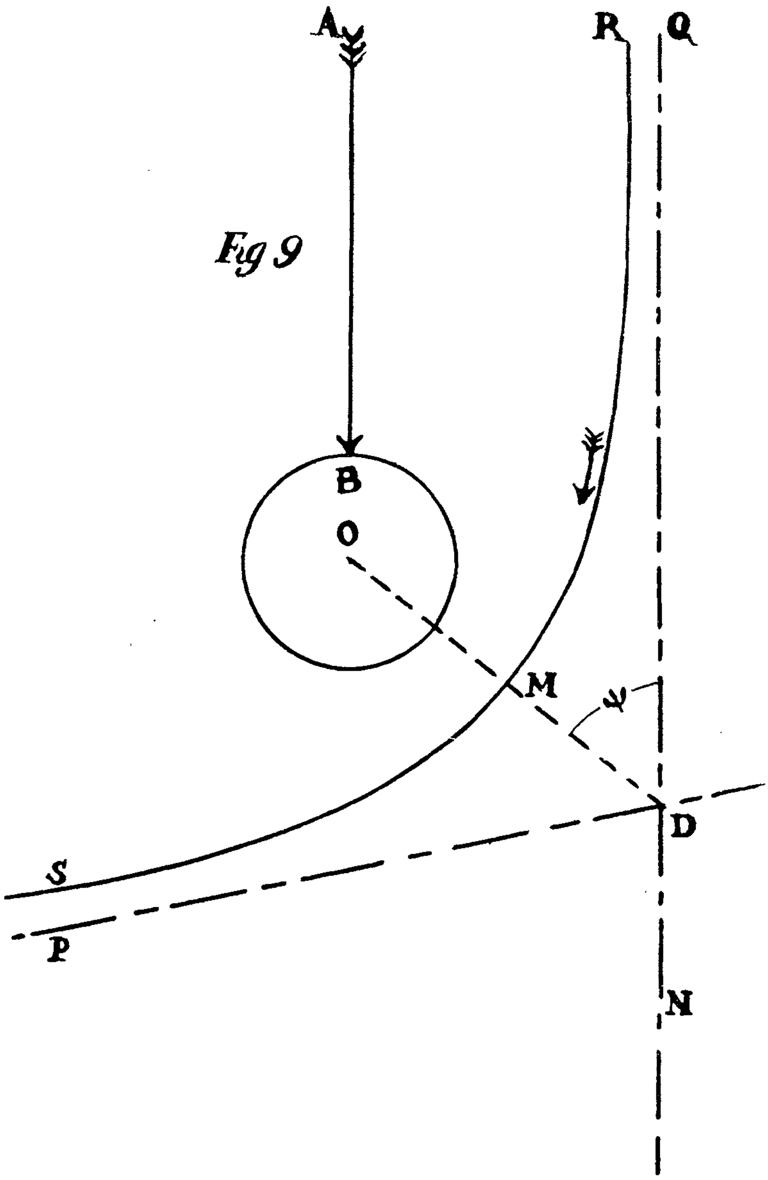


Fig 9

approach, of the two bodies. Equation (20) gives a relation between the perigee distance and the perigee velocity W. If we add the following (paragraph 65),

$$\tan \frac{1}{2} = \eta \frac{U}{W}$$

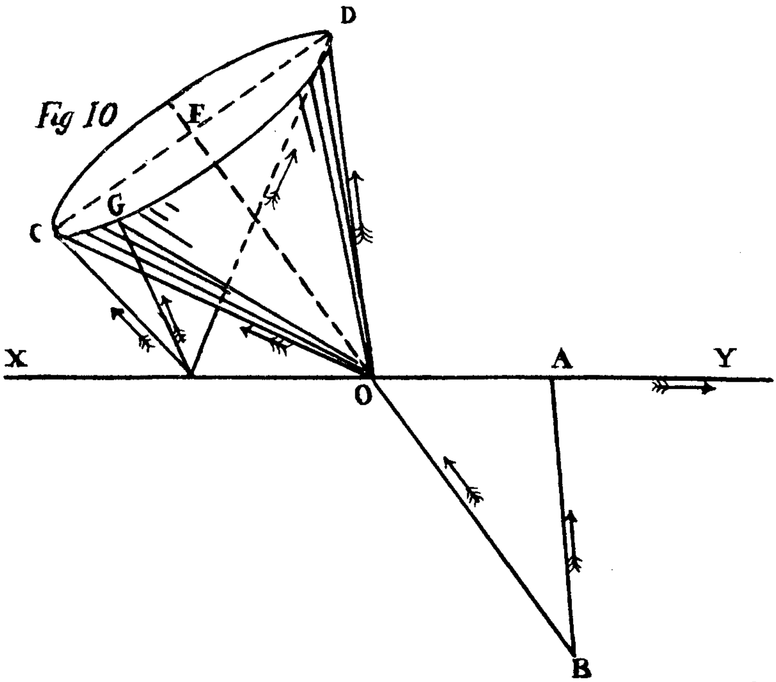
we have a very useful relation between the perigee distance OM and the angle $2\psi =$ QDP between the asymptotes of the hyperbola. The deviation the planet O produces on the direction of the relative motion of the meteor is evidently represented by the angle PDN $= 180° - 2\psi$; hence (20) and (21) give a very simple way to calculate the deviation of the motion when we are given the perigee distance, and to calculate the perigee distance when given the deviation of the motion. This supposes, to be precise, that the branches of the hyperbola are exactly parallel to their asymptotes at the point where the meteor enters the attraction sphere of the planet and where it leaves.[1] This hypothesis is so close to the truth, even when the attraction sphere extends only to some dozens of diameters of any of the planets, that the error is negligible.

73. The hyperbolic motion being symmetrical with respect to the perigee, the relative velocity at the point of entry and at the point of departure of the meteor within and outside the attraction sphere is the same. We suppose further that it is equal to the relative velocity U of the planet and of the meteor, which would take place if the two bodies did not attract each other. Hence, we may conclude that the attraction of a planet that passes very near to a meteor does not result in changing the velocity of their relative movement, but only the direction of this movement. It is easy to see that the changing of direction is greater when the undisturbed relative velocity U is rather small, and when the two bodies will be close to one another at the instant when the meteor passes perigee.

74. The results are very different if we consider the absolute motions (figure 10). Let XY be the orbit described by the planet in space, with a motion that we suppose rectilinear and uniform throughout the time in which the meteor is found within the attraction sphere. Let OA be the velocity of this movement, and BA the direction and amount of the unperturbed velocity of the meteor;[2] the meteor will seem to fall upon the supposed planet at O with the direction and relative velocity BO. As the meteor passes through perigee, it will suffer a certain deviation from the attraction of the planet, the magnitude of which is dependent upon its perigee distance. Moreover, instead of continuing in its course, OF, relative to the planet, it will follow without change of velocity the direction of one of the sides of the right cone DOC, whose angle at the vertex FOC = FOD is identical to the aforesaid deviation. Let OG be this new direction of relative motion. To obtain the direction of the absolute motion, that which takes place after the cessation of the action of the planet, it will be

1. Concerning the definition of the radius of this sphere, look ahead at paragraph 75.

2. This and the other velocities are indicated on the figure by arrows.



enough to compare the new relative motion with the motion of the planet. We then make OE = OA, OG = OB, and draw EG. This line represents the magnitude and the direction of the obsolute velocity of the meteor after its departure from the attraction sphere of the perturbing body, and the direction of the movement is from E towards G.

75. When we assume the planet and the meteor are attracted by the sun, BA represents the orbital velocity of the meteor at the moment in which it penetrates the attraction sphere, and EG the velocity in the new orbit after the conclusion of the action of the planet. We may assume the dimensions of the attraction sphere with respect to the distance of the sun as negligible; at the same time we may assume them very great with respect to the perigee distance of the meteor. In this way we are freed from making any hypothesis about the radius of this sphere, which would complicate exceedingly the consideration of all these problems, and would hinder the development of general conclusions. In our suppositions (which are admissable for any of the planets because of their small mass with respect to that of the sun) we are able to take BA as the orbital velocity at the point of intersection of the two orbits, and to regard EG as the new orbital velocity at the same point. Thus simplified, the discussion of the effects that a planet can exercise to change the orbit of meteors that approach it without encounter, becomes a very simple problem, and yet the conclusions closely approximate the truth. Our procedure

is in substance a simplification of that developed for similar cases by Laplace, and applied to Lexell's Comet by Burckhardt and Leverrier.[1]

76. Let us now consider instead of a single meteor an entire stream, which falls on the planet O with the relative velocity OB = U. Some of the elements of the stream will be swept up by the planet, and others will suffer more or less deviation; the greater changes are for those meteors that go closest to the surface of the planet. Calling R the radius of the planet (considered as spherical), retaining the other notations of the preceding formula, and letting D be the greatest deviation, we calculate from the formulas:

$$\left.\begin{aligned} W^2 &= U^2 + 2\,\mu g r^2/R \;, \\ \tan \tfrac{1}{2}\psi &= U/W \;, \\ D &= 180° - 2\,\psi \;, \end{aligned}\right\} \qquad (22)$$

After perturbation, those meteors which go near the surface of the planet will assume for their relative motion the directions of the generating lines of the cone COD, whose angle at the vertex is FOD = D. It is obvious that the shooting stars passing at a greater perigee distance have a smaller deviation; hence their relative motion after perturbation will follow the direction of a line within this cone. It follows that the directions of the geocentric motions after the perturbation are contained in the oblique cone CED, that has its base in common with the other cone and for the vertex the point E determined by OE = OA.

77. If we consider the case most interesting for us, in which the earth is the perturbing planet, the angle D of the greatest deviation for a given meteor stream is equal to double the greatest value ϕ of the zenith attraction that corresponds to that stream. This one can easily prove. The angle at the vertex, FOD, is acute and, in general, varies from 34°40′ to 1°24′ (paragraphs 66-67); it is easy to see that the absolute maximum and minimum velocities after perturbation (and the greatest and least major axes of the new orbit followed by the meteors) correspond to the two generating lines CO and OD of the conical surface which lies in the plane of the triangle AOB; then, if we make OC = OD = OB, EC and ED will be the two extreme velocities. The calculation from the given OA and AB depends solely upon the solution of the triangles OAB, EOC, EOD combined with the use of formula (22), for which in the present case $\mu = 1$, $R = r$.[2]

78. Using such simple principles to examine the effects that the earth's attraction produces upon the November meteors, I found that the angle of maximum deviation of the relative motion for a meteor touching the earth is 1°28′. If we assume the revolution of these meteors equal to 33.25 years, in the extreme case above indicated, the

1. See the formulas of Laplace, *Mecanique Celeste*, vol. 9, section 12, where a similar simplification is indicated; the calculations of Burckhardt in paragraph 18; that of Leverrier with remarkable perfections, *Annales de l'Observatoire de Paris*, vol. 8, p. 203.

2. When the point E is inside of the cone, this proposition needs some modification, as the reader will see. This is true (as happens when Jupiter or Saturn is the perturbing planet) if the angle at the vertex, FOD, is greater than 90°, and if the cone occupies more than half of the space about its vertex. A discussion of all cases that could occur would be lengthy and useless.

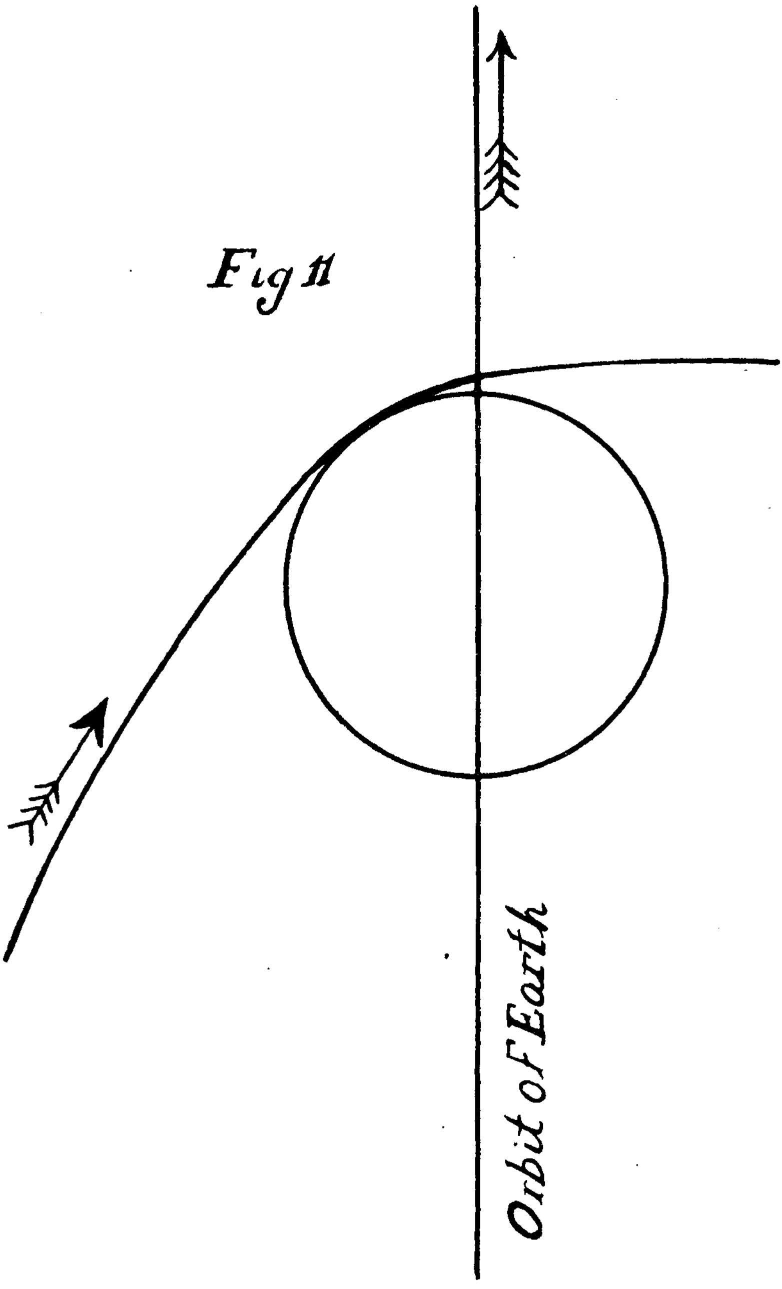
orbit that results from the perturbation can be shortened to 28.67 years or lengthened to 49.92 years. We then see that the effect of a passage of a meteor near to the earth can be a considerable change in the time of revolution. Although the densest cloud of the Leonids is not very long, and although it encounters the earth only every 33.25 years, a small part which at some revolution passed near the earth has changed its period and occupied the entire orbit in the form of a rarified ring-like stream. This is perhaps the reason that almost every year a small display of these meteors is seen, while a great display is rare.

79. If we assume that one of these meteors, skirting the earth and passing beyond has the maximum deviation of 1°28′ in its relative motion, it is easy to see that, if after one more revolution it falls on the earth, its radiant will be 1°28′ away from that of the other meteors. If we assume that by some singular chance, the meteor on its second approach to the earth grazes the surface and passes on, and falls upon the earth after one more revolution, the radiant will be observed in a third position distant by 1°28′ from the second, and not more than 2°56′ from the radiant of the other meteors. We see then, that notwithstanding the radical changes in the periods of revolution, the radiants of the perturbed meteors of November cannot move a great distance from the radiant of the main stream. And further, a great number of revolutions must occur, and a shooting star must pass close to the earth many times to cause a noticeable change in its radiant.

80. This leads to the conclusion that the preciseness of the phenomena of radiation, always diminishing with the course of years, can still be great, although the orbits of single meteors may be dispersed and undergo very noticeable variations in their periods. A meteor stream can radiate with almost geometric exactness from a single point, and yet its elements may describe many different orbits in space. This phenomenon ought to be especially noticeable for streams whose motion is almost exactly parabolic. The attraction of the earth will then change some orbits into ellipses of very different periods, some very short and others into hyperbolas. So the stream will slowly be dispersed, continually losing some of its members to stellar space. On the contrary, those meteors that are deviated into orbits of shorter periods, become more permanent, and are able to complete a great number of revolutions without being deviated into a hyperbola or a parabola. For example, the Leonids will always form a stable stream, and none of the meteors that compose it can be changed by the earth into an open orbit, except after many passages close to our planet.

81. The meteoric streams which come from the anti-apex radiants and nearly follow the earth in the direction of its movement, have much less stable radiants because of the high value which the deviation of the component meteors can attain. Such deviation for a meteor that touches the earth can reach 34°40′. The earth can produce this great a displacement upon the radiant of a meteor. And we note that for streams discussed here, the number of meteors noticeably deviated

Fig 11



in their course is incomparably much greater than for a stream similar to that of November, which comes almost from the direction of the apex. These streams, too, are the ones whose major axes and periods change the most because of the earth's attraction. These reflections, and others already expressed in paragraphs 16 and 66, give more than enough reason for the great difficulty encountered in the classification of shooting stars according to radiants, difficulties which chiefly pertain to the streams that appear in the early evening hours.

82. To see to what degree the attraction of the earth can modify the major axes and periods, I have worked out the circumstances under which a body of parabolic velocity must move in order to be thrown by the perturbing force of the earth into an orbit of the least possible period. Assuming the earth moves with its average velocity, I have found that the motion ought to be direct, and the parabola ought to cut the earth's orbit (assumed circular) at an angle of 18°. In this hypothesis the body describing the parabola must overtake the earth before its passage (figure 11) and skirt the surface. It then will pass from the attraction sphere of our planet, following a direction inclined 25° to the orbit of the earth, and will describe in the plane of this orbit an ellipse, the semi-major axis of which is 2.65 and the period 4.31 years. This is the smallest orbit into which the attraction of the earth can force a body moving originally with parabolic velocity. If, all other circumstances remaining equal, we assume that the perigee is equal to double the earth's diameter the new orbit will have a major axis of 5.04 and a period of 11.31 years. In the following table are given the major axes and the corresponding periods of various perigee distances, assuming always the circumstances just mentioned:

Distance of perigee in radii of earth	Semi-major axis of new orbit	Corresponding period
1	2.65	4.31
2	5.04	11.31
3	7.43	20.26
4	9.90	31.15
5	12.46	43.98
6	14.77	56.76
7	17.19	71.27
8	19.64	87.04
9	22.08	103.75
10	24.45	120.90

If we assume that a meteoric stream, instead of a single body, follows the parabola, some of its parts will be deviated into orbits of short period, others into orbits of long period, and a considerable part into hyperbolic orbits. Thus we see what variety of effect arises from a single passage of the earth across a meteoric stream.

83. I have used the principles explained in paragraphs 74-76 for obtaining some explanations about the famous question of the origin

of the famous November shooting stars. In my third letter to Father Secchi,[1] I had attempted to explain the origin of these and other similar annual streams, assuming that a mass of rare cosmic material, arriving from the depths of stellar space and deviated by the perturbing force of some great planets into an orbit of short period, would become successively scattered so as always to occupy, with its parts becoming independent of one another, this entire orbit or at least a considerable portion of it. I will have ample occasion to speak on the degree of probability of this hypothesis. It is enough at present to mention that Leverrier, director of the Imperial Observatory at Paris, who came to an analogous idea, thought he recognized in Uranus the disturbing planet[2] and he was lead to this conclusion chiefly by the circumstance that the present orbit of the November meteors seems to approach closely the orbit of Uranus. The approach of the original cosmic mass and the planet would have taken place, according to the conjecture of Leverrier, about the year 126 A. D.

84. One ought here to recall that the orbit described by the November meteors is subject to rapid variation of position and perhaps of form, as is certainly clear from the motion of the node, determined by the observations of Professor Newton, and confirmed by calculations of Professor Adams.[3] Hence to be able to affirm the conjunction of a planet and a cosmic mass, which generates meteors, at a given moment, one would have to follow step by step, ascending backward in time, all the changes that occurred in the meteoric orbit. That certainly can not be done today and we may doubt that we shall be able to do it with any exactness in the future. The nearness of the meteoric orbit to the orbit of Uranus, then, tells us nothing about the position of the two orbits in the centuries past. Indeed, whosoever examines with care the question, will find it possible, via a suitable hypothesis about the variations of the elements, to have the orbits of the meteors intersect the orbits, not of Uranus alone, but also of Saturn and of Jupiter. However, it is impossible to say with any certainty which of these intersections more probably took place in the time prior to 902 A. D., when known observations of the meteoric swarm of November began.

From what precedes, it is much easier for us to judge just what degree of change Uranus had to produce, to produce the existing ellipse of about 33 years out of the anterior orbit of a mass as rare and as large as we must assume for that whose dispersion caused the Leonids. Reasoning rigorously, one must consider whether the anterior orbit may have been one of short period. That cannot be supposed probable: first, because it would be "explaining a thing by itself", and second, it would be difficult to explain why the dispersion of the mass had not taken place before, at least in part. We assume then that the anterior orbit was a very lengthened conic section, suitable for bodies that arrive from the depths of stellar space.

1. *Bullettino Meteorologico dell'osservatorio del Collegio Romano*, 1866, no. 11, November 30.

2. *Comptes Rendus*, Vol. LXIV, p. 94 and following.

3. *Ibid.*, p. 651.

86. Then in fig. 12, S is the sun, MQ the orbit of the perturbing planet, MR the present orbit of the meteors, and let us admit that, in a time not much different from the present, the two orbits intersected in M, and that at this point the transformation of the old parabola of the meteors into a new orbit took place. If MQ is the path of the planet (almost circular), the angle of the tangent MQ with the radius MS, can be calculated with a certain approximation, regressing in time with the help of the known motion of the nodes of the present meteoric orbit, and likewise the velocity of the planet at M. In every case the angle SMr varies little from a right angle, and the velocity very little from the circular velocity. Similarly the radius vector MS at the point M can be obtained with sufficient precision for the point M where the node was at the time under discussion. Since the major axis and the eccentricity of the meteor orbit MR have remained almost constant since 902,[1] we can assume its form and size as constant; when given the radius vector MS, we can find, with small uncertainties, the angle SMr, that the radius vector makes with the tangent Mr. If we make the very probable supposition that the mutual inclination of the two orbits does not have sudden excessive variations, we are able with the help of the angles SMr and SMq to compute the angle qMr, and thence to derive the relative velocity of the meteors and of the planet at the point of intersection M. The form and relative position of the orbits is such that the final result depends very little upon the secular variation of the elements of the meteor, and in the last analysis this result carries little uncertainty.

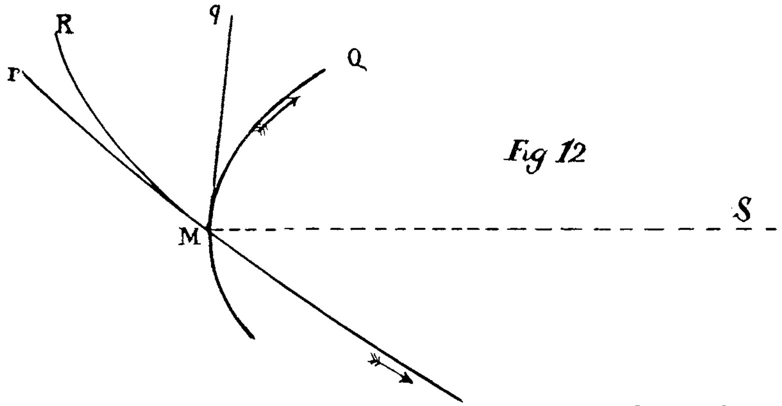


Fig 12

87. Let us pass to figure 13, which represents in scale the phenomenon that ought to occur at the point of intersection of the orbit of Uranus and of that of the meteor, according to the hypothesis of Leverrier. Representing with EO = OA the velocity of the planet in the direction indicated by the arrow, we have (taking the average orbital velocity of the earth as unity and assuming that O, the point of intersection of the two orbits, has on the orbit of Uranus the longitude of 231°)

1. Since the interval of the periodic return of the November swarm has been always constant, the radius vector at the descending node, has been always constant.

$$EO = 0.23355.$$

The absolute velocity of the meteor at that point is represented by EC = 0.09981. The angle OEC between them is 133°.8; we find the relative velocity to be CO = 0.31334.

This ought to be the relative velocity anterior to the perturbation. Then for the path anterior to this close approach we know (1) the relative velocity of the two bodies, Uranus and the meteor swarm, (i. e., the Uranus, that which we have given; (3) the absolute velocity of the meteor, which is the parabolic velocity corresponding to the point P of the orbit of Uranus; and an easy calculation gives for its value 0.32660. We know then the three sides of the triangle OAB (figrues 10 and 13), and we are able to find the angles BAO and BOA, which the absolute velocity BA and the relative velocity BO of the meteors make with the direction OA of the orbit of Uranus, before the perturbations. They are, respectively, 65°.6 and 71°.7.

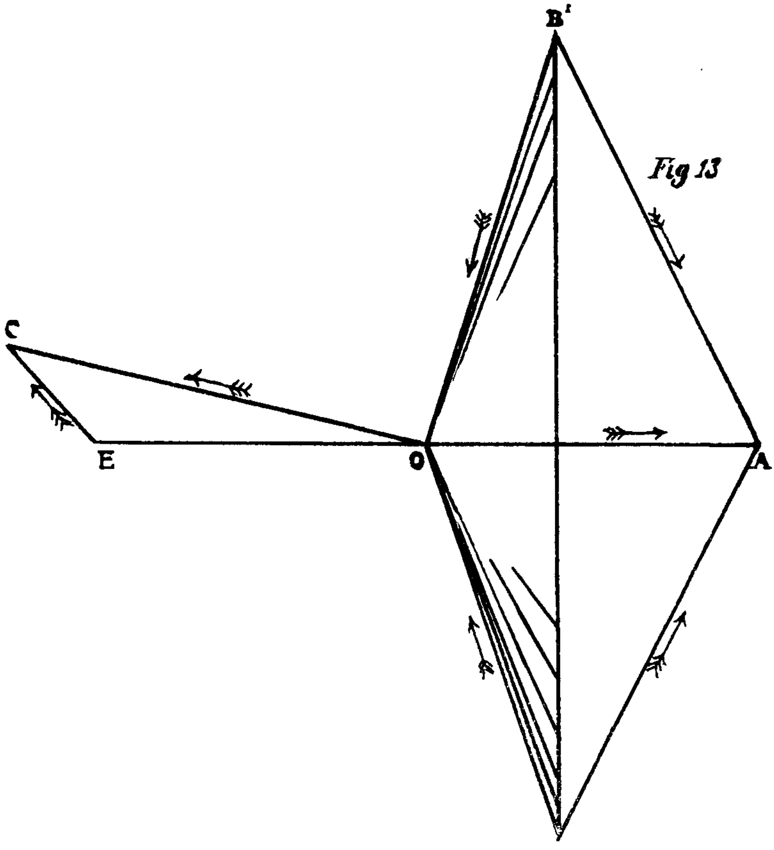


Fig 13

88. Rotating the triangle OAB about OA, we know that the direction of the relative motion of the meteor swarm before the perturbation must have followed one of the generating sides of the cone BOB′ generated in this rotation. Of the angles that these generating lines make with CO (direction of the relative motion after the perturbation) the minimum is COB′, the maximum COB; calculating these angles, we find that the deviation caused by Uranus on the direction of the meteor swarm considered in its relative motion is comprised between the limits given by COB′ = 95°.6 and COB = 121°.1; to which, according to formulas (20) and (21) there correspond the perigee distances

$$P_1 = 1.28 \text{ radii of Uranus}$$
$$= 6.13 \text{ radii of the earth}$$
$$P_2 = 2.70 \text{ radii of Uranus}$$
$$= 12.93 \text{ radii of the earth.}$$

We arrive then, at this singular result, that if Uranus transformed the original orbit of the swarm of Leonids (that we assume parabolic or almost so) into the actual orbit of 33 years, the perigee distance of the two bodies must have been between 1.28 and 2.70 radii of the planet, or between 6.13 and 12.93 radii of the earth. It is obvious that a perigee distance less than the limit P_2 assumes necessarily that the anterior orbit was hyperbolic, while a perigee distance greater than P_2, inevitably supposes an elliptical orbit. For perigee distances between P_1 and P_2 the first orbit could have been any conic section.

89. Could a passage of the metéoric mass as such a short distance from Uranus as is here indicated by the external limit P_2, have taken place without a total dispersion of the mass into totally different regions of space? We doubt it strongly, and because of good arguments. The system of the November meteors, since 902, has made twenty-nine complete revolutions. During this long interval of almost ten centuries, it remained fine and compact, and still occupies only a small part of its ellipse. We conclude that the orbits described by these innumerable bodies are almost identical in form, size and position; the major axes in particular ought to be extremely little different from each other, and their differences can be, at the most, a few thousandths of their lengths. Such circumstances are extremely important for our question. It shows us that when the meteoric cloud was drawn into its present orbit, the disturbing planet produced almost exactly equal effects on all the component parts. This means that the minimum distance between the stream and the planet must have been considerable in comparison with the dimensions of the stream itself. Now these dimensions could have been of an order inferior to the diameters of the large planets; it is enough to recall that in the inside of this stream was contained all of Tempel's comet (1866 I), which occupied, at its last appearance, a volume not less than Jupiter. The conclusion is that the disturbing planet has deviated the stream from its original orbit, yet did not approach it very closely.

90. So we see, in a general way, the improbability that Uranus could have deviated the Leonids from a parabolic orbit into its present one. We do not have other ways of avoiding this improbability, other than supposing a very small diameter for the meteoric stream. In order to judge numerically this other side of the question, I shall assume that while a particle of the stream described with respect to Uranus its relative orbit, passing at preigee distance ρ, another particle, traveling in the same plane as the first, passed at the perigee distance $\rho + d\rho$, and I propose to investigate the difference that arises in the major axis of the orbit of the meteor after perturbation. U being assumed equal for all the parts of the cloud, the differentiation of (20) will give

$$\rho \, d\,W = -\frac{\mu g r^2}{W} \; \frac{d\rho}{\rho} \tag{23}$$

From (21) we conclude

$$\tan \psi = \frac{2UW}{W^2 - U^2} = \frac{UW\rho}{\mu g r^2} \;, \tag{24}$$

whose differentiation gives

$$d \tan \psi = \frac{U}{\mu g r^2} \left\{ W d\rho + \rho dW \right\}$$

that equals, from the preceding formulas (23) and (24)

$$d \tan \psi = \frac{d\rho}{\rho} \left\{ \tan \psi - \tan \frac{1}{2} \psi \right\} \tag{25}$$

Let us admit for the most favorable cases that ρ is equal to 2.70 radii of Uranus; $\psi = \frac{1}{2}$ COB $= 60°.5$, and in this case

$$d\psi = 0.287 \frac{d\rho}{\rho} \;.$$

Now, since COB $= 2\psi$, and the first direction BO is assumed equal for the two particles, it is evident that if COB is increased by the quantity $2d\psi$, COE will be increased at least as much and CO $=$ U remaining constant, we have a variation of the absolute velocity CE after the perturbation, expressed by

$$2d\psi U \sin C.$$

Calling Y the velocity CE, we have then

$$dY = 0.574 \frac{d\rho}{\rho} U \sin C$$

and we have here $U = 0.31334$, $C = 33°.5$; therefore

$$dY = 0.0993 \frac{d\rho}{\rho} .$$

Finally if a is the semi-major axis of the ellipse described by the meteor after the perturbations, ρ the radius vector at the point where the perturbation occurs, there will exist the well-known relation

$$Y^2 = \frac{2}{\rho} - \frac{1}{a} \;,$$

where the average velocity of the earth is unity. From this we have

$$da = 2a^2 \; Y \, dY = 0.1986 \, a^2 \, Y \; \frac{d\rho}{\rho} \;.$$

In the actual orbit of the Leonids, a equals 10.340, and Y = CE = 0.09981. We finally have

$$\frac{da}{a} = 0.205 \frac{d\rho}{\rho} \tag{26}$$

91. Never since 902 have the Leonids produced a spectacular shower for two consecutive years. We conclude that the abundant part of their stream does not occupy over 1/ (33.25 x 29) of their orbit. And since these meteors have already been observed in twenty-nine revolutions, the difference of the time of revolution between the maximum velocity and the minimum velocity will not exceed 1/ (33.25 x 29) of a revolution, and the difference of the semi-major axis of the largest orbit and minimum orbit will not surpass 2/3 of this fraction, or 1/1446 of the semi-axis itself. This fraction is the upper limit that we can allow for the value da/a of the formula (26). Hence we conclude that the upper limit admissible for $\frac{d\rho}{\rho}$ is 1/296; which limit, in our hypothesis of $\rho = 2.70$ radii of Uranus or 12.93 radii of the earth, is equivalent to less than 1/100 of a radius of Uranus, to about 1/24 of the radius of the earth, or 271 kilometers. The diameter of the meteoric cloud could not have been greater, if Uranus put it on the path it describes at present. An even more close limit could be found, by assuming ρ less than the external limit fixed in paragraph 88. The possibility of admitting such a small diameter for the meteoric cloud, from whose dissolution the shooting stars result, we do not wish to discuss here, as it is impossible to put the discussion upon a reasonably sound basis. We cannot avoid the necessity of these small dimensions except by admitting a much greater perigee distance. But for this case the original orbit must have been an ellipse. If the data forces us to admit that at perigee the cloud was at a distance of 10 radii from Uranus, a calculation similar to those above will show that the original orbit could not have had a period greater than 50.14 years. We repeat that that is not impossible, but that it is hardly probable.

92. All these difficulties do not exist for Jupiter and Saturn, the orbits of which are much more favorably situated to approach the ellipse described by the November meteors. Making for Saturn the calculation indicated in paragraphs 87 and 88, and determining for it the two limits of ρ outside of which a parabola is inadmissible for the original orbit, we conclude

P_1 = 1.11 equatorail radii of Saturn
= 11.06 radii of the earth;
P_2 = 10.19 equatorial radii of Saturn
= 102.00 radii of the earth.

The second distance is great enought to permit the meteoric cloud to pass beyond, without much dispersnon. For Jupiter we obtain

P_1 = 1.64 equatorial radii of Jupiter
= 19.09 radii of the earth;
P_2 = 27.27 equatorial radii of Jupiter
= 317.42 radii of the earth.

This last limit is more than fivefold of the distance of the moon from the earth, and somewhat exceeds the distance of Jupiter from his fourth satellite. The powerful mass of Jupiter would have had the force to change a parabolic orbit or a lengthened conic section into the actual orbit, and that too without causing the meteoric cloud to enter in the sphere where the four satellites move.

93. Summing up this discussion, we conclude: (1) that if the November meteors have been brought into their present orbit by the perturbing action of a planet, this could easily have taken place from the influence of Jupiter and Saturn; (2) for Uranus, that is not impossible, but it is hardly probable. Other than the difficulties already enumerated, we observe that the sphere inside of which the perigee must have fallen, has for the hypothesis of Uranus, the radius of 12.93 radii of the earth, while for Jupiter it has 317.42 radii and for Saturn 102.00 radii. The simple probability that the course of the meteoric cloud was able to meet one rather than the others of these three spheres so different in volume, shows what ought to befall the Uranus-hypothesis. As for the earth, it is impossible that it was the perturbing planet; calculating for it the limits P_1 and P_2 we find that both fall inside the planet mass. Even on the impossible hypothesis, that the swarm touched the surface of the earth, the original orbit could not have a period greater than 49.92 years or less than 28.67 years. For the same reason the earth, if it perturbs any of the November meteors, can not change them into an orbit with a period outside of the limits just now indicated (paragraph 78). When we assume the perigee distance greater than the earth's radius, the possible limits for revolution in the original orbit are greatly restricted, converging towards 33.25 years, which is the actual period of revolution.

94. Of the arguments used up to now on the question raised by Leverrier, only a part are valid, if, instead of supposing that shooting stars arise from the dissolution of meteoric clouds or of comets, we wish to have them arise from the nuclear emissions of the latter, as Faye of the French Academy has proposed.[1] In this case the perturbations of the planet are no longer made upon an incoherent mass but upon a compact nucleus. Of course we could not use the reasoning deduced from the dispersion of the perturbing mass. But the arguments based on the different extensions of the spheres that limit the perigee distance compatible with the original parabolic state of the orbit (preceding paragraph) and based on the position of the orbits of the perturbing planets with respect to the orbit of the meteor swarm considered in its revolutions prior to 902, still have the same weight. We will examine further in another section the different theories that can be imagined concerning the origin of the meteor swarms.

1. *Comptes Rendus de l'Academie des Sciences*, Vol. LXIV, p. 553.

VIII

ON THE TRANSFORMATION OF CELESTIAL MATERIAL INTO METEORIC STREAMS

95. Up to this point we have considered problems derived chiefly from the geometric theory of the apparent paths and the real paths of the meteors. The results obtained are simple and rigorous consequences of the supposition that the path described in space by the meteors is identical in nature and distribution with the orbits of the comets. This can not now be subject to doubt. But at the same time we ought to confess that we are completely ignorant of the nature and the cause of the analogy found recently between the comets and shooting stars. Research on the nature and cause of the relationship evidently involves considerations much less determinate and much more difficult than those which appear in the preceding discussion.

In making a frontal attack on questions of such a mysterious nature I have more a desire to try out the way than a hope to arrive quickly at the truth. Here it is necessary to abandon from time to time the guiding Ariadne's thread of geometry and follow the difficult and Protean pathway of cosmological speculations. It is not that there are not enough observed facts to risk the passage, but their true interpretation becomes much more difficult, when we have to compare happenings in the past with those of the present; often we can explain the same thing in two or three ways, equally plausible to our ignorance, but always mutually exclusive. Let it not be said that we wish to imitate those who affect a sovereign disdain for this sort of investigation. Probability deriving from conjecture cannot possibly, by itself, establish a science; but a combination of such sometimes indicates where the truth is to be found, and strikes the first spark of light for some dark and unexplored subjects. Scientific history is full of examples that demonstrate this.

96. In the first paragraphs of this paper, I have already indicated briefly which facts prove absolutely the connection existing between the comets and the meteors. The hypothesis that led to the discovery of these facts is that the shooting stars formed originally a very rare mass in interstellar space. From this single and very simple fact, to which inductions of various kinds can lead us, there derive as necessary and geometric consequences: (1) the formation of the meteoric streams; (2) the affinity of their orbits with those of the comets; (3) the presence of the comets themselves in certain streams, as integral parts of the same. This is not, however, the only hypothesis that will serve to account for all we observe; others have been proposed, and we shall take them into consideration. Thus, Faye has derived meteoric streams from the nuclear emissions of the comets; Secchi seems inclined to attribute them to the tail. Finally, Erman, with a truly ingenious artifice, has tried recently to deduce the formation of the meteoric streams from the action of a resisting medium, like that to which Encke attributed the acceleration of his comet. The discussion

of all these ideas is not without interest. I shall begin by examining the theory that derives the meteoric streams from the dispersion of cosmic clouds, caused by the force of universal gravitation alone, and I will examine the objections that can be raised against it.

97. In the well-known hypothesis that Laplace imagined to account for the formation of the planetary system, the common characteristics of the primary and secondary planets serve as a basis for the conjectures about the successive dynamic developments which the primeval nebula underwent. They also give an infallible method to recognize which among the celestial bodies already belonged to the system at the time of its formation, and which are extraneous to this formation. Comparing the properties of the orbits of the planets and those of the paths of the comets, Laplace did not hesitate to announce that the comets are strangers to our system. He considered them small nebulous wanderers among the stellar systems, and formed by the celestial material of which the universe is filled, according to the well-known speculations of Herschel.[1] This simple and natural supposition accounts sufficiently well for the form of orbits of the comets, and for their irregular distribution in space. At the same time we are lead to conclude that the universe is populated not only with fixed stars and gigantic accumulations of material, but also by smaller bodies, generally invisible, though much more numerous, that are not observable to us except when the solar attraction causes them to pass through the nearest parts of our system. Nothing is more natural than to assume an identical origin for the shooting stars. The meteoric streams, like the comets, have in other times formed a part of the infinite swarm of bodies with which the stellar space is crowded. Originally, these swarms probably did not form streams, but wandered through space in the form of masses, which the analogy of nebulae obliges us to assume extremely rare and of irregular construction. If in the vicinity of the sun a system took the form of a continuous stream, in the shape of a conic section, that was only a consequence of the manner with which the sun attracted it.

98. Now the transformation of these masses of very rare material into streams, curved into conic sections about the sun as a focus, is not merely a possibility but is rather a phenomenon that necessarily takes place every time that such a mass approaches the sun until it crosses the orbit of the earth. This is a strong argument in favor of the hypothesis considered here. Of these facts I gave (in my second letter to Father Secchi) a proof which could not leave any doubt in the mind of the reader, though the reasoning all turns on a particular case, and contains some errors in the calculation.[2] Perhaps some will be glad to see here another demonstration which is much more general, though certainly not more rigorous and not more obvious.

1. Laplace, *Exposition du Systeme du monde*, sixth edition, 1835.

2. In running hastily over the letter cited, the keen reader will notice that in an ellipse with a semi-major axis which is ten thousand times that of the earth's orbit, the time of revolution is 1,000,000 years—not 2,830,000 years as is mistakenly asserted there. The numbers derived from this are inexact, but the demonstration is still valid.

99. In that region of celestial space where the attraction of the sun commences to become preponderant over that of the neighboring stars let us imagine that there moves a mass of cosmic material of any shape whatsoever; and let us assume that the reciprocal attraction of its parts is nothing, or at least that we can regard it as negligible with respect to the attraction of the sun. Such a body moving principally under the influence of the sun, will describe a conic section, whose dimensions are very great in comparison to those of the earth's orbit; it is only in the case in which the perihelion distance and the parameter are very small that the body can reach the inner regions of the solar system. We assume, necessarily, that the orbit is an extremely elongated conic, very nearly a parabola. Further, since the parameter must have a magnitude comparable to the parameter of the earth's orbit, the velocity with which the radius vector of the body will describe the area ought to be of the same order as the velocity with which the radius vector of the earth describes its area. On these assumptions it is evident that, when the dimensions of the mass are very small in comparison with its distance, the different orbits pursued by the elements will be planes only slightly different, and similarly the directions of the major axes of all these orbits will be only slightly divergent from each other; because these major axes can not make a very large angle with the radius vector, except when the average irregularity in these lengthened orbits is very small; this case we exclude.

100. For greater simplicity we will consider a mass, of which all the parts are situated in the same plane, the plane of the orbit. Let us define this plane by the coordinates x, y, with origin at the sun. Let us consider a particle for which at a given instant, x, y, r are coordinates and the radius vector. We assume that these quantities are many thousands of times the semi-major axis of the earth's orbit, denoted by s. The velocity with which the particles move, has the components ξ and η along the two axes; as we have said in the preceding paragraph, this velocity in general ought to be very small with respect to the average orbital velocity *u* of the earth. We have, from a common formula, the semi-major axis a of the orbit pursued:

$$\xi^2 + \eta^2 = su^2 \left\{ \frac{2}{r} - \frac{1}{a} \right\}, \tag{27}$$

the parameter (and the eccentricity[1]) can be obtained from

$$x\eta - y\xi = u\sqrt{s}\,\sqrt{a(1-e^2)} \tag{28}$$

The eccentric anomaly E of the material point in its orbit at the instant considered is obtained from the well-known equation

$$r = a(1 - e\cos E). \tag{29}$$

From this it is easy to compute the interval *t* between the moment considered and the passage of the particle through its perihelion; we have in fact:

$$2\pi\sqrt{\frac{s^3}{a^3}}\,.\,t = E - e\sin E, \tag{30}$$

when the unit for t is the sidereal year, and E is counted positively

1. The relation of parameter (p) and eccentricity (e) is $p = a(1 - e^2)$.

from the perihelion backwards in a direction contrary to the movement.

101. Let us now consider a second particle of the mass. Because we assume that this body moves with equal motion in all its parts (except for its foreseen dispersing), the components ξ and η of the velocity, for the second particle, will equal that of the first, while the coordinates of the second particle differ from those of the first by certain amounts dx, dy, which are of the order of the dimensions of the mass. We suppose these dimensions are very small in comparison with the distance of the mass from the sun. Moreover, generally speaking dx, dy are quantities very small in comparison with r. Let us determine the variation that is produced in the elements of the orbit by the variation of the coordinates x, y. Differentiating (27) in the hypothesis of and constant, we find:

$$\frac{da}{a} = \frac{2a}{r} \cdot \frac{dr}{r}, \tag{31}$$

from which we see that the variation of the major axis of the orbit is of the same order as the variation produced in the radius vector by changes of the coordinates x, y into x + dx, y + dy. We must except the case in which 2a/r is a very large quantity; in that case, to a small change of the radius vector there corresponds a very great change of the major axis. This takes place particularly when the conic section described by the mass is almost parabolic, for which $a = \infty$.

102. Differentiating the equation, we find

$$e\,de = \frac{1}{2} \cdot \frac{da}{a} (1-e^2) - \frac{x\eta - y\xi}{us} \left\{ \frac{\eta dx}{u.a} - \frac{\xi dy}{u.a} \right\} \tag{32}$$

When we consider a highly elongated orbit we readily see that the variation de is of an order much inferior to the variations dx/a, dy/a, or to the variations dx/r, dy/r. Letting p be the parameter of the orbit, we observe that $p/a = 1-e^2$; substituting this value in the preceding equation, and substituting for da/ the value found from (31), we obtain

$$e\,de = \frac{p}{r} \cdot \frac{dr}{r} - \frac{x\eta - \xi y}{us} \left\{ \frac{\eta}{u} \cdot \frac{dx}{a} - \frac{\xi\, dy}{u.a} \right\}$$

The factors dr/r, dx/a, dy/r are of the same order as the ratio of the dimensions of the mass to its distance from the sun; but we observe that in the first term of the second member there is still the factor p/r which is necessarily small according to our hypothesis; in the second term there are the factors η/u, ξu, which from (27) we know to be very small. As to the factor

$$\frac{x\eta - \xi y}{us},$$

it expresses the ratio of the area described by the mass in a unit of time to the area described by the earth in the same time; a ratio that, because of the supposed smallness of the parameter of the orbit of the mass (paragraph 99), is a finite quantity and not much different from unity. We then conclude that for nearly any parabolic orbit the increment de, of the eccentricity is of the second order in comparison with the variations dx/r, dy/r.

103. From equation (30) we immediately have by differentiation the changes that passage from one point of the mass to the other induces in the time of perihelion. We obtain

$$2\pi\sqrt{\frac{s^3}{a^3}}\,.dt = \frac{r}{a}\,dE - \sin E\,de,$$

and from (29) we find dE from

$$e\sin E\,dE - \cos E\,de = \frac{a}{r}\left\{\frac{da}{a} - \frac{dr}{r'}\right\};$$

In this equation we can neglect the terms in de, since that order is inferior to the order of the remainder; thus there will remain

$$2\pi\sqrt{\frac{s^3}{a^3}}\,.\,dt = \frac{r}{a}\,dE = \frac{1}{e\sin E}\left\{\frac{da}{a} - \frac{dr}{r}\right\} \qquad (33)$$

and dividing this equation by (30) we obtain

$$\frac{dt}{t} = \frac{1}{E - e\sin E}\cdot\frac{1}{e\sin E}\left\{\frac{da}{a} - \frac{dr}{r}\right\}$$

Substituting for da/a its value taken from (31), we get . . . .

$$\frac{dt}{t} = \frac{1}{E - e\sin E}\,\frac{1}{e\sin E}\cdot\frac{dr}{r}\left\{\frac{2a}{r} - 1\right\}$$

104. This last expression shows that when the ratio of r to a is not very great or very small, and when E is not near to 0° or to 180°, the relation dt/t is of the same order as dr/r. The difference of the perihelion passage of the different parts of the mass is then, of the time t, a fraction of the same order as dr/r, and this last quantity is evidently of the same order as the angular diameter of the mass, observed from the sun. Then if the conic section described by the mass is such that to arrive at perihelion millions of years are necessary (a thing not utterly outside probability), the time dt easily runs up to tens, hundreds, and thousands of years. When initially the mass occupies the aphelion of the orbit, and we have E = 180°, the expression of dt becomes indeterminate, at least when we consider an almost parabolic orbit. It is evident that in both cases the same circumstance is true for the relation dt/t. The first of the two has been chosen as an example in my second letter to Father Secchi.

105. This is what will happen. The bundle of orbits pursued by the different parts of the mass considered as independent bodies, will be close-packed and narrow in the regions nearest to perihelion. It will be curved very similar to a parabola with the sun at one focus. The different parts of the mass will come successively to perihelion at very different epochs, and indeed the mass will be distributed upon an elongated, almost parabolic arc, and will pass (piece by piece) to perihelion in a time more or less long, depending to a large extent on the original dimensions of the mass before it was transformed. In that way the sole and simple effect of the solar attraction is enough to convert into meteoric streams the masses of very rare material, that we find dispersed through space. If the bundle of orbits along which the stream moves is encountered by the earth, the earth will receive a meteoric shower at a fixed time of the year, and this lasts as many years as the entire stream takes to pass perihelion. It is plain, from

what we said, that after the end of the passage the stream will return only after an extraordinarily long time, or will not return at all; so that out of the stream there will not remain any observable traces except a few meteors deviated by the earth's attraction into orbits of short periods, which show (approximately at least) the radiant point of the old stream but become from time to time more dispersed (see, apropos of this, paragraph 80). It is, then, possible for a spectacular meteoric shower to leave as residue a small shower, and this happens more easily for the streams of direct motion (paragraph 81).

106. For all the preceding consequences to have their full effect, it is necessary that the reciprocal attraction of the component parts of the mass be zero, or at least negligible with respect to the differences in the attraction the sun exercises upon the different component particles of that system. If *R* be the distance of the mass from the sun, *M* the mass of the sun, δ the density of the supposedly homogeneous mass of spherical form, it is evident that when

$$\delta < \frac{3}{2\pi} \frac{M}{R^3} \tag{34}$$

the internal attraction between the parts of the system yields to the dissolving force of the solar attraction.[1] For every given density δ, it is then easy to calculate the limit of distance R, below which the mass will begin to undergo dissolution. And inversely, for every given distance we can obtain the density below which a homogeneous mass will not be held compact and coherent in its parts by its own attraction. In this way we arrive to a truly unexpected result. As an example, if we make R equal to the semi-major axis of the earth's orbit, and if we assume the density of the sun equal to 1.5 that of water,[2] we obtain for the density limit of a stable mass $\delta = 1/3{,}370{,}000$, the density of water being equal to unity. This density, for which 3 grams of material make only 10 cubic meters, corresponds to that of the atmosphere under a pressure of 0.174mm. We ordinarily attribute a much lower density to the atmosphere of a comet; and, if these remain coherent, it is without doubt because of the attraction of a central nucleous, whose density is much above that which we have assumed for our mass of material.

107. In a much elongated orbit, R is subject to great variations, and it happens that a mass which remains coherent in the parts farthest from its orbit, little by little ceases to be so on approaching the sun, and is completely dissolved when it reaches perihelion. When such dissolution has taken place, it is almost impossible that it can, on moving way from the system of the sun, reconstruct itself under the influence of the reciprocal attraction of the parts. In fact it is not probable that the orbits described by the separate parts are, after passing perihelion, completely similar. Further, the divers epochs of perihelion passage cause the planets to produce varying perturbations in the several orbits; hence the mass will return to celestial space in a state of dispersion increasing with the distance from the sun.

1. I do not believe it necessary to give here a fuller discussion of this point. The reader can find it in letter III to Father Secchi.
2. Modern work gives 1.41.

108. As there is no limit to the degree of condensation which we imagine celestial material can reach, we can easily imagine that masses exist so dense that they are preserved even in the perihelion passage and in this case we can hardly say the meteoric masses differ from an ordinary comet. But as the comets, approaching a great planet, are very frequently forced to describe elliptical orbits with periods more or less lengthy, we can conceive what happens in the system we considered. In this case the attraction of the perturbing planet, and sometimes the effect of the perihelion distance, a distance much diminished because of the change in the orbit, cause the cloud to dissolve little by little into independent parts, these parts describe orbits of slightly different periods, and finally extend progressively along the ellipse described by the system. This arc is elongated little by little, occupying a larger and larger portion of the ellipse, and after a certain number of revolutions the ring will close, becoming an annular ring. This series of mutations is occurring now in the case of the Leonids, which originally consisted, apparently, of a mass similar to that about which we have just now reasoned. Not so long ago they were deviated by a great planet, probably by Jupiter or by Saturn (see paragraphs 83-95); the original orbit was changed to the present ellipse of 33.25 years. At that time the bond that united the different parts was loosened, and now the transformation into annular streams has progressed so far that all its material requires a year (or perhaps more) to pass to perihelion. The time will come when the Leonids will appear every year, as do the Perseids; but the density of the cloud will be much diminished, as it becomes a ring and the phenomenon will be much less splendid, the same quantity of meteors being distributed over a greater volume. Finally it is noticeable that the mass of the Leonids contained, before dispersion, a nucleus, or a portion of greater density. This nucleus did not undergo the fortunes of the rarer parts, and was not dispersed. As a separate heavenly body it circles in the midst of the meteors that were once united to it. It forms, as we know, what we call the comet 1866 I.[1]

109. The annular meteoric streams then, are, in the universe of the shooting stars what the periodic comets are in the universe of the comets. According to every probability the streams and the comets that pass perihelion only once are much more numerous than those, the peculiar position of whose orbit with respect to the planets cause them to appear periodically. But since a comet or a stream which is not periodic is seen only a single time, while a periodic comet or stream is visible for a great number of year (I speak of what generally happens) the number of the periodic appearances can be not much less than, or equal or even superior to, the number of non-periodic appearances. The comet appearances of the last decades fully show this,[2] and the decades to come will show it still better. So then if one were to aver

1. I proposed this theory on the formation of the annular streams in letter III to Father Secchi (published November 30, 1866). The noted Leverrier also proposed it, with some further development, at the following, January 21, 1867, session of the Paris Academy of Science. See *Comptes Rendus*, Vol. LXIV, p. 94.

2. For example, in 1838 we observed four comets of short periods and four comets of unknown periods or very long periods passed to perihelion.

the truth of the conjecture of Weiss,[1] and if we should find that the greater part of the meteoric streams are produced by periodic and annular streams, it would be false to conclude that the streams which are not periodic and not annular, described in paragraph 104 and 105, exist in smaller number than the others, or do not exist at all. They ought to be very numerous, even if each one appears only a single time, or is subject to a very long return trip.

110. All the preceding conclusions, of such geometric rigor that no one would wish to dispute them, will become so many immediate facts of nature as soon as we have ascertained the principal basis, namely the existence of rarefied material in the interstices of the stellar universe. Herschel, in his celebrated work of 1811, described all the different degrees of concentration of the celestial material which we can observe with our instruments, beginning with rare and diffuse nebulae spread over large areas of the sky, whose existence we can only guess at with telescopes of the greatest aperture, and proceeding through successive steps to the fixed stars, which we now have to regard as the densest type of material.[2] These remarkable speculations constitute a truly astrogonic history of the universe, and spectral studies have splendidly confirmed their basis, namely, the existence of material in the nebulous state. If the gradation of density and the combination of rare and dense material, described by Herschel, exist in the great accumulations which the telescope reveals, is it not natural, or even necessary, to assume that also in the minor accumulations the same variety is to be found? Of these smaller accumulations some are dense enough not to be dispersed by the sun and the planets; coming from space they appear as single bodies with a nucleus or very definite center of condensation, which describes a parabola, without abandoning any part of itself along the path it describes. Others consist of both rare and dense parts; approaching the sun the dense matter is still kept in a state of cohesion, while the rare is abandoned along the pathway. We see then a principal body (or principal bodies) accompanied by a stream, both describing the same orbit in space. Finally, there exist masses of material too rare to remain coherent in any part; their dissolution, produced by the solar and planetary attraction, transforms them into meteoric streams not containing any body or principal mass.

111. It is evident that the simple comets, the comets accompanied by meteoric streams, and the meteoric stream without comets are particular cases belonging to a single and unique order of facts. They are simple and rigorous consequences of a single fact, that we can hardly deny, i. e., the varying condensation of the material that fill celestial space. If the reader has absorbed the force of this argument, he will surely not find it singular that meteoric streams exist separate from, or united with, the comets. Rather, he will marvel that no one ever foretold *a priori* the existence of the meteoric streams. From what we have said in paragraph 106, when a comet is dissolved and transform-

1. *Astronomische Nachrichten*, no. 1632.
2. "Astronomical observations relating to the construction of the heavens," *Phil. Trans.* 1811.

ed into streams it does not need to become extremely rarefield, even when a nucleus exists within its mass. It seems that the heat of the sun augments the volume, helping to diminish the internal attraction, and produces the conditions for dissolvibility. It is quite possible that many of the comets reaching perihelion abandon along their orbit the rarest and the outermost parts of the atmosphere that surrounds the nucleus.[1]

112. The objection has been raised that swarms of very rare meteoric material (such as are needed to produce meteoric streams) have never been seen.[2] To that it is easy to respond that in the neighborhood of the sun these swarms are transformed into streams which certainly exist and are not visible except when the bodies of which they are composed enter our atmosphere. But if they ask to see the meteoric material not yet transformed into streams, it is sufficent to cite the catalog, included by Herschel in the aforementioned work of 1811, of diffuse nebulae some of which occupy 8 or 9 square degrees. If it is hard to accept this argument, we can always show very rarefied nebulous material, whose dispersion is impeded by the action of a central nucleus, in the atmosphere of the comets.

113. But if the masses of rare material, transformable into meteoric streams, are hardly visible, precisely because they are so rare and because they are transformed into streams, that ought not to prevent our seeing, now and then, one of these very dense systems or masses which because of their great density have not been dispersed. Several such masses have been seen. I will not cite here the well-known examples of Biela's comet and of Liais' Comet, nor the secondary nucleus observed by Otto Struve and by Winnecke in Donati's Comet, nor the first comet of 1853, whose nucleus was multiple according to the observation of Father Secchi.[3] One might say that they have nothing to do with the case in point. Just as a double star is a formation extremely different from a group of stars, so a double comet cannot be referred to as an example of such masses as are here intended. But the example that I will cite bears directly on true amorphous masses of irregular and weakly concentrated celestial material, seen near us. These were very similar to what we imagine the Leonid swarm was before its dissolution.

114. Nine years after its invention, the telescope was used to study the structure of the comets, and that occurred at the appearance of the second comet of 1618. Its nucleus, that at first seemed single, split into a veritable swarm of small nuclei. Although made with imperfect telescopes such as then were available, the observations of the different astronomers are too much in agreement to admit of doubt. I shall reproduce textually the principal observations; let the reader use his own judgment.

115. *Observaions of Pt. Cysat.*[4]

1. Do not confuse this dispersion along the orbit with the dispersion that takes place in the tail in a direction of the radius vector, which I shall explain below.
2. See Faye in *Comptes Rendus,* Vol. LXIV, p. 554.
3. Bulletino Meteorologico, Vol. V, p. 129.
4. Taken from the *Cometographia* of Hevelius, pp. 341-42. The dates are according to the Gregorian calendar here, and also in the following accounts.

"On the first and fourth days of December we observed a comet carefully every day through the telescope (a double one, one of these was almost six, the other nine or ten feet long). The nucleus of the luminous head of the comet appeared round in shape, with an unbroken and compressed light, although not bright or glistening, of such diameter that its whole diameter could occupy two-thirds of the diameter of Jupiter. The nucleus of the luminous head of the comet was dense, but leaden and faintish. Around it was poured a light that was rarer and paler, a border about twice as wide as the diameter of the nucleus . . . The nebulous corona which surrounded the nucleus was in turn surrounded by a third radiance, of far weaker and dimmer light, which nevertheless wås not more dense than the light of the comet, but seemed to be the comet spread out, and therefore we were unwilling to add it to the head of the comet. The head, then, consisted of a 'marrow' or a dense nucleus, and an even wider border encircling it, with a much dimmer light. The diameter of the nucleus was about two minutes; the width of the border was three minutes, and the whole diameter of the head was eight minutes.[1]

"*December 8, 1618*: Not only the whole head of the comet (I mean the nucleus and the encircling radiance) but also the isolated nucleus, twice larger than Arcturus, was seen as being three or four minutes

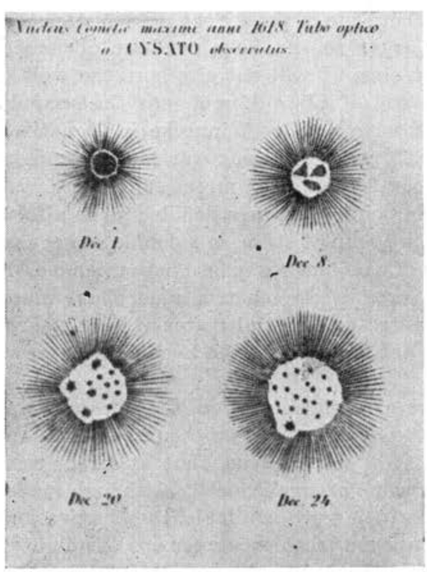


Figure 14.

1 Let the reader reflect that the micrometer was not yet invented; then the contradiction of these estimates with the preceding estimate of two-thirds the diameter of Jupiter will not cause surprise. Please look at the sketches of Figure 14, faithfully reproduced from *Cometographia of Hevelius.*

in diameter (although on the first day it was far smaller); neither was it round any longer, but split into three or four globes of irregular shape cohering to each other just as the 'companions' of Saturn are accustomed to appear."[1] (Fig. 14)

"*December 17*: In place of that recently compact nucleus several very minute little stars have appeared with a very dim light spreading around and between them as gleaming through a nebula or a white light, and this seemed much clearer and more distinct on the following day (the eighteenth).

"*December 20*: The middle, or nucleus, which on the first day had appeared just as a solid and round light, is clearer. It appeared separated into many little stars so that now there were masses of many very small little stars of which three seemed more steadfast and more distinct than the others. And of these, the largest was about like a star of the fifth magnitude. Apart from that mass of little stars a small star shone in the bordering light, which first was thought to pertain to the rest of the mass, but later it became plain, after an hour and a half, that it was a fixed star. Moreover, this little star too was far smaller than the smallest satellite of Jupiter. Finally, the diameter of this nucleus or of the ball of the stars now was five or six minutes, certainly noticeably larger than on the first of December.

"*December 24*: Both the nucleus (or ball and mass of little stars) and the radiance surrounding it occupied a far greater space than before but with a light much thinner and more dim. Of the three distinct stars seen recently now only one was continuously seen. There were very many others, but they could not be separately counted, because, although they were certainly seen to sparkle often, nevertheless not all of them at the same time continuously and constantly, but interruptedly, one after another springing into view, just as in a very clear sky the very smallest fixed stars are seen with the naked eye. Finally there were today single ones far more widely scattered from each other than on the previous day so that the diameter of the nucleus was at the minimum about six minutes, the width of the encircling fringe was five minutes and the whole about sixteen minutes. This was the last day it was possible to observe through the telescope. In the adjoined drawing our words are pictured." (See Fig. 14)

116. *Observations of Wendelin.* "The very head of the comet when I first examined it in the telescope on the twenty-ninth of November, I saw shining just as if three or four glowing coals were burning on a large hearth. I saw, I say, the comet as a triple globe, and indeed I noticed those three coals change position somewhat before my very eyes just as it would be if one looked at a fire, and on the following days more coals were seen, just like our charcoal, which splits into many parts when it is kindled."

117. The comet 1618 II, the singular appearance of which we read here, passed perihelion November 8, 1618; on December 6 its ano-

[1] That is, the ansae of the ring.

maly had reached 90°, and the distance of the sun was double the perihelion distance. From the beginning to the end of December its distance from the earth was about doubled; in spite of that the angular diameter of this complex system, that Cysat called a nucleus, grew very much. We then see that with the increasing distance from the sun the dimensions of such a nucleus, or rather that system of nuclei, rapidly increased. If we admit as plausible the data of P. Cysat with respect to the dimension, we have the following table:[1]

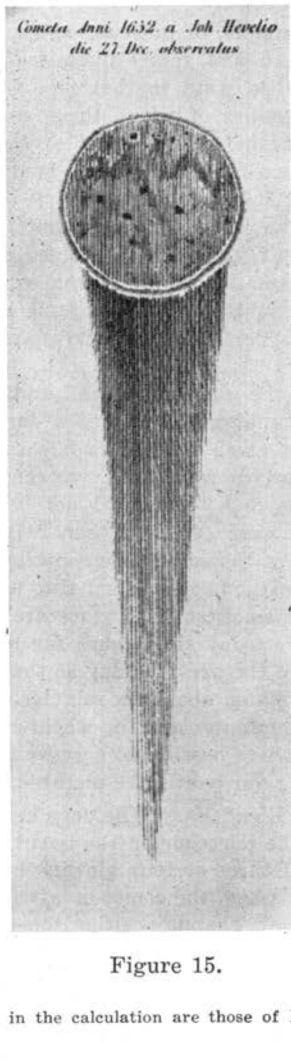


Figure 15.

1. The elements used in the calculation are those of Bessel, published in the *Berliner Jahrbuch* of 1808.

Day	Distance from earth	Distance from sun	Apparent diameter nucleus	True diameter (d of earth = 1)
Dec. 1, 1618	0.37	0.71	2′	2.4
8, 1618	0.37	0.86	4	4.9
24, 1618	0.43	1.14	6	8.6

It then appears evident that the irradiation of the sun is not the force which causes the expansion, but rather the incipient dispersion of the mass produced by the forces described above. We do not wish, however, to insist too much on this conjecture, which needs further confirmation.

118. The comet (1618, II) just now considered, though of peculiar structure, was abundantly furnished with the material whence comets develop, as we see in the article about it which we have. Not so the single comet of 1652 (if comet it may be called), which is the best example that we can cite in favor of our thesis. It showed the appearance of an irregular and heterogeneous mass, almost sperical in form and of large volume, provided with a tail not in proportion to its dimensions. We refer to our Fig. 15, which is a copy of telescopic drawings by Hevelius. The account of this astronomer is the most complete and accurate that we have, though his good faith has been doubted by noted authorities. We shall reproduce the description of Hevelius and those of principal contemporary observers, leaving the reader to judge in his own conscience whether or not the doubts mentioned have a foundation. We shall then see how dangerous it is to deny or doubt an observed fact, only because it does not square with the received theories.

119. The comet of 1652 was seen for the first time in America by Father John Königk, a Jesuit, the fifteenth of December of that year. One must say that its aspect was very extraordinary at that time, since the Father wrote some time later to Father Kircher: "In 1652 on the 15th of December a double comet appeared, with separate tails and a third projecting from one of these."[1] The comet was at that time invisible in Europe; from the lack of testimony at the same time, it is not possible to get a clear idea of the meaning of that description. On December 18 it was seen by David Christians in Giessen who describes it thus:[2] "I observed a new appearance, and a new star with a diffuse, faint, and cloudy light, which in general was very like that circle, or congeries and conglomeration, of stars called the Pleiades; except that from the beginning and for several days following, to about today (December 18) it seemed somewhat bigger than that circle of stars, so that if anyone were to look at its extremity closely, he would liken it in apparent size to a little wheel about nine inches in diameter, although on account of the shadowy aspect of the dull light it could not be seen by any means so plainly as the planets or fixed stars."

120. Hevelius saw the comet for the first time December 20, 1652, at six o'clock in the evening. 'The head was round of unusual size,

1. Hevelius, *Cometographia*, p. 352.
2. *Ibid.*, p. 889.

Proceedings of the Iowa Academy of Science, Vol. 50 [1943], No. 1, Art. 6

scarcely less than the full moon; a tail, or an unusual and abundant beard extended six or seven degrees. Moreover, the light of the head is pale, and partly dull, and less clear. It seemed very like a moon overspread by a very thin cloud; the tail luxuriated with a light quite similar, but weaker and paler as yet, and terminated in a very fine edge."[1]

"*December* 23: The tail extended toward the northern eye of Taurus, and in the same manner in which it was piled up before. The phenomenon was much diminished as to the size of the body and the size of the beard.[2] At 11 hours and 15 minutes the diameter of the comet was observed by the directional (azimuthal) quadrant as twenty-five or twenty-six minutes in several observations. The color of the head was pale and bluish covered with white.[3]

"*December* 26: The body of the comet appeared somewhat smaller, but nevertheless the diameter, according to the great quadrant, extended twenty-four minutes. Scarcely anyone will believe this.[4]

"*December* 27: The length of the tail was estimated as about 4°. Further, with a certain very long telescope (which revealed, among other difficult objects, the satellite of Saturn, too) I looked at the comet's body.[5] Moreover, the whole disk, (which extended twenty minutes or more), could not be seen at the same time in that telescope. It shed a rather dull and feeble light, and in the disk, toward the tail and the left, four or five small bodies or nuclei appeared, somewhat denser than the rest of the body. Two of these seemed a little larger than the three others, although as yet divers others, very minute, showed themselves here and there sparsely over the disk, yet were on the verge of invisibility. Hence it was not possible to distinguish and draw them clearly. And to the right we saw a somewhat curved and bent light, much clearer than the rest of the body, just as if there were a swarm of many very minute little bodies. Moreover, the light was not so intense and vivid as that of other fixed stars, but a little duller."[6]

"*January* 3, 1653. We saw a feeble light but not a tail. The diameter of the body was estimated as seven or eight minutes; very like the very feeble light of some nebulous star.[7]

"*January* 7. The whole body was small and weak, the light of this very pale, the diameter about five minutes.[8]

"*January* 10. It disappeared to the naked eye. To those armed with a longer telescope it showed itself somewhat. There we caught it, much reduced in head and brilliance. . . Moreover the small body was very thin, so that no nuclei appeared in it. Indeed hte material, except where spread like a shadow, seemed thinned out by some scattered fis-

1. Hevelius' *Cometographia*, p. 1.
2. *Ibid.*, p. 3.
3. *Ibid.*, p. 7.
4. *Ibid.*, p. 8.
5. This remark was probably added by Hevelius some years later—the Huyghenian satellite of Saturn was not discovered until 1655.
6. *Ibid.*, p. 326.
7. *Ibid.*, p. 327.
8. *Ibid.*, p. 327.

sures and pathways, all of which nevertheless were discerned with difficulty and with care."[1]

Hevelius could not observe the comet after January 10.

121. *Observations of Cornelius Malvasia at Bologna.*[2] "The first hour of the night of the twenty-first of December a comet was found around the stars of Orion's shield, nebulous and large, its diameter almost equal to that of the moon. In the telescope the body did not present a uniform appearance: in the center it had a white disk looking like the moon amid the stars, of the size of the moon as seen with the naked eye, and even a bit larger."

122. *Observations of Wendelin.* "On the twenty-first of December at eight in the evening an unknown star in the shield of Orien, bigger than any of the nebulous stars, shone evilly with a pale hue similar to that of boxwood, mournful and obscure. It was as big as the moon, or larger.[3] Then I got out the telescope and explored it for a period; I saw in it several very small stars, and one of them was bigger than the others and oblong, in the midst of the others. One would say it was a fire-place where the wood had been consumed and left glowing ashes, with coals and sparks intermingled. In short, it looked to me like the comet I saw last year in the hand of Bootes."[4]

123. I omit citing other testimonials which agree that in the beginning the head of the comet was as big as the moon, that the light was pale, and the disk scattered over with brighter patches. The descriptions that I have repeated, together with the drawings of Fig. 15 (which reveal certainly very little skill in this kind of picture, but agree perfectly with the written account) is sufficient, I believe, to convince the most suspicious, that the comet of 1652 was of an unusual appearance, and that it consisted principally of a spherical mass of irregularly condensed material in the inside, and containing, besides a formless accumulation that we can consider as the principal nucleus, a certain number of small nuclei, and a very great number not precisely discernable in the telescopes of that time. Moreover, the same principal accumulation seems to have consisted of a mass of small nuclei, (observation of Hevelius, December 27). The tail on the contrary (if we may call it such) was hardly visible; several authors do not mention it; and all, or almost all, confess that in the beginning they could not bring themselves to consider this singular apparition as a comet, and only the nature of its apparent motion could induce them to place it in that class.

124. With the help of the elements of Halley, having calculated the distance and the diameter of the comet for the days in which this diameter was observed by Hevelius, I obtained the following results:

1. *Ibid.*, p. 327.
2. *Ibid.*, p. 325.
3. *Ibid.*, p. 304.
4. *Ibid.*, p. 328.

Proceedings of the Iowa Academy of Science, Vol. 50 [1943], No. 1, Art. 6

Day	Distance from earth	Distance from sun	Apparent diameter	True diameter in terms of earth's
Dec. 20	0.13	1.07	30′	13
23	0.16	1.11	25.5	14
26	0.22	1.14	24	18
Jan. 3	0.44	1.25	7.5	11
7	0.54	1.29	5	9

We see that the variations of the diameter do not exceed the uncertainty of observation, and especially of the last ones, in which the comet was not well visible. The minimum distance of the comet from the earth was about 0.12 and occurred about December 19. Taking 15 of the earth's diameters as the average value, and supposing that the density of the spherical mass was that which is determined by formula (34) as the necessary limit to the stability of the system (if the distance of the sun is equal to unity, or if R = 1 in the formula cited), the result is that the mass of the comet must have equalled that of a sphere of water with a diameter 10 times less than the diameter of the earth. Suppose that the density of the earth is six[1] times that of water. We might conclude that the mass of the comet was less than 1/6000 that of the earth. This presumes that in the comet the density of the head was uniform. Anyhow, since there does not appear any trace of deformation in the head, the mass of the nucleus does not seem very great,[2] our computation gives then an approximate idea of the limit, below which the mass of the comet cannot descend.

125. If the preceding examples make it clear that masses of very rare and irregularly concentrated material exist in space, and can be attracted by the sun into the more interior parts of our system, the second comet of 1811 shows us instead this same celestial material reaching a great height of concentration, a comet that approaches the category of objects properly called stars. W. Herschel has given us an accurae tdescription in the *Philosophical Transactions* of 1812.[3] It consisted almost exclusively of a very definite nucleus of planetary appearance, surrounded by a thin halo, and hardly discernable in those powerful reflectors. If traces of light had not been seen in the direction opposite the sun, Herschel observes that this comet had hardly merited such a name. He regarded it as a body in an advanced state of consolidation, not containing more than a small portion of nebulous material.[4]

126. Before closing the present investigation, we will add some discussions of the way in which we imagine shooting stars might arise from sparse meteoric material in celestial space. The manner in which the shooting stars appear quickly suggests isolated bodies, solid at least in part, and scattered very thinly, even in the most dense parts of the stream.[5] We have every reason to suppose that the inter-

1. The modern value is 5.52. *Translator.*
2. If the density of the nuclei had been much more considerable than that of the less luminous envelope in which they floated, the figure of equilibrium of the globular mass would not have been so exactly spherical, as the observers represent it.
3. *Philosophical Transactions,* Vol. CIII, p. 229.
4. *Philosophical Transactions,* Vol. CIII, p. 236.
5. See in this connection the calculation of Father Secchi in *Bullettino Meteorologico,* Vol. V., p. 132, and mine in the *Bullettino,* Vol. V., p. 115.

vals separating them are entirely void. And if shooting stars appear in groups or in waves, that merely signifies that, as in the fixed stars, we have here too examples of double and multiple systems. The number of these bodies is extraordinarily great even in the streams of mediocre density, and the frequency of telescopic meteors shows certainly that the meteoric stream is a river of dust, the grains of which present all the possible states of division, from the dimensions of the greatest meteorites down to the finest and most impalpable dust. It is exactly on this idea that Father Cavalleri has given a very probable explanation of diffused light. that was observed in the last Leonid shower and in other similar cases.[1]

127. We can raise this question: can we not imagine streams of continuous and extremely rarefied material, such as the original material of Herschel, the by-product of which we see as these meteoric streams. This idea has been advanced, and sustained with favorable arguments, by Father Serpieri.[2] *A priori* we have no reason to deny the possibility of such streams, or at least we do not understand why continuous streams could not be generated from continuous material. But we are certain that the meteor stream really is composed of discreet material, with intervals completely void; and the intersection and interpenetration of several streams at the same point of space is established. The researches of Heis and of Greg show that on every night the meteors fall from several simultaneously effective radiants, and this signifies, that, at that point where the earth is, several meteor streams intersect without disturbing each other. That, we find, is natural enough for discontinuous streams of dust-like structure, and impossible for continuous streams, as for example, rarefied gas or other such material. Consider the great number of streams that must fill the planetary spaces, in order that five or ten or more will intersect in every point; and then judge what horrible chaos would arise if, all of a sudden, these streams became continuous, and thus capable of restraining and modifying each other.

128. It would be erroneous, however, to conclude from this constitution of the meteor streams that the celestial material of the universe is a mingled dusty nebula. The deduction is not rigorous, and generally speaking probably is false; because spectral analysis has by this time proved certainly that many nebulae, belonging to the class which the telescope cannot resolve are simply masses of gaseous material barely lighted, and of a high temperature. Also, the structure of many meteorites proves that masses of incandescent vapor must have existed in celestial space. He who can show me how the crystals of *olvina,* which are scattered in the inside of the meteoric mass of the *"iron of Pallas,"* could penetrate there without an antecedent vaporization of the iron itself — he will be a veritable Apollo. One will ask then if continuous material can generate discontinuous streams?

1. *Rendiconti dell'Instituto Lombardo,* Vol. 4, p. 85 and following.
2. *Bullettino Meteorologico de Collegio Romano,* Vol. 6, p. 17 and 27. See *Bulletino Met. del Coll. Raffaello d'Urbino,* 1867, fasc. 2, p. 12 and following.

129. Here again we find very simple consequences of the different ways of accumulation and of the different degrees of concentration of the original material. When a gaseous mass of compressed spherical form, without branches or divisions, is cooled and condensed by the irradiation that takes place at its surface, the process takes place more slowly when the dimensions are very large. The outer portions are condensed quickly, but the irradiating molecules conduct new heat to the internal part; hence the diminishing of temperature is by degrees, and the mass diminishes successively in volume and becomes more compact, and ends by condensing into a single body, without dividing or dispersing. According to the theory of Faye, such is the process now going on in the sun, already completed on the earth, and completed still earlier on the moon.

130. But if instead we have a mass of vapor of an irregular and notched form, with interstices, divisions, branching, and interruptions, the work of cooling is quicker in the thin parts and those parts projecting farther out. It is clear that in such a case there can arise from the condensation several principal nuclei, now and then a solitary nucleus; and finally there can be numerous and irregularly or regularly distributed centers of condensation. Consider the figures of the stellar clouds according to W. and J. Herschel, and according to Rosse. This formation can make accumulations of every order, beginning with a principal nucleus, and ending with minute dust.

131. It is possible for a spherical mass of material to have a strong condensation at the center, and yet have extremely rare vapor towards the circumference and in the most outer layers. Condensation then can take place quickly in the outer layers near the surface, before the necessary heat is lost from the center. We shall have as a final result a principal body in the center of a myriad of smaller bodies. The central body can then be in a vaporous state, and the bodies surrounding it completely condensed. Such a system, if drawn into the vicinity of the sun can produce a comet with an accompanying meteor stream.

132. Finally we can postulate a very rare and homogeneous mass, thin along one or two of its dimensions. The concentration can then take place simultaneously in all the mass; it will show an infinite number of centers of condensation; the mass will become a dusty cloud and can, approaching us, produce a stream without a comet. A very good illustration of such a condensation of material is afforded by the crystalizing of bodies in a supersaturated chemical solution.

133. This, then, is how phenomena very different in appearance can arise from the multiform action of a single cause, the different concentration of the celestial material under the influence of gravitation. That same material, in different circumstances, produces the fixed stars, the planets, the comets, the nebulous masses, and the shooting stars. This is then the v, α, η, of Anaxagoras, the beginning of everything in the physical universe! It has been easy, especially after Galileo, to describe the great bodies of the firmament; but they appeared isolated, forming in certain ways the framework of the world.

Now these cosmic rivers, which run through the intervals between the stars, maintain communication between all the parts, and are the principal agent of the universal circulation. What functions they are destined to fulfill, we do not yet know.

134. The Abbe Raillard[1] is inclined to assign to our meteor streams the function of distributing temperature. He assigns to some of them the periodic cooling, which Erman was the first to notice towards the middle of May. According to Erman the cooling takes place when the stream is interposed between the earth and the sun, subtracting a part of the heat; according to Raillard, the stream itself coming from regions of lower temperature, would cool the earth by the simple fact of immersion. We can also imagine, that a nebula in the state of incandescent gas, and transforming itself into streams, might produce upon the earth the phenomenon of the final burning, thus fulfilling the prophecy expressed by the rugged but terrible verses of the Sybilline oracles:

"*Slumber will hold the seasons; the seeds of the world will be sterile,*
Air and the earth, and the sea, fiery light of the sky,
Days and nights, the pole, will fall together a-flaming;
Nature's face will become fearfully desert and drear."

I find myself obliged to confess insufficient preparation for a discussion of this nature, and ask leave not to take part therein.

IX

DIFFERENT OPINIONS ABOUT THE RELATION THAT EXISTS BETWEEN THE COMETS AND THE METEOR STREAMS

135. The analogy and the reciprocal relation which exists between the comets and the meteor streams has been discussed in the preceding paragraphs by means of their common origin. Taking as true our theory, which is a simple extension and particularization of the immortal views of W. Herschel, it follows that in a certain sense the meteors can be regarded as so many comets, although the smaller mass and the much different degree of condensation have produced an apparent contrast of form. In every case we must remember that the comets are bodies of higher order[2] and if we call "comet" every mass

1. *Les Mondes*, Vol. XIII, p. 606; Vol. XII, p. 648.

2. I have already mentioned the idea (see my letter III to Father Secchi), that the comets, supposedly isolated, can have a relation with meteoric streams similar to that which the great planets of the solar system have with the minor planets between Mars and Jupiter. In this case every meteor would follow a zone in which an infinite number of comets move, and each meteor should be considered different from comets only because of its mass. Such was the opinion that I had formed of this before the coexistence of the comets 1862 III and 1866 I with the Perseids and Leonids was discovered. But further reflections upon this argument, as well as some very thorough observations that Otto Struve was kind enough to communicate to me by letter, forced me to abandon entirely the idea of regarding every meteor as the equivalent of a comet. This does not remove the possibility of seeing meteors comparable in mass to a comet, or comets of very small volume. To the examples that I mentioned in the letter cited, by the graciousness of Professor Littrow, I am now in a position to add the single and perhaps (until now) unique observation described by Jahn in Volume XXIII, p. 237, of the *Astronomische Nachricten*, to which the aforementioned professor has called my attention. He tells of a comet with three tails, which in about the 26 minutes it was visible, traversed an arc of about 40°. Without doubt it passed very close to the earth, and was proportionately very small. See the reference cited. That happened July 3, 1845.

of material describing an elongated orbit about the sun, we can then say truthfully, that the meteors arise from the dissolution of the comets. After the development given in previous paragraphs it would be useless to do more than to explain the meaning of all these expressions. Such might lead us to the danger of making questions upon simple words.

136. Whenever we speak of the dissolution of the comets, this ought to be interpreted in the sense used up to this time; that is, we are concerned with the dispersion of parts of a mass of material under the influence of attraction alone (which means the solar attraction for non-periodic streams, and also in part the attraction of a perturbing planet for the streams of short periods). It has been shown that this cause is abundantly sufficient to produce all the observed phenomena; and every time that this cause acts, its effect, if the effect takes place, is none other than the formation of a stream, which is elongated on the orbit of the former body about the sun. If then, in some one of these bodies that arrive from the depths of space, some other kind of dispersion is seen, in which the particles do not extend on the orbit, but in other directions, we shall be obliged to conclude that this dispersion is of a kind different from that we have considered just now. This is precisely the case for the comets with a tail, which seem to lose their material as they advance in space. This loss does not occur along the orbit, but in the direction of the radius vector, which normally is almost perpendicular to the orbit at the time the tail is greatly developed.

137. Since we consider the formation of the cometary tails as a material phenomenon, and not purely optical, it is impossible to suppose that the material of which these very long appendages are composed will not be dispersed into space, at least in most cases. When every connection of this tail-material with the nucleus of the comet is removed, this material is arranged in the form of ample layers in the plane of the comet's orbit. A thin stream is not formed, but a layer of material in motion, the particles of which describe orbits of different natures, all in the same plane. Now it is clear, that the phenomenon of the meteor radiant supposes a thread-like stream, all the orbits of which can be regarded as parallel at any given point. A stream in form of a layer, as that generated by the tail of the comet, cannot diverge from a single apparent radiant, but truly from a series of infinite points forming a continuous curve on the face of the stellar hemisphere—because only in special circumstances and for a few points of the stream can we imagine that all the paths of the particles are parallel and described with equal velocities.

138. This does not seem to be a case to apply the well-known rule of Newton, in which he advises: To natural effects of the same kind, the same cause ought to be assigned.[1] If it were possible to explain the formation of the comet's tail by gravitation only, combined with a force of expansion or projection, residing in the nucleus, it would be

1. "Effectuum naturalium eiusdem generis eaedem assignandae sunt causae, quatenus fieri potest." *Principia*, lib. III, Regula Philisophandi II.

worth while to try to reconcile the discordances and the differences noticed from time to time between the thread-like streams as they are calculated by the attraction theory, and actually observed, and the stratiform streams that the comets necessarily produce because of their caudal emissions. But if there is one definite thing in the physical theory of comets, it is this: that the movement of material of the tail is caused by an unknown force of nature, which nullifies the effect of gravitation, and produces effects even contrary to those of gravitation. I am astonished that this point is not evident to all. Without doubt it is well to guard against the introduction of new causes, and new classes of phenomena if they are unnecessary. But, when many facts lead us to the same hypothesis, and when this offers the simplest and most natural way of resolving insuperable difficulties, common sense dictates that this be not rejected because it contains something new in the order of nature.

139. The luminous jets, which the nuclei of many of the great comets customarily emit are very well known. We see these jets arise from the part of the nucleus nearest to the sun, and the force of the projection that raises them seems great. The material which composes them expands rapidly, forming a kind of helmet, or a luminous sector. These sectors invariably have the property of running backwards, throwing off the material of their edge in the direction of the tail of the comet. Such destruction can occur in all parts of the sector, when its axis of symmetry is turned to the sun; but it happens frequently, too, that when the axis is inclined, in virtue of certain oscillatory movements, the destruction is greater in one part than in others and it also happens now and then the whole is destroyed on one side, giving rise to a parabolic jet. There are more or less evident examples of such phenomena in the great comets that appeared in 1665, 1744, 1819, 1835, 1858, 1861 and in 1862. This destruction of the jets causes the material ejected by the nucleus to move toward the sun finally to mingle with that of the tail; and it seems in many cases that the splendor and the greatness of this appendage are due principally to the material of the luminous jets.

140. The divers attempts made to explain these singular phenomena by simple combinations of the initial movement of the projection of the jets with the parabolic movement of the nucleus have been fruitless up till now. Roche, considering the form of the comets as results of simple equilibrium of a fluid under the gravitational action of the nucleus, and by introducing a repulsive action of the sun, succeeded in reasoning how a phenomenon could be produced somewhat like the jets.[1] But however beautiful and ingenious we wish to term Roche's theory, no one who observed the comets of 1858, 1861, and 1862 can admit that it represents even approximately the phenomena that indubitably occur in nature. These jets are now and then double, as in the comets of 1744, 1835, and 1858.[2] Donati's Comet of 1858 also show-

1. H. Resal: *Traite Elementaire de Mecanique Celeste*, p. 286.
2. See the drawings of Heinsius, of Struve, and of Bond.

ed four jets and even more at one time, as we see from the drawings of Bond. Evidently, we do not here have a fluid in equilibrium, but material projected with force from certain regions on the surface of the nucleus, which are better adapted to this work of ejection; and if such material folds back to reach the tail and even form it in great part, this happens simply because an unknown force pushes it in the direction opposite to the sun. Such a force, which seemed necessary even to Kepler and Euler to explain the formation of the comet's tail, must have intervened to explain the formation of the jets, but in a rather more artificial way, than in the theory developed by Roche.

141. If, leaving the complex and various actions that customarily are manifested about the nucleus, we follow the development of the tail in space, we find before us a mass of very simple, and to a certain point, calculable, operations. This long stream of luminous material is regulated in its course by the velocity with which it separates from the nucleus, combined with the action exercised chiefly by the sun, but also in part perhaps by the nucleus, on the material liberated. The fact that the greatest part of the comet's tail is curved in the plane of the path described by the nucleus is testimony that actions other than these, generally speaking, do not intervene to determine the form and the curvatures of the tail. One should add the circumstance, that many times the thinning of the tail allows us to regard it as a linear system of points. All this is extremely favorable to the research on the relations between the observed form of the tail, and the forces that determine this form. The problem becomes comparatively simple. Consider a point of the caudal material which, at a determined time, is at the end of the luminous addition, in a known position of space. This point arrived there, parting from the nucleus, close to which it once was. Is it possible by simple gravitation to explain this transfer, and construct the tail without other suppositions?

142. The problem has been proposed and resolved in this form by the great Bessel, and no one can doubt that this is the just and direct way to solve it. This is not a mere hypothesis. Bessel, treating Halley's Comet in this way with calculation,[1] was led to announce, "The presence of the tail does not leave any doubt about the existence of a force that works on the material in a different manner than universal gravitation,"[2] to say in another place "It is impossible to doubt a real or apparent repulsive action of the sun on the comet's tail,"[3] and in a third place, "The ordinary form of the tail is inexplicable with ordinary gravitation."[4] In this he did not express an hypothesis, but the actual mathematical result of the facts observed in the tails themselves, and which one may not doubt if he weighs part by part the rigor of the reasoning of Bessel. This repulsive force, as the cautious astronomer of Königsberg well warns, can have, or cannot have, its origin in the sun, although it operates in a direction contrary to that

1. *Astronomische Nachricten*, numbers 300, 301, 302.
2. *Ibid.*, paragraph 15, p. 229.
3. *Memoria citata*, p. 225.
4. *Ibid.*, p. 225.

of the great luminary; similarly it can be true, or untrue as well, that it decreases with the square of the distance from the sun, without thereby being any less real for that.

143. It is impossible to determine the numerical value of the force in question, without making some particular hypothesis on the law with which it operates. Bessel, having performed his calculation on the assumption that the sun is its center, and that it varies as the inverse square, determined, by his own observations on Halley's Comet, the constant of this repulsion; and found that taking the constant of gravity = +1, that of the repulsion exercised on the tail of the comet was, in 1835, equal to -1.812, almost double the universal attraction, and effective in an opposite direction. In 1858, Pape made a similar discussion of Donati's Comet, and found that for the principal tail the action of the sun, far from being repulsion, ought to be regarded as an "elective attraction," the constant of which he found to be +0.612. But the secondary and almost rectilinear tail observed by Bond and by Winnecke gave a repulsion more than five times gravitation, with the constant -5.317.[1] Finally the author of the present writing having subjected to a similar calculation the observations on the comet of 1680, that Newton has transmitted in the *Principia*,[2] found it was possible to represent the position of the extremity of the tail by assuming the action of the sun zero on the parts of the comet, that is, by taking the constant of the repulsion or of the "elective attraction" equal to zero.

144. Although these numerical results have no more value than the hypothesis on which they are founded, they indicate clearly (and the multiple tails confirm sufficiently) that the repulsive or "elective" action in the direction of the radius vector varies from one comet to another, also from one tail to another of the same comet. But it is necessary to admit it in a greater or less degree in all the comets with a great tail. Here then in the tails is testimony of the existence of this force, which confirms the result of mere inspection of the luminous jets (paragraph 140). I beg the reader to observe that these two testimonials about the fact of the repulsion are independent of each other. Is it then reasonable to doubt still? For myself I conclude: There exists in the comet a kind of particular material (which for brevity I shall designate with the name "comet material") on which the sun exercises a lesser attraction than on the remaining material, an attraction which in most cases is turned into repulsion. In spite of the presence of this material in the body of the comet, the comet obeys the laws of Kepler; from which we can argue, either that the mass of that material is negligible in comparison with the body of the comet, or that such material has unusual properties. The development of the tail depends exclusively on the abundance of this material, and on the efficiency with which the sun works on it. Separating from the comet, it is in the power of its own "elective attraction," and determines the

1. *Ibid.*, Vol. XLIX, p. 342-346.

2. Ed. of Glasgow of 1822, Vol. IV, p. 175.

formation of the tail. It is possible, that at this time it carries with it some of the ordinary material; in that case we have a natural explanation of the different intensities of repulsion that the different tails show. Such material mixed in small quantities in a mass such as the comet of 1652, could produce that rare and insignificant beard that accompanied the aforesaid comet. And through the effects of its release from the more or less dense cometary body nearing the sun, perhaps many a singular phenomenon can be explained. But, since we do not wish here to go into the intricate question of the nature and the phenomena of the comets, it is sufficient to have shown the existence of the repulsive force in the jets and in the tail, which was our purpose.

145. This repulsive force established, we quickly comprehend that neither jets nor tails can give rise to shooting stars, because the shooting stars are formed of material that obeys all three laws of Kepler, especially the third—a phenomenon that excludes any idea whatever of "elective attraction." Were it not so, we would not see them accompanied by comets in the same orbit, and in the case of the Leonids we would not have seen the comet 1866 I still in the vanguard of the swarm after the considerable number of revolutions (certainly greater than 29) that the whole system has made after its dissolution into a stream. The constant of the solar attraction, that rules the motion of the shooting stars, is therefore equal to the general constant, which rules the motion of the planets and the comets; or at least if there are differences they are without doubt imperceptible. I believe that this argument will always render impossible any attempt to deduce the formation of the shooting stars from nuclear or caudal emissions of the comets; this is independent of the reasons already suggested in paragraph 137 and 138. The material of the tail, hardly separated from the nucleus, moves rapidly away from the sun, describing a hyperbola, and cannot form a stable formation like the meteoric streams.[1]

146. Professor Erman, who was the first to establish in rigorous terms that the course of shooting stars is an astronomical question, has lately published an article on this point. After expounding in a historical way the chief progress made since 1840, he examines the different possibilities offered to explain the manner of generation of the meteoric streams. Instead of assuming with Laplace that the comets make a part of the stellar world, and that only by the combination of their movements with proper motions of our system do they come to pass near the sun, he considers the comets and shooting stars as members *ab antiquo* of the solar system, although he regards them as independent of the planets. While the orbits of the planets are sub-

1. I discussed the theory of the nuclear and caudal emissions of the comets at some length, first to explain better what I mean by dissolution of the comets into streams; second because the nuclear and caudal emissions do seem to furnish the more natural explanation, though not the truest, of the meteors. Faye has treated this thing with his usual elegance and sharp-wittedness in Vol. LXIV of the *Comptes Rendus*, p. 552 and following. Here, above, I have developed the reasons that prevented me from accepting his opinions. The connection of the comets with the swarms of shooting stars is not arbitrary in our hypothesis, as Faye affirms, but it is a fact dependent on the very generation of the stream and of the comets. See paragraphs 110 to 112 above.

ject to those rules which all know, according to Erman the orbits of the non-planetary bodies can be regarded as determined by chance in all their elements. Going back to the time in which the great parent nebula of our system extended beyond the orbits of all the planets, we see that the resistance of its material ought to have contributed to the rapid curtailment of the major axis of the orbit of the comets or of the shooting stars. Hence the shrinkage of the orbits, which has produced short-period comets, and which according to Erman could have produced other orbits equally short, or shorter, for the meteors. In this way he tries to establish the possibility of those orbits of very short periods, not at all analogous to the known bodies of the solar system, which were determined for the Perseids and Leonids by different calculations.

147. If the question included only the Perseid and Leonid streams, it could be termed solved, since it is beyond a reasonable doubt that the latter have an orbit of 33¼ years, while the former have an orbit of more than 100 years (though not certainly, at least very probably). But considering in general the possibility of an orbit of revolution of just several months, and having any eccentricity and inclination whatsoever, it seems to me comparison with the comets is not very favorable to it; in fact, while there are some comets with periods of 5, 6, and 7 years (there are at least six), only one, which is Encke's, has a period of about 3.29 years; until now no other has been found with a shorter period of revolution. This is the reason why I have always regarded as synonomous the words "comet's orbit" and "orbit of long period," attributing to the bodies that describe such orbits a velocity approximately equal to a parabolic velocity. I have not assumed that all the shooting stars ought to have parabolic or hyperbolic orbits, though that opinion has wrongly been imputed to me.[1] No one will have difficulty in admitting for the shooting stars the possibility of orbits of a few months or even of a few days, as soon as it is proved (as is not now the case) that meteor currents do exist that are moving in such orbits.

148. The resistance of the medium of the solar nebula of Laplace, while it could serve to explain the short-period orbits of non-planetary bodies, also provides a simple, and in our opinion elegant, way to explain the formation of annular (ring-form) meteoric streams. The resistance of a medium to the progression of a body does not depend solely on the density of that medium, but also on the size, density, and shape of the body itself. If we then imagine that a swarm of small bodies of differing mass, shape, and density, revolve about the sun and cross a resisting medium, their velocities will be unequally affected by the unequal resistance. There soon will arise a diversity of revolution-periods that changes the original swarm into a continuous ring. This way of generation could evidently be considered valid if we assume, either with Laplace that the comets come one at a time from stellar

1. Erman: *Archiv fur die wissenschaftliche Kunde von Russland*, Vol. XXV, Berlin, 1867.

space, or with Erman that the comets have been with the solar system from the beginning. We shall be able to consider it more or less probable, according as it is more or less probable that the resisting medium produces effectively comet orbits of short period.

149. We are ready now to prove that of the two causes capable of producing short period orbits, the resistance of the parent nebula and perturbations produced by the great planets, the second is much more probable than the first. At the present time this is evident, since today the resistance of the parent nebula, if any, is inappreciable. Faye's Comet has demonstrated that brilliantly in recent years. On the contrary, almost under our eyes the massive Jupiter has brought into the internal part of its system, and deviated into orbits of short periods the comets of Lexell and Brorsen. Hence we can conclude with certainty that because of the great number of comets such events have not been rare in the history of our system, and the deviation of the Leonid swarm that we assumed (paragraphs 108 and 109) enters into the limits of common probability. But I say that the remaining monuments to the ancient evolution of the planetry system testify eloquently, that throughout all time the perturbations of the planets, principally, caused non-planetary bodies to traverse orbits of short periods.

150. The solar nebula is assumed to have been endowed originally with a rotary motion, whose velocity increased with the condensation of the nebula. If this is so, it is clear that the comets of direct motion ought to have met less resistance than those of retrograde motion. Therefore, among the orbits of the periodic comets, the shorter periods ought to correspond to the retrograde comets, at least in general. On the contrary, if we assume the planetary perturbations as the cause, it is evident that the greater changing of the orbits occurs in comets of direct motion. It would take too long to demonstrate this assertion; let it suffice to show two examples. Upon a direct comet pursuing a parabolic orbit inclined 18° to the orbit of the earth,[1] and placed according to the conditions indicated in paragraph 82, the attraction of our planet can change the parabola into an ellipse of 4.32 years of revolution; while on the retrograde Leonids, following an orbit inclined 18° to the earth's orbit,[2] the attraction of the earth can change the period of 33.25 years to one of 28.67 years (see paragraph 93). Now, among the known comets, fourteen have a period under 100 years, and two only, Halley's Comet and the comet of 1866, have retrograde movements; observe, too, that their periods are 76 and 33 years respectively. This shows clearly that the planetary perturbations shorten the periods. For these reasons it does not seem opportune to employ the resistance of the parent nebula to explain the formation of the annular streams of shooting stars.

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1. Notice that we say *to the orbit* and not *to the plane of the orbit.*
2. The same as footnote 1.

151. I will investigate finally the question of the possible relation between the shooting stars and the zodiacal light. Biot, in 1836, introduced some arguments in favor of the opinion that the zodiacal light is a cloud of small planetary bodies surrounding the sun, whose encounter with the earth would cause a meteor shower. If we could prove that the orbits of the shooting stars are almost circular in form and slightly inclined to the plane of the ecliptic, no one could doubt that the hypothesis of Biot would be very probable. The relation between the shooting stars and the comets makes it more difficult to conceive how bodies describing orbits of every possible inclination could produce a phenomenon so intimately tied up with the plane of the ecliptic as the zodiacal light. Faye did not doubt that we could remove this difficulty.[1] He observed that the orbits of the comets of short periods deviate only slightly from the plane of the ecliptic, which is a natural result of the way in which such short periods are produced. But neither does the number of the comets of short periods compared with the others seem great, nor, does their adherance to the plane of the ecliptic seem to be so close and constant as to produce a considerable surplus of light along the zodiac. We may not expect an answer to this question from a discussion of such uncertain data. I will produce instead another argument, which definitely demonstrates that the zodiacal light cannot be produced by the meteoric cloud composed of bodies similar to shooting stars.

152. The beautiful luminous pyramid, which appears during spring in the west after sunset and during autumn to the east before dawn, is very well known. Perhaps much less known is the fact that this pyramid does not form the whole phenomenon, but is only the most visible and easily observed part. If one observes attentively the zodiacal light in a favorable region, as in the tropics, and also certain places in our temperate zone, one finds, besides the main band which forms a luminous lenticular cloud about the sun, another band similar in form but incomparably less in apparent dimensions and of incomparably much paler light; the center is constantly at the point of the ecliptic diametrically opposite to the sun, while its axis like that of the principal light, follows the ecliptic. This is what the Germans call "Gegenschein," and what we call "counter glow." Nor is this all. This lesser band, according to the atmospheric conditions is now more, now less, intense; now more, now less, long; but a trained eye, under favorable conditions of the atmosphere, can always see that one or the other, or both, its extremities extend until they reach the ends of the main band. Under this form the zodiacal light forms a great luminous band, extending over all the zodiac, whose maximum of intensity coincides with the location of the sun,[2] while another maximum, much less perceptible, is at the opposite point; two minima occur in two points which from

1. *Comptes Rendus*, Vol. LXIV, p. 554.
2. At least one must assume so, but one cannot of course observe the zodiacal light in the region closest to the sun.

my observations are about 130 degrees from the center of the Gegenschein.

153. In 1730, P. Pezenas saw the zodiacal light appear simultaneously in the east and west, occupying all the visible parts of the zodiac;[1] but his observations include some circumstances that leave us in doubt whether on that day he saw the zodiacal light or an aurora borealis. More decisive is the report of Humboldt,[2] who, navigating in March, 1803, the equinoctical sea between 12° and 15° north latitude, after narrating the magnificence of the western pyramid, wrote the following words: "While the zodiacal light was very lively in the west, we observed constantly to the east a whitish light, of pyramidal form. It was so intense, that the brightness of the sky in that direction was augmented sensibly. Even the sailors were marveling at this double light in the east and west, and I am inclined to believe that the white eastern light was a simple reflection of the west. In fact, they both disappeared at the same time."

154. It was not until 1855 that the astronomer Brorsen discovered at the Observatory of Senftenberg, what he called the Gegenschein (counter glow), determining with accurate observations its location and nature; and the juncture of it with the western pyramid did not escape him.[3] "We see this light not only at the spring equinox, but also at the autumnal equinox . . . It is a fact, of which I am convinced by repeated observations, that the most luminous region of this light is situated exactly opposite the sun . . . Further, it appears from observations that towards the middle of April the light of opposition unites in a luminous band with the western pyramid, etc." The discovery of Brorsen was completed by Rev. G. Jones, an American minister, who more than any other observer has diligently followed the appearance of the zodiacal light. He wrote in November 18, 1856, from Quito, a city than which it is hardly possible to find a more suitable place for this kind of observation:[4] "I see every night, and during the whole night, a luminous arc from the east to the west crossing the whole sky. This arc, about 20° wide, is visible at all hours when it is clear but is brightest and most striking when the ecliptic is perpendicular, at which time it resembles a second Milky Way. It is evidently the zodiacal light."

155. For seven years I have profited by favorable occasions to judge, from my own observations, the true nature of the zodiacal light. I have found a complete agreement with all the things expounded. Although the climate of Milan is not extremely favorable, the Gegenschein could be observed with sufficient frequency, and it certainly would be regarded as an ordinary phenomenon. The observation is especially easy, if the center of this light is in Leo

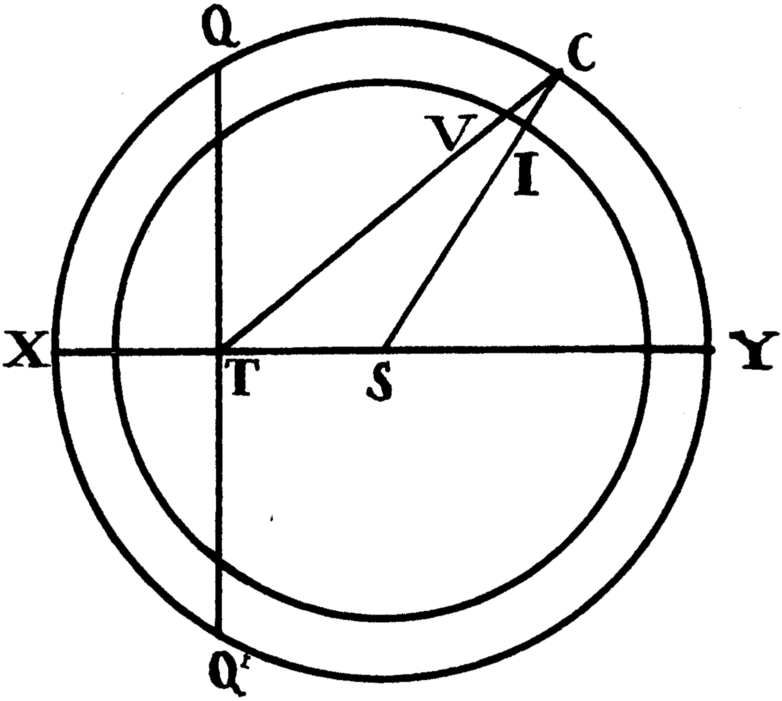
1. *Memoirs of the Acadfemy of Science of Paris*, 1731.
2. *Astronomische Nachrichten*, number 989.
3. *Astronomische Nachrichten*, number 998.
4. Gould: *Astronomical Journal*, number 100.

or in Virgo. I very rarely see it when the center is in Pisces or Aquarius. But it is almost impossible to distinguish it with certainty when the center is in the southern signs of the ecliptic, or confused with the branching of the Milky Way, which forms a great obstacle. Lastly, I will add that on the night of May 3, 1862, about 11:50 P. M., I saw the zodiacal light in the west continue across the visible hemisphere like a bridge passing across the constellations of Gemini, Leo, Virgo, Libra, and Scorpio with a width of about 15°. The air at that time was extraordinarily clear, and an aurora borealis followed shortly afterwards.

156. This digression on the appearance of the zodiacal light hardly belongs to our field, but since we are concerned with establishing the truth of phenomena so difficult to observe and so little known, I have given more detailed explanations than was needful in most cases. Famous authors on astronomy have been ignorant of the observations of Brorsen and of Jones, or at least they have omitted them. I hope what I have said is enough to induce experienced observers to verify, as I have, the truth of these observations, whose importance is so great for the theory of the zodiacal light. If in fact, one wishes to admit with Cassini and with the greater number of astronomers that the zodiacal light is located about the sun as a very flattened ellipsoid of revolution or as a system of almost circular concentric rings, or as a disc extending in the plane of the ecliptic, it is evident from the Gegenschein that the boundaries of the zodiacal light exceed the orbit of the earth. But we can still add to this: (1) that the zodiacal light can not result from a group of phosphorescent or self-luminous bodies; (2) that the zodiacal light does not result from the reflection of a cloud of solid bodies, as meteorites.

157. About the sun, S, (figure 16) let us imagine, in the plane of the ecliptic, a circular ring of small cross-section uniformly scattered with luminous or phosphorescent bodies. The earth, T, is in the inside of this ring: TC is a line of sight that crosses the ring in the direction VC. It is easy to demonstrate from photometric principles that if the ring is homogeneous with respect to the light of its bodies, the luminous impression in the direction VC, or the quantity of light that the observer at T will see scattered upon a square minute of the celestial sphere is independent of the distance TC, and proportional only to the depth VC of the luminous layer along the direction of the line of sight. By studying triangle VCI we can easily see, that such depth VC is proportional to the secant of the parallactic angle TCS; hence we conclude, that the maximum illumination of the sky will be produced by the ring at the points QQ′ of quadrature, where the parrallactic angle is greatest, while the minimum is at the points X, Y, of opposition and of conjunction with the sun. If we now consider, instead of a ring, a disc composed of homogeneous, concentric rings (if we like, of variable light density from one to the other), the effect that the disc will produce upon

Fig 16



the observer is that of a luminous band. But it is clear that in the direction TX the partial effect of the single rings always corresponds to a minimum. Then also the result of their effects of the total effect will give a minimum. Hence, at the point of opposition we have a minimum of light; that is exactly the contrary of what we observe in the zodiacal light. Thus, the zodiacal light can in no way arise from the effect of luminous or phosphorescent bodies.

158. Let us assume now that XQY is a homogeneous, ring-shaped cloud, composed of opaque bodies with a low albedo. All the inclinations of all the elements of their surface can be regarded as accidental, hence the effect is the same, as when all the bodies have a spherical form. We then assume that all these bodies are spherical and illuminated by the sun. They will then reflect light in about the way the moon does; but as one may not assume mountains on them, the laws of reflection will turn out as for unpolished spheres, which is not exactly true for the moon.[1] Adopting the formula which Lambert[2] has established for reflection produced by

1. V. Zollner: *Photometrische Untersuchungen,* paragraphs 14-27.
2. *Photometria,* paragraph 1047.

a sphere of low albedo in any phase we have, from consideration of the figure, the expression,

$$J = A\ [\sin v + (\pi - v) \cos v] \sec v,$$

from which we can calculate the intensity J of the light per square minute of the celestial sphere in the direction TC, for which the angle TCS = v. The quantity A is constant for all the points of the ring-shaped cloud, if its size is infinitesimal with respect to the radius of the ring. The expression for J can then be written as

$$J = A\ [\pi + \tan v - v];$$

and if one reflects that v, which is the parallactic angle, is always less than 90° (because T is supposed within the ring), we comprehend quickly that J increases and decreases with the increase and with the decrease of v; hence the maxima will occur at the quadratures, and the minima at conjunction and opposition, exactly as for the case considered in the preceding paragraph.

159. If then instead of a ring we imagine a system of rings, or a disc, or a much flattened ellipsoid, evidently in the direction TX we have a minimum of intensity. And since the observations of the zodiacal light show a maximum of light intensity at the point opposite the sun, then the impossibility of the aforementioned light resulting from a cloud composed of opaque bodies of low albedo is apparent. Likewise it will be impossible for it to consist of dark bodies, partly luminous by phosphorescence and partly because of reflection. Now, the material of shooting stars is solid, at least in part; it probably is the same as that of the meteorites, opaque bodies, which, so far as we know, have a low albedo. For that reason it seems very difficult to suppose, that the zodiacal light arises from an infinite mass of shooting stars, wandering in space, shining by their own light, or illuminated by the sun.

SOME HISTORICAL NOTICES

160. Among the shooting stars there are occasionally some that leave in the sky a more or less fleeting trace, which gives to these bodies the aspect of a fast moving comet. The great bolides have such appendages, too, and were sometimes described in ancient narratives as comets, and confused with them. I believe that this was the view-point of Cardan, when he likened to a comet the great bolide, which let fall 1200 stones on the territory of Crema on September 4, 1511.[1] Without doubt the same argument induced Kepler to regard some shooting stars as small comets: "The shooting stars are inflamed viscid material. Some of them are consumed in their fall, others fall to the Earth, drawn down by their mass. It is likely that some of them have been heaped together out of feculent material which has mingled with the ether, and from the ether they enter the air in a straight line, like minute comets, though the

1. See Humboldt, *Cosmos*, III, p. 582, edition of Milan. *Cardan*, *Opera*, Lyons, 1663, III, p. 279.

cause of the motion of each is not known."[1] At any event Kepler omitted the shooting stars from astronomy, because they did not participate in the diurnal motion common to all the celestial bodies. It seems that his ideas were not completely fixed on the nature of meteors.

161. Halley thought that a disseminated material in celestial space became concentrated in falling continually towards the sun, and encountering the earth, it produced the phenomenon of the shooting stars.[2] This hypothesis was very much like the result of the preceding investigations. Maskelyne, more daring than Halley, made celestial bodies of the meteors, and also seemed inclined to place them among the comets. He wrote the following in a letter to the Abbe Cesaris, an astronomer of Milan, on December 12, 1783: "I beg you to receive my manuscript kindly, which I recently published to stir up men both educated and uneducated to observe the meteors called *Fireballs*. Perhaps they will prove to be comets . . . Be pleased, learned Sir, to grant me your aid in this matter, which seems important to me. In this way what advances Natural Philosophy can perhaps advance Astronomy itself."[3] It does not seem that the appeal made by Maskelyne to the educated and the uneducated for assiduous observations of fiery meteors has produced a great effect.

162. It has not been in our age alone, then, that men thought of comparing the fiery meteors to comets: the preceding citations show it. Even the idea of uniting to the comets the theory of the generations of those meteors is not very recent. In his famous work about the fiery meteors,[4] Chladni made a step in this direction, the importance of which has appeared only recently. In establishing the cosmic hypothesis he regarded two cases as possible. Either the meteor is a mass of independent material which was never a part of a great celestial body, or it is the product of the destruction of a celestial body previously existing. Chladni considers this second hypothesis as possible, but retains the first as more probable. He observes that we cannot doubt that there exist in celestial space many small bodies endowed with movement, which are observable when the bodies pass before the sun. According to Chladni, these dispersed masses are accumulations of the original cosmic material, from which the great stars of the universe are formed also. Many of the nebulae which we call irresolvable would be nothing other than portions of this extremely rarefied material, and dispersed throughout large spaces. Chladni thought such nebulae differed from the comets only in their size, volume, isolation, and also perhaps in having a greater density. Now, the smaller masses, which appear under the form of bolides and shooting stars, do not seem to differ essentially

1. Kepler *Opera*, édition of Frisch., Vol. VI, p. 157.
2. Coulvier-Gravier and Saigey: *Introd. Historique*, p. 5.
3. *Memorie della Societa Italiana*, III, p. 345, Verona, 1786.
4. *Ueber Feurenmeteore, and Ueber die mit Denselben herad Gefallenen Massen*, Vienna, 1819.

from comets. It is also probable, he said, that the comets consist simply of clouds composed of masses, mostly vaporous and pulverized, which are held together by reciprocal attraction. That this attraction cannot noticeably disturb the planetary movements is a proof of the exceeding tenouosness and dispersion of the material in those nebulae, through which we often observe the fixed stars.[1]

163. This famous idea of Chladni was never completely forgotten in Germany. Echoes can be found in different subsequent publications, and particularly in the *Popular Astronomy* of Littrow.[2] In 1859 the Baron of Reichenbach published a Work on the Reciprocal Relations between the Comets and Meteorites, entirely based on the point of view of Chladni.[3] He imagined that every comet is a concentration of primitive material, according to the laws of gravity, which finally was converted into a cloud of minute and extremely numerous crystals. From the accumulation produced by the reciprocal attraction of these crystals, he supposed that there arose meteorites; which, according to Reichenbach, could not have been other than a kind of conglomeration; every one of them derived from the condensation of a comet. It is, at least, rather doubtful that the simple dynamic action of gravitation can give rise to such compact and durable masses as the meteorites. But although we do not wish to admit all parts of this strange speculation, perhaps it is possible that it contains some truth; see paragraphs 128-133. If I proposed to give the complete history, I could cite the opinions of several other authors, who suspected an analogy between meteors and comets. Among these, I will name Abbe Raillard, who lately republished the ideas put out by himself on this problem in 1839;[4] and Dr. Foster, who stated that the years marked by the appearance of great comets have been more numerous in shooting stars also, and especially in white meteors.[5]

164. No one, among the authors just cited, was able to give to the suspected analogy or relation between meteors and comets a probability greater than that of a simple conjecture. If my information is correct, the first to try to obtain a more substantial foundation for the cometary theory of shooting stars was Boguslawski, who tried to represent by a parabola the apparent orbits observed in some meteors of August 10, 1837.[6] Not having been able to consult his original work, I cannot say what success he had. But I am certain that this idea was not developed further subsequently, either by Boguslawski himself, or by anyone else. Erman, in his well-known work, has established the parabolic orbit as a limit to which the periodic shooting stars could reach but his theory of the "darkening" demanded many short periods not only for the Perseids, but also for the Leonids, and absolutely excluded orbits of long period, as we see in his more recent work along

1. *Feuermeteore,* p. 395. See also Kaemtz: *Meterologie,* Vol. III, p. 316.
2. Die Wunder des Himmels, fifth edition, 1866, p. 504, 533, 709.
3. *Poggendorff's Annalen der Physik,* Vol. CV, p. 438.
4. *Les Mondes,* Vol. XII, p. 649; and Vol. XIII, p. 606. See paragraph 234 above.
5. Essai sur l'Influence des Cometes, etc. Bruges, 1842.
6. Coulvier-Gravier and Saigey: *Introd. Historique,* p. 103.

this line.[1] When the phenomenon of the diurnal variation was better known from the work of Herrick and of Coulvier-Gravier, and was proved a result of the combination of proper motion of the meteors with the orbital motion of the earth, Professor Newton quickly understood that the law of diurnal variation could offer some explanation on the absolute velocity of meteors in space, and from the discussion of the observations of Coulvier-Gravier he established that their average velocity must be greater than that of the earth, and therefore that their orbits are quite eccentric.[2]

165. The phenomenon of the diurnal variation also suggested the cometary theory of shooting stars, which I developed in the letters to Father Secchi, already cited many times. From a theory really incomplete I had the venturesomeness, or rashness, to conclude that the average absolute velocity of the shooting stars ought to be little different from the parabolic, and that the orbits of the meteors must be elongated conic sections, like those of the comets. I say that this conclusion, though later proved true, was then rash; I have shown in fact in the present Memoir, that the diurnal variation of the frequency of the shooting stars depends upon so many and such complex causes, that it will never be possible to establish the mathematical theory in a rigorous way. We can give the explanation for the principal effects, but the quantitative determination of its proportions of maximum and of minimum will probably never be determinable *a priori.* Faye, therefore,[3] has rightly maintained that it would never be possible to determine the absolute velocity of the meteors from calculations based on simple hourly and annual statistics. It follows that the calculation I proposed in the first letter to Father Secchi cannot be regarded as the expression of the facts of nature; and only by fortuitous compensation of neglected circumstances did it come about that the results derived from the calculation approximately expressed the truth. And if, at another time, I saw fit to hold on this point a different opinion,[4] I did it at a time when I had not subjected the phenomenon of the diurnal variation to an analysis so complete and so rigorous as that which the reader has seen in the present work.

1. *Archiv fur die wissenschaftliche Kunde von Russland,* Vol. 25.
2. *Memoirs of the National Academy of Science,* Vol. 1, *Annuaire de l'Obs. de Bruxelles,* 1866, p. 201.
3. *Comptes Rendus,* Vol. LXIII, p. 1097.
4. *Les Mondes,* Vol. XIII, p. 212.

INDEX

The numbers refer to paragraphs, not pages