Meteorites in history: an overview from the Renaissance to the 20th century

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Abstract: From ancient times through to the Renaissance reports of stones, fragments of iron and 'six hundred other things' fallen from the sky were written down in books. With few exceptions, these were taken as signals of heaven's wrath. The 18th century Enlightenment brought an entirely new approach in which savants sought rational explanations, based on the laws of physics, for unfamiliar phenomena. They accepted Isaac Newton's dictum of 1718 that outer space must be empty in order to perpetuate the laws of gravitation, and, at the same time, they rejected an old belief that stones can coalesce within the atmosphere. Logically, then, *nothing* could fall from the skies, except ejecta from volcanoes or objects picked up by hurricanes. They dismissed reports of fallen stones or irons as tales told by superstitious country folk, and ascribed stones with black crusts to bolts of lightning on pyritiferous rocks. The decade between 1794 and 1804 witnessed a dramatic advance from rejection to acceptance of meteorites. The three main contributing factors were E.F.F. Chladni's book of 1794, in which he argued for the actuality of falls and linked them with fireballs; the occurrence of four witnessed and widely publicized falls of stones between 1794 and 1798; and chemical and mineralogical analyses of stones and irons, published in 1802 by Edward C. Howard and Jacques-Louis de Bournon. They showed that stones with identical textures and compositions, very different from those of common rocks, have fallen at different times in widely separated parts of the world. They also showed that erratic masses of metallic iron and small grains of iron in the stones both contain nickel, so they must share a common origin. Meanwhile, in 1789, Anton-Laurent de Lavoisier had revived the idea of the accretion of stones within the atmosphere, which became widely accepted. Its chief rival was a hypothesis that fallen stones were erupted by volcanoes on the Moon. During the first half of the 19th century falls of carbonaceous chondrites and achondrites, and observations on the metallography of irons, provided fresh insights on the range of compositions of meteorite parent bodies. By 1860 both of the two main hypotheses of origins were abandoned, and debates intensified on whether all meteorites were fragments of asteroids or some of them originated in interstellar space. This paper will trace some of the successes and some of the failures that marked the efforts to gain a better understanding of meteorite falls from the end of the 15th century to the early 20th century.

The stone of Nogata, Japan, 861

On the night of 19 May 861 a brilliant flash and deafening explosion stunned the people of Nogata-shi on the island of Kyushu, Japan. The next morning villagers retrieved a heavy black stone from a hole it had made in the garden of the Suga Jinja Shinto shrine. The priests, never doubting that the stone had fallen from the sky, preserved it as a special treasure of the shrine. No written records of the event survive, but the story lived on by oral tradition.

In 1922 the head priest at the shrine sought an expert opinion on the stone from Dr Kunihiko Yamada, the principal of the Chikuho Mining School. Dr Yamada wrote that beyond any doubt the stone was a meteorite, judging from its irregular shape and its surface features. However, his report did not come to the attention of scientists, nor was there any reference to it in the *Annals of Old Shimosakai-mura*, a collection published in 1927 of historical facts and legends of the shrine and its neighbouring village. Finally, in September 1979, a radio broadcast describing the stone and its legendary history was heard by an amateur astronomer who passed along the information to Professor Sadao Murayama, of the Tokyo Museum of Science.

Dr Murayama lost no time investigating the story. He visited the shrine and saw that the stone was, indeed, a stony meteorite covered by a dark fusion crust. He determined its weight at 472 g and arranged with the head priest,

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0305-8719/06/$15.00

M. Iwakuma, for a small sample to be taken off for scientific studies. He then joined a consortium of four other scientists, led by Dr Masako Shima of the National Science Museum of Tokyo, to analyse the stone. They classified it as an L6 chondrite and proposed to call it 'Nogata', the modern name of the place where it fell. This name was accepted by the Nomenclature Committee of the Meteoritical Society in 1979, and in 1980 it was duly published in *The Meteoritical Bulletin*, as is required for all new meteorite names. In 1983 Dr Shima and her colleagues issued a detailed report of the mineralogical, chemical and isotopic composition of the stone.

At the shrine, the stone was stored in a wooden box (Fig. 1) with a date inscribed on the lid equivalent to 19 May 861, by the Julian calendar. Both the box and the style of the inscription post-date the 9th century, but the ^{14}C age measured on the box lid corresponds sufficiently well with evidence from the oral histories to persuade scientists that this stone is, in fact, the one that fell on that night in May 11 centuries ago. This makes Nogata the earliest witnessed meteorite fall in the world of which a specimen still exists.

The story of the Nogata stone indicates that the 9th century priests readily accepted it as fallen from the sky and preserved it on their premises for well over a millennium. This reflects a remarkable degree of cultural stability in that area of Japan. However, sequestered as it was, the historic stone of Nogata played no role in the observations and disputes that took place over the turn of the 19th century and ultimately led to the founding of meteoritics as a science.

Fig. 1. The Nogata chondrite that fell in Japan on 19 May 861, beside the opened box in which it was stored for centuries at the Suga Jinja Shrine. The stone, which fitted snugly into the box, is approximately 5 cm across. (Courtesy of Masatake Honda, Nihon University.)

The stone of Ensisheim, Alsace, 1492

The situation was very different with respect to the earliest witnessed fall in the West of which pieces are preserved. Shortly before noon on 7 November 1492, a horrendous explosion, heard over upper Alsace and parts of Switzerland, heralded the fall of a large stone outside the city walls of Ensisheim in Alsace. A boy watched dumbfounded as the stone plunged into a nearby wheat field, making the ground shake and opening a hole about 1 m deep. Townspeople soon surrounded the hole and dragged out a heavy, black stone. Then they fell upon it, whacking off pieces to carry away – for medicine, or magic, or keepsakes.

Presently, the Landvogt arrived and forbade all further destruction. He ordered the stone to be hauled into the city, and placed by the door of the church. They estimated its weight at about 135 kg. Today, the largest surviving mass of the stone, weighing 56 kg, still remains in Ensisheim (Fig. 2). Unlike the stone of Nogata,

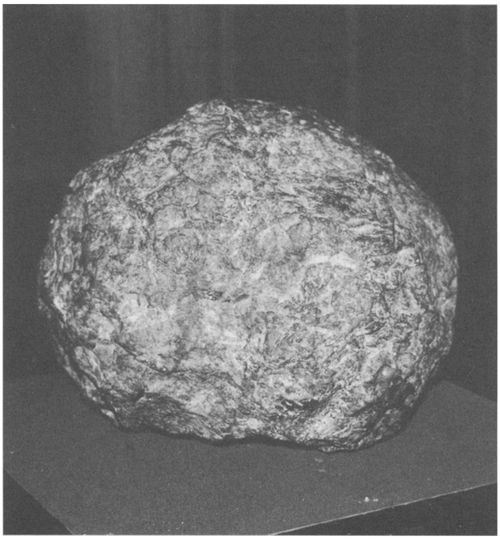


Fig. 2. The largest remaining mass of the stone that fell at Ensisheim on 7 November 1492, on display at La Régence Ensisheim's 16th century Hotel de Ville. This specimen, which has been rounded by centuries of chipping, is about 32 cm high and 28 cm wide; it weighs 56 kg and constitutes about 40% of the original stone. Patches of shiny black fusion crust can be seen near the tip. (Courtesy of T.C. Marvin.)

this one did not languish unseen and unsung, nor did it owe its survival to any measure of cultural stability. Alsace occupies one of the most fought-over borderlands of the world – that between France and Germany. Ensisheim was repeatedly pillaged and burned during the Thirty Years War (1618–1648) as armies swept back and forth through it and left the city all but depopulated. Perhaps the stone survived the carnage mainly because it looked like nothing more than a worthless rock.

In 1793 (Year 3 of the Republic), the Revolutionary government of France liberated the stone from the church, where it had hung from the choir loft for 301 years, and placed it on public display in the Bibliothèque National in nearby Colmar. While it was there, several kilogrammes were taken off as gifts to important visitors (including Ernst F.F. Chladni who received a 450 g specimen), and for chemical analyses. Ten years later, in 1803, the stone was returned to the church in Ensisheim. In 1854 the church tower collapsed and a neo-gothic church was built in its place in 1863. Meanwhile, the stone had been transferred across the city square to the elegant 16th century Hôtel de la Régence, from which the Hapsburgs had administered upper Alasce. In 1992 the stone served as the centrepiece of a fine new museum of meteorites that opened in time for the Quincentennial celebration of the fall (Marvin 1992).

This spectacular fall was the first such event to take place after the invention of printing, and it spawned a dazzling 15th century exercise in publicity and propaganda. In 1492 Ensisheim was an imperial city of the Hapsburgs, and the stone fell just as King Maximilian (1459–1519), son of the Holy Roman Emperor, Friedrich III, was leading his army towards it on his way to battle the French. On his arrival, he sent for the stone and asked his advisors about its meaning. Traditionally, strange things seen in the sky or fallen from it were taken as omens of evil. But, after due consideration, his advisors did what prudent advisors have done on numerous occasions throughout history: they told Maximilian that the stone was sent as a sign of God's favour to him. Greatly pleased, Maximilian struck off two last pieces, one for himself and one for his friend the Archduke Sigismund of Austria, and then he returned the stone to the people of Ensisheim with orders to preserve it intact in their parish church as eternal testimony to this great miraculous occurrence.

Within weeks Sebastian Brant (1457–1521), the leading German scholar and poet of the time, authored two broadsheets entitled *On the Thunderstone fallen in the Year '92 before Ensisheim*, which were published by Johann von Olpe in nearby Basel. Each sheet (Brant 1492) was headed by a woodcut depicting the fall, followed by poems describing the event in Latin and in the German vernacular, which Brant was studiously introducing into the literature. The woodcuts differ somewhat, as do the Latin and German verses, in their styles and the topics to which they allude. Presently a printer in Reutlingen and one in Strassburg issued similar broadsheets (Heitz 1915), which despite some variations in the woodcuts and texts still prominently displayed Brant's name as the author. In a modern sense these two sheets were most probably pirated, but Brant may not have objected because the extra sheets served to double the publicity for his message.

The fact of the fall was unquestioned; people believed that all sorts of things fell from the sky, and, as a true savant of the Renaissance, Brant made these beliefs respectable by citations from antiquity. He began each of his poems with lists taken mainly from Book II of the *Historia Naturalis* of Pliny the Elder (*c*. 23–79) written about 77 AD. Manuscripts of Pliny's work had circulated widely in Europe during the Middle Ages and four editions had been printed since 1469. The following is a passage from the Latin poem in Figure 3:

> Portents were seen of old, and horrendous signs
> Shining in the sky: flames, crowns, beams . . .
> Milk raining from the sky, grains of steel,
> And iron, bricks, flesh, wool, and gore;
> And six-hundred other things written down in
> books.

Of these items, the flames and beams may have been fireballs, and the steel, iron and bricks were most probably meteorites. Brant referred to a stone marked with a cross and secret signs that fell in the reign of King Friedrich II, and then, halfway through his poem, he described the event at Ensisheim:

> There came a horrendous explosion; a thunderbolt
> clanging in the air
> Multisounding: and there fell a burning stone,
> Shaped like a Grecian Delta, triangular with three
> sharp corners,
> Singed and earthy and metalliferous,
> It fell obliquely through the air
> As though hurled from a star like Saturn.
> Ensisheim felt the force of it; all Suntgaudia felt it
> As it plunged into a field and devastated the
> ground.

1492

Von dem donnerſtein gefallẽ im xcij. iar: vor Enſiſhein.

De fulgetra anni xcij.
Sebaſtianus Brant.

Perlegat antiquis miracula facta ſub annis
Qui volet: et noſtros comparet inde dies.
Viſa licet fuerint portẽta / horrẽdaqꝫ mõſtra
Lucere e celo: flamma / corona / trabes /
Aſtra diurna / faces / tremor et telluris hyatus
Et bolides / Typhon / ſanguineuſqꝫ polus /
Circulus: et lumẽ nocturno tpe viſum /
Ardentes clypei et / nubigeneqꝫ fere.
Montibus et viſi quondã concurrere montes
Armorũ et crepitus / et tuba terribilis.
Lac pluere e celo viſum eſt / fruges qꝫ calybsqꝫ
Ferrũ etiam / et lateres / ⁊ caro / lana / cruor /
Et ſexcenta aliis / oſtenta aſcripta / libellis:
Prodigiis auſim vix ſimilare nouis.
Viſio dira quidẽ Friderici tempore primi:
Et tremor in terris / lunaqꝫ / ſol qꝫ triplex.
Hinc cruce ſignatus Friderico rege ſecundo
Excidit inſcriptꝰ gramate / ab hymbre lapis.
Auſtria quẽ genuit ſenior Fridericꝰ / in agros
Tercíꝰ hunc pprios. et cadere arua videt.
Nempe q̃dringẽtos / pꝰ mille pegerat annos
Sol nouieſqꝫ decem ſignifer / atqꝫ duos.
Septẽ preterea dat idus / metuenda nouẽbris:
Ad mediũ curſum tenderat illa dies.
Cum tonat horrẽdũ: crepuitqꝫ per aera fulmẽ
Multiſonũ: hic ingens concidit atqꝫ lapis.
Cui ſpẽs delte eſt / aci eſqꝫ triangula: obuſtus
Eſt color / et terre forma metalligere.
Miſſus ab obliquo fertur: viſuſqꝫ ſub auris
Saturni qualem mittere ſydus habet.
Sẽſerat hũc Enſhei. Sũtgaudia ſẽſit: ĩ agros
Illic inſluit / depopulatus humum.
Qui licet in partes fuerit diſtractus vbiqꝫ:
Pondꝰ adhuc tamẽ hoc ꝯtinet / ecce vides.
Qui mirũ eſt potuiſſe hyemis cecidiſſe diebꝰ:
Aut fieri in tanto frigore ꝯgeries?
Et niſi anaxagore referant monimẽta: molarẽ
Caſurũ lapidẽ. credere et iſta negem.
Hic tñ auditus fragor vndiqꝫ littore Rheni:
Audiit hunc Vri ꝓrimꝰ alpicola:
Norica vallis eũ / Sueui / Rhetiqꝫ ſtupebãt:
Allobroges timeant: Francis certe tremit.
Quicqd id ẽ / magnũ portẽdit (crede / futurꝫ
Omen: at id veniat hoſtibꝰ oro malis.

Anno Dni
1492.

Sych wundert mancher fremder gſchicht.
Der merck vnd leß ouch diß bericht.
Es ſint geſchen wunder vil
Im lufft / comet vnd füren pfil.
Brinnend fackel / flammẽ vnd kron.
Wild kreiß vñ d zirckel vmb den mon
Am hymel. blůt / vnd füren ſchilt /
Regen noch form der thier gebildt.
Stoß bruch des hymels vnd der erd /
Vnd ander vil ſeltzen geberd
Tratzlich zerſtieſſen ſich zwen berg /
Grüßlich trümett / vnd harneſch werck /
Iſen / milch / regen ſtahel korn
Ziegel / fleiſch / woll / von hymels zorn
Als oüch ander der wunder glich
Dann by dem erſten Friderich
Noch ert bydem vnd finſterniß
Sach man drij ſünn vnd mon gewiß
Vnd vnder keyſer Friderich
Dem andern / fiel ein ſtein grüßlich
Sin form was groß / ein crütz dar jnn
Vnd ander geſchrifft vnd heimlich ſynn
By wil des dritten Friderich
Geboren herr von Oſterich
Regt har jn diß ſin eigen landt /
Der ſtein der hie ligt an der wandt.
Als man zalt viertzehenhündert Iar.
Vff ſant Florentzen tag iſt war
Nüntzig vnd zwei vmb mittentag
Geſchach ein grüſam donnerſchlag /
Drij zentner ſchwer fiel diſer ſtein
Hie in dem feld vor Enſißhein /
Drij eck hat der verſchwertzet gar
Wie ertz geſtalt vnd erdes var
Ouch iſt geſehen in dem lufft
Slymbes fiel er in erdes klufft
Clein ſtück ſint komen hin vnd har
Vnd wit zerfüert ſüſt ſichſt in gar
Tůnow / Necker / Arh / Ill / vnd Rin
Switz / Vri / hort den klapff der Jn /
Oüch doent er den Burgundern ver
Jn forchten die Franzoſen ſer
Rechtlich ſprich ich das es bedůt
Ein bſunder plag der ſelben lut

Von Maximiliano. Romiſchem kuning:

Ich für dich recht o Adler milt.
Erlich ſint wapen in dim ſchilt
Brüch dich noch eren gen dim findt
An dem all truw vnd ere iſt blindt
Schlag redlich vnd mit froüden dran
Trib vmb das radt Maximilian.
In dim geuell das glück jetzt ſtat
Ach ſũm dich nit / kũm nit zů ſpat
Mit ſorg den vnfal vff diß Jar
Nit vorcht din findt als vmb ein har
Sig / ſeld / vnd heyl von Oſterich

Burgundiſch hertz von dir nit wich
Romiſch ere vnd tütſcher nacion
An dir o höchſter künig ſtan
Nym war der ſtein iſt dir geſant
Dich mant gott in dim eigen lant
Das dü dich ſtellen ſolt zů wer
O küning milt für vß din her
Vling harneſch vnd der büchſen werck
Trümnt zerſchöl / franzöſiſch berck
Oüch mach den groſſen hochmůt zam
Rett ſchirm din ere vnd gůtt n nam.

Rûton vrſach
.J. .B.

Fig. 3. The only surviving original of Sebastian Brant's first broadsheet describing the fall of the 'donnerstein' at 'Ensisshein' in 1492. The Latin and German verses describing the fall are followed by an address to Maximilian, the Roman King. The inked lines and notations are of unknown authorship. (Reprinted by courtesy of Ueli Dill, Keeper of Manuscripts at the Öffentliche Bibliothek der Universität Basel.)

Good Renaissance humanist that he was, Brant then paid his respects to an ancient writer:

> Unless the fall of stones had been described by
> Anaxagoras,
> I would state that such things are not to be
> believed.

Pliny had written that Anaxagorus of Clazomenae (*c.* 500–428 BC) had so mastered mathematics and astronomy that he predicted the fall of a rock from the Sun. On the appointed day in 464 BC a brown stone the size of two millstones plunged to Earth at the Aegos Potamos district of Thrace (the north shore of the Hellespont) where it still might be seen in Pliny's own day. Given such authority, Brant felt secure in reporting the fall of the stone at Ensisheim, which he says he would not have believed otherwise – even though the explosion had been heard by hundreds of people and the stone was retrieved from the hole it made and put on display in the church.

Brant did not compose his broadsheets simply to spread the story of the fall of the stone. Brant was an ardent supporter of Maximilian, and he declared that the stone had been sent from on high as a pledge of his victory. Toward the end of each sheet he addressed a paean to Maximilian, the Roman King, urging him to make haste in his war with France:

> The Roman honour and German nation
> Stand by you, oh highest King.
> Take as truth that the stone was sent to you,
> God warns you in your own land
> That you should arm yourself.
> Oh mild King, lead out your army
> Let armour clang and roar of guns
> Let triumph resound:
> Curb the swollen pride of France
> Preserve your honour and your good name.

The four broadsheets bearing Brant's call to Maximilian would have been passed from hand to hand, read to crowds and tacked on walls in three cities where they may have reached several thousand people within weeks. Maximilian won his impending battle, and after that Brant declared in additional poems that the stone was a pledge of divine favour that would continue throughout Maximilian's lifetime.

We should note that this benign interpretation of the fall applied only to Maximilian and only in German lands. It did not remove the touch of evil from fallen stones in general, and, indeed, one illustration of the Ensisheim fall, based in part on Brant's broadsheets, depicts it as ominous (Fig. 4). The stone, seen falling from the sky and lying on the ground, and the mounted knight pointing upwards towards it, were copied from Brant, but everything else is completely different. The little village of Battenhem has become the walled city of Bauenhem. A rat-like creature occupies the space of the knight's squire; a wind-face appears in the swirling dark clouds above the stone; four dead birds fall from the sky; a large animal enters a burrow; and a salamander (a creature believed to be resistant to fire) creeps away from the fallen stone. One delightful Alsatian feature is a cartwheel mounted on a chimney to attract migrating storks to nest there, but a huge owl, an ancient omen of evil, surveys the scene from the top of the adjacent chimney. This picture, titled, *Sebastianus Brant de fulgetra anni 1492*, and followed by a handwritten copy of Brant's Latin poem, was pasted into the manuscript of the massive *History of the Sienese* by Sigismondo Tizio (1458–1528), a parish priest at Siena. Tizio received Brant's broadsheet from the Sienese Cardinal, Francesco Piccolomini, at Rome. However, Tizio did not complete his Volume VI, which spanned the years from 1476 to 1505, until 1528 when he could look back on the fall as signifying unmitigated disasters. To him, the first would be the crowning of Rodrigo Borgia as Pope Alexander VI. Tizio wrote that Cardinal Piccolomini had refused to accept bribes from Borgia before the election, which occurred just 3 months before the stone fell. Subsequently, Italy was invaded by the French in 1494, and the spread of syphilis in Europe was widely attributed to Columbus' return from the Indies in 1493 (Rowland 1990).

How did Brant describe the fall phenomena? At different times, Brant called the mass a thunder stone, a lightning stone and a burning stone, and he listed the peoples who heard the explosion: the Swiss and Uri among the Alps, the Noricians, Swabians, Rheticans, Burgundians and, of course, the French, whom he said it made to tremble. We can conclude that the explosion was heard over some 40 000 km^2 (e.g. Marvin 1992, p. 63).

The woodcuts on Brant's sheets depicted lightning flashes (of a standardized type) on both sides of the stone, but neither Brant nor any other contemporary source described the incandescent fireball that must have coursed northwestward over much of southern Europe. However, we do have credible evidence of the fireball in at least two illustrations.

Diebold Schilling's 1513 *Schweizer Bilderchronik des Luzerners*, handwritten on parchment, depicts the fall of the Ensisheim

Sebastianus Brant de fulgetra anni 1492

Perlegat antiquis miracula facta sub annis
Qui volet: et nostros comparet inde dies
Visa ~~licet~~ fuerint portenta hōrendaque monstra
Luxere celo flamma corona trabes
Astra diurna faces tremor et telluris hiatus
Et bolides thiphon: sanguineusque polus.
Circulus et lumen nocturno tempore visum
Ardentes clypei nubigeneque ferae
Montibus et visi quondam concurrere montes
Armorum et crepitus et tuba terribilis
Lac pluere celo visum est frugesque calibsque
Ferrum etiam et lateres et [illegible] lama rude

Fig. 4. A depiction in ink and wash of the fall of the stone at Ensisheim mounted above a handwritten copy of the first 12 lines of Brant's Latin poem in Sigismondo Tizio's *History of Sienese*. In a strange shift of perspective, Brant's mountainous skyline in Fig. 3 is replaced by a meandering river. The inscription above the clouds reads: 'Amsam (Ensisheim) is a city in upper Germany which falls under the Emperor's jurisdiction and is one day's journey above Basel'. (With thanks to Don Rafaelle Farina Prefect of the Biblioteca Vaticana, for permission to reproduce this illustration from MS Chigi G.II.36.)

Fig. 5. A depiction in ink and tempera colour on parchment of the explosion of the Ensisheim fireball and the fall of the stone into a field. In place of the boy who was the sole witness to the fall, this fanciful scene shows a field being harrowed and sowed by two men with a large horse. (From folio 157 of Diebold Schilling's manuscript *Schweizer Bilderchronik des Luzerners* of 1513 at the Zentral- und Hochschulbibliothek Luzern; courtesy of Susi Stöckli of the Korporationsgemeinde der Städt Luzern.)

stone in a beautiful painting in ink and tempera colour (Fig. 5). It shows a fiery red cloud with yellow–orange fringes from which the big, grey stone has just emerged. Thin red streaks trace the course of the stone from the cloud to the ground, where two men with a large horse are harrowing and sowing a field – presumably of winter wheat. In this painting, as in the woodcuts on Brant's broadsheets, the artists depicted the witnesses they fancied rather than the unnamed boy whom the records list as the one authentic eyewitness to the fall.

The other illustration is an oil painting depicting the explosion of a swiftly moving body at cloud level in the sky. This painting (Fig. 6), in which long red rays flare out from a small, yellowish projectile, is unique in the history of art. The subject is neither a star nor a comet. In fact, there is *nothing* it could be except an exploding meteoritic fireball. The painting is unsigned and undated but it appears on the reverse side of a small (24.3 × 18.7 cm) wood panel depicting the penitent St Jerome and his lion, which always accompanied him after he drew a thorn from its paw. St Jerome, himself, and the landscape and vegetation around him point to the unmistakable artistry of Albrecht Dürer (1471–1528). Dürer spent November of 1492 in Basel, just 40 km south of Ensisheim, where he could have seen the fireball and heard the explosion. Two art historians, Fredja Anzewlewski in 1980 and Hartmut Böhme in 1989, have argued that this painting is Dürer's depiction from memory of the Ensisheim fireball explosion. By comparing it with paintings Dürer made in Italy, Anzelewski concluded that Dürer painted St Jerome, and most probably both sides of the panel, in 1494 when he was in Venice.

The panel remained unknown until the 1960s when it was discovered in England in the private collection of Sir Edmund Bacon, Baronet, and loaned to the Fitzwilliam Museum in Cambridge. In 1996 the picture, as part of Sir Edmund's estate, was offered for sale, and historians of meteoritics despaired at the thought that this extraordinary depiction of a fireball might disappear into private hands. Then came the good news that the panel was purchased with the assistance of the National Heritage Lottery Fund, the National Art Collections Fund and Mr J. Paul Getty Jnr and is on display in London at the National Gallery of Art, where it is titled *A Heavenly Body* and dated to *c.* 1495–1496.

The gallery's brochure suggests that this painting depicts Dürer's version of the end of the world, rather than a specific event such as the Ensisheim fireball. But such a fireball explosion might well have struck Dürer as a vision of the end of the world. Böhme (1989) pursued his argument further and maintained that Dürer depicted the Ensisheim fireball once again in 1514 in his engraving *Melencholia I* (Fig. 7). The body in the sky commonly is called a comet. But it clearly is approaching the Earth at high velocity and lighting up the landscape. Furthermore, it seems to be exploding. Comets never move swiftly, never explode and never approach closely enough to cast light or shadows on the Earth. As one more piece of the puzzle, we will remember that Brant wrote that the stone fell obliquely as though cast from a star like Saturn. Saturn is the cold, forbidding planet that rules human feelings of melancholy, which are masterfully expressed in the demeanour of Dürer's great winged figure.

Yet another viewpoint was expressed by David Pingree, the specialist in the history of ancient and medieval astronomy and astrology. Pingree (1980, p. 257) then at Brown University, argued that the body is not a comet but must be a star or a planet as indicated by the rays extending from it in all directions. But he added that they cannot be rays of light because the presence of the rainbow shows that the Sun is still above the horizon and shining from the west – the direction from which we view the scene. Pingree concluded that the rays are emanations of divine energy by which, according to astral magic, the planets effect their influence in the world. In his view, the celestial body must be Saturn *rising* in the east!

Widely differing interpretations are to be expected from a picture with such an assemblage of occult objects and symbols as one finds in *Melencolia I.* However, in a detailed analysis of each object and its placement within the scene, Professor Wolf von Engelhardt (1993), of the University of Tübingen, agreed with Böhme that Dürer's celestial body is the fireball of the Ensisheim meteorite.

The stone of Albareto, Italy, 1766

At 5 o'clock one afternoon in mid-July 1766 a tremendous explosion, followed by fierce whistling sounds, astonished people over a wide area of the Po valley in northern Italy. As they watched, a body came streaking down from the north; some said it was fiery, others that it was dark and smoky. (Both were right – it depends on just where a witness is situated with respect to the trajectory of a falling meteorite.) The meteorite struck the ground at Albareto, near Modena, with such force that a cow was

Fig. 6. Oil painting of an exploding fireball by Albrecht Dürer, who was living in Basel in November 1492 and may have witnessed the event. This depiction appears on the reverse side of a small wood panel with a portrait of the Penitent St Jerome. Art historians estimate that Dürer painted both sides of the panel some time between 1494 and 1496. (By courtesy of Vivien Adams of the National Portrait Gallery, London.)

Fig. 7. *Melencolia I*, a copper engraving by Albrect Dürer, 1514. The body in the sky is believed by several scholars to be Dürer's second depiction of the Ensisheim fireball. (Courtesy of the Smithsonian Institution Libraries.)

knocked off its feet and two women clung to trees to avoid falling. People close enough to hear the impact found a black stone at the bottom of a hole about 1 m deep. They said it was still warm when they dug it out. They then hacked it to pieces, and carried the fragments all over the town.

This hacking to pieces of newly fallen stones has been reported in numerous instances. We have seen that it began to happen to the stone of Ensisheim in 1492, and it may account for the loss of one of the three fragments of a stone that fell at Novo Urei in Russia on 4 September 1886. That piece allegedly was ground up to be eaten by the local villagers. If so, they may have regretted it because the recovered fragment, weighing 1.9 kg, proved to be the first known example of the rare variety we call ureilites, consisting mainly of olivine and pigeonitic pyroxene but also containing microdiamonds, which could have done great damage to their teeth. Hacking to pieces also may account for the puzzling scarcity of meteorites in China for which the third edition of the British Museum's *Catalogue of*

Meteorites (Hey 1966) listed only 10 meteorites for that huge country but 33 for Japan. Perhaps most of the meteorites that fell during the long history of China went directly into the pharmacopoeia.

Soon after the event at Albareto, the Jesuit Father Domenico Troili (1722–1792), custodian of the library of the ruling family of Este in Modena, collected eyewitness reports and obtained a specimen he described as being very heavy, magnetic and partially covered by a dark crust that appeared to have been burned by fire. He noted that under his microscope the broken surfaces looked like sandstone with shiny particles of metallic iron and bronzy grains he called 'marchesita', an old Arabic name for pyrite. Within weeks, Troili issued a 120-page book entitled *About the Fall of a Stone from the Air, Explanation* (Fig. 8). True to the spirit of the Enlightenment, Troili sought for what he called a scientific, as opposed to a superstitious, explanation of the stone. Troili, concluded (1766, p. 104) that: 'The true cause of the fall of a stone in Albereto (*sic*) in mid-July, 1766, is a subterranean explosion that hurled the stone skyward'.

DELLA CADUTA
DI UN SASSO
DALL' ARIA
RAGIONAMENTO
DEDICATO
ALLE ALTEZZE SERENISSIME
DI
BENEDETTA,
ED
AMALIA
PRINCIPESSE DI MODENA
DA
DOMENICO TROILI
Della Compagnia di Gesù

IN MODENA MDCCLXVI.
Per gli Eredi di Bartolomeo Soliani Stamp. Ducali.
Con licenza de' Superiori.

Fig. 8. The title page of Domenico Troili's book of 1766: *About the Fall of a Stone From the Air, Explanation.* Dedicated to their most serene highnesses, Benedetta and Amalia, Princesses of Modena, by Domenico Troili of the Company of Jesus. (By permission of the Houghton Library, Harvard University.)

Volcanism was the familiar process for hurling stones into the air, and Italy had its share of volcanoes. However, soon after his book appeared, Bishop Giuseppe Fogliani of Modena informed Troili that he and others strongly disagreed with his volcanic explanation. The Bishop charged Troili with leaving out details of the event at Albereto in order to save himself from having to discuss other, much better, modes of origin. The Bishop ascribed it to a lightning bolt. These two learned men of the 18th century agreed on three things:

- a stone had fallen from the sky;
- it originated on the Earth;
- it had been hurled skyward by a natural process.

But they disagreed, vehemently, about that process. The fall took place only a short time after the American statesman, scientist and inventor Benjamin Franklin (1706–1790) demonstrated with his kite experiment that lightning strokes are electrical phenomena. Franklin immediately described his procedures and observations in the *Pennsylvania Gazette*, and the news spread widely before the formal publication of his letter on the subject (Franklin 1754). People everywhere were calling on the 'electric fluid' to account for puzzling phenomena.

In December 1766 Troili wrote a 71-page *Lettera Apologetica* expressing all due respect to the Bishop but stoutly defending his volcanic hypothesis. However, before he sent it, Troili discovered in the archives a copy of a letter, dated 20 February 1767, from the physicist Giambattista Beccaria (1716–1781) to Benjamin Franklin. Beccaria (1767) wrote in defence of Franklin's ideas on the nature of electricity, and in opposition to those of his rivals. Then, in a postscript, Beccaria criticized Troili's explanation of the fall of the stone. Beccaria said he agreed with the Bishop that the soil at Modena is full of the nearby water and that a thunderbolt had driven through the stone, which was metallic, and hurled it into the air while covered by its own flash, so it could not be seen until it fell back down. He chastised Troili for stating that the flash occurred far to the north of Albareto, because it had to be directly overhead at 'Alboretium'.

Troili (1767) added an eight-page postscript to his *Lettera Apologetica*, in which he pointed out that a single bolt of lightning would not suffice, because flashes were reported far to the north of Modena. Furthermore, he reported that the gardener to His Most Serene Highness, the Sovereign Duke of Modena, told him he was so frightened by the explosion and whistling that he feared a canon ball from the nearby fortress might land in the garden. Once again, Troili stoutly defended his volcanic explanation. The Bishop did not publish his opinion, but Troili's book and his subsequent letter leave no doubts about his views on the origin of the stone (Marvin & Cosmo 2002).

A century later Wilhelm Karl Haidinger (1795–1871), Curator of Minerals at the Imperial Mineral Collection in Vienna, reviewed this history and proposed the name *Troilite* for the bronzy mineral Troili had called 'marchesita'. Chemists had had great difficulties with this mineral. Many doubted it was a pure phase. But by the early 1860s it was accepted by Haidinger's friend, the chemist Friedrich Wöhler (1800–1882), as stochiometric iron sulphide (FeS), occurring exclusively in meteorites. Haidinger (1863) wished to honour Troili as the first person to describe the fall of a meteorite from space. He acknowledged that Troili, himself, described the stone as one hurled aloft from a cleft in the Earth, but Haidinger argued, in effect, that since *we* know the stone of Albareto was a meteorite, and *we* know that it fell from space, we should credit Troili as the first person to report the fall of a meteorite from space. With this flagrant exercise in 'presentism', Haidinger sought to crown Troili with the laurels that belong to Ernst F.F. Chladni, whom we shall be discussing shortly.

Unfortunately, Haidinger's remarks were taken up in the 20th century by Harvey H. Nininger (1887–1986), the American meteorite collector–dealer–researcher, who wrote in his books that, although Chladni has been credited as the first to evaluate the arrival of meteorites from space, Troili gave a perfectly valid account of one 30 years earlier (Nininger 1952, p. 7). More recently, in 1998, Peter H. Schultz, of Brown University, cited Nininger as rightfully crediting Troili with the pioneering breakthough of documenting a fall and proposing a cosmic origin (Schultz 1998, p. 101). Thus, it is that reporting on historical events may go astray when it is derived from the secondary literature.

On p. 58 of his book, Troili (1766) wrote that before it was smashed to pieces the stone would have weighed about '25 libbre' (12 kg). Accordingly, the original weight of the Albareto stone is listed as 12 kg in the first three editions of the British Museum's *Catalogue of Meteorites* issued by George T. Prior (1862–1936) in 1923 and by Max H. Hey (1904–1984) in 1953 and 1966. However, in the *Appendix to the Catalogue of Meteorites* by R. Hutchison, A.W.R. Bevan and J.M. Hall (Hutchison *et al.* 1977), the original weight of the stone is reduced from 12 to 2 kg. This was done on the advice of Dr Giovanna Levi-Donati, a meteoriticist and historian in Perugia, who recommended the change because much less than 2 kg of the stone survives today (Bevan pers. comm. 2002). The 5th edition of the Catalogue (Grady 2000, p. 3) continues to list the weight as 2 kg. Prior clearly had read Troili's book – some of his remarks echo Troili's – and Hey followed Prior. Now, it would seem appropriate in future writings to restore Troili's own estimate of 12 kg for the original weight of the meteorite. Despite the dissemination of fragments at the time of its fall, pieces of Albareto, which is classified as an ordinary L4 chondrite, are catalogued in several museums, with the largest specimen, weighing 600 g, in the museum in Modena.

The fall at Lucé, France, 1768

At 4:30 in the afternoon of 13 September 1768, harvesters at Lucé, in Maine, were startled by sudden thunderclaps in a clear sky, followed by a loud hissing noise. They looked up just in time to see a stone plunge into a nearby field where they found it half buried in the soil. They said it was too hot to pick up. A piece of it was acquired by the Abbé Charles Bacheley (1716–1795), who forwarded it to the Royal Academy of Sciences in Paris, of which he was a corresponding member. The Academy appointed a committee of three chemists to examine the stone: August-Denis Fougeroux de Bonderoy (1732–1789), Louis-Cadet de Gassicourt (1731–1799) and Antoine-Laurent de Lavoisier (1743–1794). The chemists found the stone to have a thin black crust partially covering an interior of grey cindery material scattered with an infinite number of shiny metallic grains of a pale yellowish colour. They performed bulk analyses that yielded three main constituents: vitrifiable earth 55.5 wt%, iron 36% and sulphur 8.5%. Today, we recognize this as the first chemical analysis of a meteorite in modern times.

On 15 April 1769 Lavoisier read the report of Fougeroux, Cadet and Lavoisier to the Academy, although Lavoisier was, by far, the junior member of the committee. The chemists concluded, unanimously, that the stone was not a thunderstone and had not fallen from the sky; it was a fragment of pyrite-rich sandstone that had been struck by lightning. They hypothesized that the lightning bolt had blown away a thin covering of soil and melted the surface of the stone, but that the heat was too transitory to penetrate into the interior. By this reasoning, they worked out the earliest (but erroneous) explanation for the molten surfaces and unmelted interiors of newly fallen meteorites.

During the investigations of Lucé, the committee received a second stone reported to have fallen near Coutances in the Cotentin of lower Normandy. Today, this stone is listed as 'Nicorps' because it is thought to have been the stone said to have fallen after a loud explosion at Nicorps, in the Cotentin, on 11 October 1750. It, too, had a thin black crust and, although it emitted a less sulphurous odour, it was similar in other respects to the stone from Lucé. The committee members regarded this resemblance as strong evidence that thunder strikes preferentially on pyrite-rich rocks. The committee report by Fougeroux, Cadet and Lavoisier was dated 1772 but published in 1777.

A third stone, from Aire-sur-la-Lys, reached the Academy too late to be included in the report, but Fourgeroux and Cadet analysed it during Lavoisier's absence, due to his tax-farming duties (which, unfortunately, would lead him to the guillotine in 1794). Fourgeroux and Cadet found the third stone to be essentially identical to the other two. A reference to it was included in a brief summary of the committee report that was inserted by Jean-Paul Grandjean de Fouchy (1707–1788), the perpetual secretary of the Academy, into the history section of the Academy's 1769 volume (published in 1772). This summary suggests that the perfect resemblances between the three stones, widely separated in location and time, along with their differences from any other known rock, should invite physicists to examine this subject more closely. Perhaps they could shed new light on the electric fluid and its action on thunderstones (Fouchy 1772). Today, pieces of the Lucé stone, an L6 chondrite, are cataloged in numerous museums. The other two stones are long lost, but are generally believed to have been genuine meteorites.

The Pallas iron, Siberia, 1772

In 1772 Peter Simon Pallas (1741–1811), a German professor of natural history at St Petersburg, paused at the town of Krasnojarsk, in Siberia, during his scientific travels through the Russian Empire (Pallas 1776). From there, he sent his aide southward on a mission that, quite by chance, took him to the village of Ubeisk, where he saw a large mass of metal riddled with cavities, some of which were filled with yellow glassy material, lying outside the house of the local blacksmith, Yakov Medvedev. In 1749, Medvedev had been showing iron ore deposits to Johan Mettich, a government mining engineer, when the two of them came upon a rounded mass of metal, 70 cm in diameter, on a high ridge of Mt Bolshoi Emir. The following winter Medvedev went back and dragged, slid and hauled the heavy mass down the mountainside and across 20 km of partly swampy territory to his village. He had not succeeded in forging it, because it was too malleable in its natural state but it became too brittle on heating, so he placed it outside of his door. Some of the local people venerated it as a gift fallen from heaven.

The aide carried a piece of it to Pallas, who immediately saw that this was a most remarkable specimen deserving of further study. Pallas did not say whether or not he visited the find site, but he described it in such detail that some Russian scientists are convinced that he did (Gallant 2002, p. 121). Pallas described the bedrock of Mt Bolshoi Emir as grey schist locally banded with magnetite that showed no signs of having been worked as iron ore. There were no traces of ancient smelting operations nearby, nor were there any of volcanism in the region. Pallas remained non-committal on whether the mass could have fallen from the sky, but he conceived an idea that it might have formed in a pocket in a vein, the rest of which had eroded away. He made a sketch of it looking smooth and rounded, although he described it as being pitted like a sponge (Fig. 9). In 1980, despite the immense difficulties of working on the steep slopes in the vicinity of Mt Emir, a Russian team mounted a cast-iron disk, 2 m

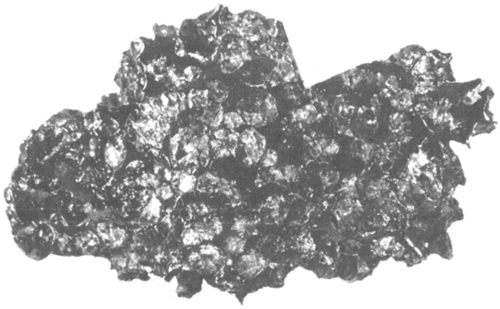


Fig. 9. A specimen of the Pallas iron, about 8 cm across, showing the rough texture of the metal due to the loss of many crystals of peridot. (Courtesy of the Department of Mineral Sciences, Smithsonian Institution, Washington, DC.)

across, on a cement base marking the site where the Pallas iron was found (Gallant 2002, p. 139).

In 1773 Pallas arranged to have the mass transported from Ubeisk 230 km downriver to Krasnojarsk. From there, it was sent to the Imperial Academy at St Petersburg, a process that book more than 4 years. The heavy mass was sledged across the winter landscape to a port on the east bank of each river in its path. There it remained until summer, when it could be rafted across the water and left on the west bank to await the next winter's sledging season. People took samples of it at each of its stops so its weight dwindled by several kilogrammes during its travels (Gallant 2002, p. 114). At last, the mass arrived at St Petersburg in May 1776, where it was placed in the Kunstkamer, the hall of curiosities begun by Peter the Great. It was called the 'Pallas iron', and specimens of it were sent to natural historians throughout Europe (Ivanova & Nazarov 2006). In 1825 Gustav Rose (1798–1873), Director of the Mineralogical Museum at the University of Berlin, classed all stony-iron meteorites of this particular variety as 'pallasites'.

El Mesón de Fierro, Campo del Cielo, Argentina

In 1576 the governor of Tucumán province, in what is now northern Argentina, commissioned Capitán Hernán Mexia de Miraval to search for a huge mass of iron from which the nomadic Indians said they obtained the metal they used on their weapons. The Indians claimed that the mass had fallen from the sky in a place they called 'Piguem Nonraltá', which the Spanish translated as 'Campo del Cielo' ('Field of the Sky'). de Miraval and eight men followed Indian guides eastward out of the fortified settlement of Santiago del Estero into the Chacos – vast stretches of soft, powdery, flat-lying soils with no rocks and no watercourses. They followed trails established by the nomadic seekers of honey and wax in the region. After a long, difficult march, frequently harassed by Indians whom they believed to be cannibals, de Miraval came upon a large mass of metal projecting out of the soil. He assumed he had located a potential iron mine and carried a few samples back to Santiago del Estero, where a blacksmith described them as iron of unusual purity. It was against the law in colonial territories to develop iron mines without a warrant from the Crown, and none was forthcoming. In 1584 de Miraval and one of his officers drew up an official document in Santiago del Estero detailing the difficulties of the expedition and their discovery of the iron. Both the governor's original commission and de Miraval's document were deposited in the Archivo General de Indias in Seville (Alvarez 1926).

And there they lay, unread, for the next 340 years. De Miraval's discovery was so quickly forgotten that, as early as 1630, Martin Ledesma Balderrama, Lieutenant Governor of Santiago del Estero, wrote a detailed account of the lands, rivers, climate, vegetation, animals and peoples of the region, in which he made no mention of de Miraval's expedition or his ore samples. He simply repeated the Indian legends of an enormous mass of iron lying in the Chaco (e.g. Marvin 1994, p. 157).

The Indians continued to bear metal-tipped weapons and to tell stories of iron falling from the sky amid raging fires. In 1774 don Bartolomé Francisco de Maguna, at Santiago del Estero, led a search into the Chaco for the iron. Some 90 leagues to the east, de Maguna came upon a large mass of iron with a nearly smooth surface sloping gently upward out of the soil. He called it a 'gran barro o planchon de fierro' ('a large bar or plate of iron'), which was to become widely known as 'el Mesón de Fierro' ('the table of iron'). Maguna thought it was the tip of an iron vein and took samples, one of which, weighing about 1 kg, was analysed in Madrid and reported to consist of 80% iron and 20% silver.

This news stirred high hopes, particularly at the court in Madrid, that the Chacos bore treasures beyond all the silver of Peru. However, analysts in Buenos Aires and in Peru found no silver at all in de Maguna's samples; nor did they find any in the samples collected by a subsequent expedition led by don Francisco de Ibarra in 1779. Meanwhile, in 1778 nearly 91 metric tonnes (t) of mercury, sewn into pigskins, were shipped from Spain to Argentina for beneficiation of the silver ore (Alvarez 1926). We have no information on what became of the mercury. In 1783 Lieutenant Rubin de Celis, of the Royal Spanish Armada, was sent to evaluate the iron deposit, and, if it seemed promising, to found a colony at the site. Don Rubin led 200 men eastward from Santiago del Estero and when he found the Mesón de Fierro he dug a trench around it, tilted it up and exploded gunpowder in the hole. He found no extensions of metal at depth or to either side. He drew a map of his route on which he located the Mesón de Fierro at 27°28′S. He also had sketches drawn to scale of the top surface (Fig. 10) and a side view of the mass, showing it to be thin and lumpy and full of cavities. His men wore out 70 chisels taking off 12 kg of samples – a common experience of those attempting to

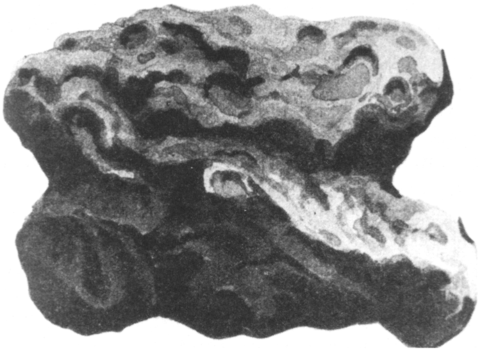


Fig. 10. Top surface of the Mesón de Fierro from a sketch by Don Rubin de Celis after its excavation. He recorded its maximum dimension as 3.54 m and estimated its weight at about 15 000 kg. We may wonder about its nickname because this lumpy specimen bears no resemblance to a 'Table of Iron'. (From Alvarez 1926, p. 21.)

sample iron meteorites. Nickel–iron is ductile, but tough and tenacious, and a blade may enter it with ease but not remove anything. We can only wonder how de Miraval and others, who made no mention of their difficulties, obtained their samples.

As a rational man of the 18th century, de Celis did not believe the iron had fallen from the sky. Even less did he suppose it had been transported into the Chaco by humans, so he searched for signs of volcanism. Some 6 leagues to the east, he came upon a brackish spring beside a gentle rise, 1–2 m high. He decided this must be the volcanic source that had expelled the mass of metal. (There was a widespread belief back then that mountains are destroyed by volcanic fires consuming them from within.) He estimated the weight of el Mesón at only 15 000 kg and abandoned it as worthless. And there it lies to this day, despite diligent searches for it during the past two centuries, most recently with the aid of magnetometers on the ground and in the air. Now and then, rumours circulate that el Mesón de Fierro has been found, but, to date, its discovery has not been confirmed.

Don Rubin de Celis sent samples to the Royal Society in London and to other leading institutions, and he wrote a detailed report of his expedition that was published in both English and Spanish in the *Philosophical Transactions of the Royal Society* (Celis 1788). In 1799 the French chemist, Josef-Louis Proust (1754–1826), in Madrid, obtained half an ounce of the metal and applied a new quantitative analysis for nickel, that had been published as recently as 1797 by Sigismund Hermbstädt (1760–1843) in Berlin. Proust (1799) found 90% iron and 10% nickel in the metal, and questioned whether this precious alloy was a product of nature or of artifice. Proust could not have known that he was making the first analysis of nickel in an iron meteorite (Marvin 1994, p. 161).

In the early 19th century, when scientists finally acknowledged that stones and irons fall from the skies, Europeans credited don Rubin de Celis, from Spain, and Argentines credited don Bartolomé Francisco de Maguna, from Santiago del Estero, with the discovery of el Mesón de Fierro. But both were preceded by don Hernan Mexia de Miraval, who found it in 1576. His official description, written in 1584, was unearthed in the archives at Seville in the early 1920s (Alvarez 1926). Since then that document has ranked as the earliest record of the examination of a meteorite by Europeans in the Americas. However, sequestered as it was, de Miraval's report contributed nothing toward an understanding of meteorites. Don Rubin de Celis, in contrast, contributed significantly to the budding new science by making samples of the metal available to several institutions in Europe. None of these three explorers believed that el Mesón fell from the sky, but the Indians believed it and they told the authentic story from the beginning.

How could a 15 t mass of iron become 'lost' in the flat, dusty soils of the Chaco? Perhaps the mass was tilted back into its deepened hole and buried by an annual accretion of mud from shallow floodwaters that spread thinly over parts of the Chaco. In addition, thorny bushes now cover wider areas of the Chacos than they did in don Rubin's time. But neither mud nor bushes should conceal a large mass of metallic iron from airborne magnetometers. Perhaps we may conclude that there was no single Mesón de Fierro. Perhaps de Miraval, de Maguna and de Celis found different large irons. In fact, their accounts of the distances they travelled and of the metals they found differ considerably. de Miraval spoke of a large mass of metal projecting above the soil; de Maguna (two centuries later) spoke of a great bar or plate of iron sloping gently upward from beneath the soil; de Celis found a mass almost buried in clay and ashes (Alvarez 1926). These may well have been three different irons in what we now recognize as Campo del Cielo, one of the longest meteorite strewnfields of the world.

Campo del Cielo trends N60°E for 75 km across the Chacos (Cassidy *et al.* 1965). It has yielded some 44 000 t of irons (without counting el Mesón de Fierro), ranging in weight from a few milligrammes to the 33 t el Chaco iron located by a metal detector in 1969 at a depth of 5 m (Cassidy 1970). The largest irons occur near the mid-point of the strewn field, with smaller ones at both ends. The mid-part of the field also contains 20 shallow impact craters, which measure 20–100 m across, including at least two explosion craters that have thousands of small iron fragments strewn around them (Cassidy *et al.* 1965). Both de Maguna and de Celis had mapped a few of these craters as 'pozos' (rounded depressions) some with and some without water in them. This unusual distribution of large irons and craters suggests that a huge body, coursing through the atmosphere at an angle of about 10°, broke up in mid-flight where it dropped its largest fragments (Cassidy & Reynard 1996). The Campo del Cielo iron is a coarse octahedrite (group IAB) that is unusually rich in silicate inclusions. The presence of the silicates may have facilitated the break-up of the main mass.

de Celis' route map showed el Mesón lying a little to the west of what we now view as the NE end of the strewn field – far removed from any other large irons or craters (Fig. 11). To reach this site, de Celis' search party of 200 men must have trampled through part of the strewnfield without noticing any other irons, although in more recent years irons have been detected by their metallic ringing when knives or hammers have been dropped on them. Whether or not the Mesón de Fierro exists, the abundance of iron meteorites indicates that an impact occurred of such magnitude that it excavated craters and could have set off great fires. Samples of charred wood taken from beneath irons buried in crater floors give ^{14}C values that date the fall to about 4000 years ago, or approximately 2000 BC (Cassidy & Reynard 1996, p. 438). At that time, ancestors of today's Indians may possibly have seen the fires and the falling irons (Marvin 1994).

Franz Güssmann's treatise on native iron, 1785

In 1785 Franz Güssmann (1741–1806), a mathematician and professor of natural sciences at Vienna, published *Lithophylacium Mitisianum*, a two-volume, 634-page systematic mineralogy text. Under *Ferrum Nativum*, Güssmann (1785) described the Pallas iron and an iron said to have fallen from a fireball in 1751 at Hraschina, Croatia. Güssmann believed that both masses of iron had fallen from the sky, but, just as Troili had done 19 years earlier, he hypothesized that they originated on the Earth. He argued that they were melted in the Earth by stupendous electric fires, which launched them into the sky as a mortar throws a bomb. Despite his central position in scientific circles in Vienna, Güssmann's discussion of native irons seems, much to his distress, to have passed unnoticed.

The fall at Barbotan and Agen, France, 1790

At about 9:30 in the evening of 24 July 1790, a brilliant fireball coursed over southern France

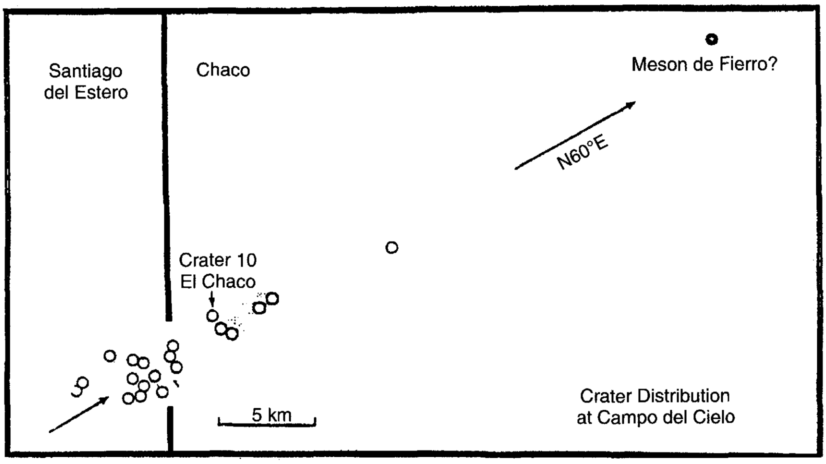


Fig. 11. Sketch map of a 40 km-strip in the central part of the Campo del Cielo strewnfield, which trends N60°E for 75 km. This view shows the distribution of the craters and the find site of the 33 400 kg el Chaco iron excavated in 1969 from beneath Crater 10. Don Rubin de Celis wrote that the Mesón de Fierro lay at latitude 24°28′S; here it is indicated where the path of the fireball crosses that latitude. (From Marvin 1994, fig. 4.)

in full view of thousands of people. Some said it remained visible for 50 s – a very long time for a firefall. A horrendous explosion followed and stones showered down over a wide area including the villages of Barbotan and Agen. Excited stories by witnesses soon reached the teacher and naturalist Jean F.B. Saint-Amans (1748–1831) at Agen, who shared his amusement over them with his friend Pierre Bertholon (1741–1799), the editor of the *Journal des Sciences utiles* in Montpellier. Saint-Amans then decided to match one absurdity with another by demanding an official testimonial to the event. Much to his surprise, Saint-Amans soon received a deposition, signed by a mayor and his deputies, stating that at least 300 citizens in his city had witnessed the fall. To Saint-Amans this simply was new proof of the credulity of country people so he induced Berthelon (1791, p. 228) to publish a report of the event to which Berthelon added the following statement, which has become famous in the annals of meteoritics:

> How sad, is it not, to see a whole municipality attempt to certify the truth of folk tales ... the philosophical reader will draw his own conclusions regarding this document, which attests to an apparently false fact, a physically impossible phenomenon.

Abbé Andreas Xaver Stütz on allegedly fallen stones, 1790

Also in 1790 the Abbé Andreas Xaver Stütz (1747–1806), Assistant Director of the Imperial Natural History Collection at Vienna, published a paper entitled: 'On some stones allegedly fallen from heaven'. Stütz' purpose was to discredit the idea that stones fall from the sky and to explain the reports of such events by applying the principles of physics. In particular, Stütz (1790) discussed the following three examples.

Eichstädt, Bavaria

In 1785 Stütz had received a small specimen from his friend, Baron Homspech of Eichstädt, along with a notarized document stating that at 12:00 noon on 19 February of that year a worker at a brick kiln heard a violent thunderclap and saw a body fall from the clouds. He rushed to the site and found a black stone he said was too hot to pick up until it cooled in the snow. The country rock of the area was a siliceous marble entirely different in composition from the stone. Stütz identified the sample as a fragment of ash-grey sandstone with tiny grains of malleable iron and yellow iron ochre scattered through it. He said it was covered by a thin crust of malleable iron streaked by a fiery melt.

Tabor, Bohemia, 1753

Stütz remarked that a previous director of the Imperial Collection, the Baron Ignaz Edler von Born (1742–1791), had a specimen in his private collection consisting of refractory iron ore mixed with greenish stone and covered with a slaggy crust. In his catalogue, von Born had written: '... some credulous people claimed that the stone had fallen from heaven in a thunderstorm on 3 July 1753'.

Stütz named no names, but one credulous person von Born may have had in mind was Father Joseph Stepling (1716–1778), a mathematician and physicist who had published a description of this fall as having occurred near Prague during a thunderstorm. In 1756 Stepling's report was read to the Royal Society in London, which responded by thanking Stepling for his communication without making any comment on its content (Burke 1986, p. 35).

Hraschina (Agram), Croatia, 1751

The reports from Eichstädt and Tabor reminded Stütz of a 71 lb mass of iron in the Imperial Collection that was said to have fallen 49 years earlier near Hraschina in the Bishopric of Agram, Croatia: 'Many a mouth already has been distorted with derisive smiles with respect to that mode of origin' wrote Stütz (1790, p. 399). He examined the large iron and compared it with his specimen of the Pallas iron. He found the one from Hraschina lacked the yellow glass of the Pallas iron, but the effects of fire were unmistakable on both of them. He then retrieved from the archives the document, written in Latin, that had been submitted along with the iron from Hraschina – the same document that Güssmann had reported on 5 years earlier. But although both men were prominent scientists in Vienna and both had access to the archives of the Imperial Collection, Stütz made no mention of Güssmann's discussion of the great iron of Hraschina or of his hypothesis that it had been melted and hurled into the sky by stupendous electric fires.

Back in 1751 this event had been investigated by the Bishop of Agram at the behest of the Emperor Franz I and the Empress Maria Theresa, whose subjects had been much alarmed by the fireballs and explosions. The Bishop sent his report and a large specimen of iron to Vienna. The report, written in Latin, contained sworn statements of seven witnesses from widely separated localities who said that at 6:00 p.m. on 26 May 1751 they saw a brilliant ball of fire split into two balls linked by fiery chains. An immense explosion occurred and was followed by a great rumbling as of many carriages rolling along. Some witnesses saw a large mass of iron plunge into a newly ploughed field, making the ground shake, as in an earthquake. Others saw a small mass of iron fall into a meadow. Stütz (1790) translated the Bishop's report into German and included it in his own paper.

Stütz wrote that the artless manner of the descriptions and the close agreement of all seven witnesses, who had absolutely no reason to agree on a falsehood and also the similarity of this story to that told of the Eichstädt stone, made it seem at least probable that something real lay behind these accounts. By something real, however, Stütz did not mean the possibility of falls of iron from the sky. Stütz (1790, p. 407) wrote:

> Of course in both cases it was said that the iron fell from heaven. It may have been possible for even the most enlightened minds in Germany to have believed such things in 1751, due to the terrible ignorance then prevailing of natural history and practical physics; but in our time it would be unpardonable to regard such fairy tales as likely.

He warned, however, that we must not simply deny phenomena that we cannot explain, as he, himself, might have done at an earlier time. Fortunately, new writings on electricity and thunder had recently come into his hands describing experiments in which iron oxide had been reduced to metal by the discharge of an electrical machine, and he reasoned that lightning, which is an electrical stroke on a large scale, had produced the masses of metallic iron by a bolt from the clouds. He suggested the same mode of origin for the Pallas iron. Fortunately, despite his rejection of their histories, Stütz preserved both the Eichstädt stone (an H5 chondrite) and the Hraschina iron (a class IID medium octahedrite (Fig. 12) in the collection in Vienna where they remain today (Brandstätter 2006).

Antoine-Laurent de Lavoisier, atmospheric origin of fiery meteors, 1789

In 1789 Lavoisier (1743–1794), published his magnificent textbook that laid the foundations of modern chemistry. An English translation appeared the following year (Kerr 1790). In several passages, Lavoisier spoke of gases and dust, consisting of earthy and metallic elements, rising daily from earth through the ordinary air and forming inflammable strata at great heights. If these strata are ignited by electricity, he said, the dust may consolidate into metals and stony matter that produce fiery meteors. Thus, in the late 18th century, Lavoisier gave a new impetus to an old hypothesis that solid bodies may accrete within the atmosphere. This idea customarily is attributed to Aristotle, although he, in fact, taught that solid bodies form on the ground (e.g. Burke 1986, pp. 10–14 and 326). It also is said to have been favoured by the Persian scholar and physician, Avicenna (980–1037), who described falls of both stones and irons that formed in the atmosphere in his manuscript, *De congelatione et conglutinatione lapidum*, which became available in a Latin translation about 1300. Also by the French philosopher and mathematician René du Perron Descartes (1596–1650), who argued that flashes of lightning can cause stones to congeal

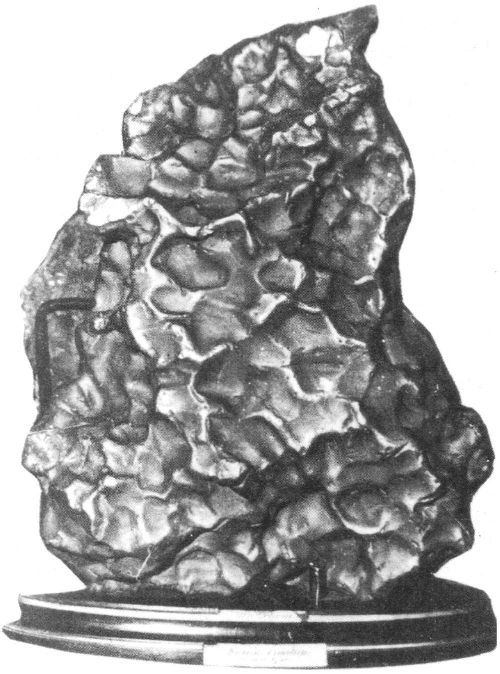


Fig. 12. The large 40 kg iron that fell at Hraschina, in Croatia, in 1751. Its striking texture has been preserved intact except for a small slice taken near the tip that was etched to show its Widmanstätten figures. The iron is on exhibit at the Natural History Museum in Vienna. (From Schreibers 1820, plate 1.)

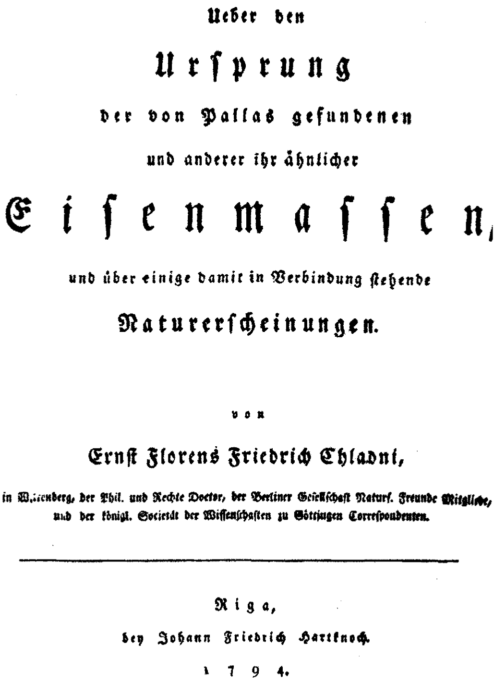
from dust in the atmosphere (Burke 1986, p. 13). The idea had other supporters, but it had been abandoned in the early 18th century as being against physics and common sense. At the turn of the 19th century, however, it once again would become one of the most favoured hypotheses of meteorite origins.

Ernst Florenz Friedrich Chladni, 1794

In 1794 Ernst F.F. Chladni (1756–1827) of Wittenberg, a physicist (Fig. 13) who already was winning fame for himself as the 'Father of Acoustics', published a 63-page book titled *On the Origin of the Mass of Iron found by Pallas and of Other Similar Ironmasses, and on a few Natural Phenomena Connected Therewith* (Fig. 14). The "few natural phenomena" were meteors, fireballs, and falls of stones and irons. In his opening paragraph, Chladni declared, forthrightly, that fireballs form around masses of heavy, compact matter, which enter the atmosphere from outer space and fall as meteorites. He named the Pallas iron as the prime example. He devoted the rest of his book to demolishing earlier hypotheses of the nature of fireballs and then presenting the evidence to support his claims (Marvin 1996).

Chladni.

Fig. 13. Ernst Florenz Friedrich Chladni. (Frontispiece of Walter Flight's book, *A Chapter in the History of Meteorites*, 1887.)



Ueber den

Urſprung

der von Pallas gefundenen

und anderer ihr ähnlicher

Eiſenmaſſen,

und über einige damit in Verbindung ſtehende

Naturerſcheinungen.

von

Ernſt Florens Friedrich Chladni,

in Wittenberg, der Phil. und Rechte Doctor, der Berliner Geſellſchaft Naturf. Freunde Mitgliede,
und der königl. Societät der Wiſſenſchaften zu Göttingen Correſpondenten.

Riga,

bey Johann Friedrich Hartknoch.

1794.

Fig. 14. Title page of Chladni's 1794 book, *Ironmasses* ... in which he laid theoretical groundwork for the new science of meteoritics. (From reprint edition, 1974, University of Arizona Press.)

Chladni was, of course, challenging the conventional wisdom of the late 18th century scholarly community, which sought rational explanations based on known principles of physics. Since the beginning of that century savants had lost the reliance that Renaissance men had had on writings from antiquity, and they had learned that all of the strange objects – pyrite concretions, shark's teeth, belemnites, stone axe heads – that formerly were believed to have fallen from the skies during thunderstorms or in lightning bolts, could be accounted for as natural minerals, fossils or the works of primitive craftsmen. Physicists were convinced that stones cannot form within the atmosphere, and they accepted the dictum of Isaac Newton (1642–1727) that outer space must be empty of all solids in order to permit the permanent functioning of the law of gravity. In his philosophical treatise, *Opticks*, Newton (1718, p. 343) wrote:

> And therefore to make way for the regular and lasting Motions of the Planets and Comets, it's necessary to empty the Heavens of all Matter,

> except perhaps some very thin Vapours, Steams, or Effluvia arising from the Atmospheres of the Earth, Planets, and Comets and study of from such an exceedingly rare Ætherial Medium as we described above.

So, if no stones were up there, no stones could fall – unless they were hurled aloft by volcanoes or hurricanes. Occasional reports of fallen stones were not to be believed because they always came from ignorant country people.

In several passages written at different times, Chladni (e.g. 1803, p. 323; 1809, p. ix; 1819, p. 4) wrote that he got his first idea for studying fireballs and fallen bodies from a conversation with the aged Georg C. Lichtenberg (1742–1799) at Göttingen, one of the leading physicists and natural philosophers of Europe. Chladni said that when he was in Göttingen in February 1793 he asked Lichtenberg for his thoughts about fiery meteors and stones fallen from the skies. Lichtenberg replied that if all circumstances about fireballs were considered they could best be thought of not as atmospheric but as cosmic phenomena – foreign bodies that enter from outside the atmosphere. He suggested that Chladni should search the *Philosophical Transactions* and other sources for reports of fireballs for which good trajectories had been recorded and, for comparison, to search for reports of fallen masses.

Lichtenberg, himself, has provided us with no record of such a discussion with Chladni. In his *Staatskalenders* for 1789–1799, which consist chiefly of names of persons he saw at Göttingen and letters he sent and received, Lichtenberg listed seven meetings with Chladni that took place between 25 January and 8 February 1793 (Promies 1971, pp. 770–771). On 25 and 26 January Lichtenberg noted visits by Chladni along with others; on the 28 January he wrote that he spent an agreeable evening with him at The Three Princes, and on the 31 January he heard him play in public. (On that date he also noted that a report had just arrived that the King of France had been beheaded on the 21 January! Thus, we learn that this news had taken 10 days to travel from Paris to Göttingen.) On 7 February Lichtenberg remarked that Chladni had brought him a copy of his essay (giving no indication of its topic), and on 8 February Chladni called to bid him farewell, so Lichtenberg gave him letters of introduction to Olbers and Ramberg in Bremen. These diary entries leave little time when the two of them could have discussed fireballs except, possibly, on the evening of 28 January.

Once Chladni's curiosity was aroused he sought a solution. At that time, direct observations and controlled experiments were the most favoured key to new scientific knowledge (just as they are today), but both were out of the question for studying fireballs and fallen bodies. Chladni (1819, p. 6) wrote that after talking with Lichtenberg he spent 3 more weeks at Göttingen searching the library for records of them. Evidently, he did not revisit Lichtenberg while there, but he did compile the records that constitute the basis of his book. He listed the 20 best-described fireballs that had been observed between 1676 and 1783, and compared their beginning and end points, their apparent sizes, velocities, and the number and magnitude of their explosions.

Chladni included a description of one of history's most famous fireballs, which was witnessed by thousands of people at 10:30 p.m. on 17 July 1771. It first appeared over Sussex, England, passed over Paris, and ended in an immense explosion over Melun, 50 km further SW. Some witnesses said it was the size of the full Moon and estimated that it covered the whole distance of 290 km in 4 s. But Jean-Baptiste Le Roy (1720–1800), who conducted a formal inquiry on behalf of the Royal Academy of Sciences, arbitrarily lengthened the estimated time to 10 s in order to achieve the more credible velocity of 29 km s^{-1} – equal to that of the Earth in its orbit around the Sun (Le Roy 1771, p. 665). Witnesses near Melun reported seeing glowing pieces near the ground after the fireball exploded, but Le Roy suggested that components of the lower atmosphere had been ignited by the fireball. To calm the fears of those who feared a fireball might torch a city, he explained that no fireball could strike the Earth because, having no solid nucleus, the flaming mass would self-destruct when it entered the dense lower atmosphere. Le Roy remarked that fireballs might be some sort of electrical phenomena, but he then added the refrain (still commonly repeated by scientists) that the subject required more study.

Chladni disputed all of the common explanations of fireballs. He said they could not be generated by the northern lights because they come from every direction in all seasons, nor by electricity because there are no conducting vapours at the high altitudes where they first appear, and, unlike jagged bolts of lightning, they follow smooth paths indicative of heavy, compact nuclei moving under the pull of gravity. The nuclei, he concluded, must enter the atmosphere from outer space at cosmic velocities, and those that survive passage through the atmosphere fall as meteorites.

Chladni compiled reports of 18 witnessed falls of stones or irons, spanning the centuries from the fall of an iron at Lucania, in Italy, described by Pliny in 77 AD, to the three in France – at Lucé, Nicorps, and Aire-sur-en Lys – reported by the Academy (Fouchy, 1772; Fourgeroux *et al.* 1777). He listed the three falls described by Stütz in 1790: at Eichstädt, Tabor and Hraschina. Chladni viewed all three as genuine meteorite falls, and he opposed the suggestion by Stütz that they were ordinary rocks somehow transformed by powerful bolts of electricity. With respect to the Tabor stone, Chladni agreed with those 'credulous people' who believed it had fallen after an explosion (but not a thunderclap). Some of the falls he listed had only cursory descriptions, but they all shared one or more similarities with those at Eichstädt or Hraschina: a violent explosion or series of them in a clear sky, a great flash or fiery trail across the sky, and falls to Earth of stones or iron with black crusts that were said to be hot or warm to the touch and smelling of sulphur. Despite differences in details, he found the descriptions to be so astonishingly similar from place to place and century to century that (having reluctantly trained as a lawyer at his father's behest) he concluded the witnesses were describing actual phenomena. Among those familiar to us, he included a discussion of the fall at Ensisheim in 1492, based on literature that had become rather muddled by that time, and he briefly mentioned the fall at Albareto in 1766, for which he had only sketchy information. Chladni did not include the spectacular fall at Barbotan and Agen in 1790, presumably because news of it had not yet reached him.

Chladni then turned to large masses of native iron found in areas remote from ore deposits or smelting operations, and he declared that they, too, had fallen from space in fireballs. He began with the Pallas iron, which he had included in his title. He called its yellow glassy-looking component 'olivine', before he ever saw a specimen of it. He discussed Rubin de Celis' mass of iron from South America at some length, and also discussed a large mass of iron dug up from beneath the pavement at Aken (Aachen) in Germany. This piece eventually proved to be an industrial product.

Chladni's linking of meteorites with fireballs was one of his most discerning insights. It led to his three main hypotheses that have withstood the test of time.

- Masses of stone and iron do, in fact, fall from the sky.
- Incandescent fireballs form due to frictional deceleration of the solid bodies as they plunge through the Earth's atmosphere.
- The solid masses, unrelated to the Earth or Sun, originate in cosmic space either as small bodies that never accumulated into planets, or as fragments of planets disrupted by explosions from within or collisions from without.

Chladni noted that all fallen bodies are partly or wholly composed of iron, an element that is abundant on Earth in rocks and in living things, and must make up a good part of Earth's interior, as shown by its magnetic field. He speculated that other celestial bodies may contain iron and common elements such as sulphur, silica and magnesia. His view of the Earth as one among several bodies of similar chemical composition places him among the early visionaries who anticipated the rise of the planetary sciences.

Chladni made some serious errors. He assumed, for example, that meteors trace the paths of small particles that enter the upper atmosphere, briefly heat to incandescence and then pass on out again. Also, he assumed that a falling body is about as large as its fireball, and therefore some of them would be up to a mile or more across; but he said they all would melt completely, expand to large sizes and, buoyed by the atmosphere, make relatively soft landings on the Earth. Despite such mistakes, Chladni's fundamental concepts of fireballs and meteorites were so right, so early, that we honour him today for his leadership role in the founding of meteoritics as a science.

Responses to Chladni's book

In April 1794 Chladni's book was published in two cities: Riga, to reach German readers in northern Europe; and Leipzig to reach astronomers and physicists in Germany. Most of the published reviews in Germany were neutral or negative all through the rest of that year (e.g. Anon. 1794). Critics argued that:

- Chladni based his conclusions on folk tales that violated common sense and the laws of physics. Why don't stones ever fall in cities, they asked.
- Fireballs were 'known' to be streams of flaming gases or friable materials in the atmosphere with no solid nuclei.
- Chladni's idea of small bodies in space violated Aristotelian–Newtonian physics, which held that all space beyond the moon is completely empty of solid materials.

Unfazed by such august authorities as Aristotle and Newton, Chladni felt that he had already answered that objection when he remarked in his book that to deny the presence of small bodies in space is as arbitrary as it is to assert it: neither can be proved *a priori*, and observations, not hypotheses, should decide the matter.

On 10 October 1794, the German naturalist, geologist and explorer Baron Alexander von Humboldt (1769–1859) wrote to his friend, Carl Freiesleben (1769–1859), the mineralogist at Freiberg: 'By all means read Chladni's infamous book on ironmasses' (Hoppe 1979, p. 27). In later years, however, Humboldt, who had started his career as a disciple of Abraham Gottlob Werner (1749–1814) and his neptunist school of Earth history, accepted volcanism when he encountered it on an immense scale during his travels in the Americas from 1799 to 1804. In the same period he accepted meteorites when he read the literature on the falls that had taken place and the chemical work that had been done on them in England, France and Germany. While he was in Mexico, in 1804, Humboldt sent for samples of a large iron meteorite that had been discovered at Durango. He carried 4–5 kg of the Mexican iron back to Europe and gave a sample to Martin Heinrich Klaproth (1743–1817), Professor of Chemistry at Berlin. Klaproth reported nickel in the metal (Humboldt 1811). In *Kosmos*, Humboldt's five-volume exposition on the Earth in the universe (Humboldt 1845–1862), which first appeared in 1845, Humboldt praised Chladni's 'remarkable acuteness' in linking fireballs with those stones which have been known to fall though the air, and the motion of the former bodies in space (Sabine 1855, volume 1, p. 111). As traced by Hoppe (1991), Humboldt's thought evolved in such a way as to lead him to view volcanism as the expression of the internally active Earth, and meteorites as the expression of interaction between the cosmos and the Earth.

Even as early as 1794, not all of Chladni's German colleagues disapproved of his book. In recent archival research, Wolfgang Czgka, at Potsdam, discovered an unpublished letter written by Johann F. Blumenbach (1752–1840), a physiologist and natural historian at Göttingen, to Sir Joseph Banks (1743–1820), the president of the Royal Society in London. In the letter, dated 24 September 1794, Blumenbach remarked on how pleased he had been, during his recent trip to London, to receive from Banks a specimen of the famous mass of iron from a desert in South America, and also a specimen of the mass found by Pallas in Siberia. 'You know', wrote Blumenbach, 'how enigmatical these phenomena have been for the mineralogist, but now I think myself very happy, to send you the key to this riddle' (in Czegka 1999*a*):

> ... one of our natural philosophers, Dr Chladni, who demonstrates with an immeasing [amazing?] apparatus of learning & sophistry that these Iron-masses belong by no means to mineralogy, but to meteorology & astronomy ... they were not formed in the earth, nor in the atmosphere of our planet, but in the remote cosmical regions ... these little lumps were hardly any thing else, but metallized shooting stars...

Blumenbach enclosed a copy of Chladni's book with this letter to Banks. At the end of Blumenbach's letter, Sir Joseph wrote: 'Thanks for books'. But no letter of thanks or any other response from Banks to Blumenbach has been found in the archives.

Czegka's discovery of Blumenbach's letter is of special interest to us for two reasons: first, it demonstrates that at least one leading German natural philosopher fully accepted Chladni's theory of cosmic origin, and expressed enthusiasm for it, soon after his book was published. He saw Chladni's explanation as a significant breakthrough to the riddle of iron masses lying in remote places. Unfortunately, his letter was not published, but Blumenbach must have expressed himself the same way to his colleagues, so we may assume that his favourable view of Chladni's book was 'in the air' if not in print. Second, the letter indicates that Sir Joseph Banks had a copy of Chladni's book in his possession as early as September 1794. Previously, we had believed (e.g. Marvin 1996, p. 562) that Chladni's book first reached England 2 years later, in the summer of 1796, when Sir Charles Blagden (1748–1720), Secretary of the Royal Society, gave a copy to Edward King (1735–1807), a Fellow of the Royal Society who was writing the first book in English on meteorites.

Despite a few such favourable responses, Chladni's assertion that meteorites fall from the sky met with such widespread disbelief that it might have remained in doubt for decades. However, by sheer chance, his book proved to be extraordinarily well timed: just 2 months after its publication, stones began to fall from the sky. Between June 1794 and December 1798, four well-publicized falls were witnessed at Siena in Italy, Wold Cottage in England, Évora Monte in Portugal and Benares in India. This series of falls served to change many minds. Actually, three more witnessed falls occurred within the same period in Sri Lanka, the Ukraine, and Salles in France, but news of them did not spread until after the debates were essentially over.

The fall at Siena, June 1794

At 7:00 p.m. in the evening of 16 June 1794, a single high cloud, emitting smoke, sparks like rockets and flashes of slow red lightning, suddenly was seen to be rapidly approaching Siena from the north. A series of tremendous explosions rent the air, the cloud flamed red and a large shower of stones fell at Cosona, on the outskirts of Siena. Men, women and children saw and heard stones strike the ground all around them. Some of the stones reportedly scorched leaves, and one of them was said to have plunged through the brim of a boy's hat and scorched the felt. Two astonished English ladies reported seeing stones plunge into a pond that seemed to boil. Subsequently, the government drained the pond and recovered the stones, which the locals had begun selling to English tourists at such brisk prices that a cottage industry had sprung up to create bogus fallen stones (Chladni 1797, p. 18).

This fall changed history: first, because the witnesses were so numerous that the fall could not be denied; second, Siena was a university town where it drew the attention of learned professors; and third, because it also came to the attention of prominent Englishmen in Italy. The Abbé Ambrogio Soldani (1736–1808), Professor of Mathematics at Siena, immediately began collecting reports and stones, and within 3 months Soldani (1794) published a 288-page book, *On a Shower of Stones that fell on the 16th of June at Siena.* His book decisively raised the topic of fallen stones from the level of folk-tales to that of learned discourse (Marvin 1998). Soldani was particularly interested in stones that appeared to show crystalline forms, and he included an illustration (Fig. 15) of what he described as imperfect pyramids and parallelepipeds with quadrangular, triangular or quasi-hexagonal bases. He hypothesized that the stones had formed in the high cloud where metallic and earthy dust in the atmosphere coagulated into a pasty material with a strong impetus toward crystallization.

Soldani sent a stone to the mineralogist Guiglielmo Thomson (1761–1806), at Naples, who described it as having a black melted crust and a 'quartzose' interior scattered with grains of pyrite. He crushed a sample of it and drew a

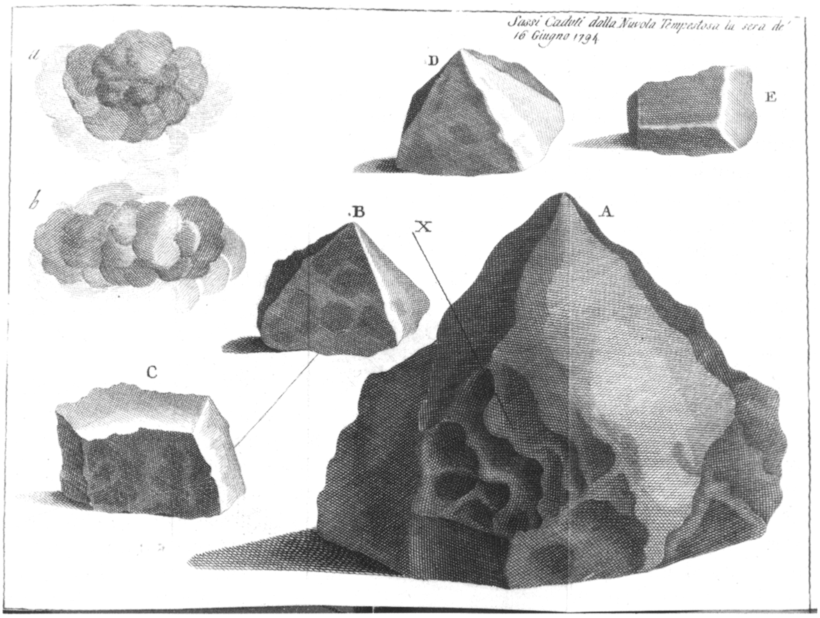


Fig. 15. The endplate of Ambrogio Soldani's book of 1794 on the fall at Siena. The letters depict: (**a**) the high dark cloud as it first approached Siena; (**b**) the cloud a few minutes later after it had spread out. A, B, C, D and E are stones from the shower that Soldani selected as showing a strong impetus toward crystallization of pyramids, quasihexagons and parallelpipeds. The inscription at the upper right reads: 'Stones fallen from the stormy cloud on the evening of 16 June 1794'. (Courtesy of the Smithsonian Institution Libraries.)

magnet through the powder, thus performing the first mineralogical separation of a meteorite. He recovered grains of metallic iron that he found to be in a state of perfect malleability. This discovery astonished him because the iron appeared to have cooled from a molten state, and there was a universally held conviction that metals crystallized from a melt are always brittle. In his book Soldani included seven letters from Thomson who described the iron grains and showed the Siena stones to be very different from any known rock on Earth (Thomson 1794*a*).

In a postscript to one of his letters, Thomson (in Soldani 1794, p. 264) remarked that a friend, who did not wish to be named, had suggested that the Sienese stones had escaped from the Moon by the process described by the celebrated Herschel – namely the eruption of a lunar volcano. William Herschel (1738–1822), the German-born musician and astronomer residing in England had been knighted and named the 'King's Astronomer' by King George III after he discovered Uranus in 1781. Subsequently, Herschel (1787, p. 230) reported witnessing three volcanic eruptions on the Moon between 1783 and 1787. Without appreciating the distance from the Moon to Earth, or realizing that a body escaping the Moon's gravity field would go into orbit around the Earth or the Sun, Thomson added that the Moon must have been directly over Italy at the time of the eruption that dropped stones on Siena.

Thomson carried a stone to Domenico Tata (1723–1800), Professor of Physics and Mathematics in Naples. Tata had not heard the news from Siena, but when Thomson told him he had brought him a stone that had fallen from the sky, Tata asked Thomson to keep it hidden while he described it in detail. This was nothing new to him, said Tata. Back in 1755, his friend, the Prince of Tarsia, had sent him a stone with a notarized description of its fall after thunderous detonations at Tata's estate in Calabria. Tata eventually placed the stone in a glass case in which it gradually became covered with efflorescence and crumbled to bits (an eventuality with which we all are familiar today). Tata said he had intended to publish a description of the fallen stone but he had been dissuaded by friends who told him he would be ridiculed by 'Savants' and, worse yet, by 'Half-Savants', who are the more to be feared.

In December of 1794, Tata published a 74-page *Memoir on the Siena fall* in which he included a 19-page letter from Thomson giving a more detailed mineralogical description of the stones than he had prepared in time for Soldani's book (Thomson 1794*b*). Tata (1794) also reported the earlier fall at Calabria in 1755, and he mentioned Stutz' paper of 1790 in which he described the specimens of Eichstädt and Hraschina. Tata had learned of Stutz' paper from Thomson, who, in turn, had been alerted to it by Captain François Tihausky, Director of His Majesty's Cannon Foundaries in Naples. Stütz, himself, had refused to accept as genuine the falls he described from eastern Europe, but by the latter part of 1794 those falls looked plausible to the scientists in Italy. Both Tata and Thomson greatly admired Soldani's diligent research on the Siena fall, and agreed with him that the stones had congealed within the high fiery cloud that had been seen approaching the city. Thomson (in Tata 1794, p. 64) called the material of the fallen stones 'soldanite'.

Meanwhile, Sir William Hamilton (1730–1803), the English ambassador in Naples, had received a stone given by Soldani to a distinguished Englishman residing in Siena, Frederick Augustus Hervey (1730–1803), the 4th Earl of Bristol and Bishop of Derry. Soldani had dedicated his book to Hervey, so he sent him the stone and a detailed description of it. On 12 July 1794 Hervey forwarded Soldani's letter and the stone to Hamilton in the care of Sir Joseph Banks in London (Fig. 16) – presuming that Hamilton would be in England. But Hamilton was in Naples, so Banks sent Hervey's letter and the stone back to Italy with a remark that the old Bishop must be telling tall tales (Pillinger & Pillinger 1996, p. 596).

During his many years of living in Naples, Hamilton kept detailed records of the activities

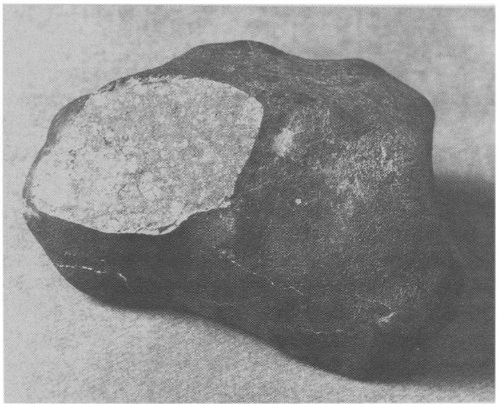


Fig. 16. One of the earliest stones from the Siena shower to reach England in 1794. Originally it was suspected of having been erupted by Mt Vesuvius. (Courtesy of Robert Hutchison, The Natural History Museum, London.)

of Mt Vesuvius, and he began to turn volcanology into a modern science. To Hamilton, the stone looked familiar. He thought he had seen many similar stones on the slopes of Mt Vesuvius, but when he went looking for them he found none. Hamilton knew that Vesuvius had burst into full eruption just 18 h before the fall at Siena, and his first thought was that perhaps the stones had been flung from its crater 250 miles towards the NW to Siena. When he considered the parabola, however, he suggested that the stones might have been ejected from Mt Radicofani, a long dormant volcano much closer to Siena. Finally, Hamilton was struck with another idea: knowing to what great distances the ash sometimes travelled, he pictured a plume of vesuvian ash rising to a prodigious height and wafting towards the NW for some 250 miles until it mixed with a stormy cloud and accumulated into lumps that fell over Siena. He said the exterior vitrification observed on the lumps may have been due to the action of the electric fluid on them.

Hamilton (1795, p. 103) included one paragraph on the fall at Siena in a long report on eruptions of Mt Vesuvius that appeared in the February issue of the *Philosophical Transactions of the Royal Society*. His paragraph carried the news of the fall to Germany, where it caught the attention of the astronomer Heinrich Wilhelm Matthäus Olbers (1758–1840) in Bremen. Olbers immediately gave a lecture on the Siena fall at the Bremen Museum in which he speculated on an idea of his that the stones might have been ejected by a volcano on the Moon. But he was concerned about the small proportion of lunar ejecta that would be likely to hit the Earth, so he published nothing on this subject at that time. Hamilton's paragraph in such a widely respected journal may have persuaded many people that stones actually do fall – at least within a few hundred kilometres of active volcanoes.

The fall at Wold Cottage, Yorkshire, December 1795

The following year a large stone fell in the heart of England. At 3:30 in the afternoon of 13 December 1795, a day of overcast skies, something whizzed through the air startling several persons at Wold Cottage in Yorkshire. A series of explosions followed, and a young ploughman, John Shipley, glanced upwards just in time to see a stone emerge from the clouds and plunge into the soil very close to him. It made the ground shake and spattered him with mud and sod. Shipley and two other farmhands rushed to the place of the fall and found a large black stone that had penetrated 12 inches of soil and 6 inches of the underlying limestone. They said the stone was warm and smoking, and smelling of sulphur.

About 1 month later, the landowner, Captain Edward Topham (1751–1820), a flamboyant editor, pamphleteer and playwright, transferred his home from London to his estate at Wold Cottage. This may have been a great advantage for the history of meteoritics, as Topham had the authority and, indeed, the celebrity, to attract widespread attention to the story of the meteorite fall (Pillinger & Pillinger 1996). Topham already had seen a notice or two in the London papers of this remarkable event on his Yorkshire property, so, after his arrival, he obtained sworn testimony from the three witnesses to the fall of the stone, and from several more who had heard the sounds or felt the concussions. On 8 February 1796 Topham sent a detailed letter describing the stone and the testimony of the witnesses to the managing editor of *The Oracle*, the local newspaper. It was published on 12 February. Six months later, Topham carried the stone to London and put it on public display in Piccadilly across the street from the popular Gloucester Coffee House. Persons who paid the entrance fee of 1 shilling received a handbill with an engraving of the stone and the verbatim testimonies of the witnesses. One of the visitors was Sir Joseph Banks, who obtained a specimen of the stone, very probably from Captain Topham himself.

Topham (1797) published the text of the handbill with its engraving in *Gentlemen's Magazine* (Fig. 17). Two years later, still enjoying the uniqueness of this event on his land, he erected a monument at the site of the fall and planted trees around it. Today, with the trees long gone, the monument stands in an open field with its weathered inscription still telling us that on this spot, on 13 December 1795, there fell from the atmosphere an extraordinary stone: 28 inches broad, 30 inches long and weighing 56 lbs; this column in its memory was erected by Edward Topham in 1799. This is the only monument that has been erected at the the site of a meteorite fall, but two have been erected at meteorite find sites. In the 1890s an obelisk was emplaced in the arid interior of Bahia, Brazil, where the huge Bendego iron had been discovered, and, as noted above, a large disk was mounted in 1980 on a ridge of Mt Bolshoi Emir to mark the find site of the Pallas iron (see Ivanova & Nazarov 2006).

In 1804 Topham sold the Wold Cottage stone to James Sowerby (1752–1822), the natural

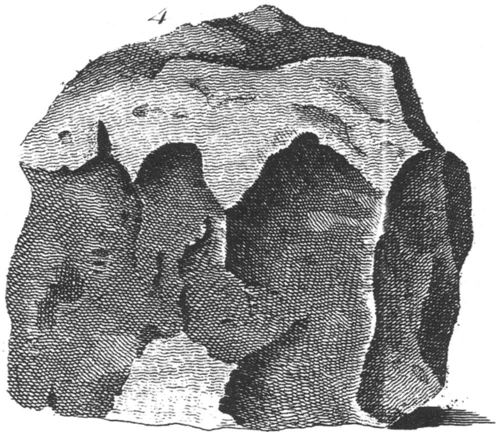


Fig. 17. Engraving of the Wold Cottage stone as it appeared on Captain Topham's Handbill. He described it as about 70 cm in its longest dimension. (From *Gentlemen's Magazine*, 1 July 1797, fig. 1.)

historian, mineralogist and illustrator who owned a museum in London. In his book, *British Mineralogy*, Sowerby (1806, p. 1) declared *Ferrum Nativum, Meteoritic iron* to be a unique addition to the minerals of Britain since it had fallen there like 'Phaeton from Heaven'. A few years later, a tourist guidebook, *Beauties of England*, extolled Wold Newton in Yorkshire for the fall nearby in 1795 of a piece of the Moon (Pillinger & Pillinger 1996, p. 597). In 1835 Sowerby's heirs put up the stone for sale and it was purchased for the British Museum (Natural History). In 1995 meteoriticists held a symposium to celebrate the 200th anniversary of the fall. Wold Cottage is the largest meteorite to have fallen in the British Isles, and in Europe is second in size only to the stone of Ensisheim.

Bibliothèque Britannique: 1796

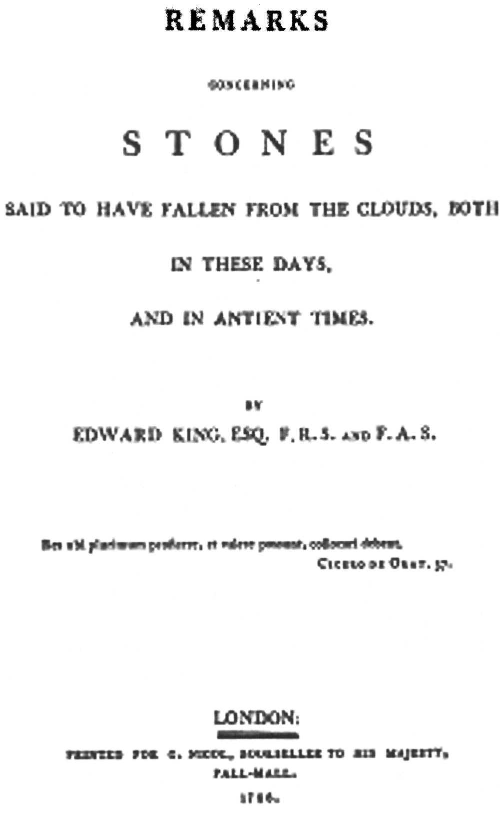
Another event of importance to the history of meteoritics was the co-founding in 1796 of a new journal, *Bibliothèque Britannique*, by the Swiss natural philosopher Marc-Auguste Pictet (1752–1825), in Geneva. His rationale was to make French translations of English scientific articles available on the continent during that period of general unrest. From the first, Pictet published letters and articles on fallen stones, often with favourable editorial commentary; but he also published contrary views by vocal opponents of falls including the Swiss geologist Guillaume-Antoine De Luc (1729–1812) in Geneva, and the French geologist and mineralogist Eugène M.L. Patrin (1742–1815), who was serving as director of the national manufacturing organization at St Etienne. Numerous items in *Bibliothèque Britannique* crossed the channel in both directions. In England they would be reprinted or excerpted in the *Philosophical Magazine* or *Gentlemen's Magazine*. In France they would appear in the *Journal de Physique, de Chimie, d'Histoire Naturelle et des Arts*, established in 1777, or in the newer *Annales de Chimie et de Physique*, founded in 1789, or in the *Journal des Mines*, founded in 1792. In Germany, two new journals appeared in 1796 and 1797, respectively: the *Göttingisches Journal der Naturwissenschaften* and the *Magazin für das Neueste aus der Naturkunde*, founded by Johann Heinrich Voigt (1751–1823), Professor of Mathematics and Physics at the University of Jena. Voight's *Magazine* immediately began publishing articles by and about Chladni. There was much interchange between all of these journals, so the literature fairly hums with the news and controversies that erupted during the formative years of meteorite studies.

Edward King: the first book in English on meteorites, 1796

As we noted earlier, Sir Charles Blagden gave an English translation of Soldani's book to Edward King early in 1796. Reading Soldani's book prompted King (1796) to write the first book in English on meteorites (Fig. 18) to which he gave the descriptive subtitle:

> REMARKS CONCERNING STONES SAID TO HAVE FALLEN FROM THE CLOUDS, BOTH IN THESE DAYS, AND IN ANTIENT TIMES: An Attempt to account for the Production of a Shower of Stones, that fell in Tuscany, on the 16th of June, 1794; and to shew that there are Traces of similar Events having taken place in the highest Ages of Antiquity. In the course of which detail is also inserted, an Account of an extraordinary Hailstone, that fell, with many others, in Cornwall, on the 20th of October, 1791.

King began his book as a history but he ended it as journalism. First, he discussed the fall at Siena as described by Professor Soldani, who believed the stones had been generated in the air from mineral substances arisen from the Earth. King preferred Hamilton's idea that they formed from vesuvian ash, and he drew an



REMARKS
CONCERNING
STONES
SAID TO HAVE FALLEN FROM THE CLOUDS, BOTH
IN THESE DAYS,
AND IN ANTIENT TIMES.

BY
EDWARD KING, ESQ. F.R.S. AND F.A.S.

LONDON:
PRINTED FOR G. NICOL, BOOKSELLER TO HIS MAJESTY,
PALL-MALL.
1796.

Fig. 18. The title page of Edward King's book of 1796; the first book on meteorites to be written in English. (Courtesy of the Smithsonian Institution Libraries.)

analogy between the consolidation of these stones in fiery clouds and of hailstones in cold, watery clouds – a comparison that Hamilton had touched on. The very idea of fallen stones was so new at that time that it seemed only natural to compare them with the familiar icy stones. King then traced the subject of fallen stones and irons back to the Bible.

Twice, King was finishing the book when he stopped to add something new. First came a report of a fall at Wold Cottage in Yorkshire on 13 December 1795. King excerpted the story and stated that he neither believed nor disbelieved it; he awaited more evidence. But King soon had the evidence at hand: Sir Charles Blagden showed him a fragment of Wold Cottage and then King went to see the stone itself. He noted that it had a black crust on what looked like a kind of grit stone sprinkled with pyrites and rusty spots. He then reviewed the record of the historic fall at Ensisheim (which he mistakenly dated to 1630), and the stones of Eichstädt and Hraschina as described by Stütz in 1790.

Once again King was close to finishing his text when Sir Charles gave him a translation of Chladni's book, which King described as 'a very singular tract'. King outlined Chladni's list of witnessed falls and his linking of them with fireballs. He remarked that he would not presume to interfere with Chladni's hypothesis, but that Chladni's facts, '... which he affirms in support of his ideas, deserve much attention' (King 1796, p. 27). When King finally ended his book, he had to add a postscript: Sir Charles had given him a stone from Siena, so King compared it with Wold Cottage. Both stones, he said, had black crusts and gritty interiors with grains of metal and pyrite and rusty spots where the latter had decomposed. He especially noted the sort of minute 'chequer' work of very fine white lines on the black crust of the Siena stone – a feature familiar to all meteoriticists. Thus, King published the first comparison of stones from two fresh falls, saying they looked much alike but very different from the chalks of Yorkshire.

King's book was privately published but it seems to have won a broad readership. Soon after it appeared it received a scathing review in *Gentleman's Magazine* (Anon. 1796*a*) written, no doubt, by the editor Sylvanus Urban, who accused King of multiplying lying miracles on ordinary occasions, and being willing to admit the evidence of a few peasants and women. However, more supportive reviews appeared in England and on the continent.

The fall at Pettiswood, Ireland, 1779; reported in 1796

Shortly after King's book appeared, a Mr William Bingley of Pettiswood, County Westmeath, Ireland, sent to *Gentleman's Magazine* a detailed description of a fall that had taken place on his farm in 1779. Bingley (1796) wrote that after a great peal of thunder, a stone had struck the wooden part of a harness and the terrified horse had collapsed. Afterward, the whole neighbourhood smelt of sulphur. Bingley had never told this story to anyone, he said, for fear of ridicule. But now, in view of the writings of King, Soldani and Topham, he was bringing it forward. He had two pieces of the stone, which is taken today as a genuine meteorite, although no sample of it has survived.

Nicolas Baudin, 1796, reviews the fall of 1790 at Barbotan

In 1796 Nicolas Baudin (died *c.* 1798), Professor of Physics at Pau who had witnessed the Barbotan event of 1790, published a detailed account of the brilliant ball of fire, which appeared to him to be a little larger than the full Moon, streaking northwards and breaking up into many glowing pieces that fell in different directions. There followed an immense explosion, like the discharge of many pieces of heavy artillery. It made the ground tremble and sent echoes thundering along the Pyrenees. Baudin (1796) said that many small stones fell, along with several weighing 18–20 lbs, and one weighing 50 lbs, which plunged 2–3 ft into the soil. The stones were heavy for their volume, dark on the outside and greyish inside with many tiny points of brilliant metal. Baudin rejected hypotheses of a volcanic origin because there were no volcanoes in the Pyrenees. He tried to envisage a huge stony mass forming within the atmosphere by the violent action of the fireball, and then breaking up into pieces that cooled so rapidly they were cold when collected. This appears to be the first written statement that fallen stones were not hot to the touch. Clearly, Baudin expected that they would be, so he added that perhaps the larger stones would have been warm if they had been found immediately. Finally, he cited descriptions of falls by Plutarch and Pliny.

An extract of Baudin's article appeared in *La Décade* of 29 February 1796, but the editors felt obliged to add a long footnote (Anon. 1796*b*, p. 396) scoffing at the very idea of fallen stones. They said Baudin would have been more philosophical if he had begun by doubting the fact of fallen stones. As they saw it, the dazzling light and noise of exploding meteors stun people into thinking things burst all around them:

> ... they run, they look, and if they find, by chance, some little-bit black stone, surely this stone just fell. As the fable spreads, people all over the countryside search for stones and find thousands of them. (Note by the Editors of *La Décade*.)

In retrospect, we might suppose that, given the falls at Siena and Wold Cottage, 1796 was getting rather late for the editors of a journal to hold such contrary views. Some other editors did not share them. Chladni (1798) objected to Baudin's assumption that the stones that fell at Barbotan formed in the atmosphere. He argued that substances dissolved in the rarified atmosphere at a height of 20 German miles (approximately 148 km), where fireballs originate, could precipitate only into fine powders and never into such monstrous, solid masses. He reiterated once again his own hypothesis that the solid masses come from the 'expanse of the universe', and that small masses exist out there that must fall down when they approach too near to our Earth.

The fall at Évora Monte, Portugal, 1796

Early in the afternoon of 19 February 1796 two loud explosions, reminiscent of those of military mines, were heard and a stone fell at Évora Monte in Portugal. By sheer chance Robert Southey (1774–1843), the future Poet Laureate of England, passed through the town soon afterwards and obtained a copy of the testimony sworn by witnesses before a magistrate. Southey included the Portuguese text with an English translation in Letter XXI of his *Letters Written During a Short Residence in Spain and Portugal*, published in 1797. Southey (1797, p. 355) introduced this topic by declaring: 'We sometimes hear such phenomena mentioned in history, and always disbelieve them'. But Southey had been away from home too long; he was unaware of the falls at Siena and Wold Cottage, which had led some of the learned people in England to believe in falls of stones from the sky. Southey performed a service to us by publicizing this fall, and the description rang true. Today, catalogued as 'Portugal', the meteorite is accepted as valid, even though the stone itself is long lost (e.g. Marvin 2003).

The fall at Benares, India, 1798

At 8:00 in the evening of 19 December 1798 a dazzling fireball, casting strong shadows on the landscape, exploded across a serene sky and showered stones over Krakhut, a village about 14 miles from Benares in India. Many stones plunged 6 inches into the damp soil, and one crashed through the roof of a hut and wedged itself into the hard soil floor. John Lloyd Williams (*c.* 1765–1838), a Fellow of the Royal Society residing at Benares, collected eyewitness reports and sent a detailed account of the event to the president of the Royal Society in London (Williams 1802).

Simultaneous observations of meteors by two astronomers, 1798

Chladni (1819, p. 7) wrote that Lichtenberg had not, at first, liked his book. He allegedly told several friends that he felt as if he had been hit on the head by one of Chlandi's stones. Lichtenberg did not say this in writing, but in any case he changed his views after learning about the falls at Siena and Wold Cottage. Lichtenberg (1797) wrote 'Steinregen zu Siena', his only article about a meteorite fall. In it he rejected several hypotheses of origin and ended with the conjecture that the Siena stones might best be seen as the type of phenomenon Chladni had discussed in his remarkable book.

That same year Lichtenberg was delighted with a suggestion put forward by Chladni that two astronomers, some distance apart, should observe the same portions of the night sky simultaneously, noting the timing and apparent paths of meteors so that their real heights and their real flight paths might be calculated. Lichtenberg assigned this task to two of his students, the astronomers and mathematicians Johann Friedrich Benzenberg (1777–1846) and Heinrich Wilhelm Brandes (1777–1834). Chladni believed that meteors and fireballs originated at altitudes of about 20 German miles (148 km), but the majority favoured 1 German mile (7.4 km), which was taken to be the height of the atmosphere.

Benzenberg and Brandes began their vigils on clear nights in September and October 1798 from opposite ends of a baseline 8.79 km long stretching from Lichtenberg's garden cottage to Clausberg, north of Göttingen. But after their first three nights of observations they realized that the meteor region was much higher than 1 German mile; accordingly, they lengthened their baseline to 15.61 km. In all, they observed 402 meteors, of which 22 were simultaneous. From these they calculated that meteors are visible between altitudes of approximately 170 and 26 km, and they move at velocities of 29–44 km s^{-1} (Czegka 2000). Lichtenberg wrote to Benzenberg on 3 November 1798 praising the experiment for demonstrating that the meteors did not originate within the atmosphere; in a postscript sent separately on the same day, Lichtenberg added: 'God forbid that such fiery bodies ever shall strike our Earth while flying at 5 miles per second. At least, I hope that nothing like that ever shall fall on my head' (Joost & Schöne 1992, vol. 4, p. 796). The report by Benzenberg & Brandes (1800) did not change minds overnight and, indeed, their longest baseline was still too short, but they made a spectacular beginning to systematic meteor studies.

Chladni was not alone in believing in a high meteor region. After the appearance of a brilliant fireball seen over SW Germany on 17 November 1623, Wilhelm Schickard (1592–1635), a mathematician–astronomer at Tübingen, estimated that it occurred at a height of 148 km. He wrote that this would have heavy consequences on the Aristotelian theory of the origin of fallen stones in the upper atmosphere (Czegka 1999*b*). However, the Aristotelian theory was still widely accepted and Schickard was immediately challenged by an astronomer at Strassburg, who also had seen the fireball. Neither of them had made any measurements, so Shickard, who was arguing against the conventional wisdom, lost his case.

Analysis of the stone of Ensisheim: Bartold, 1800

In 1800 Charles Barthold, Professor of Chemistry at the newly established Ecole Central de la Haut Rhin in Colmar, chipped off a sizable sample of the stone that was on display in the Bibliothèque Nationale in that city. He performed a bulk chemical analysis, and reported 42% silica, 20% iron, 17% alumina, 14% magnesia, 2% lime and 2% sulphur (Barthold 1800, p. 171). These were the first determinations of silica, magnesia and lime to be made on any meteorite (Sears & Sears 1977, p. 29). But Barthold had no idea that this stone was a meteorite. From his results he concluded that it was a common type of argillaceous–ferruginous rock that most probably had been washed down a steep mountainside in the Vosges by a torrential storm. He said that the glitter of pyrite probably deceived the people into proclaiming its miraculous origin; no attention should be paid to the old story that it had fallen from the sky.

Edward C. Howard and Jacques-Louis de Bournon analyse fallen stones and irons: 1800–1802

Early in 1799, when Sir Joseph Banks received word of the Benares fall, he decided it was high time for serious science to be applied to the issue of fallen stones. He gave his specimens from Siena and Wold Cottage to the distinguished young chemist, Edward C. Howard (1774–1816) and asked him to analyse them. In December 1800 Banks presented the Royal Society's prestigious Copley Medal to Howard, for his discovery of fulminate of mercury, and took the occasion to remark that Howard's analyses of certain stones: '... generations in the air by fiery meteors', probably would open '... a new field of speculation and discussion to

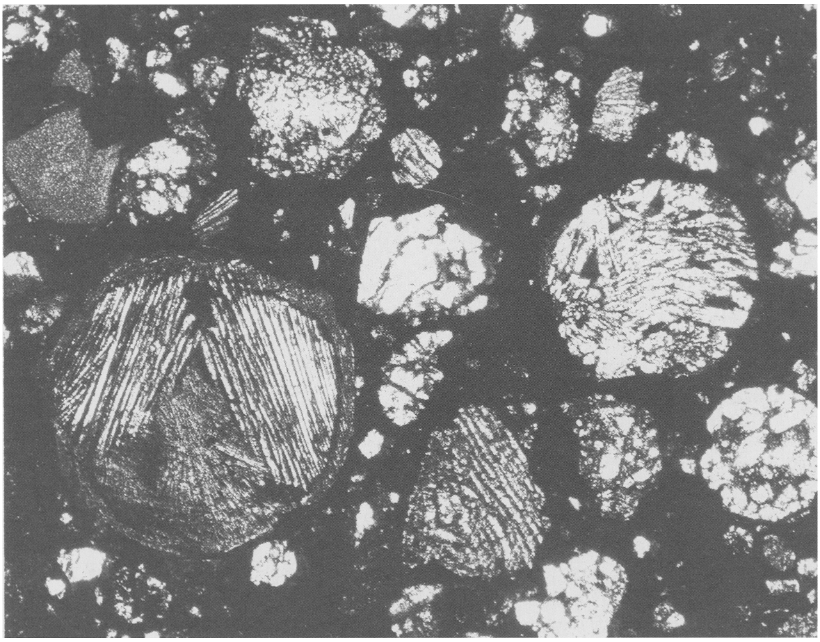


Fig. 19. Chondrules and fragments of them displayed in a thin section of the Tieschitz chondrite that fell 15 July 1878 in the present Czech Republic. The various chondrules display sheafs of barred olivine or olivine phenocrysts in glassy matrixes. (Photomicrograph courtesy of John A. Wood, Smithsonian Astrophysical Observatory.)

mineralogists as well as to meteorologists' (Sears 1975, p. 218).

Clearly, President Banks fully accepted the fall of stones from the sky, but he took it for granted that they formed within the atmosphere. Although we know that Blumenbach had sent a copy of Chladni's book to Banks in September 1794, along with his enthusiastic recommendation of it, we do not know whether Banks read it. In any case, Banks' remarks concerning Howard's analyses clearly show that he preferred Lavoisier's idea of an atmospheric origin to Chladni's hypothesis of cosmic origin.

Howard assembled a suite of four fallen stones: Siena and Wold Cottage from Banks; Benares, sent to him by John Lloyd Williams; and Tabor, from the English botanist and mineral collector the Right Honourable Charles Francis Greville (1749–1809), who had acquired it by purchasing the collection of Ignaz von Born from his estate. Howard also obtained samples of four so-called 'native irons': erratic masses, wholly or partly of iron, of the type that Chladni had reasoned must have fallen from the sky. These included: pieces of the Mesón de Fierro, which Rubin de Celis had given to the Royal Society; a mass of metal from Siratik in Senegal, loaned by the English chemist Charles Hatchett (*c*. 1765–1847); a sample of the Pallas iron; and one of the 'Bohemian iron' (which we now know as the Steinbach stony-iron) from Greville.

Working with Howard was the French émigré mineralogist Jacques-Louis Comte de Bournon (1751–1825), who fully understood the value of separating the stones into their component parts to be analysed separately. This was a completely new approach. All previous analyses of fallen stones had been made on bulk samples. Using a small magnifying glass, de Bournon separated each stone into four fractions that he called: 'curious globules', 'martial pyrites', 'grains of malleable metal' and 'earthy matrix'. Six decades later Gustav Rose (1863), would give the names 'chondrules' (from the Greek for 'little grains') to the 'curious globules', and 'chondrites' to the stones containing them (Fig. 19). In the same year, strictly by coincidence, Wilhelm Haidinger in Vienna would propose the name 'Troilite' for the 'martial pyrites'. Fortunately, all four of the stones examined by Howard and de Bournon were chondrites. An achondrite or a carbonacous chondrite, with no chondrules and no metal, could have confused things royally.

Howard applied the alkali fusion technique to the silicate fractions and Hermstaedt's technique of analysing for nickel in the metals. He found several per cent of Ni in all the irons and in the metal grains of the stones – thus conclusively linking the two as closely related phenomena. Howard measured about 10 wt% of Ni in the Mesón de Fierro and wrote that he found great satisfaction in agreeing with a chemist so justly celebrated as Mr Proust. Both Proust and Howard got their values a bit high: modern analyses show that the Campo del Cielo irons contain about 7.0 wt% Ni.

Concurrent events: the first two asteroids discovered; falls debate: 1801–1802

To fully appreciate the excitement caused by the discovery of the first asteroid, we may look back to the formulation of the so-called 'Bode's law' or the 'Titius-Bode law' of planetary distances. Today, this 'law', which never had any basis in celestial dynamics, has dwindled to the status of a curiosity, but in the latter part of the 18th century some astronomers, particularly in Germany, saw it as being of fundamental significance. The names given to it reflect its confused origins, which become curiouser and curiouser as one looks into them (Jaki 1972). In 1766 Johann Daniel Titius (1729–1796), Professor of Mathematics at Wittenberg, published a German translation of the book *Contemplation de la Nature*, written in 1764 by the famous Swiss natural scientist Charles Bonnet (1720–1793). In a gesture difficult to fathom, Titius inserted a passage into Bonnet's text pointing out that if one divides the distance from the Sun to Saturn into 100 units, Mercury lies at 4, Venus at 7, Earth at 10, Mars at 16, Jupiter at 52 and Saturn at 100 units. These distances (commonly expressed as decimals, which define the Earth–Sun distance as 1.0 Astronomical Unit) corresponded reasonably well with the actual planetary distances. Titius (in Bonnet) noted a wide gap at 28 units between Mars and Jupiter, and refused to believe the Creator would leave it empty. He speculated on undiscovered satellites of Mars. Titius signed a dedicatory epistle preceeding Bonnet's preface, but inasmuch as he did not put his name on the title page, nor did he indicate that he had added anything to the text, Titius could scarcely claim credit for noting this relation, which he called 'wonderful' (Titius 1766, pp. 7–8).

In the second edition of his translation of Bonnet's book, Titius (1772) placed his name on the title page and switched his passage to a footnote, which he initialled. That same year Johann Elert Bode (1747–1826), in Berlin, published the second edition of his own popular astronomy textbook (Bode 1772) in which he added a footnote on planetary distances and drew attention to the gap between Mars and Jupiter. He said he expected a large planet to be found there. His language sounded much like that of Titius, but Bode would not acknowledge his reliance on Titius until 1784. Meanwhile, in 1783 Titius, himself, wrote in the fourth edition of his translation that the pattern of planetary distances was nothing new: it had been described 40 years earlier, in 1724, by the German mathematician and natural philosopher Christian Wolff (1679–1754). Wolff had, indeed, listed the planetary distances approximately as Titius did, but the historian of science, Stanley Jaki, declared that he did it mainly as a rule of thumb for students and not as a serious contribution to astronomy. He regards Titius' reference to Wolff as not only misleading but patently false (Jaki 1972, p. 1016). We shall not trace further the twists and turns and attempts at fine-tuning that followed, except to observe that while French astronomers saw the law as something of a numbers game, Bode and others in Germany took it seriously and looked forward to finding a new planet between Mars and Jupiter.

Then, on 13 March 1781, William Herschel announced to the Royal Society his discovery of a new body he thought was a comet, although it lacked a coma and a tail. Within weeks it proved to be in too circular an orbit for a comet, hence Herschel had found a new planet in the sky. This sent shockwaves around the world. Not only had Herschel found a planet that was unknown to the ancients; he had doubled the size of the solar system. The new planet was twice the distance of Saturn from the Sun. Herschel (1782) calculated its orbit and proposed the name 'Georgium Sidus', in honour of King George III. This name, simplified to the 'Georgian planet' was used in England for decades, while Europeans called it 'Uranus', a name suggested by Bode, who recalled that in Graceo-Roman antiquity Uranus was the father of Saturn who was the father of Jupiter. Incidentally, after its discovery astronomers found that sightings of Uranus had been recorded at least 11 times between 1690 and 1769 by observers who did not recognize it as a planet – just as Herschel had not, at first. Bode (1784) pointed out that this planet orbited at a distance of 18.9 units, which was reasonably close to the 19.6 units predicted by the law. (Its distance was later corrected to 19.2 units, which is even closer.) Uranus lent a new credibility to what became widely known as 'Bode's law'.

The discovery of Uranus inspired the Baron Franz Xaver von Zach (1754–1832), the Hungarian-born court astronomer to the Duke of Saxe-Gotha, to search for the missing planet between Mars and Jupiter. He began looking for it in 1787 but quickly realized the efforts of several observers would be needed. Von Zach called a meeting at Gotha in 1788 at which the leading French astronomer Joseph Jérome le François de Lalande (1732–1807) proposed a co-operative effort in which colleagues would choose portions of the night sky in which to make systematic searches. This idea languished for 12 years until September 1800, when six leading astronomers met at the home of the German astronomer Johann Hieronymous Schröter (1745–1816), who had built and equipped one of the world's leading observatories at Lilienthal, near Bremen. Those present agreed to ask each of 24 astronomers to search 1/24-th of the sky along the zodiac (Jaki 1972). One of those to be invited was Giuseppi Piazzi at Palermo.

Giuseppi Piazzi (1746–1826), Director of the Observatory at Palermo in Sicily, was hard at work making corrections to an inaccurate star chart, when on 1 January 1801, the opening night of the 19th century, he discovered a body of faint luminosity in the constellation Taurus, the Bull. The following night, he found the body had moved by 5′, and for each of the next two nights it moved the same distance. At first, Piazzi supposed he had found a star or a comet, except that it lacked a coma or tail. He continued his observations when the weather allowed until 23 January. He then sent letters describing the body's apparent positions as of 3 and 23 January to three astronomers, von Zach, Bode and Barnaba Oriani, in Milan. By 1 February 1801 the body had moved through a geocentric arc of 3°. Then Piazzi fell ill and soon afterwards the body passed too close to the Sun to be seen again until late summer. With no idea of its orbit, however, nobody would know where to look for it.

von Zach published Piazzi's observations in the first issue of his *Monatliche Correspondenz* (Zach 1801), where they were seen by the brilliant young German mathematician Carl Friedrich Gauss (1777–1855), who later would become Director of the Astronomical Observatory at Göttingen. In 1794 Gauss had devised a method of determining the path of a celestial body using data from a very limited time period and making no assumptions as to the form of its orbit – except that it had to be a conic section. Gauss had not given his method a serious test, so he was elated at the chance to apply it to such an important problem as the search for Piazzi's body. Gauss (1801) published his results in November of that year to show observers where to look for it. On 31 December, almost exactly 1 year after Piazzi's discovery, von Zach recovered the tiny planet at a distance of only about 0.5° from where Gauss predicted it. Olbers also found it 2 nights later. Gauss (1809) described the methods he used, including the introduction of his inverse-square distance law of gravitational attraction and the reduction of his data by the method of least squares, which still is in daily use for minimizing errors in all sciences. At the time, von Zach remarked that it was doubtful if the planet would have been found again without Gauss' calculations. Piazzi (1802) proposed to name the new planet 'Ceres Ferdinandea', in honour of Ceres, the patron goddess of agriculture and of Sicily, and his own patron, King Ferdinand IV of Sicily. But the King's name soon was dropped and the small planet between Mars and Jupiter became 'Ceres'.

Bode (1802) published a treatise on the new planet between Mars and Jupiter, the eighth member of the solar system, pointing out that it fitted perfectly into the distances indicated by the 'law'. Then, on 28 March 1802, Olbers was searching for Ceres when he discovered a second small body between Mars and Jupiter. Gauss calculated its orbit, and Olbers, assuming it was a planet, proposed the name 'Pallas'. Bode, who by then was both the Director of the Berlin Observatory and editor of the *Astronomisches Jahrbuch* he had founded, would not hear of it. Another planet in that zone would upset Bode's law, which he held to be sacrosanct. Olbers sought to solve the problem by suggesting that the two bodies were fragments of a larger planet that had exploded or been impacted by a comet. He predicted that more pieces of it would be discovered. Bode continued to argue that the new body was a comet while Gauss, Olbers and others were calling it a planet. Herschel (1802) sought a solution by inventing a new name, 'asteroids', for small bodies that were neither stars, nor comets, nor standard planets. The name was unwelcome to many, who would have preferred 'planetoids' or, even, 'cometoids'. But 'asteroids' was widely adopted and still is commonly used along with 'minor planets'.

Time has not been kind to Bode's law. No theoretical justification has been found for the spacing of the major planets, except for the lack of one between Mars and Jupiter: gravitational perturbations by Jupiter prevented the accretion of a large planet there and left that space almost entirely empty. Although the asteroid belt may contain a million small bodies, at least 1 km in diameter, their total mass equals only 2% of the mass of the Earth's Moon and one-third of that is taken up by Ceres.

Debates on falls

In 1801 Marc-August Pictet published an extract of Chladni's book in *Bibliothèque Britannique* (Pictet 1801*a*) and thereby aroused a storm of protest among opponents of fallen stones. Perhaps the most vocal of these were De Luc (1801*a–c*) in Geneva and Patrin (1801, 1802) in France. Both of them rebuked Pictet for publishing the extract of Chladni's book and for his favourable editorial comments on it. They argued that only 'natural' (meaning 'familiar') causes should be sought for what may appear to be falls of stones and for large erratic irons. Pictet's opponents did not wholly agree with one another, but they all excoriated him, not only for his favourable treatment of Chladni's book, but for subsequently reporting on a visit he had made to Howard's laboratory. There, he saw four 'fallen' stones with identical interiors covered with black crusts that were exactly alike but completely different from any other known rock. Pictet (1801*b*) said he no longer could doubt the fact of their having fallen from the sky whatever their mode of origin might have been. The debates, well spiced with sarcasm, were extracted in journals in England, France and Germany (c.f. Marvin 1996, pp. 565–571).

The report by Howard and de Bournon: 1802

Beginning in February 1802, Howard's report appeared in four parts in the *Philosophical Transactions of the Royal Society*. The text was read in three successive meetings of the Royal Society, where it is said to have been heard by an unusually large audience because the readings were interspersed with updated observations on the new asteroid, Ceres. In an early version of co-authorship, Howard's report included two sections signed by de Bournon describing the mineralogy of the stones and irons (Bournon 1802*a*). Howard also included a letter from John Lloyd Williams describing the Benares fall.

After describing in detail the mineralogy and textures of the samples and the methods applied in their chemical and mineralogical analyses, Howard (1802, p. 211) summed up the similarities of the stones:

> They all have pyrites of a peculiar character. They all have a coating of black oxide of iron. They all contain an alloy of iron and nickel. And the earths which serve them as a sort of connection medium, correspond in their nature, and nearly in their proportions.

Howard remarked on the differences between his analyses of stones and those reported earlier by Fougeroux *et al.* in 1777 on the Lucé stone, and by Barthold in 1800 on the Ensisheim stone. Both of these were bulk analyses with no findings of nickel. Howard believed nickel would have been detected if the metals had been measured separately. Barthold had reported 17% alumina in Ensisheim, but Howard found none in his four stones. He suggested that if Barthold's alumina were mainly silica their results would be closer. Subsequently, the eminent French chemist Antoine-Francois de Fourcroy (1755–1809) analysed a sample of Ensisheim and found 2.4% Ni and no alumina (Fourcroy 1803, p. 303).

To Howard, the strong similarities he and de Bournon had found in stones that had fallen at different times in widely separated countries, together with the similarities of eyewitness reports of falls, removed all doubt as to the authenticity of falls of stones and irons. He said that to disbelieve them on grounds of mere incomprehensibility would be to dispute most of the works of nature. He added that it no longer would be necessary to defend the fact of falls to people of impartial judgement, but, he added, it would be useless to argue with those who chose not to believe in them.

Howard's manuscript in the archives of the Royal Society shows numerous alterations, some of which were most probably made by Howard himself, and others by Edward Grey, the secretary of the Royal Society. Several alterations downgraded assertions to possibilities (Sears 1976, p. 135). For example, Howard's original title was: 'Experiments and observations on certain stony and metalline substances which have fallen at different times on the Earth; also on various kinds of native iron'. This was changed to '... substances which *are said to have* fallen at different times ...'. Finally, having presented the results of his own chemical analyses and de Bournon's mineralogical observations, Howard (1802, p. 212) closed his paper by stating:

> From these facts I shall draw no conclusions, but submit the following enquiries:
> 1st. Have not all fallen stones, and what are called native irons, the same origin?
> 2dly. Are all, or any, the produce of the bodies of meteors?

By these rhetorical questions, Howard asks each reader to consider fallen stones to be genetically related to native irons, both of which differ from the Earth's crustal rocks. And he asked if they may originate in fireballs. Just as Sir Joseph Banks predicted, the analyses by Howard and de Bournon provided a firm chemical–mineralogical foundation for a new branch of investigation, which we now call meteoritics.

Reverberations

Early in 1802 extracts and some full translations of Howard's paper began to appear in journals in France and Germany, and chemists everywhere began to analyse separated fractions of stones using the alkali fusion technique for silicates and looking for nickel in the metals. Howard's report did not silence the opposition immediately, but changes of mind already were in the air.

The conversion of Saint-Amans

In March, 1802 Jean F.B, Saint-Amans, whom we last saw in 1790 scoffing at the idea that stones had fallen at Barbotan, read Pictet's description of the stones in Howard's laboratory and wrote an excited letter to *Bibliothèque Britannique* (Saint-Amans 1802). Pictet, he said, had reminded him of the stone he had received along with the Mayoral deposition declaring the authenticity of the Barbotan fall. He had forgotten all about that event, but now he rushed to his cabinet and found that, by sheer chance, he had saved his specimen. To his surprise, indeed his delight, it looked exactly as Pictet had described Howard's four fallen stones. He found it to be remarkable that 'fallen' stones from different countries present the same characteristics. Now, he was convinced that, however absurd the allegation may have appeared, one must hurry up to ascertain the facts. He wished to visit Howard's laboratory and would bring along his stone for comparison.

Howard's paper summarized in Bibliothèque Britannique

In the space immediately following Saint-Amans' letter, Pictet (1802) published an extract of Howard's paper detailing the techniques Howard and de Bournon had used and the importance of their results. He cited the nickel content of the metals as evidence of their origin outside the Earth. But Pictet's matter-of-fact tone sorely annoyed De Luc, who responded that he already had rebutted Chladni's idea of rocks from space, and he had shown it to be inconceivable that large rocks can form in the atmosphere or be transformed by lightning. He claimed that many common rocks – grits, sandstones, granites, volcanics – look just like Howard's rocks, and the testimony to falls was not to be trusted, as it came from superstitious country folk. De Luc (1802, p. 102) declared that *Nothing* falls from the sky: no pieces of planets, no thunderstones, no concretions of volcanic vapours. De Luc did not mention Howard's finding of nickel in the irons.

Eugène Patrin (1802) unleashed a 17-page diatribe in the June issue of the *Journal de Physique*, in which he accused Howard and de Bournon of presenting marvellous stories just to please the majority of readers. He listed seven facts they had stated in error. de Bournon responded in high dudgeon (Bournon 1802*b*), disputing Patrin's statements point-by-point. How did Patrin explain nickel in these stones and none in deposits of pyrite? If Patrin believed that bolts of lightning had transformed veins of iron ore into the 1600 lb mass of metal in Siberia and the 30 000 lb mass in Argentina, what bolts they would be! Patrin, himself, must love marvels. He must choose whether he believes that the lightning introduces nickel into the iron or changes some of the iron to nickel. In summarizing his arguments de Bournon said it was beyond the laws of nature to find, time after time, the same unusual type of stone where people have seen them fall, whatever the social rank of the witnesses. Patrin (1803, p. 392) conceded all points to de Bournon with regrets for his previous attacks. Thereafter, he remained silent on this issue.

Analyses by Louis-Nicolas Vauquelin, 1802

In the spring of 1802 Howard visited the chemist Louis-Nicolas Vauquelin (1763–1829) in Paris, and found that he had analysed stones from Barbotan and Siena, with results similar to his own. Howard urged him to publish them. Vauquelin (1802*a*, p. 308) did so with the comment:

> While all Europe resounded with reports of stones fallen from the skies, and savants divided in their opinions of them, Mr Howard, an able English chemist, was pursuing in silence the only route which could lead to a solution.

In October 1802 Pictet read Howard's results to the National Institute of Sciences and Arts (the Revolutionary successor to the Royal Academy), and in February of 1803 the Institute heard a reading of Vauquelin's analyses. Also in 1803, Klaproth (1803, p. 338) published his analysis of a stone from Siena. Klaproth wrote that he had obtained stones and analysed them soon after the fall in 1794, but he had not published his results because the subject of fallen stones was so controversial. Now, Klaproth joined the majority of savants by accepting stones fallen from the sky.

Lunar volcanic origin: Laplace's hypothesis? 1802

Early in 1802 the French mathematician Pierre-Simon de Laplace (1749–1827) raised the question at the National Institute of a lunar volcanic origin of fallen stones, and quickly gained support for this idea from two physicist colleagues Jean Baptiste Biot (1774–1862) and Siméon-Denis Poisson (1781–1840). The following September, Laplace (1802, p. 277) discussed it in a letter to von Zach.

The idea won additional followers when Biot (1803*a*) referred to it as 'Laplace's hypothesis', although Laplace, himself, never published an article on it. We have seen that this hypothesis had been mentioned briefly in 1794 by Thomson in Naples, and in 1795 by Olbers at Bremen. There were others; in fact, this idea can be traced at least as far back as the 17th century when P.M. Terzago (1664) wrote that a rock which fell on a Franciscan monk and killed him in 1650 had come from a volcano on the Moon. Terzago's statement illustrates the general rule that every bright idea has been thought of before; what is important is to think it again when it can be either disproved or integrated into scientific knowledge of the day.

By the spring of 1802 many scientists fully accepted the fact that solid bodies, unlike any known terrestrial rocks, fall from the sky and two main modes of origin were being discussed: the stones accrete in the upper atmosphere, or they are hurled to Earth from volcanoes on the Moon. At that time, most scientists considered the Earth and Moon to belong to a closed system to which nothing could be added and nothing lost. This system was the locus of all the messy things – clouds, rain, snow, hail, meteors, fireballs – that we observe in the sky. Ejecta from the Moon would be part of that system, but Chladni's hypothesis of stones from cosmic space was too radical a departure from the time-honoured view that outer space is empty.

French scientists frequently are accused of rejecting fallen stones for too long. There even is an oft-repeated (but false) story that the Academy of Sciences passed a formal resolution saying that stones do not fall from the sky. It is of special interest, therefore, to note that some of the leading intellectuals in France fully accepted fallen stones early in 1802, and the issue would finally be resolved for the general public a year later by a shower of stones in France.

The shower at L'Aigle, Normandy, 1803

At 1:00 p.m. on 26 April 1803 a brilliant fireball, followed by three enormous detonations, heralded a great shower of nearly 3000 stones at L'Aigle in Normandy. The first person to publish an account of it was Citizen Charles Lambotin, a student of mineralogy and dealer in natural history objects, living in Paris. Lambotin was alerted to the event when a man in his boarding house showed him a letter about it written on 3 May by one Citizen Marais at L'Aigle. Lambotin immediately sought more information from Marais and commissioned a search for stones. Within weeks, he had received enough information to write a paper (Lambotin 1803) that appeared in the Prairial (18 May–18 June) issue of the *Journal de Physique*. He also had acquired enough stones to sell them to all the collectors of Paris. Citizen Marais produced the first map ever drawn of a meteorite strewnfield, which he showed as being more rounded on the west and north than it was to the east and south (c.f. Marvin 1996, p. 571). His map was not finished when Lambotin's article went to press. Not until 16 years later would Lambotin's article, accompanied by Marais' map, be inserted by Eugène Patrin, the editor, into the first edition of the *Dictionnaire d'Histoire Naturelle* (Lambotin 1819).

On 19 June, Fourcroy reported to the Institute that he and Vauquelin had analysed stones from L'Aigle and found them to be similar in chemical composition to all other fallen stones. He announced their support for Chladni's hypothesis of stones fallen from space. At the same time, Jean-Antoine Chaptal (1756–1832), Minister of the Interior, sent the youthful Biot to L'Aigle to gather detailed information on the event. His purpose in doing so remains unclear, although Burke (1986, p. 55) speculates it may have been to gather data specifically for testing Laplace's idea of the lunar origin of stones. Biot acquitted himself brilliantly by producing a detailed report including an accurately drawn map showing the strewn field as an ellipse. Early in July he outlined his findings in a letter to Chaptal, and on 17 July Biot read his report to the National Institute, which acclaimed it as providing definitive proof of fallen stones. The Institute printed his 45-page report in August (Biot 1803*b*). Meanwhile, Biot sent Pictet a copy of his letter to Chaptal saying that by his faithful reporting on fallen stones and on the works of Chladni and of the English scientists Pictet had earned a certain right to receive any new observations. So Biot's report of what he called '… without doubt the most astonishing phenomenon ever observed by man' appeared first in *Bibliothèque Britannique* (Biot 1803*c*, p. 394). We shall not pursue this story further, as the fall at L'Aigle is the subject of another chapter (Gounelle 2006).

Later in the same year, the historian Eusebius Salverte (1771–1839), in England, described the intellectual volte-face that had taken place (Salverte 1803):

> The ancient historians all make frequent mention of the productions of stones [fallen from the atmosphere]. No doubt was maintained respecting them in the Middle Ages; but the difficulty of accounting for them induced us not only to suspend our belief until called forth by more regular observation, which was very prudent, but also, which was less reasonable, to carry with us in this research a predetermination to see nothing, or to deny what we had seen.

Thus, within 9 years of the publication of his book, Chladni's hypothesis that fragments of stone and iron fall from the sky was fully vindicated and he received the widespread recognition for it that he deserved. In 1804 Thomson, in Naples, submitted a French extract of Tata's book on the Siena fall to *Biblioteque Britannique*. At the end Thomson appended the remark (in Tata 1804, p. 267):

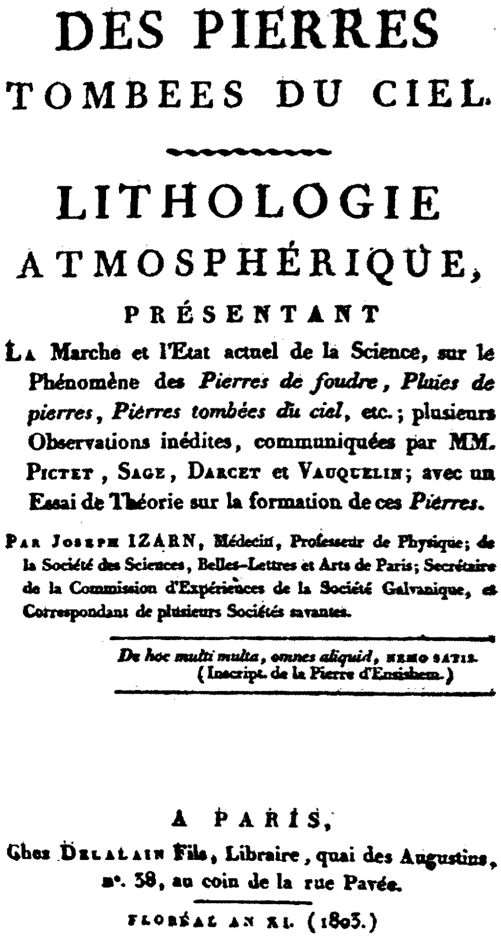
> … if communications had been better in 1794, there would have been more familiarity with the important phenomenon of meteoric stones than there was not long ago in France, and the time taken laughing at it would have been more usefully employed examining it.

Chladni continued to publish articles on meteorites and he wrote one more book, *Über Feuer-Meteore* (Chladni 1819), in which he compiled all the information on meteorites he could glean from the literature and from visits to localities of meteorite falls. But Chladni's linking of falls with fireballs was not vindicated in 1803 – no fireballs were reported with nearly half of the witnessed falls – and it would not be vindicated until the 1830s when the physics of fireballs became better understood. Indeed, Chladni's hypothesis of a cosmic origin of the stones would continue to be almost universally rejected until the 1850s.

Lithologie Atmosphérique, Joseph Izarn, 1803

A short time after the fall at L'Aigle, a 422-page book, arguing that fallen stones originate within the atmosphere, was published in Paris (Fig. 20). The author, Joseph Izarn (1766–1834), was a medical doctor and physicist who made it clear in his extended title that he was reviewing this subject mainly as it had developed in France (author's translation):

> Stones Fallen from the Sky, or Atmospheric Lithology; Presenting the Advance of Science on the Phenomenon of Lightning Stones,



DES PIERRES
TOMBEES DU CIEL.

LITHOLOGIE
ATMOSPHÉRIQUE,
PRÉSENTANT
LA Marche et l'Etat actuel de la Science, sur le Phénomène des *Pierres de foudre*, *Pluies de pierres*, *Pierres tombées du ciel*, etc.; plusieurs Observations inédites, communiquées par MM. PICTET, SAGE, DARCET et VAUQUELIN; avec un Essai de Théorie sur la formation de ces *Pierres*.

PAR JOSEPH IZARN, Médecin, Professeur de Physique; de la Société des Sciences, Belles-Lettres et Arts de Paris; Secrétaire de la Commission d'Expériences de la Société Galvanique, et Correspondant de plusieurs Sociétés savantes.

De hoc multi multa, omnes aliquid, NEMO SATIS.
(Inscript. de la Pierre d'Ensisheim.)

A PARIS,
Chez DELALAIN Fils, Libraire, quai des Augustins, n°. 38, au coin de la rue Pavée.
FLORÉAL AN XI. (1803.)

Fig. 20. The title page of the book by Joseph Izarn (1803), in which he argued for the formation of meteorites within the atmosphere. (Courtesy of the Smithsonian Institution Libraries.)

> Showers of Stones, Stones Fallen from the Sky, etc.; with Many Unpublished Observations Communicated by MM. Pictet, Sage, Darcet, and Vauquelin with an Essay on the Theory of Formation of These Stones.

In Part I, Izarn (1803) listed all the reports of fallen bodies that had been published in France, plus some extracts from foreign journals, between 1700 and 1803. In Part II, he compiled a table of 34 falls of matter for which he could find references beginning with the Biblical account of Sodom and Gomorrah and continuing to 1798. Most were falls of stone, two were of iron, and several were of sulphur, mercury or viscous matter. He then listed the four main hypotheses of origin and the names of scientists, past or present, who favoured them. Those that we have discussed include: (1) terrestrial volcanoes or hurricanes: favoured by De Luc and Barthold; (2) lightning striking pyritiferous rocks: argued by the French Academicians in the 1760s, and Patrin in 1802; (3) concretions in the atmosphere: favoured by Soldani, Hamilton, King and Salverte; and (4) masses foreign to our planet: Chladni, Laplace, Biot, Poisson and Pictet. Here, Izarn failed to appreciate the crucial distinction between an origin within the Earth–Moon system and Chladni's favoured origin in cosmic space.

Izarn began Part III by quoting a most perceptive statement by Vauquelin, who had said that we should freely avow we are entirely ignorant of the origin of fallen stones and the causes that produced them, so we should resist expressing opinions on this subject until we learn more. Izarn failed to take this excellent advice, and devoted the rest of his book to arguments for the origin of stones within the atmosphere. He discussed Howard's results in detail and saw no problem with the presence of nickel in the iron. He claimed that the atmospheric theory had the great advantage of including no hypotheses and being founded only on the best-established principles of physics.

Izarn's book received friendly reviews in France, mostly favourable ones in England and a scathing review in Germany by Ludwig Gilbert (1803, p. 437), editor of *Annalen der Physik*. Gilbert (1803) said that Izarn was a stranger to most principles of physics, that many of his ideas were illogical, and that he did not understand Dalton's theory of atmospheric gases or the works of his distinguished compatriots, the chemists Fourcroy and Claude Louis Berthollet (1748–1822). Nevertheless, numerous articles favourable to an atmospheric origin followed the publication of Izarn's book.

The fall at Weston, Connecticut, 1807, and the Thomas Jefferson myth

In September 1803 the American President, Thomas Jefferson (1743–1826), received news from his close friend, Andrew Ellicot (1754–1820), that Robert Livingston (1746–1813), the US Minister to France, had sent him strong evidence that stones had fallen from the sky in France and that the local philosophers were debating whether they originated in the atmosphere or in volcanoes of the Moon. Jefferson took this news lightly saying he was not surprised to hear of the raining of stones in France, nor yet had they been millstones, as there were more real philosophers in France than in any other country on Earth but also a greater proportion of pseudo-philosophers (Burke 1986, p. 86). Two years later, in 1805, Ellicot received a packet of publications from France that fully convinced him that stones, differing from ordinary stones, do, in fact, fall from the sky and are formed within the atmosphere. When he wrote of this to Jefferson, Jefferson (in Bergh 1907) replied, on 25 October 1805, that he had not seen all the papers but he had read Izarn's *Lithologie Atmosphérique*. He could not say that he disbelieved, nor yet that he believed it, as chemistry was too much in its infancy to satisfy him that lapidific elements exist in the atmosphere and can be formed into stones there. Jefferson seems to have been more concerned about the chemistry of the atmosphere than he was about the fallen stones.

Two years later, at 6:30 in the morning of 14 December 1807, a brilliant exploding fireball, seen coursing southward from Canada to New York, showered stones over Weston, Connecticut. Two professors at Yale College, the geologist, mineralogist and chemist Benjamin Silliman (1799–1864), and the chemist and college librarian, James L. Kingsley (1778–1852), immediately obtained samples for analysis. By that time at least 150 articles about meteorites had been published in European journals since the appearance of Howard's paper in 1802 (Brown 1953), and American scientists were thoroughly familiar with the European literature. Silliman and Kingsley knew they should conduct analyses on separated fractions and look for nickel in the metals. Meanwhile, they published an account of the fall in a Philadelphia newspaper.

One 37 lb stone fell in the oat field of a Mr Daniel Salmon, who sent it to New York to be examined by the mineralogist and well-known collector Archibald Bruce (1777–1818). In a letter to President Jefferson, Mr Salmon

(1808) quoted Mr Bruce as saying that his stone was, beyond any doubt 'of meteoric production'. It matched those Bruce had seen in the collections of Mr Greville in London and of the Marquis Etienne M.G. de Drée (1760–1848) in France, and also the fragment in his own possession of the meteorite that fell at Ensisheim in 1492. Salmon asked Jefferson if he should send this new visitor in the United States to the president and the national legislature for their consideration.

Jefferson replied on 15 February that the descent of this supposed meteoric stone from the atmosphere presented so much difficulty as to require a careful examination, but he believed a more effectual examination would be made by a scientific society such as the Philosophical Society of Philadelphia rather than by members of Congress. Jefferson added (in Bergh 1907, p. 440):

> We certainly are not to deny what we cannot account for... It might be very difficult to explain how the stone you possess came into the position in which it was found. But is it easier to explain how it got into the clouds from whence it is supposed to have fallen? The actual fact, however, is the thing to be established, and this I hope will be done by those whose situations and qualifications enable them to do it.

Here we see that Jefferson was cautious about committing himself on the stone's mode of origin, but he specifically avoided denying that the fall occurred, and he recommended that it should be studied by those most scientifically qualified to do so. Shortly thereafter, on 4 March 1808, Silliman described the stones at a meeting of the Philosophical Society, of which Jefferson was the president but not presiding at that session. The following year, Silliman & Kingsley (1809) published their full report, including their chemical analyses of the stones, which, they said, were similar in composition to those analysed by Howard, Vauquelin, Klaproth and Fourcroy, who were their guides in this investigation. With respect to the origin of the stones, they favoured the hypothesis of the late president of Yale, Thomas Clap (1703–1767). In his paper, which was published posthumously in 1781, Clap argued that fireballs are earth-orbiting comets in long, elliptical orbits with perigees of approximately 25 miles and apogees of about 4000 miles. Such a comet, in their view, had made a close approach to the Earth and dropped stones as it passed over Weston. (Incidentally, Clap's was the earliest paper on meteorites to be published in America, and it remained the only one for the next 28 years until the publication by Silliman & Kingsley.)

While he lived, Jefferson never wrote, nor was he ever quoted as saying, anything more about fallen stones. How, then, are we to make sense of the popular tale that when he heard of the fall at Weston Thomas Jefferson declared: 'It is easier to believe that those two Yankee professors would lie than that stones would fall from heaven'?

Jefferson died on 4 July, 1826 and the New York Lyceum held a memorial service for him the following October. The invited speaker was the Honourable Thomas Latham Mitchill (1764–1831), a professor of chemistry and natural science at Columbia. Towards the end of his long oration, Mitchill (1826) recounted an anecdote that he said had occurred in 1807 when Mitchill was serving in Congress. Friends in Connecticut sent him a description of the fall at Weston and a stone, which he received in Washington a full day before anyone else heard the news – including the representatives from Connecticut. In response to avid solicitation, Mitchill loaned the description and the stone to a senator, living in his boarding house, who was to dine with Jefferson that very day and wished to show these rare trophies to 'the philosopher of Monticello'. The senator returned deeply disappointed. Jefferson, he said, had responded to his story with scornful indifference saying he could explain it in five words: 'It is all a lie'.

This second-hand report of a statement, posthumously ascribed to Jefferson two decades after the event by a person not present at the scene, would not be acceptable in a court of law – especially when the defence attorney could point to Jefferson's measured response, written shortly thereafter, to Mr Salmon about his fallen stone. In any case, Mitchill said nothing about Yankee professors, so we may relegate them to the status of a tall tale added by some unknown wag at a later date. Given the complete lack of primary sources for Jefferson's alleged remark, and a reasonable date on which he could have made it, a dutiful historian simply will declare Jefferson to be innocent of all charges. And, incidentally, may we all hope never to have friends like Mitchill eulogizing us.

Discoveries of two more asteroids: Juno 1805 and Vesta 1807

In 1805 the third small planet between Mars and Jupiter was discovered by Karl Ludwig Harding (1765–1834), an assistant of Schröter's at Lilienthal. Harding named the asteroid for another goddess, Juno. Their orbital elements suggested that the three small objects might be remnants of an exploded planet. Chladni (1805, p. 272) was delighted. He wrote that he had been fascinated since his childhood by the wide gap between Mars and Jupiter, and had predicted that a planet would be found there. Also, he recalled that in his book of 1794 he had listed debris of a disrupted planet, although not necessarily one from our own solar system, as his second choice of a source for meteorites. (His first choice was that meteorites are small bodies in space that never had accumulated into planets.) Two years later, in 1807, Olbers found the fourth asteroid, for which he accepted Gauss' suggestion of naming it 'Vesta'. Calculations convinced Olbers that the four asteroids did not start from a single body. (He was right, but his evidence was insufficient; the four bodies could have started from the same body and been perturbed into different orbits.) Although he had discovered two asteroids, Olbers was not yet prepared to suggest that they might be sources of meteorites.

Carbonaceous chondrites

Alais, the first carbonaceous chondrite, 1806

At 5:00 p.m. on 15 March 1806, thunderous detonations heralded the fall of two soft, black stones, weighing 4 and 2 kg, in the vicinity of Alais in France. They had loose, friable textures, low densities (*c.* 1.7 $\mathrm{g\,cm^{-3}}$), and emitted a strong odour of bitumen. They contained no chondrules and no grains of metallic iron. Except for their fusion crusts, they looked so much like black, slightly lithfied soil that they probably would not have been picked up if they had not been seen to fall. An analysis published later that year by Louis Jacques Thénard (1777–1857), Professor of Chemistry at the Collège de France in Paris, showed that they contained about 2.5 wt% of carbon along with magnesium, nickel and iron oxides (Thénard 1806).

Alais was the earliest known meteorite of the class we call carbonaceous chondrites (despite their general lack of chondrules). In 1834 the distinguished Swedish chemist Jöns Jacob Berzelius (1779–1848) observed that Alais, unlike other stony meteorites, consisted mainly of clay minerals (Berzelius 1833). When he first detected water in it, he was inclined to throw out the sample because water was unknown in meteorites. On further examination Berzelius concluded the water was indigenous. He also found carbon dioxide gas, a soluble salt containing ammonia, and a blackish sublimate consisting of silica, magnesia, iron oxide, alumina and 12 wt% of elemental carbon. He compared the carbonaceous component to humus, but warned that, regardless of any similarities, the meteoritic material might have formed under different conditions so it might not be at all analogous to carbonaceous substances on Earth.

The second carbonaceous chondrite fell 32 years later at 9:00 a.m. on 13 October 1838 when an exploding fireball deposited a shower of black stones at Cold Bokkeveld in the Western Cape Province of South Africa. This stone was more solid and heavier than Alais, and had some chondrules in it. The third one fell 19 years after that at 10 p.m. on 15 April 1857 at Kaba, near Debreczen in Hungary. In 1858 and 1859 two chemists in Vienna, Friedrich Wöhler (1800–1882) and Moritz Hörnes (1815–1868), carried out a series of analyses, separately and together, on the Kaba stone. Wöhler & Hörnes (1859) stated that the carbonaceous matter in carbonaceous chondrites was organic in origin. After a careful study of their original text, Bartholomew Nagy at the University of Arizona (Nagy 1975, p. 44) concluded that they used the term 'organic' in its traditional meaning of 'biological' origin.

Light and sound effects during flight

Wöhler (1858) may have been the first scientist to state outright that surface heating during the few seconds of atmospheric flight does not penetrate to the interior of falling stones, which remains cold. This extraordinarily important fact remains underappreciated to this day.

Fireballs do, indeed, last for only a few seconds, or tens of seconds. They are incandescent mixtures of ionized gases and dust that form around bodies that enter the atmosphere from space at supersonic (cosmic) velocities and decelerate due to friction with air molecules. A fireball continuously melts and strips away a thin surface layer of the body, always exposing its cold interior; droplets fly off, vaporize and recondense in a smoky or luminous trail. In the last second of flight before the body loses all of its cosmic velocity, the molten material covers the cold body with a fusion crust.

Shock waves, generated while the body is travelling at supersonic velocities, emit one or more sonic booms that startle the countryside. Observers near the flight path often hear electrophonic sounds, such as whistling, sizzling or crackling. The incoming body compresses a column of air ahead of it, and the collapse of air back into the empty path behind it makes great rumbling sounds that may last for minutes. Most falling stones or irons burst into pieces once or twice during flight. All meteorites (except for crater-forming ones) lose their supersonic velocities at heights of 10–30 km above Earth's surface. At that moment the fireball extinguishes, melting stops and the body falls the rest of the way through the cooling atmosphere. This process has been compared to applying torches to a massive lump of cold iron for a few seconds and then switching to forced cooling by jet air streams (Buchwald 1975, vol. 1, p. 8).

On the ground, a meteorite will be cold or barely warm. Some of them are so cold that on hot, humid days they quickly become covered with hoar frost. If falling stones were to heat significantly we never would recover a carbonaceous chondrite containing water. Nevertheless, to this day, reports of meteorites that scorch leaves, start fires or are too hot to touch are routinely told to curators, even when the specimens brought to them are pieces of bog iron ore, industrial slag or even black limestone. We must ascribe these reports to unrealistic human expectations of what should occur in a meteorite fall. Indeed, most descriptions of falls are so implausible that we may well ask how Chladni fared so well in collecting his reports. But, over the years one major change has taken place: reports of falls filling the air with sulphurous fumes mostly ceased more then half a century ago. '*Why did meteorites lose their smell?*' asked Sears (1974, p. 299). He noted that they contain too little troilite for the purpose and concluded that sulphurous fumes were expected only as long as the old sermons about 'fire and brimstone' were in fashion.

The Orgueil carbonaceous chondrite, 1864

The most famous carbonacous chondrite of the 19th century fell at Orgueil, in France, at 8:00 p.m. on 14 May 1864. A luminous white fireball, seen to turn dull red during an immense explosion, preceded the fall of 20 stones strewn over an area of about 2 square miles. The distinguished French geologist, petrologist and chemist August Daubrée (1814–1896), gathered reports of the fall and analysed samples. Like Alais, Orgueil had no chondrules and no iron grains. Daubrée (1864) reported to the Academy of Sciences that it looked like lignite coal but it was very friable and disintegrated to a black, powdery substance in water. Daubrée found that it contained significant quantities of chlorides and more carbon than the other three carbonaceous meteorites.

In 1868 the French chemist Pierre Eugène Marcellin Berthelot (1827–1907), who is famous for showing in 1860 that all organic compounds consist of carbon, hydrogen, oxygen and nitrogen (CHON), experimented with hydrogenation to unravel the secret of the carbonaceous substance in Orgueil. Berthelot (1868) said this method could transform all organic substances, including charcoal and coal, into hydrocarbons similar to those in petroleum. And, indeed, he succeeded in obtaining saturated hydrocarbons from Orgueil. He could not identify the hydrogenated product, but he said that whatever it was it presented a new analogy between carbonaceous matter in meteorites and carbonaceous substances of organic origin on the Earth.

A full century later, in the 1960s, amino acids and all of the other essential building blocks of life would be identified in carbonaceous chondrites. But none of them are linked into proteins, so none could be assigned a biological origin. Suffice it to say that, to date, no material of biological origin has been positively identified in any meteorite.

Carbonaceous chondrites are very rare meteorites: only about 560 of them are known today. They make up only 3.7% of the 15 190 chondrites listed by Grady (2000). The carbonaceous chondrites are now subdivided into seven classes that range from being soft and black and free of chondrules to hard and grey and rich in chondrules, and, in some instances, they contain the astonishing calcium–aluminium-rich inclusions (CAIs) that will be discussed in a later chapter (McCall 2006*a*).

Stannern, the first achondrite, 1808

At 6:00 in the morning of 22 May 1808 thunderous detonations heralded the fall of a shower of stones at Stannern in Moravia (present Czech Republic). The Bratislavan natural historian and Director of the Viennese Natural History Collection, Carl Franc Anton Ritter von Schreibers (1775–1852), was appointed to an imperial commission to investigate this fall from which 66 specimens, weighing a total of 52 kg, were collected. Some broken pieces of Stannern looked like pottery shards, but those with black fusion crusts confirmed Stannern to be a meteorite. This fall sowed great confusion among scientists because it was the first stone with an igneous texture that had no chondrules and no grains of nickel–iron metal. Thus, these two features no longer could be depended on as being diagnostic of a meteoritic origin. Josef Moser, an apothecary in Vienna who took an interest in fallen stones, published a bulk analysis later that year showing that Stannern was very different from all other fallen stones. His report

(Moser 1808) prompted Vauquelin to analyse a sample. Vauquelin (1809) confirmed Moser's results and classified Stannern as a new species of stony meteorite. Two decades later, Aristides Brezina (1848–1909), the custodian of the Vienna Collection, would name these stones 'achondrites' (Brezina 1885).

Stannern was markedly richer in calcium and aluminium than chondrites were, and by mid-century it was shown to contain plagioclase feldspar, which, until then, had been unknown in meteorites. Stannern, and all similar stones, were eventually classified as plagioclase-pyroxene achondrites of the type called eucrites, for their strong resemblance to terrestrial eucritic basalts.

The second achondrite, which fell at Chassigny, France, on 3 October 1815, could not have presented a greater contrast with Stannern. It is a dunite, consisting of more than 90% olivine, 5% clinopyroxene, less than 2% each of feldspar and chromite, plus minor accessory phases. The olivine is somewhat richer in iron than dunites from the Earth's lower crust and upper mantle. Chassigny remained unique until 2004, when a second chassignite was recognized in a box of supposed terrestrial rocks from Morocco (Norton 2005, p. 27). The two chassignites belong to the small group of about 34 (and counting) meteorites that came from Mars after being blasted from the surface of that planet by impacts that sent them into Earth-crossing orbits. The Martian meteorites often are called SNCs, an acronym for Shergotty–Nakhla–Chassigny, the first three achondrites to be recognized as martian (Grady 2006). Thirty-seven achondrites have been identified as coming from the Moon by the same process (Kojima 2006). The remaining achondrites, of which only about 585 are known worldwide, are lavas and cumulate rocks from asteroids that underwent igneous differentiation at a very early stage in solar system history (Bowden 2006).

Metallography of iron meteorites: Alois von Widmanstätten, 1808

In 1808 Alois Beck von Widmanstätten (1753–1849), Director of the Imperial Industrial Products Collection in Vienna, cut and polished a small slab from the Hraschina iron to study the structure of the metal. He heated it over an open flame, and watched a pattern develop due to the differing rates of oxidation of at least two metals. He then etched the slab with weak nitric acid, and this revealed a strong pattern of criss-crossing lamellae enclosing patches of smooth metal in the interstices. von Widmanstätten came from a family of printers so he experimented with inking the etched surface and printing it on paper. This displayed the metallurgical pattern in minutest detail at the natural scale: light grey lamellae 0.6–0.8 mm thick, bordered by very thin, bright lamellae enclosing angular fields of smooth grey metal. He printed the patterns of several additional irons, and continued to study the structures for many years. Owing to the pressure of his duties, he never found the time to publish his 'nature prints', but he showed them to his colleagues in Vienna who began to call them 'Widmanstatten figures', and to refer to them by that name in their publications (e.g. Neumann 1812; Schweigger 1813). von Schreibers named the textures 'Widmanstatten figures' in his 97-page supplement to Chladni's book, *Über Feuer-Meteore*, of 1819, and he included a print of the Elbogen iron (Fig. 21) as a prime example (Schreibers 1820, p. 7). This established the international usage of 'Widmanstätten figures' (or 'patterns' or 'structures'), which has dominated the literature on iron meteorites ever since.

In the 1820s and 1830s more than one investigator dissolved out the three types of iron visible in the figures and determined their differing

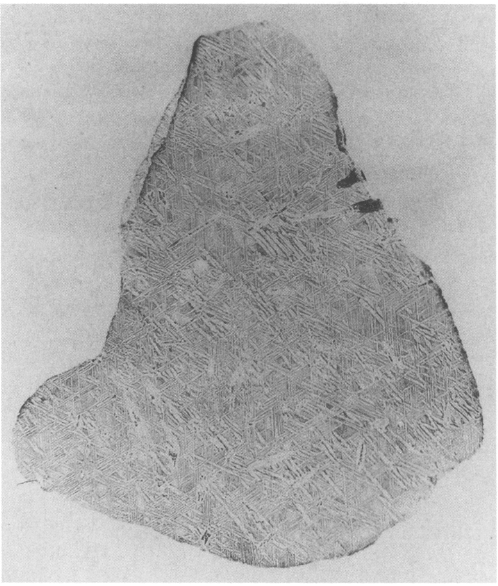


Fig. 21. A 'nature print' made by Alois von Widmanstätten of a slice of the Elbogen iron meteorite he had polished, etched and inked. (From Schreibers 1820, plate 9.)

nickel contents. But not until 1861 did the Baron Karl Ludwig von Reichenbach (1788–1869), a German industrialist and chemist with an interest in meteorites, name the three metal components: 'kamacite' (light grey lamellae with <6% Ni), 'taenite' (thin, bright lamellae with 6–15% Ni) and 'plessite' (dark grey fine-grained metal filling the interstices) (Reichenbach 1861). Plessite subsequently was shown to be an intimate mixture of kamacite and taenite.

von Schreibers wrote that all irons have Widmanstätten figures, and, despite the finding of two or three irons without them, these figures were taken as diagnostic of a meteoritic origin until 1847, when an iron fell at Braunau in Bohemia (Czech Republic) at 3:45 a.m. on 14 July 1847. Two fragments of the iron, weighing 18 and 22 kg, fell on the grounds of a Benedictine Monastery. The Abbot, fully aware of the scientific value of the iron, had the larger fragment cut into pieces and sold to universities and museums. He then used the proceeds to build the Abbey a small hospital, which he referred to as a hypothetical gift from heaven. Reports immediately circulated that the Braunau iron had no Widmanstätten figures. Later that year Haidinger (1847) declared that Braunau was homogeneous with a cubic structure. It was the prototype of the class we now call 'hexahedrites', which have less than 6 wt% of nickel. Irons containing more than 15% of nickel also form a compact structure lacking Widmanstätten figures to which Gustav Tschermak (1836–1927), the German-born Director of the Mineralogical–Petrological Institute at Vienna, gave the name 'ataxites' (Tschermak 1872).

But the great majority of iron meteorites do display Widmanstätten figures and are called 'octahedrites' because their lamellae lie parallel to the octahedral planes of a face-centred cube. This structure was long suspected but was not proved to be so until the 1880s due to the efforts of both Tschermak and Brezina.

The story of the Widmanstätten figures became more complicated in 1939 when the Oxford historian Robert T. Gunther discovered a paper entitled 'Saggio de G. Thomson sul ferro malleable trovato da Pallas in Siberia', published in 1808 in the *Atti dell'Accademia delle Scienze di Siena*. The paper described the complex metallurgical patterns the author had observed in a polished and etched section of the Pallas iron. But who was G. Thomson? Gunther found no citations of this paper in the 19th century literature, so it seemed that G. Thomson must have published in too obscure a journal for his paper to be noticed.

Fortunately, von Schreibers had mentioned that the stone from Siena in the Vienna collection had first been described by one G. Thomson in Naples (Schreibers 1820), to whom it had been sent by Père Soldani in Siena. von Schreibers also remarked that news of the Siena fall was spread abroad mainly because three learned Englishmen – Thomson, Hamilton and Lord Bristol (Hervey) – had taken an interest in it. Furthermore, he noted that in 1808 Soldani had reported receiving a written scientific communication back in 1803 from Thomson in Naples. Gunther (1939) concluded that G. Thomson must be the same person as the W. Thomson, a physician–chemist–mineralogist who had suddenly resigned his membership in the Royal Society and his positions at Oxford in 1771 and left England for Italy. Thomson had died in 1806 so Soldani must have published his Italian paper of 1808 posthumously.

In this paper Thomson (1808) discussed the malleability and the structure of the Pallas iron. He cut and polished a section of it and applied dilute nitric acid to clean off the lap dust. This treatment revealed a complex pattern formed by three kinds of iron, which differed in their reflectivities and dissolved at different rates. The most soluble of the three occurred in relatively broad, light grey lamellae and in bands swathing each grain of olivine – showing that the olivine and the metal crystallized simultaneously. The least soluble formed thin, bright lamellae bordering the broader ones. The sets of lamellae intersected one another at angles of 76° and 104°, and enclosed rhomboidal or triangular fields of metal with a fine-grained texture. Thomson wrote that the lamellae appeared to occur in an octahedral pattern, although it was not quite a regular one. To illustrate his article, Thomson drew these patterns by hand 'with a scrupulous exactitude', and said he suffered eye-strain in the process. No doubt he did. The broadest expanse of metal in his drawing is only 2.3 mm across!

Thomson also looked at a small piece of the Mesón de Fierro, in which he noted a pattern of parallel bands, and at grains from L'Aigle that proved to be similar to those in Siena. All of these metals were crystalline *and* malleable. This posed a serious problem because iron crystallized from melts was universally 'known' to be brittle. Thomson expected the differing values of nickel in the lamellae to affect their densities, but he said he would find it difficult to believe they would affect their malleability (although it does). He declared that the rule specifying that iron crystallizing from a melt must be brittle may apply in general, but it doesn't follow that this should be so without exception. He suggested that pure metals cooling and crystallizing very slowly in large, volcanic systems may be malleable, but he did not specify how such a system might apply to metals in meteorites. Thomson rejected Chladni's hypothesis of cosmic origin, and joined Soldani and Tata in favouring an origin within igneous clouds like the one observed at Siena. His closing remarks on the Pallas iron are disappointingly vague considering his remarkably fine description and illustration of the newly observed structure of meteoritic iron.

Thomson's paper of 1808 was discussed by the Austrian chemist Friedrich Adolf Paneth (1887–1958) in an article published posthumously in 1960. Paneth concluded that Thomson must have discovered the patterns almost simultaneously with von Widmanstätten. He said that Thomson had clear priority of publication, particularly for his illustration, which was the first visual reproduction of the 'Widmanstätten figures'. Nevertheless, he believed von Widmanstätten deserved to have his name attached to the figures because he had discovered them independently and gained recognition of them by distributing his prints.

In 1962 Cyril Stanley Smith (1903–1992), Professor of Metallurgy and History of Science at the Massachusetts Institute of Technology, also reviewed this problem. Smith agreed with Paneth that, despite Thomson's prior publication, von Widmanstätten's widely distributed reproductions and his continuing studies of the figures justified their being named after him. However, Smith (1962, p. 971) emphasized the importance of Thomson's clear statement that the popular superstition that a crystalline metal must be brittle is false. Smith added that the converse observation – that malleable metals could be crystalline – was not generally accepted for many decades after that. This shows us what a dilemma Thomson faced in trying to account for meteoritic iron that was both malleable and crystalline. Paneth and Smith both concluded that Thomson's article published in Italy in 1808 was a translation of some earlier paper he had written in English. As evidence, Smith (1962, p. 971) noted the date, 6 February 1804, printed in English at the end of Thomson's article of 1808, but he remarked that it seemed most unlikely that the original text ever would come to light.

The original English text never has come to light, but one more major discovery was at hand: in the mid-1960s Marjorie Hooker (1908–1976) of the US Geological Survey, who was compiling a bibliography of Thomson's writings, found a two-part article by G. Thomson in French in the October and November 1804 issues of *Bibliothèque Britannique*! This article clearly is a translation from English as shown by the first five words of its title: 'On the Malleable Iron, etc. Essai sur le fierro malleable trouve en Siberie par le Prof. Pallas. (Traduction libre)'. In it Thomson presented the earliest version that has been found to date of his drawings of the metallurgy of the Pallas iron (Fig. 22). Hooker reported her discovery in 1974 at the meeting of the International Mineralogical Association in Berlin (Hooker & Waterston 1974, p. 72). Subsequently, Clarke (1977), Clarke & Goldstein (1978) and Marvin (1996) discussed this problem and remarked on the surprising lack of attention paid to Thomson's paper of 1804. Neither his paper of 1804 in French, nor its translation of 1808 into Italian, was listed by Chladni in his book of 1819, although Chladni was a voracious reader and compiler of articles on meteorites. Nor were they mentioned by von Schriebers in 1820. But no one has suggested changing the name of the metallurgical pattern to 'Thomson figures' until now: a writer on meteorites is proposing exactly that (Kichinka 2004). He argues that we should right a two-centuries old wrong and honour Thomson for his clear priority in publishing 'Thomson figures'. But inasmuch as Thomson's papers of 1804 and 1808 failed to attract the attention of his contemporaries, they contributed nothing to the advancement of knowledge of iron meteorites in the early 19th century. von Widmanstätten, in contrast, clearly did contribute to this knowledge, so he is the one who deserves to have his name attached to the figures. Such a conclusion is tacitly supported by C. Rowl Twidale (2004, p. 298), who reviewed numerous examples in which findings of an earlier author have been eclipsed by those of a later one who (knowingly or unknowingly) published them without attribution. He supports a time-honoured argument that credit in the sciences goes to the person who convinces the world, not to the one to whom an idea first occurs. In any case, to reach back into history and make any change today would bring no comfort to Thomson, but it would bring acute discomfort to scientists who would clutter the literature by always writing: 'Thomson figures (formerly called Widmanstätten figures)'.

Otumpa, a Campo del Cielo iron, 1816–1826

In 1803 a large iron, weighing nearly 1 metric tonne, was discovered at a place called Otumpa in what we recognize today as the strewnfield

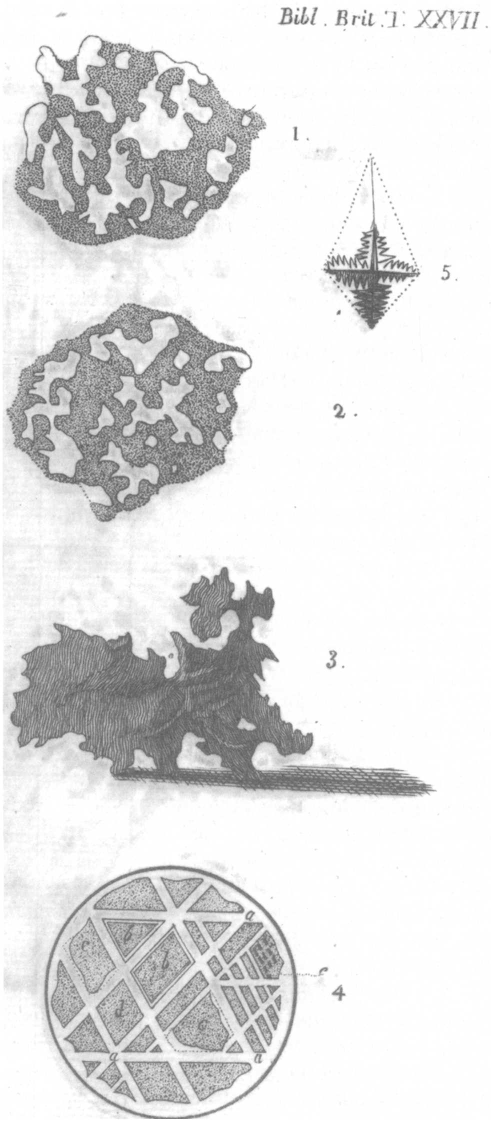


Fig. 22. Fragments of the Pallas iron hand-drawn by G. Thomson at Naples. Items 1 and 2 are polished surfaces showing peridot (white) in a matrix of Ni Fe (stippled). Number 3 is a rough fragment of the least soluble of the three metals Thomson observed in the meteorite. Number 4 is the earliest depiction of the metallurgical pattern of alternating metal bands and fields in an iron meteorite. Number 5 is a fragment of insoluble metal from a Foundary. (From Thomson, *Bibliothèque Britannique*, **27**, 1804; Thomson's article with this plate was republished in Italian in 1808 after his death.)

of the Campo del Cielo meteorite in northern Argentina. The iron was hauled across the Chacos for some 200 km to Santiago del Estero, and eventually shipped to Buenos Aires and deposited in the Armory. In 1816 about one-third of the iron was sliced off for forging and metal-working. The war for independence from Spain was making metal for weaponry much in demand. This metal was particularly precious because news of the meteoritic origin of the Mesón de Fierro had arrived from Europe causing an immense gain in value to the iron from Otumpa.

In 1816 the self-proclaimed Argentine Republic sent a gift of two ornamented flintlock pistols with gunbarrels of Otumpa iron to James Madison (1751–1836), the President of the United States of North America. But the United States had not yet formally recognized the new Republic and so Madison passed along the pistols to the Secretary of State, James Monroe (1758–1831), asking him to thank the Argentines in an unofficial letter.

The United States finally recognized Argentine independence in 1823 and Great Britain did so in 1825. That year Sir Woodbine Parish (1796–1882), the British Consul General, sailed to Buenos Aires and signed a commercial treaty with Argentina. To show its gratitude the government of Argentina presented to him one of that country's greatest treasures, the remaining mass of the Otumpa meteorite, weighing about 635 kg. Sir Woodbine ordered a stout wooden box built to carry the heavy mass to Britain, but no commercial ship would take it because the sailors objected that it would disrupt the compass and draw the bolts from the timbers. Ultimately, it was put aboard a British Man-of-War – a ship in which the sailors had no say in what came aboard. Otumpa, the first large meteorite to be seen in Britain, is on display today in the Natural History Museum in London.

Today, the two Argentine pistols are on display at the James Monroe Museum and Memorial Library in Fredericksburg, Virginia. In the early 1960s two minute samples of the metal were examined under a microscope and analysed by electron microprobe, and were found to have the structure of wrought iron with a negligible amount of nickel (Buchwald 1975, vol. 2, p. 374). Monroe's handsome pistols were not made from Otumpa iron after all! It seems most likely that the metal-smith found he could not work the nickel–iron by his standard methods and made the pistols of wrought iron, feeling certain that his secret would remain safe from discovery, which it did for 150 years (Marvin 1994).

Microscopy of meteorites: 1860s

Microscopic petrography

In 1864 Henry Clifton Sorby (1826–1908), in England, began studying thin sections of meteorites in transmitted light under his polarizing microscope. This opened a whole new era in research on meteorites. Sorby had already spent more than 10 years studying thin sections of terrestrial rocks in transmitted light, and he had also studied opaque ores and industrial products in reflected light. Others, including von Reichenbach (1857) in Vienna, had studied meteorites under a microscope at ×200 magnification, and still others had used microscopes mainly to determine the crystallography of meteoritic minerals. But Sorby's contribution yielded mineralogical–textural information on meteorites of fundamental importance by a technique that could be – and eventually would be – used by everybody. Besides his many other honours and prestigious positions, Sorby has been called both the 'Father of Microscopical Petrography' and the 'Father of Metallography'.

Sorby was captivated by the chondrules (Fig. 19) he saw in stony meteorites. He had found nothing like them in any rock from the Earth's crust, so he concluded they must be unique to meteorites – which, in fact, they are. Sorby wrote that chondrules look like congealed droplets of a fiery rain – a very apt description. They are minute (0.1–1.0 mm) droplets of ferromagnesian silicate glass containing crystallites or phenocrysts of olivines or pyroxenes with or without sparse accessory minerals. After he examined the fragmental textures of large numbers of stony meteorites, Sorby concluded that chondrules were their earliest constituents – the ultimate cosmic globules. In his papers of 1866 and 1877 Sorby proposed what many meteoriticists today regard as the first theory of chondrule origin – namely, that chondrules formed in the solar nebula, possibly as melted clots of condensed nebular gases, or of interstellar dust that fell into the nebula, or even as emissions sent out from the Sun itself in great prominences. He discussed their accretion into parent bodies followed by metamorphism of some of the stony materials, while the Widmanstätten patterns formed in the metallic phase by diffusion in the solid state.

Today, 130 years later, we still are debating the details of chondrule formation, although there is widespread (but not unanimous) agreement that Sorby was right about their nebular origin. We believe that chondrules (along with CAIs) formed in the nebula and are the oldest surviving solid materials that originated in the solar system (McCall 2006*a*). An understanding of their origin has been so long delayed partly because new cosmochemical data have posed seemingly intractable problems: how are tiny clots of dust to be quickly raised to melting temperatures, quickly quenched, and then accumulated with unmelted nebular dust into planetary bodies matching in bulk composition the non-gaseous elements in the Sun? We still have much work to do to understand chondrites, but the effort is worthwhile because of their importance: chondrites make up about 89% of the meteorites that have been seen to fall during the past 200 years; achondrites make up 5%, irons 6% and stony-irons 1%. This tells us much about the range of compositions in the parent bodies of meteorites.

The Canyon Diablo iron meteorite, 1891

The Canyon Diablo iron ranks as one of the most significant meteorite finds in history. It was the first iron meteorite found to contain diamonds and the first to be suspected of excavating an impact crater. Both raised problems in the 1890s that would not be resolved until the 1950s and 1960s. We will briefly outline the beginnings of the Canyon Diablo story and the narrative will be expanded upon by McCall (2006*b*).

In 1891 Grove Karl Gilbert (1843–1918), the chief geologist of the US Geological Survey, attended a session of the American Association for the Advancement of Science at Washington in which the eminent mineralogist Dr Arthur E. Foote (1846–1895) described large iron meteorites scattered around the base of a circular elevation occupied by a cavity in the non-volcanic rocks of the northern Arizona plains. Foote (1891) reported that minute black diamonds had been discovered in one of the irons when an emery wheel was ruined during an attempt to polish it. The diamonds caused immediate excitement and soon were accepted as key evidence that the irons had formed under high confining pressures in the core of a parent body at least as large as the Moon. By then asteroids were widely accepted as sources of meteorites, but asteroids are such small bodies that all those known today would form a body of less than 3% the mass of the Moon. Where could a parent body large enough to have had a diamond-bearing iron core have disappeared to? Up through the 1950s the diamonds would trump all lines of evidence that meteorites consist mainly of low-pressure minerals and probably formed in small bodies. This problem remained unresolved until 1961, when artificial shock-wave experiments on graphite produced clumps of minute diamonds identical to those in the Canyon Diablo irons (DeCarli & Jamieson 1961). Their type of experimentation led into the new discipline of shock metamorphism, which proved to be of special value for interpreting shock-wave intensities observed in meteorites and in terrestrial rocks at meteorite impact sites.

Foote offered no explanation for the crater, but Gilbert, who believed in the Earth's origin by the accumulation of planetesimals, stood up at the meeting and proposed a hypothesis that a late-falling asteroid had plunged into the Earth, excavated the crater and lodged itself beneath the floor. Gilbert sent a colleague to examine the site and then left for Arizona, himself: 'I am going to hunt a star' he wrote to a friend (in Davis 1927). Gilbert was elated at the thought of identifying the world's first impact crater, and he was particularly gratified that this mode of origin would explain three things: the crater, the irons and the association of the two. Inasmuch as no impact crater was known anywhere in the world, Gilbert (1896) devised two crucial tests for distinguishing one from a volcanic explosion crater:

- If the crater was formed by the impact of a large iron meteorite, the iron must be buried beneath the floor where it could be detected by a magnetic survey.
- Because of the added volume of iron beneath the floor, the contents of the rim should form a mound if they could be scraped off at the level of the ancient plain and packed firmly back into the bowl
- In addition, the crater should be elliptical because most meteorites strike the Earth at oblique angles. Gilbert thought this was important but he did not rank it with his crucial tests.

In the field, Gilbert's tests failed: he detected no magnetic anomaly and he calculated the same volumes (82×10^6 cubic yards) for both the rim and the bowl. Furthermore, his plane table map showed the crater to be essentially circular. Gilbert yielded up his impact hypothesis with good grace and concluded that the crater must have been blasted open by a deep-seated steam explosion (which, however, propelled no ash or lava to the site). This meant that the iron meteorites must lie around the crater by coincidence. Gilbert compared the crater to the maars of the Eifel region in Germany (low relief hollows, formed by shallow explosive eruptions), and to the Lake Lonar crater in India, which occurs in the Deccan trap rock but shows no sign of fresh volcanics. (In later years, the Lonar crater would prove to be an impact crater.) The lack of volcanics at the Arizona crater presented a major problem, but Gilbert's steam explosion was lent some plausibility by its location within a wide area of recent volcanism – including the very fresh San Francisco volcanic field only 6 km NW of the crater rim. Gilbert (1896) described his perplexities about the crater in *Science*, where he defended his line of reasoning but implied that further knowledge of crater-forming processes might, someday, reverse his conclusions.

Meanwhile, in the autumn of 1892, Gilbert spent 18 nights examining the Moon, with a geologist's eye, through the telescope at the US Naval Observatory in Washington. He discovered the immense system of grooves radiating from Mare Imbrium and concluded that a huge body had impacted that site with such energy that it excavated a crater 1200 km in diameter and sent rocks flying radially outward with such force that they scoured and grooved the surrounding terrain. With respect to the lunar craters, Gilbert assigned a volcanic origin to the smaller ones, which he compared to terrestrial maars, and an impact origin to the many large craters. As a source of the impacting bodies, he argued that a Saturn-like ring of small bodies had once orbited the Earth until the bodies coalesced to form the Moon; the large craters visible today are the scars of the final impactors, which fell almost vertically and created circular craters. He wrote that the bombardment caused the Moon to tilt this way and that, thus pockmarking the entire surface.

In his talk as the retiring president of the Philosophical Society of Washington, Gilbert presented his hypothesis of lunar impact topography to a room full of colleagues and admirers on 10 December 1892. Within the next 4 months his text was published in that Society's *Bulletin* (Gilbert 1893) and also in the popular *Scientific American Supplement.* Outlines and abstracts of it also were presented to the National Academy of Science the New York Academy of Science and other organizations. Gilbert's impact hypothesis was discussed in letters to editors for some time, but it never gained a following. Few geologists or astronomers considered the Moon to be a proper subject for study – an attitude that persisted for nearly 50 more years. For example, Gilbert's paper was wholly unknown to the American astronomer and industrialist Ralph B. Baldwin, who independently perceived the significance of the radial grooving around the Imbrium basin and presented the first quantitative evidence for an impact origin of lunar craters in his book *The Face of the Moon*, published in 1949. That book would open the way to serious research on lunar and terrestrial impact craters (Marvin 1986).

In 1902 Daniel Moreau Barringer (1860–1929), a lawyer and mining entrepreneur in Philadelphia, heard of the large irons surrounding a crater in Arizona and assumed, just as Gilbert had, that a giant iron had buried itself under the crater floor. Fearing that his presence would alert competitors to this lode, Barringer staked a mining claim (which was signed by President Theodore Roosevelt, himself) on the property before he visited it. Barringer (1905) and his partner, Benjamin C. Tilghman (1905), published several lines of evidence that are acceptable today as diagnostic of impact: huge tonnages of pulverized quartz grains suggestive of instantaneous shock; pieces of weathered iron–nickel oxide mixed into the rim materials indicating that the crater formed when the meteorite struck; and tilted and overturned sedimentary strata on the crater rim. During the first three decades of the 20th century Barringer's company sank shafts and drilled holes that revealed that Gilbert's criteria had been flawed: the bowl contains 70 ft of Pleistocene lake sediments and the rim has been lowered by millennia of erosion. They speculated that the crater-forming iron shattered into small pieces when it came to rest at depth, and this explained the lack of a strong magnetic anomaly.

Barringer's findings persuaded a few eminent scientists of an impact origin for the crater, but not always to his liking. In 1908 George P. Merrill (1854–1929), Curator of Geology of the Smithsonian Institution, wrote that the heat of impact would vaporize the meteorite and generate a mighty steam explosion when it struck water-saturated strata at depth. Barringer objected that there were no coatings of vaporized metal on the crater walls, and such a process could not occur at depth. But the First World War provided a new understanding of the power of explosive impacts to destroy projectiles and blast circular craters regardless of the angles of impact. Despite all these developments, Gilbert maintained his silence and died in 1918 without admitting to his misjudgement of the origin of the Arizona crater. As a result, the US Geological Survey remained staunchly opposed to carrying out any research on an impact origin of craters until the late 1950s.

In 1928 the *National Geographic Magazine* published a popular article on the crater entitled 'The mysterious tomb of a giant meteorite'. The author, William D. Boutwell had visited the crater where Barringer showed him the evidence for impact and told him the full history of his company's explorations in shafts and drill holes. Convinced of a meteoritic origin, Boutwell (1928, p. 723) described a glowing juggernaut of metal, probably from a small dead comet, plunging into the plain with an earthquaking explosion, sending up clouds of dust and steam, and creating the great circular pockmark in the desert. But Boutwell never mentioned Barringer at all. Instead, he gave full credit to G.K. Gilbert for originating the impact theory in 1895 and calling the world's attention to this unique wonder. He failed to report Gilbert's advocacy of a volcanic origin. Adding to the confusion, Boutwell compared the irons to the 'Bewitched Burgrave' of Ensisheim, which, he said, fell in Alsace a month after Columbus discovered America. But we will recall that the meteorite of Ensisheim was not an iron meteorite; it was a huge stone. The mass of iron called the Bewitched Burgrave was found at Elbogen in Bohemia in the 15th century (Fig. 21). Boutwell's article, which lowered science writing to the tabloid level, generated storms of protest by Barringer's friends and family, but the august *National Geographic* refused to admit to errors of any kind. It claimed, without producing evidence, that Barringer had approved the article in writing before it was published. Whatever Barringer may have approved, it certainly was not the article that appeared in print.

Barringer died in 1929 soon after receiving the results of calculations his company had requested, which, unfortunately for him, showed that the projectile almost completely destroyed itself. Today, Meteor Crater, also called the Barringer Meteorite Crater, is recognized as the best preserved and most easily accessible meteorite impact crater in the world.

In 1981, despite Gilbert's mistake in relinquishing his hoped-for impact origin of the crater, the Planetary Sciences Division of the Geological Society of America established its G.K. Gilbert Award to be presented annually to scientists who have made outstanding contributions to planetary geology in its broadest sense. The Award honours Gilbert for his recognition, 100 years ago, of the importance of a planetary perspective in solving terrestrial geological problems.

Hypotheses of meteorite origins: 1803–*c.* 1950

In 1803 once the falls of stones and irons were placed beyond doubt, the two most widely accepted hypotheses of meteorite origins were accretion within the atmosphere and ejection from volcanoes of the Moon. Both Chladni's theory of cosmic origin and the early intimations of stones from asteroids reached too far into space to gain many adherents at that time.

Atmospheric origin

As we have seen, the hypothesis of atmospheric origin was suggested after the Siena fall by Soldani, Thomson and Tata in 1794, and by Hamilton in 1795. In 1803 it was expounded at length by Izarn, and it had additional supporters in France, England and Germany. The first American scientist to favour it was Lyman Spalding (1775–1821), a chemist and surgeon of New Hampshire. Spalding read a paper arguing for atmospheric origin at a meeting of the American Philosophical Society on 2 February 1810. His text was referred to three referees, who commented in the unpublished minutes that they felt it was not for publication by the Society because it was founded on mere hypothesis, unsupported by any experiment or facts. They then took the exceptional action of tabling their own report, thus forestalling, with no opportunity for rebuttal, the publication of Spalding's paper. In 1979 I obtained a copy of Spalding's handwritten manuscript and published it (Spalding 1979) along with a note (Marvin 1979) explaining that in 1808 two of the same referees had reviewed the paper by Silliman & Kingsley on the fall at Weston and had rushed it into the forthcoming issue of the Society's *Transactions*. Silliman & Kingsley (1809), who favoured the origin of stones in Earth-orbiting comets had called the idea of atmospheric origin of stones: '... a crude unphilosophical conception, inconsistent with known chemical facts and physically impossible'. Clearly, the reviewers who saw great merit in their paper could not support publication of such a contrary one as Spalding's. In fact Spalding's paper was not a very good one, but a modern reader would find it hard to discern that it was more reliant on 'mere' hypothesis than most papers of the time.

Back in 1789, when Lavoisier remarked on the daily rise of dust to the upper atmosphere and its combustion to form solids, he had no idea that meteorites contained nickel; Izarn knew they did, and he presumably knew that most terrestrial rocks did not, but he did not see this as a problem. However, as time went on and more meteorites fell, serious doubts arose when scientists came to realize what massive volumes of dust would be required to congeal instantaneously into showers of meteorites commonly containing both chondrules and grains of metallic nickel–iron. For some time, however, it seems to have been so much harder for people to accept an origin of meteorites outside the Earth that the idea of atmospheric origin retained some support through the 1850s. One of its final advocates was an American woman, Mrs Gold Selleck (Hepsa Ely) Silliman (1859, p. 7) who wrote in her geology book:

> It seems not in accordance with ascertained science to ascribe mysterious appearances on the earth or in its atmosphere, to causes proceeding from planets, or spheres moving in space, independent of the earth and its system.

Lunar volcanic origin

As noted above, the hypothesis that meteorites were ejected by lunar volcanoes attracted a number of leading intellectuals in the early 19th century, particularly after Biot called it 'Laplace's hypothesis'. Most people intuitively assumed the lunar craters to be volcanic, partly because a succession of leading scientists had reported witnessing eruptions on the Moon. Lichtenberg was one of the earliest of these. In 1778, Lichtenberg reported having seen a red glow on the dark of the Moon back in 1775, and he had begun making morphological comparisons between terrestrial volcanoes and lunar craters (Czegka 1998). It was 9 years later when Herschel (1787) reported witnessing three volcanic eruptions on the Moon. Among others who reported seeing them were Neville Maskeylene (1731–1811), the Astronomer Royal of England, Jêrome de Lalande and Jean-Dominique Cassini (1748–1845) in France, and Johann Bode, Zaver von Zach and Johann Scröter in Germany (Home 1972, p. 8).

Given such prestigious witnesses of lunar volcanism, it was a small step to hypothesizing the Moon as a source of meteorites. Perhaps more significantly, a single source of meteorites on the airless Moon would help to explain why they are so much alike. With few exceptions, meteorites are strongly reduced, the great majority of stones have similar textures and chemical compositions, and the average specific gravity of stones (*c.* 3.34 g cm^{-3}) matches that of the Moon. For all these reasons, Chladni (1805), himself, switched his allegiance to a lunar origin of meteorites. At that time he wrote that his proudest accomplishments were to have been the first in modern times to demonstrate that falls of stones are not fabrications but actual observations, and that the masses come from outside the atmosphere. However, Chladni (1818, p. 10) reverted back to his hypothesis of cosmic origin because of his original problem: the velocities of meteors and fireballs far exceeded those of bodies that would originate on the Earth or the Moon.

On 2 November 1803 Dr J. DeCarro, the Vienna correspondent of the *Bibliothèque Britannique*, sent a newsy letter to Pictet in which he referred to articles by the excellent mathematician Franz Güssmann. Güssmann (1803), whom we last heard from in 1785 advocating the terrestrial origin of iron meteorites, had written a new article proving it to be mathematically impossible for stones to fall to the Earth from the Moon. He still favoured his thesis that irons are launched from the Earth by electrical fires, and he asked why no one had paid any attention to it. Saying that he did not wish to debate the issue, DeCarro raised two questions: first, if iron meteorites are launched upwards by electrical fires, why do observers never see them rising into the sky as well as falling from it? Second, why are they the only irons containing nickel?

Lichtenberg had shown a strong interest in lunar volcamism, but did he ever write about lunar meteorites? Chladni (1819, p. 7) said that he did, and he quoted Lichtenberg's aphorism from his *Göttinger Taschenkalendar* of 1797: 'The Moon must be an uncivil neighbor, as he is greeting the Earth with stones'. This saying is so widely quoted that it has become part of our conventional wisdom. However, in preparing to write an article about Lichtenberg and the science of his time, von Engelhardt (pers. comm. 1996) failed to locate this aphorism or any other passages in which Lichtenberg discussed the origin of meteorites from the Moon. More recently, in conducting a search of my own, I, too, failed to find Lichtenberg's famous aphorism. Perhaps some reader will point it out to us, but meanwhile we may wonder if it is one more familiar saying that never got said.

Olbers, who had lectured on a possible lunar origin of stones as early as 1795, continued to favour it (with reservations) for many years, even though he was the discoverer of two asteroids, which he saw as pieces of a shattered planet. Finally, when the great shower of Leonid meteors astonished the world in 1833, Olbers observed that the radiant of the shower remained fixed in the constellation Leo. Therefore, the meteors were not involved in the Earth's rotation system. So, Olbers (1837) finally published his conclusion that meteorites must enter the atmosphere from cosmic space.

A lunar volcanic origin retained some support until 1859, when the American astronomer Benjamin Apthorp Gould (1824–1896) calculated that of every 5 million fragments ejected by lunar volcanoes, only three would be likely to strike the Earth. By then, some 160 meteorites were known: so, at a ratio of 5 million misses per three hits, the wildly volcanic Moon should have visibly shrunk and altered its librations and nutations, but nothing of the sort had been observed. This problem had concerned Olbers from the very first, but it was Gould (1859) who administered the *coup de grâce* to the hypothesis of a lunar volcanic origin of meteorites.

Asteroidal origin

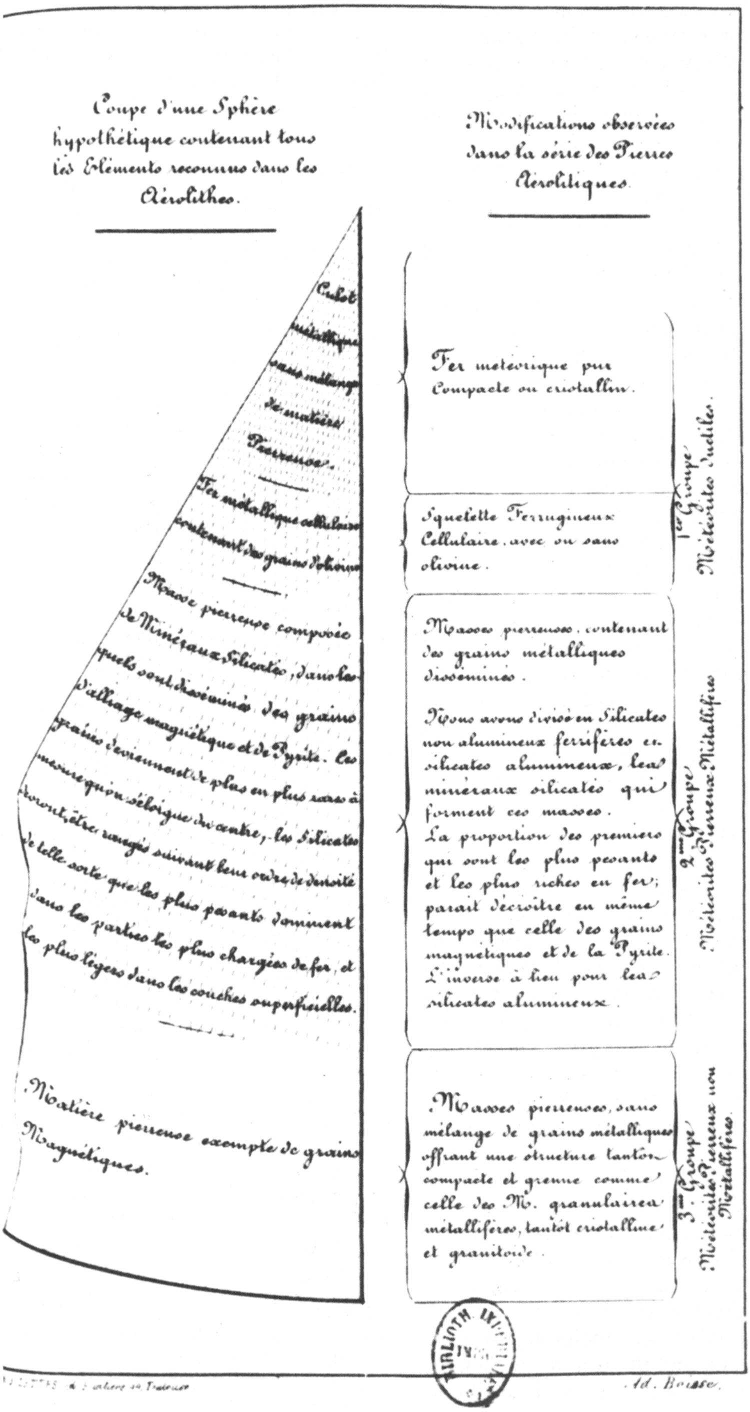
After the first four asteroids were discovered, between 1801 and 1807, no more were seen until 1845. Then 20 more asteroids were found within the next 9 years. In 1854 the English astronomer Robert P. Greg (1826–1906) pointed out that asteroids, like other planets, revolve counterclockwise around the Sun in elliptical orbits, and they are angular in shape, as shown by sudden changes in their optical reflectivity. Greg (1854) proposed that meteorites are minute outliers of asteroids, all of which are pieces of a single planet that has been disrupted by a tremendous cataclysm. Some years later, Auguste Daubrée in Paris put forward the much the same idea (Howarth 2006).

What sort of planet would that be? This question had been raised as soon as meteorite falls gained acceptance early in the 19th century. Perhaps for the sake of simplicity, many people seemed to prefer having all meteorites come from a single parent body. Various schemes of classifying meteorites were aimed at describing that parent body. Perhaps the clearest and most generally accepted of these in the 19th century was published in 1847 by Adolph André Boisse (1810–1896) in France, who sketched a hypothetical parent planet consisting of an iron core enveloped by pallasitic iron, which, is overlain, in turn, by concentric shells of stony meteorites of decreasing iron contents. Finally, the outer crust consists of achondrites (Fig. 23). Boisse presented this as a model of a meteorite parent body, but it also served as a fair analogue of the Earth.

During the 1860s, however, two lines of evidence were showing that meteorites probably come from more than one parent body. Chemical analyses revealed such a wide range of meteorite compositions that a single source seemed unlikely. Orbital calculations also showed that all 90 or so asteroids then known could not have come from a single node. More specifically, the American astronomer Daniel Kirkwood (1814–1895) showed that there are gaps (subsequently called Kirkwood gaps) in the distribution of main-belt asteroids, from which asteroids might have escaped during periodic conjunctions with Jupiter. Kirkwood (1864) argued that at such times collisions between escaping asteroids may have produced fragments that enter Earth-crossing orbits and fall as meteorites.

Interplanetary or interstellar meteorites?

By the mid-19th century some scientists favoured an asteroidal origin and others argued



Coupe d'une Sphère hypothétique contenant tous les Éléments reconnus dans les Aérolithes.

Culot métallique sans mélange de matière Pierreuse.

Fer métallique cellulaire contenant des grains d'olivine.

Masse pierreuse composée de Minéraux Silicatés, dans lesquels sont disséminés des grains d'alliage magnétique et de Pyrite. Ces grains deviennent de plus en plus rares à mesure qu'on s'éloigne du centre, les Silicates doivent être rangés suivant leur ordre de densité de telle sorte que les plus pesants dominent dans les parties les plus chargées de fer, et les plus légers dans les couches superficielles.

Matière pierreuse exempte de grains Magnétiques.

Modifications observées dans la série des Pierres Aérolitiques.

Fer météorique pur Compacte ou cristallin.

Squelette Ferrugineux Cellulaire, avec ou sans olivine.

1er Groupe Météorites Ductiles.

Masses pierreuses, contenant des grains métalliques disséminés.

Nous avons divisé en Silicates non alumineux ferrifères et silicates alumineux, les minéraux silicatés qui forment ces masses.
La proportion des premiers qui sont les plus pesants et les plus riches en fer; parait décroître en même temps que celle des grains magnétiques et de la Pyrite. L'inverse à lieu pour les silicates alumineux.

2me Groupe Météorites Pierreux Métallifères

Masses pierreuses, sans mélange de grains métalliques offrant une structure tantôt compacte et grenue comme celle des M. granulaires métallifères, tantôt cristalline et granitoïde.

3me Groupe Météorites Pierreux non Métallifères.

Fig. 23. The earliest cross-section of a hypothetical meteorite parent planet. The body consists of three concentric zones of meteoritic materials of decreasing iron content. The iron core is enclosed within a thin layer of cellular iron with or without olivine. Above that, stony materials rich in ferrous silicates and grains of Ni–Fe gradually give way to aluminous silicates with scarcer metal. The surface layer consists of iron-free achondritic meteorites. (From Boisse 1847, p. 169.)

for both an asteroidal and an interstellar origin of meteorites. This issue hinged on the velocities of meteors and fireballs with respect to the Sun (not with respect to the Earth, which will vary from about 10 to 72 km s^{-1} depending on whether the body is catching up with the Earth or colliding with it head on). Those moving at heliocentric velocities of less than 42.1 km s^{-1} follow elliptical orbits around the Sun. Bodies moving at higher velocities would be following open-ended, hyperbolic orbits, which would take them past the Sun once and then on out again into interstellar space. For the remainder of the 19th and the first two-thirds of the 20th centuries, spirited (and sometimes vituperative) debates continued on this subject. A review of the literature through the 1940s would suggest that a majority of astronomers favoured hyperbolic orbits, but their opponents always believed there must be a systematic error in these calculations. A definitive solution to this problem awaited systematic photography of the same meteors and fireballs by two or more cameras geared with synchronous clocks. After the mid-20th century large networks of cameras automatically photographing the night skies would be set up in Europe and North America. All the meteor and fireball orbits they recorded proved to be elliptical, bringing meteorite parent bodies home to the solar system (see Bowden 2006).

In 1858 Karl Reichenbach remarked that a meteorite is simultaneously a cosmological, astronomical physical, geological, chemical, mineralogical, and meteorological object. He knew that specialists in all those fields could learn much from the study of meteorites. But in expressing such excitement, Reichenbach was one century too early. In the 1920s meteorite studies still were a minor pursuit regarded by many scientists as being not quite respectable. Scarcely any books had been written, no societies established, little serious research conducted and, until 1928, there was only one suspect meteorite crater in the world. Not until the opening of the Space Age in the late 1950s would scientists begin to see meteorites as precious samples of other planetary bodies and as probes recording cosmic radiation in space. The stories of how meteorites became key factors in our understanding of the astrophysical processes of star formation, the origins of planets, including our own Earth–Moon system, and the role of impacts in modifying planetary surfaces will continue in other chapters of this Special Publication.

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