Cambridge University Press
0521836034 - The Origin of Chondrules and Chondrites
Derek W. G. Sears
Excerpt
More information

1

Historical introduction

1.1 Rocks from the sky

The ancients observed and collected rocks that fell from the sky. There are reports of the Romans, Greeks, Egyptians, Japanese, and the natives of North America and other countries collecting them, using them for trade, and putting them in places of importance such as tombs. Modern-age research on such objects opened with the pioneering work of Howard and Bournon (Fig. 1.1). Aristocrats Edward Charles Howard and Jacques Louis Compte de Bournon published arguably the first scientific investigation of these rocks or meteorites as they are now known (Howard, 1802). They found that these rocks, regardless of where in the world they fell, contained metal, sulfide, stony materials, and very often "curious globules" in varying amounts. What was also remarkable was that the metal in all these rocks from the sky – whether it was tiny metallic grains in the more stony meteorites or the large masses of "native iron," now known to be iron meteorites – was found to contain nickel, a novel and only recently discovered element. Clearly, from the first day that these rocks were seriously examined their major components, which would have to be explained, were identified. As the nineteenth century unfolded, Greek names were attached to these objects, and the globules became "chondrules" and the type of rocks that contain them became "chondrites."

Metal, sulfide, and stony materials had been seen before, but these curious globules and nickel-bearing metal were unique. Fig. 1.2 is a visual summary of the major components in chondrites as currently known: metal, sulfide, matrix, refractory inclusions (calcium–aluminum-rich inclusions, CAI), and chondrules with a variety of internal textures, some coated with rims of matrix-like material.

In the latter part of the eighteenth century there was an almost universal belief, following a report by Lavoisier and others, that meteorites were produced by lightning (Fougeroux *et al.*, 1772; Lavoisier, 1772). The burned outer surface of the meteorite might point to this conclusion, but one suspects that Lavoisier's encounter with a

Figure 1.1 Edward Howard (center) as he appears in an engraving at the Royal Institution of London. The engraving is a copy of a profile in bronze, probably made posthumously. Howard, with petrologist Jacques Louis Compte de Bournon, arguably performed the first modern study of meteorites. His report – which included the first observation of curious globules, i.e. chondrules, in meteorites – was critical in triggering serious scientific study of meteorites.

roof tile dislodged by a lightning stroke was a bigger factor. Certainly, Lavoisier's colleagues were not as attracted to the conclusion that meteorites were terrestrial rocks struck by lightning as was Lavoiser. However, between the publication of Chladni's book in 1794 and Howard's paper of 1802 there arose a widespread acceptance that meteorites actually fell from the sky and some even believed that the stones had an extraterrestrial origin. I think that this was primarily a consequence of the early chemical and physical work that revealed the similarity of meteorites to each other, regardless of country of fall, and their dissimilarity to local country rocks (Sears, 1976). However, other writers have argued that the large number of falls at the time (Burke, 1986) and Chladni's eloquence (Marvin, 1996) were primarily responsible for the swing of opinion. In any event, by 1803

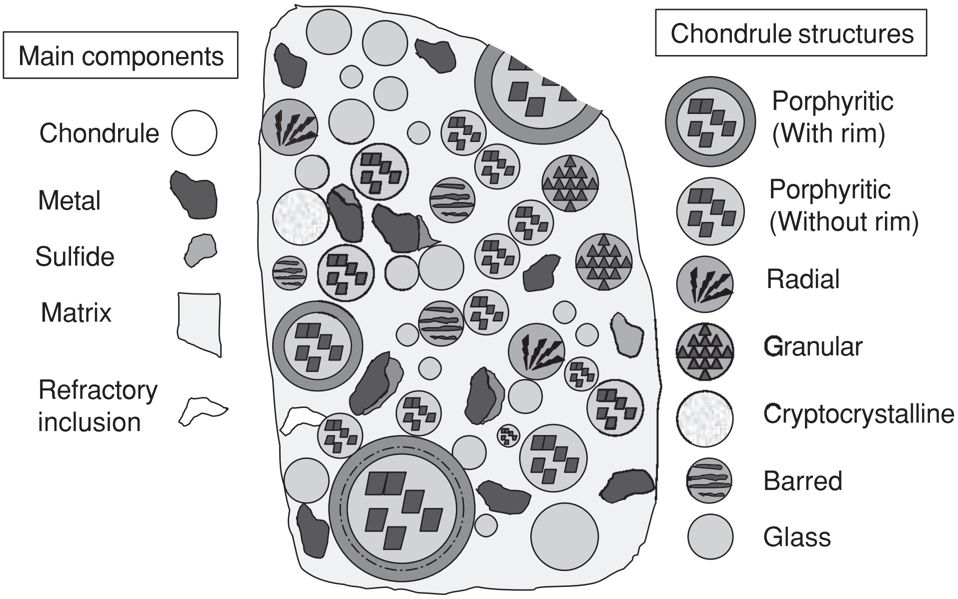

Figure 1.2 Cartoon showing the variety of components in a typical primitive (low-petrographic type) ordinary chondrite. The components are chondrules, metal, sulfide, matrix, and refractory inclusions. The term "matrix" is used for a variety of materials in meteorites. In this instance we mean the very fine-grained, rim-like matrix seen only in the most primitive meteorites. The dimensions of this hypothetical section would be about 1 cm × 2 cm.

some of the world's leading scientists were engaged in studies of these rocks from space.

From 1802 to about 1840 the most widely accepted theory for the origin of meteorites was that they came from the Moon (Olbers, 1803; Poisson, 1803; Berzelius, 1834), but there were also proponents of theories involving a terrestrial origin. A belief that meteorites were ejected from terrestrial volcanoes was largely abandoned following chemical studies, although Proust (1805) proposed that volcanoes in the Antarctic would produce rocks with meteoritic properties. His idea, however received no support. (He would no doubt have been excited to learn about the recent discovery of large numbers of meteorites in Antarctica!) There were clearly different types of meteorites, some were without chondrules and were igneous rocks resembling terrestrial basalts. Maybe they came from a different lunar volcano, suggested that giant of chemisty, Berzelius. In 1834 an American astronomer, H. Olmsted, showed that the radiant of the Leonid meteor shower did not rotate with the Earth, and this put an end to any question of a terrestrial origin for meteorites (Olmsted, 1834).

Around 1840–1850 the hypothesis that meteorites came from the Moon gave way to the idea that they came from the Asteroid Belt (Humboldt, 1849). Meteorites, said Humboldt, were "the smallest of all asteroids." It had become clear that meteorites were not coming from the Moon. The lunar volcanoes were inactive and, in any case, meteorite velocities were too high. On the other hand, about a dozen asteroids were known by 1850 and it was assumed that, since asteroids were a disrupted planet, there would be many more asteroids to be detected in the future. It seemed natural to assume that a few smaller fragments could find their way to Earth. With rare exceptions (e.g. Ball, 1910), the idea that meteorites are asteroidal (or, through them, that a few might be related to their relatives, the comets) went unchallenged for 150 years. Then in the 1980s, to show that no conclusion is absolute, we discovered that a few of the igneous meteorites are from Mars and the Moon.

1.2 Museums and collectors

It was with the growth of the major industrial cities and the professionalization of science that large national collections of meteorites started to emerge. In London, Paris, Berlin, Washington, New York, Vienna, and elsewhere, collections of meteorites under the care of a professional scientist contributed to the establishment of the research field. Some of these curators, with their access to the meteorites and scientific laboratories, became leaders in the research field. It is probably the case that from about 1850 until the second half of the twentieth century the major museums were the nuclei of meteorite research, in much the same way that the NASA headquarters in Washington DC is the nucleus of the modern US space program. But in the 1960s this was about to change.

1.3 The instruments

One force that has driven meteorite studies, as with most fields of human endeavor, is the development of new instruments. Many new methods for the examination of materials "cut their teeth" on meteorite studies, beginning with the fledgling techniques of wet chemistry in 1802, largely perfected by 1834, followed by optical microscopy of geological thin sections in the 1860s to the methods of instrumental analysis of the mid-twentieth century. In the mid nineteenth century it was found that unique observations of a rock could be made by passing light through a sample (transmitted light microscopy) or by shining light on the surface of a polished sample (reflected light microscopy) (Fig. 1.3). H. C. Sorby and N. Story-Maskelyne are names associated with these developments. Sorby is well-known in the history of geology as the inventor of thin sections to be used for studying rocks and minerals and he is probably the first of the major meteorite researchers to be university-based.

Cambridge University Press
0521836034 - The Origin of Chondrules and Chondrites
Derek W. G. Sears
Excerpt
More information

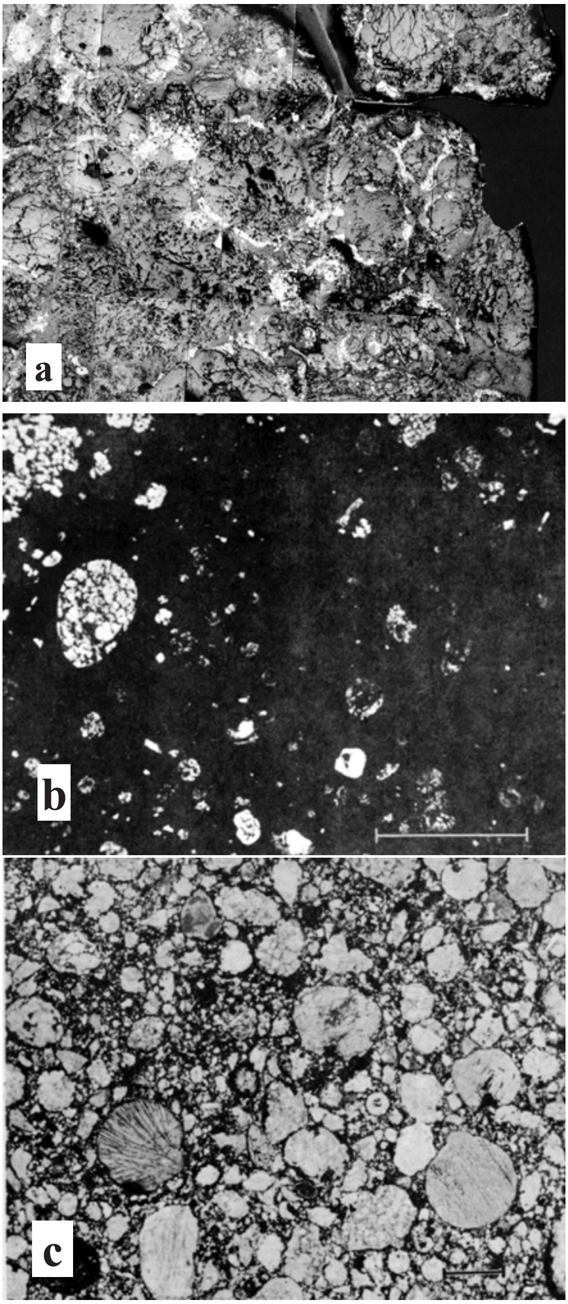

Figure 1.3 Chondritic meteorites under the microscope. (a) The Semarkona chondrite seen under the microscope with reflected light. Metal/sulfide appears white and silicates in the chondrules and matrix appear gray. The distribution of chondrules, matrix, and metal/sulfide are clearly apparent in this image. (b) The Murray CM chondrite in transmitted light. In this section, chondrules and irregular aggregates stand out clearly against the opaque matrix of hydrated silicate minerals (from Mason, 1962, p. 97). (c) The Roosevelt County H3.2 chondrite in transmitted light. Chondrules of all types are easily seen in this section (from McCoy *et al.*, 1993). In all cases the sections are about 1 cm across.

Sorby held a highly innovative position at the University of Sheffield supported by Royal Society funds so that he could be freed of the "distractions" of teaching. He used a transmitted light microscope to make the first microscopic observations of chondrules, that he described as "droplets of fiery rain from the Sun." It is significant that this was the era of astrophysics, when observations of the Sun with its sunspots, prominescences, and corona, were exciting the scientific world. Story-Maskelyne, inventor of reflected light microscopy and polished sections, was the meteorite curator at the British Museum and grandson of the famous Astronomer Royal, Nevil Maskelyne. Story-Maskelyne perfected the art of reflected light microscopy, thereby ensuring a future for metallography and opague mineral microscopy in general.

At the turn of the century spectroscopic techniques that had become popular among astronomers crept into meteorite research with the development of atomic absorption spectroscopy and through the work of the Noddacks, a husband and wife team, to systematically determine major and minor elements in meteorites. There had been hints before, but it was the American astronomer H. N. Russell, of Hertsprung–Russell Diagram fame, who convincingly showed that the chondrites contained the same elements, and in similar proportions, to those of the Sun's photosphere (Russell, 1929). A modern version of the data is shown in Fig. 1.4. In the 1950s Burbage *et al.* (1957) showed that these elements were produced by nuclear reactions associated with the evolution of stars, and now it is possible to link the isotopic properties of all meteorites with nucelosynthetic processes (Woolum, 1988).

No sooner had the idea of the similarity between chondrites and the Sun become widely accepted by researchers in the field, fine details breaking that rule began to emerge. By the 1950s enough analyses of meteorites had been acquired to be able to sift and sort through them and select only the very best, and when this was done by Nobel Laureate Harold Urey and his associate Harmon Craig in 1953, the chondrites sorted themselves into two groups – a group with high amounts of iron in its composition and with large amounts of metallic iron, and a group with low iron and low amounts of metallic iron (Urey and Craig, 1953). In this way, the H and L chondrites were born. We now recognize many such chondrite classes, all essentially solar in composition but with subtle differences in both the amount of total iron in the meteorite and in the proportion of iron in the metal state to iron in the minerals (Fig. 1.5). A few years before Urey and Craig's work, a successor to Story-Maskelyne as curator of meteorites at the British Museum, George Thurland Prior, pointed out that the less the amount of metal in chondrites the richer it was in nickel, a relationship that came to be known as Prior's Law (Prior, 1916). There appeared to be a reduction–oxidation series in the chondrites, where iron was reduced from Fe^{2+} or Fe^{3+} in the minerals to metallic Fe, or oxidized from the metallic form to the

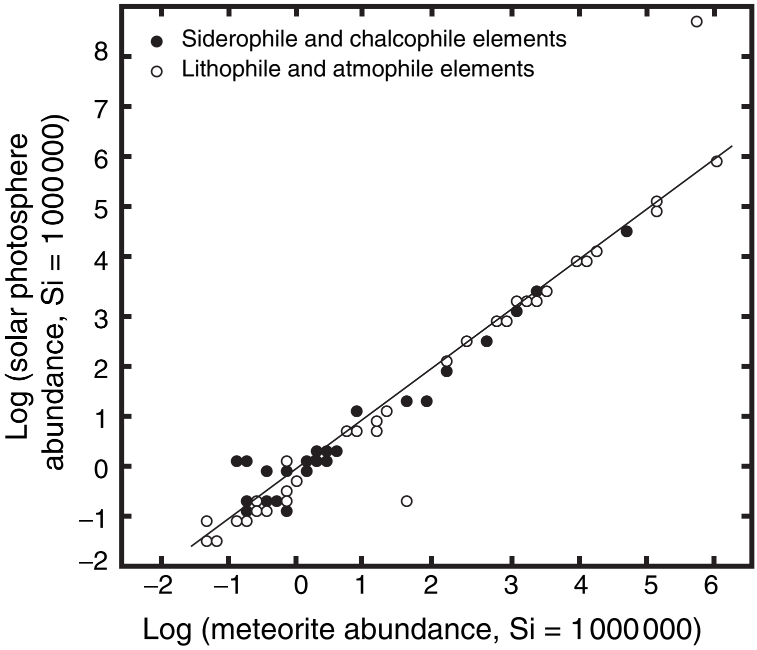

Figure 1.4 To a very good approximation, all chondrite classes are very similar to solar in composition, CI chondrites are closest, but show significant depletions in volatile elements and small depletions in siderophiles and chalcophiles. Elemental abundances in the solar photosphere are plotted against CI chondrites. Open symbols refer to lithophile (elements tending to be oxides or silicates) and atmophile elements (elements tending to be gases); closed symbols refer to siderophile (elements tending to be in the metal) and chalcophile elements (elements tending to be in the sulfides). (From Sears, 1988, who gives similar plots for other meteorite classes.)

2+ or 3+ form in the minerals. Now Urey and Craig had added that iron, probably as metal, was being removed as oxygen was being added. The removal or addition of metal is sometimes referred to as metal–silicate fractionation. In other words, we see two discrete processes; oxidation or reduction of Fe that moves samples along the diagonals in Fig. 1.5, and the removal or addition of metal which creates new diagonals (Urey and Craig, 1953; Craig, 1964). The diagonal corresponding to the Sun's Fe/Si value is shown in Fig. 1.5.

The early part of the twentieth century also saw the development of a variety of X-ray techniques such as X-ray diffraction for determining crystal structures (Young, 1926) and X-ray fluorescence for determining bulk elemental compositions (Noddack and Noddack, 1930). Eventually these X-ray techniques evolved into the electron microprobe in which a focussed beam of electrons stimulates the release of X-rays from the surface of a polished section of meteorite and these X-rays enable

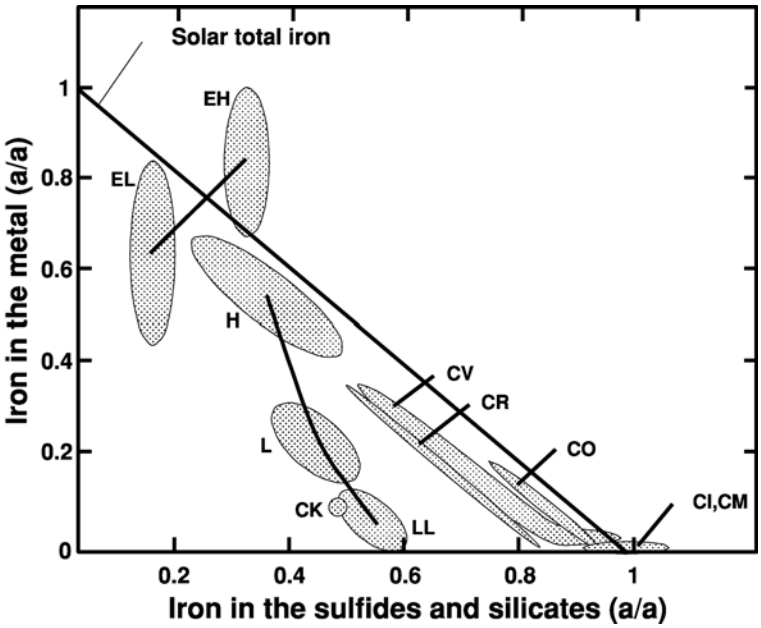

Figure 1.5 Urey–Craig diagram plotting the amount of iron in the metal against the amount of iron in the oxide and sulfide forms; in both cases the amounts are expressed as atom ratios with silicon divided by the Fe/Si atom ratio CI abundances. In this way when the ratio is one, the amount of Fe is the same in these meteorites and CI chondrites, the most primitive meteorite class. Two trends are present. When classes lie along a diagonal it means that these meteorites have uniform total iron and all that distinguishes them is the oxidation state, i.e. the amount of oxygen or sulfur that has reacted with the iron. When the meteorites lie off the diagonal there has been a loss of Fe, in other words there has been a fractionation of metal and silicates. Except for the CI and CM chondrites, the chondrite classes have experienced both processes, although to differing extents.

the identity and abundance of elements present to be determined (Castaing, 1952). Analytical techniques based on nuclear properties emerged after World War II, such as instrumental and radiochemical activation analysis (e.g. Smales *et al.*, 1957) and isotope dilution analysis but as the twentieth century closed these gave way to mass spectroscopic techniques where the charge-to-mass ratio of ions produced from a sample are separated by magnetic and electric fields. Mass spectrometric techniques are now routinely coupled with various devices to produce an ion beam. They are also coupled with many different instruments to analyze the beam after it has passed through a mass spectrometer.

Mass spectroscopy made possible an extremely important new discipline in chondrite studies concerning their chronology, determining the time at which events occurred. The types of events that can be determined is as varied as the chemistry and physics of the isotopes available, and there are a great many. It was soon

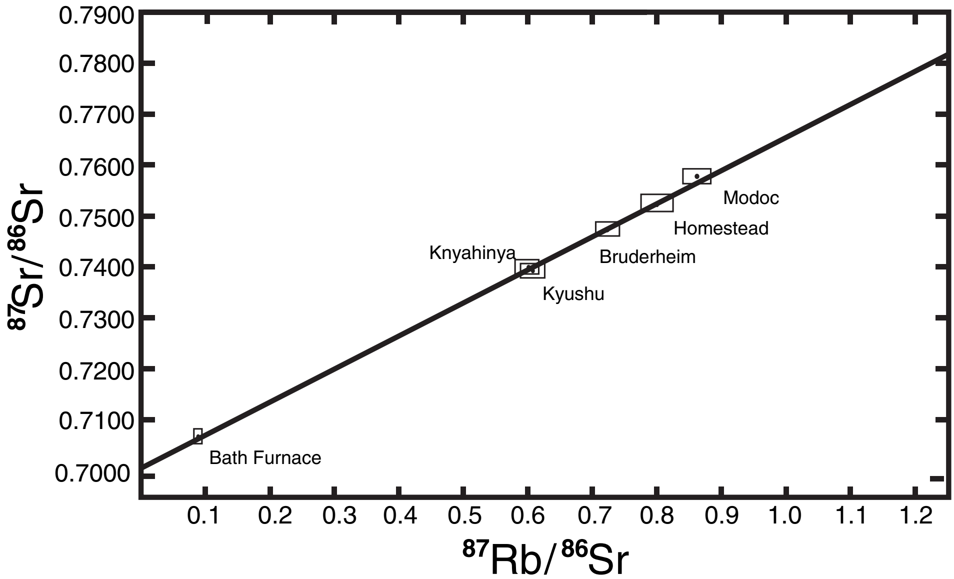

Figure 1.6 Plot of $^{87}Sr/^{86}Sr$ against $^{87}Rb/^{86}Sr$ for a suite of H chondrites indicating that they formed at the same time, 4.56 Ga ago (Kaushal and Wetherill, 1969). ^{87}Rb decays to ^{87}Sr, so the ratio of $^{87}Sr/^{86}Sr$ and the slope of the line increase with time. The age can be calculated from the slope on the line (slope $= e^{\lambda t} - 1$, where λ is the decay constant and t is time).

realized that meteorites are as old as radiometric estimates of the age of the Earth and astrophysical estimates of the age of the Sun. Figure 1.6 shows the results of a major study of one group of chondrites, the H chondrites, using the Rb–Sr system. Kaushal and Wetherill (1969) showed that the age of this group is 4.56 Ga (4.56×10^9 years). ^{87}Rb decays to ^{87}Sr with a half life of about 4.88×10^{10} years, so that the amount of daughter product builds up at a predictable rate and the duration of the process can be estimated. All that is needed, besides the half life, is the present and initial abundance of ^{87}Sr. The amount of Sr is a complex result of the amount initially made in the Universe and the various processes that have occurred to produce the rock, but these will also have affected ^{86}Sr – the major and stable isotope of Sr – in the same way that they affected ^{87}Sr, so we can eliminate them by taking the ratio of ^{87}Rb and ^{87}Sr to ^{86}Sr. The relationship is:

$$\left(\frac{^{87}\mathrm{Sr}}{^{86}\mathrm{Sr}}\right)_{\mathrm{p}} = \left(\frac{^{87}\mathrm{Rb}}{^{86}\mathrm{Sr}}\right)_{\mathrm{i}} [\exp(\lambda t) - 1] + \left(\frac{^{87}\mathrm{Sr}}{^{86}\mathrm{Sr}}\right)_{\mathrm{i}} \quad (1)$$

where λ is the decay constant ($[\ln 2]/t_{1/2}$, where $t_{1/2}$ is half life), t is time, and the subscripts i and p mean initial and present. Thus on a plot of $^{87}Sr/^{86}Sr$ against $^{87}Rb/^{86}Sr$ such as Fig. 1.6, a group of meteorites that formed at the same time lie on a line with slope [exp (λt) – 1] and with an intercept equal to the initial $^{87}Sr/^{86}Sr$ ratio. The slope on Fig. 1.6 corresponds to an age of 4.56×10^9 years. The intercept also has significance because it will have been increasing steadily since the end of element synthesis, so the later the rocks formed the higher the ratio. The intercept is another way of measuring very small differences in formation times. The Rb–Sr system can be disturbed by shock and other secondary events, and when the event is severe enough to completely reset the system the secondary event can be dated (Minster and Allégre, 1979).

Instruments have been important in driving our progress in understanding chondrites and chondrules, and a considerable body of knowledge about them now exists. However, a problem remains. In some senses, we know little more now about the origin of chondrules than we did when Sorby made his first observations (Wood, 2001). Perhaps this is in some part because the instruments at our command are not necessarily the perfect instruments for our needs. They were largely the instruments that time and circumstance enabled us to develop. The effort to learn more about the history of chondrules and chondrites, and their message for our understanding of the history of the Solar System, needs a fundamentally new way of doing business.

1.4 The space age

Probably the most important machine yet developed for further progress in understanding the origin and history of chondrules and chondrites is going to be spacecraft. For example, the Apollo program brought back nearly 400 kg of samples from six sites on the near side, equatorial region of the Moon (Heiken *et al.*, 1991). These Moon samples completely overturned many previous notions of its origin and history and of the processs occurring in the early Solar System. It is now realized, for instance, that impacts are one of the major forces in Solar System evolution. Not only does the Moon's surface show evidence for intense early bombardment by massive objects – that may also be recorded in the history of certain meteorites – but the Moon itself may be the product of a massive impact on Earth (Hartmann *et al.*, 1986).

Just as the lunar samples revolutionized our understanding of the Moon, returned samples will revolutionize our understanding of chondrites and chondrules and the early Solar System. Astronomical photometry and spectroscopy with some of the world's best telescopes has provided information on the nature of asteroids, the presumed parent bodies of chondrites, and how varied their surfaces can be. However, the asteroids remained just points of light until they were visited by spacecraft. The first images of asteroids were provided by the Galileo spacecraft on its way through the Asteroid Belt to Jupiter (Carr *et al.*, 1994). The spacecraft found a