METEORITES AND THEIR PARENT PLANETS

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and their parent planets

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CAMBRIDGE
UNIVERSITY PRESS

Published by the Press Syndicate of the University of Cambridge
The Pitt Building, Trumpington Street, Cambridge CB2 1RP
40 West 20th Street, New York, NY 10011-4211, USA
10 Stamford Road, Oakleigh, Melbourne 3166, Australia

First published 1987
Reprinted 1989, 1992, 1996

Printed in the United States of America

Library of Congress Cataloging-in-Publication Data
McSween, Harry Y., Jr.
Meteorites and their parent planets.
Includes bibliographies.
1. Meteorites. I. Title.
QB755.M465 1987 523.5'1 86-30996

British Library Cataloguing in Publication Data
McSween, Harry Y., Jr.
Meteorites and their parent planets.
1. Meteorites
I. Title.
523.5'1 QB755

ISBN 0 521 32431 9 hardback

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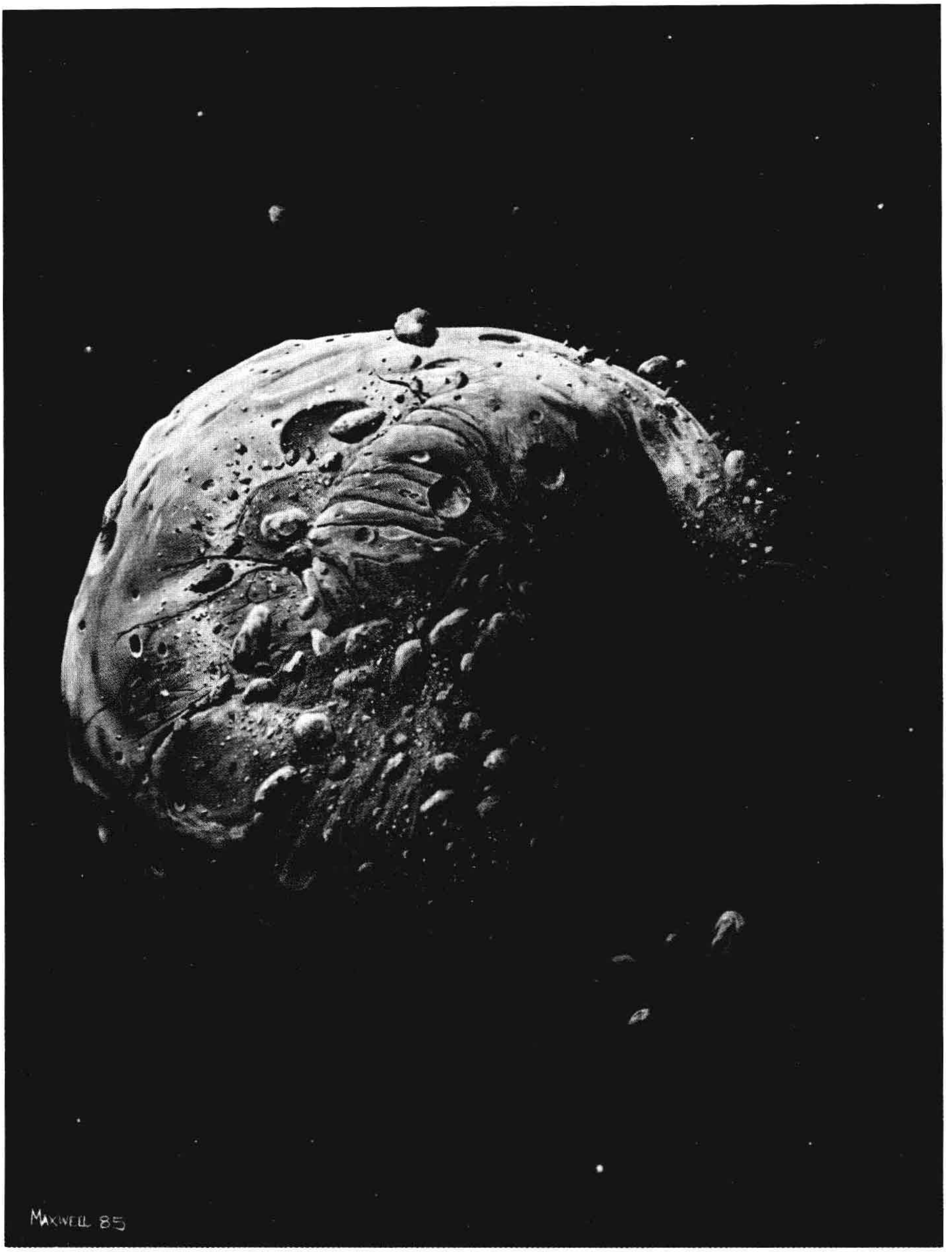
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TO MY MOTHER AND FATHER

Preface

Not so very long ago, the *earth sciences* were just that: the study of the earth. Not any more. Pick up any modern introductory geology textbook and you will find discussions of the moon and planets. Much of this new scientific turf is a legacy from astronomy, a result of the technological transformation of these bodies from dimly illuminated disks into crisply photographed worlds shaped by more or less familiar geologic processes.

The study of extraterrestrial materials, especially meteorites, does not appear to have been so readily assimilated into the earth sciences. I suggest that this is so because meteorites are commonly treated as if they were always small chunks of matter orbiting in space with no prior geologic histories. This book will employ a different tactic. My intent, as far as possible, is to trace meteorites back to their parent bodies, which are the sites of geologic processes. The bulk of this book is divided into a series of doublets – each consisting of a chapter describing certain related types of meteorites, followed by a chapter on their parent bodies. I hope this treatment will make these enigmatic objects more understandable.

Like any other science, the study of meteorites has its own vocabulary. I have attempted to minimize the introduction of new terms, but it is not possible to omit them entirely. Definitions of **bold** words in the text are given in a Glossary at the end of the book.

Any discussion of a subject this complicated may not always reach consensus; in such cases I have had to rely on my own prejudices. It is easy to read too much into meteorites, and in this book I may be more guilty of that than most. I also take responsibility for simplifying the subject by omission of some types of meteorites, when these do not provide insights into different concepts or processes.

Advances in meteorite research require the interplay of geology, chemistry, physics, and astronomy. This is a tall order, even for a subject that prides itself on its interdisciplinary (one might even say renaissance) character. I am indebted to researchers who are experts in these fields for their instructive discussions and review papers. In an introductory-level book such as this it is not possible to recognize individual researchers by name, although it would have been my preference to do so. I apologize in advance to any of my friends and colleagues in meteoritics who feel that their contributions have not been properly referenced. I acknowledge the following individuals and organizations for figures: Jack Berkeley, Doug Blanchard, Don Brownlee, Roy Clarke, Brian Mason, Ed Olsen, Robbie Score, and particularly the Smithsonian Institution and NASA. The cover and frontispiece art are the talented work of Mark Maxwell, who graciously allowed their reproduction. I am grateful to Peter-John Leone (Cambridge University Press) for being an enthusiastic advocate for this work, to Mike Lipschutz for a comprehensive and thoughtful review, and to Deborah Love, Melody Branch, and Denise Stansberry for their time and typing skills. Finally, I am indebted to my wife, Sue, and daughter, Lindsay, for patient understanding and for constant but welcome distractions, respectively.

Knoxville, Tennessee H.Y.M.

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1 Introduction to meteorites

In late 1492, three small caravels commanded by the Italian navigator Christopher Columbus boldly sailed into the New World. On November 16 of that year, the inhabitants of Cuba entertained these visiting sailors, who were no doubt luxuriating in the success of their epic voyage. Almost half a world away, the residents of the Alsatian (now French) village of Ensisheim also played host to a visitor, but this one had traveled much farther to make its appearance. On that day a stone weighing 127 kilograms streaked across the sky and impacted near the town. It must have caused quite a stir, as news of this unusual happening spread quickly. Upon hearing of the event, the emperor of the Holy Roman Empire, Maximilian I, under whose suzerainty the town fell, sought to capitalize on what he considered this omen of divine protection against the threat of Turkish invasion by ordering the stone to be placed in the local church. In accordance with medieval custom, the object was chained to the wall to prevent it from either wandering at night or departing in the violent manner by which it had arrived. This specimen, minus some fragments chipped off for museum collections in the ensuing centuries, still resides in Ensisheim today.

FROM VENERATION TO DISBELIEF

The Ensisheim incident was, of course, not the first account of the fall of a meteorite. Ancient chronicles from China and Greece document two independent meteoritic events occurring circa 650 BC, and earlier, though less definite, records of meteorite falls from Crete extend as far back as 1478 BC. The fall of a rock from the sky naturally was (and still is) a dramatic occurrence, and it is understandable that such events were described in detail and that the recovered objects were venerated. The Suga Jinja Shinto shrine in Nogata, Japan, has kept one fist-sized meteorite as a treasure of the religious center for more than a thousand years. Its date of fall

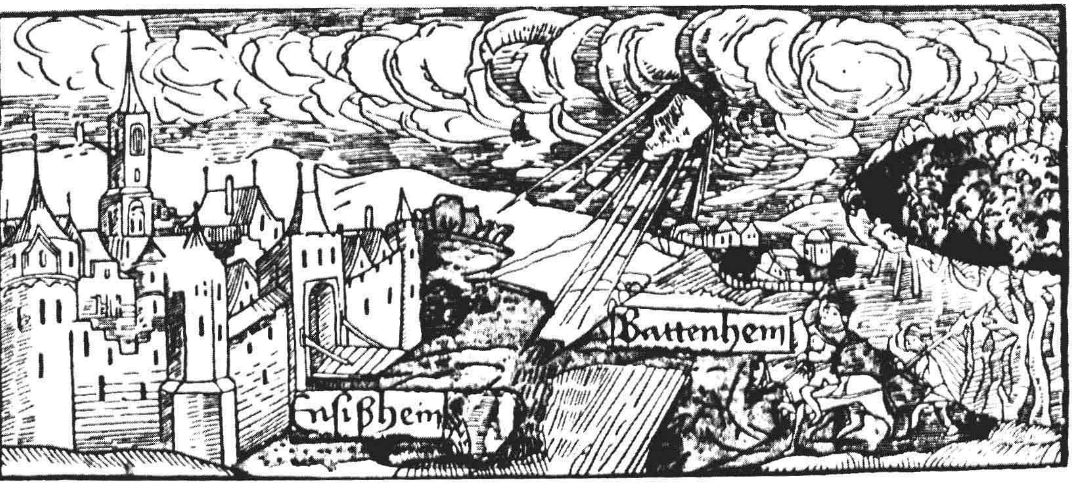

Fig. 1.1. Meteorite falls were commonly given religious significance by ancient peoples. This woodcut carved in medieval times shows the fall of a meteorite near the town of Ensisheim (now in France) in 1492. The meteorite is illustrated breaking through the clouds and also lying in a wheat field outside of the town. Upon recovery, the 127-kilogram stone was placed in the local church, where, except for some pieces removed for museum collections, it can still be seen today. Like many important events of this time, the fall and its effect on the local populace were immortalized in verse. Except for one other meteorite in a Shinto shrine in Japan, the Ensisheim stone is the oldest preserved meteorite that was actually observed to fall.

– May 19, 861 AD – is recorded in old literature as well as on the lid of the ancient wooden box in which it has been stored. A Russian meteorite fall in 1584 was apparently memorialized by renaming the town near which it fell (Tashatkan, literally "stony arrow"). The ancient Greeks and Romans enshrined and worshiped meteorites, and according to Titus Livius, one was even conveyed in a royal procession from its impact site to Rome, where it was revered for another 500 years. These objects were also valued by the Egyptians and have been discovered entombed with the pharaohs in pyramids. Prehistoric American Indians transported meteorites long distances and sometimes buried them in crypts. One meteorite discovered in a burial ground of the Montezuma Indians in Casas Grande, Mexico, was wrapped like a mummy. Even in more modern times, meteorites are sometimes accorded religious significance. The sacred black Kaaba Stone, to which Moslems in Mecca pay homage, is reported to have fallen from the sky, and some believe it to be meteoritic. Hindu religious literature states that meteorite falls herald important events, and in India it is reported that representatives of the Geological Survey must hurry to the site of any observed fall if they wish to collect the meteorite before it is enshrined by the local citizenry.

Most ancient philosophers viewed meteorites as heavenly bodies that had somehow been freed from their celestial moorings and had tumbled to earth. This explanation was not universally accepted, however; Aristotle considered them to be atmospheric phenomena. In this regard he was prescient in expressing the view of scholars in succeeding centuries, many of whom contrived to explain meteorites by terrestrial processes. Here is a typical example by W. Bingley, written in 1796:

> It is but a trite observation to say, that the clouds make frequent visits to the waters of the earth, from which they usually carry away large quantities of that element, and with it, no doubt, the substances (even with some of the fish) which form the beds. . . . It is self-evident, that the streams which ascend with the clouds are sometimes clear as crystal, at other times thick and muddy. When the latter is the case then it is that these substances may be concreted; and, by some extraordinary concussion in the atmosphere, return to the earth.

Others argued that meteorites were terrestrial rocks that had been struck by lightning, an explanation that spawned the popular name "thunderstones" for these objects.

Many scientists, however, discounted altogether the idea that stones could fall from the sky. After the fall of a meteorite was witnessed and described in a document notarized by the mayor and 300 citizens of Barbotan, France, in 1791, the noted scientist P. Berthollet lamented:

> How sad it is that the entire municipality enters folk tales upon an official record, presenting them as something actually seen, while they cannot be explained by physics nor by anything reasonable.

Meteorites could not begin to attract serious scientific scrutiny until such attitudes were dispelled.

THE EARLY HISTORY OF METEORITICS

Meteoritics is the name given to the scientific study of meteorites. The father of this discipline was undoubtedly E. F. F. Chladni, a German physicist and lawyer. His pioneering contribution was a small, 63-page book published in Riga in 1794. In it he argued that meteorites, at least those composed mostly of iron metal, with which he was most familiar, were extraterrestrial in origin. Based on evidence for their intense heating and their dissimilarity to terrestrial rocks, as well as the implausibility of other explanations, Chladni proposed a relationship between such meteorites and atmospheric **fireballs.** He correctly surmised that air friction heated objects traveling at high speed through the atmosphere, producing an incandescent glow.

Chladni's idea that meteorites were extraterrestrial amounted to scientific heresy, and his well-reasoned arguments were apparently not very persuasive to his contemporaries. Resistance to this hypothesis lingered in part because of scientific conservatism, but also because most meteorites were stones rather than chunks of metal, and thus were at least superficially similar to terrestrial rocks. However, Chladni's timing was perfect. Almost in immediate answer to his critics, in 1795 a large stony meteorite fell in the village of Wold Cottage, England. This event was important in refuting other currently popular mechanisms for the formation of meteorites (such as lightning or condensation from clouds), because the fall occurred out of a clear, blue sky. A specimen of the Wold Cottage meteorite eventually reached a young but highly respected British chemist, E. C. Howard, who decided to perform a detailed analysis. This study, done in collaboration with J. L. de Bournon, a French mineralogist exiled in England after the revolution, resulted in one of the first precise descriptions of a stony meteorite. In 1802, Howard reported concentrations of the element nickel in small grains of metal that de Bournon had separated from this stone. Nickel had earlier been analyzed in the metal of iron meteorites. Chladni's logical arguments had begun to persuade a number of scientists that iron meteorites were extraterrestrial, and this chemical link between irons and stones cleared the way for the interpretation that all meteorites had similar origins. Howard, however, was cautious in interpreting his data, although others were not.

After these two pivotal studies, changes in the attitude of the scientific community began to occur very rapidly. In 1803, a number of eminent French scientists, convinced by reputable eyewitness accounts of meteorite falls and by their own confirmations of Howard's chemical findings, threw their prestige behind the proposition that meteorites were extraterrestrial in origin. Remaining skepticism was silenced several months later when the town of L'Aigle, France, was peppered by a shower of no less than 3,000 stones. The French minister of the interior commissioned J. B. Biot, a physicist and one of the youngest members of the French Academy of Sciences, to investigate this incident. His 1803 report is commonly considered to be the turning point in the recognition of the authenticity of meteorites as extraterrestrial objects. In contrast to previous, rather dry scientific reports on meteorites, Biot's paper was dramatic and exciting. Nevertheless, its impact was made possible by the careful research of his predecessors, and the importance accorded to this work in recent times may have been overestimated.

Within a decade of the appearance of Chladni's book, his hypothesis that meteorites were extraterrestrial won general acceptance, and the science of meteoritics was launched. This is not to imply, however, that resistance to this new idea had totally vanished. America's scientifically literate president, Thomas Jefferson, apparently remained unconvinced. Upon hearing of the Weston, Connecticut, meteorite fall reported by Yale professors B. Silliman and J. L. Kingsley in 1809, he is reported to have said, "It is easier to believe that Yankee professors would lie, than that stones would fall from heaven." (This may be an embroidered version of Jefferson's comment, as its source is a secondhand report made by a person not actually present at the dinner party at which the statement was allegedly made.)

From the beginning of the nineteenth century forward, meteoritics progressed steadily to an exacting and highly interdisciplinary field. Developments during the nineteenth and twentieth centuries are much more interesting than those that led to the birth of this science, and many of these will be explored in subsequent chapters of this book.

PROPERTIES OF METEORITES

A **meteoroid** is a natural object of up to approximately 100 meters in diameter that is orbiting in space. A **meteor** is the visual phenomenon associated with the passage of a meteoroid through the earth's atmosphere. A **meteorite** is a recovered fragment of a meteoroid that has survived transit through the earth's atmosphere. Meteorites are named for the geographic localities in which they fall or are found. As a consequence, meteoritics is endowed with a heritage of exotic place names that add to the mystery of these objects.

We have already alluded to the existence of several types of meteorites – irons and stones. **Iron meteorites** consist almost entirely of nickel-iron metal alloys, whereas stony meteorites are composed mostly of silicate minerals, although many also contain small metal grains. In a third category are **stony-iron meteo-**

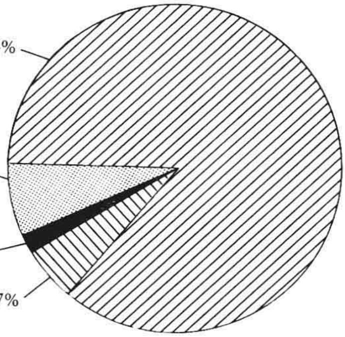

Fig. 1.2. There are significant differences among fallen meteorites in the proportions of meteorite types. The shaded areas of this pie diagram illustrate the relative abundances of chondrites, achondrites, irons, and stony-irons. The proportions of the various classes of meteorites among finds are very different, being heavily weighted toward irons and stony-irons because their distinctive properties make them easily distinguishable from terrestrial rocks. The fall statistics more accurately reflect the proportions of meteoroids orbiting in the vicinity of the earth.

rites, which have nearly equal proportions of metals and silicates. Early and widely used classification schemes, such as those developed by the European petrologists G. Rose in 1863, G. Tschermak in 1883, and A. Brezina in 1904, referred to irons as "siderites," stony-irons as "siderolites," and stones as "aerolites." The stones can be further divided into two broad categories: chondrites and achondrites. A **chondrite** is a kind of cosmic sediment, an agglomeration of early solar system materials that has suffered little if any chemical change since its formation. In contrast, an **achondrite** is an igneous rock, the product of partial melting (accompanied by changes in chemical composition) and crystallization.

The proportions of iron and stony-iron meteorite **falls** (those seen to fall and then recovered) are very small, only about 7 percent and 1 percent, respectively, of the total number of meteorites collected. Of the remaining 92 percent stones, 84 percent are chondrites. These statistics may seem surprising to anyone who has looked at museum displays of meteorites, which are often dominated by irons and stony-irons. The ratio of irons to stones among meteorite **finds** (those recovered meteorites that were not observed to fall) is much larger than that among falls, because irons survive terrestrial weathering processes better and are more readily recognized as something unusual by non-geologists who stumble upon them. Irons also tend to be larger and more spectacular in appearance than stones, so museum exhibits are often biased