Physics and Chemistry of Meteorites

Extended Abstract

Meteorites are extra-terrestrial (ET) fragments that may arrive any time at the earth’s surface from different parent bodies belonging to the Solar System. Barring these gifts as natural fall attempt has also been made to collect meteorite samples through the planetary missions spending millions of dollars. During the past three decades a vast treasure of meteorites has been unearthed from the cold desert of Antarctica and several hot deserts of Australia and Africa. Meteorite research became important only after the launching of a series of Apollo missions and ultimately first landing of Man on Moon.

The meteoritic community is exploring physics and chemistry of meteorites from the available samples on our earth. In consequence the concepts on the origin of the Solar System and its members are continuously changing to a new dimension. The starting point of the meteorite origin may be considered from two basic planetary laws – Laws of Planetary Motion and Laws of Planetary Distance. A continuous struggle between the ‘Ejection Velocity’ related to impact mechanics caused by other ET bodies and the ‘Escape Velocity’ related to gravitational force of the parent body ultimately places the meteorite to its own elliptic orbit in the interplanetary space with an acquired speed.

Meteorite during its residence in the parent body bears isotopic signatures of a set of complex physico-chemical processes that involve nucleosynthesis, first isotopic equilibration, accretion, static meta-morphism, major break-up and associated shock-event and finally major mass iso-time fractionation. Thermal event related to cooling history gives rise to differentiated silicate-rich meteorites with primary melt-textures and differentiated metal-rich meteorites with subsolidus Widmanstatten pattern of growth in Fe-Ni system.

Chondrites, the undifferentiated member of the meteorite, being the most largely documented population, provide a wide scope to the deeper probe of the Solar system and its precursors. In this context, first discovery of a refractory inclusion, called CAI (Calcium Aluminium Inclusions) in Allende carbonaceous (C) meteorite in 1973 is a milestone in the history of Space Science. Micron-sized CAI within C-chondrite indicated the presence of pre-solar grains (as detected from large isotopic anomalies in Calcium – 48 and Titanium – 50). This discovery not only ruled out the existing concepts of a perfectly homogenized solar nebula with no isotopic difference between lunar, terrestrial and meteorite samples but also proved that the signature of pre-solar memory is not erased out but may survive the formation of the Sun and its planetary members. The C-1 group having quasi-solar nonvolatile composition represents the most primitive carbonaceous chondrite and is indicative of its alteration in an aqueous environment. Hydrous mineral assemblages like serpentine, amphibole, epsomite (MgSO₄), gypsum (CaSO₄·2H₂O), calcite (Ca,MgCO₃) and presence of carbon in the form of inorganic and complex organic compounds bear testimony to such aqueous alteration.

Chondrule, the most diagnostic physico-chemical entity of Ordinary (O) chondrite and to a smaller extent of C-Chondrite has been a matter of debatable topic for many years among the researchers. Formation of chondrules by the direct condensation of droplets of metastable silicate liquid followed by subsequent crystallization, accretion and partial comminution of these droplets is now widely accepted. Large varieties of composition-texture based chondrule classification (BO, GOP, PP, RP, POP DG, C type) are related to three important kinetic factors – (i) nucleation constraints on condensation and crystallization, (ii) slow transformations and chemical reactions involving chain silicates and (iii) slow rate of ionic diffusion. Thus, chondrites are largely the agglomerates of chondrules accreted at higher temperature and automorphosed in a lower temperature condensate, called “Matrix”.

Evolution of chondrites explains a drastic change from highly reducing environment that led to the formation of E-chondrites to an oxidizing environment that led to the formation of O-chondrites whereas metal-silicate fractionation led to the chemical grouping of High metal – High iron (HH), High iron (H), Low iron (L) Low metal – Low iron (LL) in both O-chondrites and E-chondrites.

Differentiated silicate-rich meteorites (called Achondrites) not only represent a wide variety of primary mineral assemblages and primary melt-textures but also include ubiquitous “impact-brecia” texture. As many as eight achondrite groups are so far recognized and these are broadly categorized under Ca-rich variety (Eucrite, Shergottite and Howardite) and Ca-poor variety (Aubrite, Ureilite and Diogenite). Though Ca/Mg ratio rather than Fe/(Fe+Mg) is a useful index of magmatic fractionation process in achondrites but genetic grouping based on parent bodies has been considered more significant.

Genetic grouping includes (1) HED (Howardite- Eucrite- Diogenite) with cumulate texture and impact mixing (2) Aubrite with both melt and partial melting residue texture (3) Ureilite with partial melting residue texture (4) Angrite with fine to coarse grained igneous texture (5) Brachinite with metamorphosed chondrite / partial melting residue texture, (6) Lunar meteorite with impact rock-melt texture (7) SNC sharing cumulus texture with preferred orientation and fast cooling followed by slow cooling and (8) Acapul-coite – Lodranite with textures of ultrameta-morphism, partial melting and melt migration. It is interesting to note that there are a few chondrite and achondrite members that are anomalous due to presence of chondrite clast in achondrite host and vice-versa.

Differentiated metal-rich meteorites are essentially binary alloy of iron and nickel (up to 30% Ni) with minor presence of sulphides, phosphides, carbides, nitrides and oxides. Very slow rate of subsolidus cooling of the order of 0.25°C/10⁶yr to 500°C/10⁶yr generates a typical Widmanstatten structure with a large variety of Kamacite (α-Fe, Ni) band – width. Structural classification of iron meteorite based on kamacite band – width essentially reflects the primary thermal history of the Fe-Ni-CO-S-P chemical system. Chemical
fractionation of iron meteorites is essentially guided by the role of Ni- content and three trace elements viz. Ge, Ga and Ir. A wide survey of Ni-Ge-Ga-Ir relationship over 900 iron meteorites clearly deciphers provisionally 16 distinct petrochemical parents, designated as IA-IB, IIA-IE, IIA-IIIIF, IVA-IVB and unclassified or anomalous group.

These 16 chemical groups do not inter-grade with each other but show diverse trace-element pattern. Moreover, some of these groups are correlated with distinct structural classes. All the irons are shock- induced from very light shock pressure (≥ 130 to 200 Kb) to very high shock pressure (600 – 750 Kb) with a maximum shock-hardness (HV) at 300 Kb after which it decreases and finally leads to shock melting at 1000 Kb (100 GPa).

It is worthwhile to mention that besides shock-impact metamorphism chondrites also suffer a varying degree of thermal metamorphism under low confining pressure, defined by qualitative rank of Petrologic type 3 to 7. It has assumed so much importance that a binary classification scheme of chondrites into Chemical group- Petrologic type is in vogue, even today. Similarly, the iron meteorites also suffer thermal alteration and are manifested in the formation of α - zone due to atmospheric reheating and annealed Neumann lines due to shock- induced reheating.

Meteorite after leaving its parent body maintains its residence in the cosmic space maximum up to 100 Ma for stony meteorites and 2000 Ma for iron meteorites. Here it is exposed to cosmic rays that contain protons with very high electron volts. Short-lived cosmogenic nuclides (3He, 10Be, 26Al, 22Na and 54Mn) are produced in meteorite due to interaction between cosmic ray protons and meteoritic elements. These nuclides and their track-density profiling on different surfaces provide three physico-chemical signatures. These are:

1. Cosmic ray ablation and pre-atmospheric size.
2. Cosmic ray exposure (CRE) age and
3. Solar cycle modulation from galactic cosmic-ray activities.

With the departure of meteorite from cosmic residence to the terrestrial residence production of cosmogenic nuclides ceases with its entry into earth’s atmosphere. Along with this event, a complete shielding of all the past cosmic signatures of physics and chemistry of the meteorite takes place with the formation of a thin skin at its outermost surface called, ‘Fusion Crust’.

In course of movement when meteorite appears at the intersection of meteorite- orbit and earth- orbit it is easily captured by the earth’s gravitational field and starts its journey through the earth’s atmosphere which is largely inhomogeneous with two major discontinuities - one inbetween troposphere and stratosphere and the other between stratosphere and mesosphere. Flight of meteorite through the atmospheric passage generates light, heat, sound and mechanical stress all of which are witnessed by the sky watchers.

In the upper atmosphere the cosmic rays cause rise of surface temperature to several thousand degrees and a brilliant light effect. This light effect may be either Shooting Star (streaks of light that last for a few seconds) in case of a meteor or, a Fireball in case of a large meteorite fragment. Due to rise of temperature surface material of meteorite melts, vaporizes and the meteorite mass continuously decreases due to atmospheric ablation. Quick chilling simultaneously with melting generates a thin solid fusion crust on different surfaces of the meteorite. The falling meteorite with a cosmic speed comes across dust particles that impinge and produce fingerprint-like depressions or, Regmaglypts. Mechanical stress due to different pressure and density at the Stratopause (70 km altitude) and at Tropopause (15 km altitude) causes repeated fragmentations and formation of large number of faces covered with regmaglypts and fusion crusts of different generations. Whirling movement of the meteorite at this stage is generally indicated by a large variety of surface features viz., flow lines, radiating ribs, stagnation zone and different surface textures viz., smooth, close texture, scoriaceous and knobby. Simultaneously, various kinds of thundering, roaring and hissing sounds are produced due to the shock waves in front of the fireball and due to air turbulence caused due to subsequent fragmentation.

Morphological study of the meteoritic fragment helps to unravel its flight history if the morphological parameters like its size, completeness of the fragment in regard to face, fusion crust and textures are well preserved. Flight history interprets basically the last stage of its flight in terms of the number of repeated fragmentation, chronology of development of faces, constancy or change in orientation. It also ascertains the front, rear and lateral part of the fragment, degree of ablation and the pre- fall or, post- fall fragmentation.

Our planet Earth is increasing its weight continuously due to influx of these ET bodies. It is on average 10⁵ tons per year. ET contribution comes to Earth in 3 forms: (a) Very big meteorites: 1-10 km in diameter but their influx is significant over a period of million years (b) Moderate meteorites: 10 – 50 m in diameter with frequent influx every year and (c) Micrometeorites: micron size (10-800µm) dust particles with an influx of 100 tons on average per day. It is also known as cosmic dust or, Interplanetary Dust Particles (IDP) that strip off from the surface of meteorites (ablation droplets), survive the frictional heat due to large surface- mass ratio and reach to the earth’s surface as unaltered cosmic dust. It has been estimated that our planet since its birth (that is, during last 4.0 b.y.) has accrued 5,00,000 billion tons of ET matter out of which a large proportion was accumulated in its first 0.5 billion years due to intense meteoritic bombardment on the planet.

Recovery and estimate of these dust particles is conducted through (a) Airborne sampling in the stratosphere using artificial satellites, U-2 spy aircraft and rockets, (b) Surface sampling avoiding contami-nation by sedimentary, volcanic and industrial particles (c) Deep sea sediment sampling of cosmic spherules associated with deep-sea clay present in the deeper part of oceanic beds. In recent years, more rapid technique for identification of cosmic dust is the analysis of (a) Spherules of silicates/ black magnetite, (b) Ni- bearing magnetite, (c) Iridium anomaly and (d) Cosmic-ray produced 26Al influx. Radio technique is also used to estimate the flux of material entering the
atmosphere from space.

Journey of meteorite finally ends in a single fall or meteorite shower with or without formation of impact pit/impact crater and occasionally in explosion crater. In India, more than 300 fragments have been recorded in Dhajala Shower of Gujarat and the “Ellipse of scattering” so formed thus helped one to search and recover more fragments of that particular shower. Formation of impact crater entirely depends on the kinetic energy of the bolide (m, v) and the nature of the surface impacted on. Bolide coming with hypervelocity (about 70 km/sec) may create explosion crater and in such crater the impacting mass may completely evaporate due to severe rise of temperature. Lonar crater in Maharashtra, India is one such example of explosion crater.

It may so happen that the fall of meteorite goes unnoticed and may remain unidentified on the ground and subsequently it may be recognized by chance and recovered as ‘Find’. Since meteorite requires good preservation immediately after its fall in a suitable inert, dry and humidity-free environment therefore natural terrestrial weathering may partially/ completely destroy it in no time. In order to know the antiquity of meteorite find, specially those of well- preserved Antarctica samples Thermoluminiscence or, TL dating is conducted to determine the terrestrial age (residence period on earth’s surface since its fall) of meteoritic finds with a maximum limit of 100 years of residence period.

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