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The Scientific Study of Meteors in the 19th Century

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"Although they are subjects of terrestrial chemistry and physics upon and after their entry, they are like everything else which moves in planetary space before their entry, and hence are subjects to be considered under astronomy." E. F. F. Chladni, Ueber Feuer-Meteore, Vienna, 1819, p. 395.

Had Chladni's advice on the study of meteors been heeded, it is unlikely that Schiaparelli, writing in 1871, should have been forced to refute the persisting arguments against a cosmic origin of meteors. A survey of the astronomical literature of the first half of the 19th century indicates that Chladni had good reasons for making this statement; for meteors and meteorites were being studied and "explained" by chemists, medical doctors, meteorologists, and geologists, as well as by astronomers. (See, e.g., Seguin 1814, Reynolds 1818, Forster 1813, and Berzelius 1837.) Thus the forward progress in most branches of meteor science (with the notable exception of meteoritics) was slower than might be suspected from the advances in other areas of astronomy and physical science.

Yet the scientific knowledge of meteors did ultimately increase during the 19th century, and culminated with Schiaparelli's monumental work in 1871. But the exponential nature of this growth was partially due to the impetus of the fortuitous and astute observations of the Leonid shower in 1833. This paper will be concerned with several such key events in the development of meteor science (observational

*This paper is a continuation of one by Sears (1965). Any views expressed in this paper are those of the author. They should not be interpreted as reflecting the views of The RAND Corporation or the official opinion or policy of any of its governmental or private research sponsors.

METEORITICS, Vol. 3, No. 1, May, 1966

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meteor astronomy, meteoritics, and meteor physics) during the 19th century. The development will be treated with special reference to the progress of physical science in general during that era.

Because of the explosive nature of the subject, and the immense amount of literature which was published during that period, it will not be possible to discuss the history of each branch in general. As an example of this exponential rate of growth, see Fig. 1, where both the number of reported fireballs given by Greg's catalog and the number of observed falls increased sharply around 1790. Olivier (1925) gives an excellent historical survey of the subject of meteors. Although a complete history of meteoritics has not been written, the subject is treated at some length by Cohen (1894), Farrington (1915), and Merrill (1929); Krinov (1960) briefly discusses Soviet meteoritics. Astapovich (1958) briefly reviews the history of the scientific investigation of meteoric phenomena. Although several errors of fact were found in this work, it is valuable as a guide to Soviet contributions in

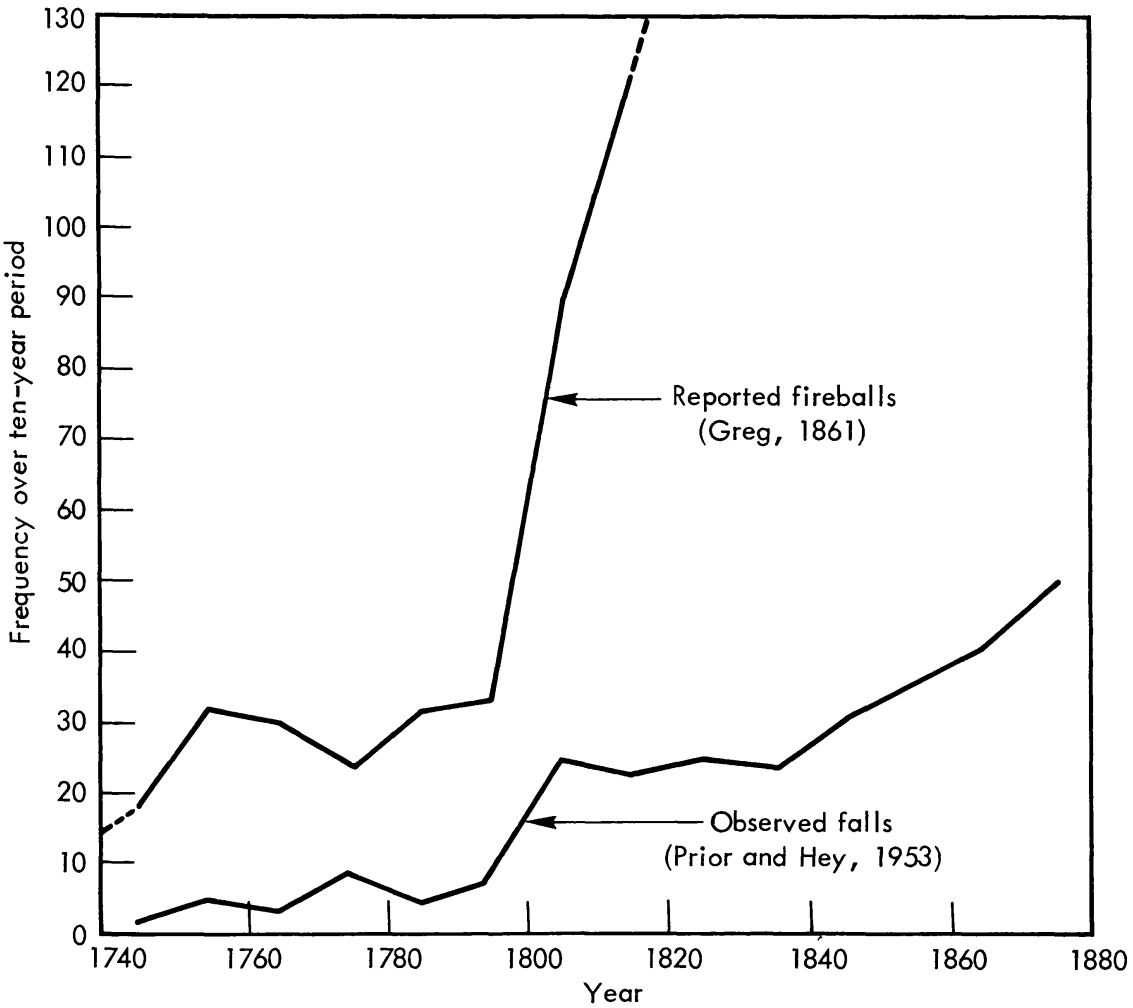

FIGURE 1—Number of observed meteorite falls and fireballs, averaged over ten-year periods.

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this field. At present, a comprehensive history of the development of meteor physics does not exist. Most specialists consider Schiaparelli as the founder of this branch of meteor science, even though much interesting work preceded his investigations.

I. CHLADNI'S CONTRIBUTION

The framework for a scientific theory of meteors was prematurely established by Chladni (1794), who suggested that fireballs and the fall of masses from the sky were real events, that fireballs, shooting stars, and meteorites were different manifestations of the same phenomenon, and that this phenomenon was caused by the entry of a solid, extraterrestrial object into the earth's atmosphere. The impact of Chladni's early paper on the scientific world has been discussed by Sears (1965).

There was much resistance to these hypotheses, but Chladni continued to publish prolifically until his death in 1827, adding great quantities of documentary data on falls and fireballs from the ancient chronicles. His stern criticisms and forceful style were always tempered by his wit. He constantly referred to everyday occurrences to explain a difficult physical point and also painstakingly explained items which might be unfamiliar to the reader. He reiterated his viewpoints in 1819 in a book (Chladni 1819) that is today much more valuable for its manner of scientific exposition than for the data it contains.* One of Chladni's shortcomings (and there are very few) was his naive acceptance of any documented account and every astronomical observation as pure fact. But his exposition of the meteor problem, and his logical treatment of the subject, was never equaled until Schiaparelli's work of 1867-71. Chladni emphasized for the first time the essential importance of considering all the data before introducing any hypotheses to explain a physical process. Hypotheses should never contradict any of the valid data. To him, a logically consistent scheme was worthless if it did not agree with observation, or if a deus ex machina had to be introduced to support the theory.

This attitude reflected the techniques of the scientific method, as compared with the rational or purely deductive treatment of science exemplified, for example, by the French Academy of Sciences prior to 1803. It is well known that the Academy maintained in the face of overwhelming evidence that the fall of stones from the sky was impossible; and that this attitude was changed only after the able investigations of the l'Aigle fall by Biot (see Sears 1965).

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*However, Botley (1965) points out that in reading my translation of Ueber Feuer-Meteore I have come across what appears to be a previously unnoticed mention of a supernova in 1245.

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During the early part of the 19th century the scientific method became ascendent over other techniques, especially in the fields of physics and chemistry. At the same time, the universal man, or the German natural-philosopher, was rapidly being replaced by the specialist—the physicist, chemist, and astronomer. (Chladni was one of

FIGURE 2—Ernst Florens Friedrich Chladni (1756-1827).

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the last great non-specialists; he achieved his fame in the field of acoustics, was well-versed in natural history, elasticity theory, chemistry, and astronomy, and made a significant contribution to meteor science.) These trends are not immediately obvious in early 19th century meteor science. But a closer inspection of the techniques employed in early studies indicates that both meteoritics and observational meteor astronomy were affected.

II. METEORITICS AND THE ORIGIN OF METEORITES

Meteoritics was formed rather early as a distinct branch of meteor science. Some of this immediate specialization was caused by the fact that meteorites were tangible objects and came quite naturally into the qualified hands of chemists and geologists for study. There was also a large number of observed meteorite falls early in the century (Fig. 1). But a great degree of this success was due to the chemical analysis, classification, and comparison of meteorites with terrestrial rocks, i.e., due to the continual application of the scientific method. Early writers such as Bonnycastle (1822) agreed that "they bear an exact resemblance to each other . . . and yet are totally different from any known terrestrial body . . . which seems to indicate that they have a common origin foreign to our globe." It was also widely believed that all large meteors produced some kind of fallen mass, although the fall was not always observed or found (see, e.g., Reynolds 1818).

The primary contribution of early investigators was the identification of chemical constituents and the study of the mineralogical structure of new finds and falls. With reference to structure, a search for the origin of the term "Widmannstätten figure" describing the visible structure of meteoric iron revealed that von Widmannstätten did not publish his research (Paneth 1960), that his discovery in 1808 had been anticipated in 1804 by Thomson (1808), and that it still remains to be shown whether Widmannstätten annealed a polished surface of the Hraschina meteorite (Krinov 1960, Farrington 1915), or whether he etched the surface (Chladni 1819). Since other contemporary research made use of etching to bring forth the Widmannstätten pattern (see, e.g., Thomson 1808 and Gillet-Laumont 1815), it is likely that von Widmannstätten did also.

Although Farrington (1915) says that meteoritics did not become a systematic science until 1860, a survey of the literature shows that conscious efforts toward some sort of classification were always being made. For example, Klaproth made the simple distinction between stone and iron in 1807 (Chladni 1819); the word "meteorite" rather than the cumbersome "meteoric iron" and "meteoric stone" was apparently first used to describe all fallen masses by Brayley (1841);

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and Smith (1855) classified meteorites into iron, stone and mixed. However, this classification was not used; instead, meteoriticists adopted the Storey-Maskelyne classification of siderite, aerolite, and siderolite. Further attempts at classification were made by Chladni (1819) and Berzelius (1837), among others. After Rose differentiated between chondrites and achondrites in 1862, the science of meteorites indeed became well-established.

However, the indication that all fallen masses had a common origin led many of these scientists to propose hypotheses for this origin—just as the unusual structure of the crust caused much speculation on physical processes occurring during passage through the earth's atmosphere. Unfortunately, some of these proposals were often made by persons not cognizant of all the physical facts, or not well acquainted with the general knowledge of physics, ballistics, and astronomy necessary for the interpretation of these facts.

(Perhaps Atkinson 1819 was a bit harsh when he said the indirect method (hypothesizing) of accounting for the origin of meteorites was the "habit of the indolent." However, it is true that incredible hypotheses, even for that time, appeared in reputable journals. This was evident as late as 1862, when Mrs. G. S. Silliman 1862 said it was not in accordance with science to ascribe mysterious appearances on earth to causes proceeding from planets. She found that "fleeting fugitive motions" of meteorites in striking contrast to the "solemn certainty and grandeur of the heavenly bodies," and therefore attributed their origin to atmospheric and chemical processes.)

The results were predictable. (For a survey of theories see Phipson 1867.) Chemists leaned toward a union of chemistry and the earth's atmosphere for an origin, completely ignoring the facts that several important meteoritic elements were not known to be present in the atmosphere, or that no known chemical reaction could impart cosmic velocities and horizontal motion to heavy masses. Meteorologists also argued for an atmospheric origin. Geologists and astronomers believed that meteorites were products of lunar volcanos (see, e.g., Benzenberg 1834, or Berzelius 1837), or were debris from destroyed planets (Olbers 1837), or were primordial cosmic matter (Chladni 1819). The experimental evidence supported all three of these hypotheses, although the existence of active volcanos on the moon was doubted by some astronomers. It is interesting to note that a lunar theory has recently been revived by Urey (1965), who believes that stone meteorites arise from collisional processes on the moon.

The reasons for this scientific chaos are clear. If Chladni's suggestion had been followed, perhaps less confusion would have resulted. But on the other hand, those physical sciences necessary for the proper interpretation of phenomena observed during the entry of a meteorite were grossly inadequate. (For example, Murray 1819 said he could not conceive of anything being ignited merely because it

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moved at a velocity of 25,000 ft/sec.) It was impossible, at that time, to explain the thin crust of meteorites without the insight obtained from a theory for the conduction of heat in solids. Until thermodynamics became quantified, it was impossible to conceive of the laws needed for the mathematical representation of physical behavior. Hence the scientists of the early 19th century had to be content with descriptive explanations based on their limited experience. The crust was attributed to friction, high-temperature air, chemical action, or electricity (Chladni 1819).

However, much of the confusion arose because fireballs and shooting stars were often considered separately, rather than as different manifestations of the same phenomenon. As we mentioned earlier, it was rapidly established that meteorites and fireballs were intimately connected, and hence those people concerned with fireballs understood that they were dealing with the motion of a solid object in the atmosphere. This was not the case when small meteors or shooting stars were considered.

Because Forster (1813) eliminated fireballs from the scheme, he was able to obtain a correlation between shooting stars and the weather. Conversely, Chladni (1819) demonstrated that all meteors were independent of the time of year, since he based most of his deductions on the behavior of fireballs. Such relationships were easy to obtain because of the relatively small number of observations. However, observations of shooting stars steadily increased during this era, and from an application of the scientific method to the accumulated data, it should have been possible for scientists to determine more concerning the nature of shooting stars than they actually did. Still, it is difficult to view observational data with a completely unbiased eye, and this, in connection with several other obstacles, such as the intangibility of the subject, delayed the orderly growth for some decades.

III. SHOOTING STARS: OBSERVATIONAL METEOR ASTRONOMY

The scientific observation of meteors began in 1798 when Brandes and Benzenberg began their simultaneous observations to determine height, direction, and velocity of shooting stars. Their observational baseline was 1.56 km, and in six nights they observed 402 shooting stars, but only 22 in common; of these 22 meteors, only four were observed completely so that beginning and end heights could be determined; and of these four, two ascended. Subsequent observations produced more ascending meteors (Benzenberg 1834).

This was a serious blow to the extraterrestrial hypothesis. If meteors came from outer space, those which ascended would have had to pass through the earth before they were observed. These data

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were surprisingly not utilized by the proponents of atmospheric origin, and appeared to bother only those who held to the extraterrestrial hypothesis. Perhaps this seeming oversight occurred because publication of the data was delayed and not widely circulated. Benzenberg (1803) wrote bitterly on the negligible support given to their efforts to publish and to continue their observations. Even Chladni (1803) decided that some meteors must be atmospheric in origin, but he finally managed to explain the ascending motion by saying that meteors must be loosely packed clumps of matter which expand due to heat during entry; the air compressed in front of the high-speed object retains its elasticity and acts as a spring, pushing the body back into space. Ignition does not occur until the meteor is rebounding. The same phenomenon is seen during fireball entry (Chladni 1817, 1818). The apparent ascending motion was finally attributed to observational error, made because of the short baseline (Bessel 1839). In the meantime, other observations were being published (e.g., Farey 1813), and data were accumulating which showed that meteors were higher and faster than fireballs, and that they often occurred in immense quantities or at certain times of the year.

One of the earliest accounts of a shower was belatedly published by Humboldt (1819) when he described the display seen on November 12, 1799, by Bonpland at Cumana (Venezuela). According to the description, the shower was also seen over a large portion of Central and Eastern America, Greenland, and as far east as Weimar. Those observers in the west, including the official United States astronomer, Ellicot, apparently did not notice the peculiar radiation from a point (Bonpland's description indicates the radiant was below the horizon). At least Ellicot observed that they went in all directions.

But it was not until the Leonid shower of 1833 that the radiation was obvious to many observers. The comprehensive treatise on this shower written by Olmsted (1834) was emphatic in pointing out the existence of a radiant which followed the course of the stars. This discovery was rapidly recognized by others as proof that there were myriads of small bodies moving around the sun; the November showers of 1831-34 were evidence to Arago (1836) that the earth intercepted these bodies once a year when their orbits coincided. Arago suggested that observers watch for other such trains meeting the ecliptic —from 20-24 April, for example. And this was done. Other star showers were discovered by research into older accounts and catalogs; immediately, investigations were begun on the geometrical relationship of these bodies with the earth-sun system. (See survey by Walker 1843.)

Olmsted's paper on the Leonid shower, and its acceptance by major scientists like Arago and Quetelet, can be considered as the starting point of the scientific study of meteors by observation and the use of celestial mechanics. We could ask why it took the 1833 shower to

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break the ice of disbelief. Why, for example, were the 1799 display, or the autumn 1798 shower seen by Brandes (Benzenberg 1834), or the annual displays in April and August all insufficient to provide evidence of a radiant, and hence the cosmic origin? There are probably many explanations for this, but the ones which appear most plausible today are the following. First, the 1833 shower was immense. Great quantities of meteors filled the sky: "an almost infinite number . . . they fell like flakes of snow" (Olmsted 1834). Under these circumstances the radiation would be very obvious. Further, the dense shower continued over a period of 4-5 hours, enough time so that the celestial motion of the radiant point with the fixed stars became apparent. The weather was also very clear in the United States at the time of the shower. These circumstances permitted the observers to accept the existence of a radiant. That it had to be located outside the atmosphere, however, was not apparent except to the most astute observers. (For example, a coincidentally strong, steady wind could have blown the radiant along with the fixed stars.) One of Olmsted's correspondents located the point of radiation and was quite disappointed not to see a cloud of material at that spot (Olmsted 1834). But the willingness of scientists to believe that the radiation came from an extra-atmospheric source, and their tendency to explain the phenomenon as caused by "planetoids," owed much to the normal progress made in astronomy during the preceding 30 years. For in that time, the existence of small planets had been proved by the discovery of asteroids. Their motions around the sun were determined and predicted by the mathematical techniques of celestial mechanics: Piazzi discovered Ceres, and Gauss calculated its orbit with such accuracy that it was found, after it had been lost in the day sky, at the exact time and place predicted by Gauss (Chladni 1819).

Thus the Leonid shower of 1833 occurred just at the right time, in the scientific sense, and provided the necessary stimulus for the rapid scientific development of meteor astronomy. There is no doubt that such events as the ultimate determination of the relationship of shower meteors and comets, and the discovery of other radiants, would not have occurred eventually, even without the 1833 shower. But once the cosmic nature of meteors became an accepted hypothesis, a tangible goal was provided for observational meteor astronomy. In order to demonstrate the cosmic origin of meteors, accurate velocities had to be determined for the calculation of meteor orbits and the prediction of periodic showers. The cosmic origin of meteors was deduced by Schiaparelli in 1862 when he showed that Comet 1862 III had the same orbit as the Perseids. The tie between comets and meteors was conclusively demonstrated when Schiaparelli's calculations of the Leonid orbit, based on the 1866 shower, were compared with the path of Comet 1866 I and found to coincide (Schiaparelli 1871).

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During the period subsequent to 1833 scientists began seriously to consider meteors as small solid objects. Although Olmsted (1834) thought that the shower meteors were light and transparent objects different from meteorites, others, as Arago (1836), Strickland (1846), and Joule (1848), thought they were solid. These considerations belong to the third branch of meteor science, which is discussed next.

IV. METEOR PHYSICS

In contrast with the other branches of meteor science, meteor physics barely became established in the 19th century, and developed into a useful deductive tool only in the 20th century. This delay is not surprising when we consider that there were no terrestrial laboratories in which meteoric velocities could be reproduced, nor could the physicist deduce the origin of the light, the mass, or the deceleration of meteors without knowledge of the composition and density of the upper atmosphere.

Hence the 19th century scientist had to extrapolate on the basis of his often inadequate experience. He had some familiarity with aerodynamics through ballistic research and experiments. This enabled him to predict that the original cosmic velocity of meteorites would be reduced in most cases to an insignificant value by the time the meteorite reached the ground. Chladni (1819) reports on research by Bessel—probably F. W. Bessel, Director of the Königsberg Observatory—that the solution depended on the logarithmic integral. Although Bessel's work is unavailable to us, it appears that the same integral was derived earlier by Brandes (1803), who speaks of one of his own earlier papers but unfortunately does not give a specific reference. The equation given by Brandes is supposed to represent the velocity of a body which had slowed down due to atmospheric resistance. The non-integrable term arose because Brandes did not neglect the acceleration due to gravity in comparison with the drag due to air resistance. Although the treatment in general shows great mathematical competence, the physical concepts are not set down clearly.

We find this lack of definition arising often in the literature of 19th century meteor physics. While their colleagues in fluid dynamics and physics were facile in the utilization of force, mass, and acceleration, we find Bezenberg (1834) or Gruithuisen (1834) still adhering to the Galilean technique of geometric ratios or the pendulum analogy for their analysis of the free fall of bodies. This is surprising when we consider that Euler had derived Newton's second law of motion (the momentum equation) in its modern form in 1736 (Truesdell 1960). Even Schiaparelli (1871) was evidently not aware of the applicability of Newton's law to the motion of meteors, for he used an energy balance which conserved the specific kinetic energy of the body by

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balancing the change in kinetic energy per unit mass with the force of resistance. This equation can be easily transformed into Newton's second law, and therefore is identical to the momentum equation presently in use (a fact apparently not known to later writers; see, e.g., Hoppe 1937).

However, Schiaparelli was not strict in his use of dimensional analysis, and often forgot the units of time when he gave velocities (i.e., citing a velocity of 3000 meters rather than 3000 meters/sec; see especially the tables in the First and Second Note of Schiaparelli 1871). In this, as well as in his references, he also showed unfamiliarity with the literature of physics.

The concept of energy conservation was, however, very well known. One of Schiaparelli's references, Regnault, published a mammoth work on the theory of heat in 1847 in which the equivalence of mechanical work and heat was stated. Mayer had stated this earlier in 1842, but the principle was not really established until Joule determined the value of the mechanical equivalence of heat in 1840-43. Joule (1848) also stated that he believed that the ignition of meteors by the violent collision with our atmosphere was a remarkable illustration of this doctrine. He estimated the amount of heat for a meteor traveling at a velocity of 18 miles/sec, and considered that the stone became heated by its location within a volume of intensely heated air. He also realized that only a small portion of the heat would be received by the stone, i.e., that the conversion process is not completely efficient.

The fact that Joule recognized the inefficiency of the conversion of the energy of motion into heat to the body is significant when it is viewed along with other concurrent developments. Most of the theories of heat were based on the caloric theory, in which heat rather than energy was conserved. Even so, it was possible for early thermodynamicists to derive the laws for adiabatic compression of a gas, and also to demonstrate that the maximum efficiency of any heating process occurred if the system were completely reversible. But Carnot's theory on the motive power of heat, published in 1824, was never utilized until Kelvin and Clausius rediscovered his work in 1851 (Kerkner 1960).

Thus Schiaparelli, in deriving the equations for heating the body, was probably only reflecting the general status of thermodynamics at that time, when he postulated that all of the pressure generated by resistance is transformed adiabatically into heat. (In an adiabatic process the energy can be recovered by reversing the process.) It was later independently demonstrated by Rankine in 1870 and Hugoniot in 1887 that the compression process in supersonic flow is irreversible; although energy was conserved, it was changed in form by the shock and could not be recovered. However, meteor scientists were

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not quick to pick up this notion; Lindemann and Dobson (1923) still assumed that the shock was adiabatic.

After the publication of Schiaparelli's work in 1871, the science of meteor physics had demonstrated on the basis of mathematics that atmospheric slowdown was due to resistance, and that the heating of meteorites was due to the effects of immersion in rapidly compressed air. Schiaparelli also demonstrated by analogy with the motion of rifled artillery shells that the motions of meteors in the atmosphere could be caused by the aerodynamic forces on an asymmetric or rotating body. But the origin of light and the structure of trails could not be explained until after spectroscopic investigations became possible and the kinetic theory of gases was developed. Although Herschel (1866) observed the spectra of shower meteors, and saw a continuum and a few lines, the instrument was too crude to indicate the presence of any particular elements. This became possible only after the instruments became refined around the turn of the century (Trowbridge 1924).

In summary, it has been shown that most of the hypotheses stated in 1794 by Chladni were proved to be true by the time Schiaparelli published his monograph in 1871. This did not prevent Berry (1961), writing in 1898, from saying that although there was evidence which pointed to an intimate connection between comets and meteors, it was "perhaps still premature to state confidently that meteors are fragments of decayed comets." However, it was still not possible in 1871 to prove scientifically the common nature of meteors, fireballs and meteorites. Although Kirkwood (1887) had long believed that they had the same origin, his views were rejected by astronomers primarily because no meteorite had ever fallen during a shower. But when the Mazapil meteorite fell during a meteor shower on November 27, 1885, this objection was removed, and further research in the 19th century could proceed on the basis that all three phenomena were closely related (Lockyer 1890).

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