

Characterization of Mukundpura carbonaceous chondrite

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Two meteorite fragments collected from the Mukundpura impact site, Rajasthan, India have been analysed using scanning electron microscopy, energy dispersive X-ray spectroscopy, Mössbauer spectroscopy, thermogravimetric analysis (TGA) and Raman spectroscopy. High Fe (22.65 wt%), Ni (1.53%) and S (3.69%) and concentrations of other elements obtained by X-ray analysis indicate that it is a carbonaceous chondrite. Mössbauer spectra show similarity with those obtained from Cold Bokkeveld and Murchison carbonaceous chondrites, and this analogy allows us to classify it as belonging to CM group of carbonaceous chondrites. TGA shows large weight loss, implying presence of significant amount of volatiles in this meteorite and Raman spectroscopy shows the presence of abundant organic matter consisting of disordered and aromatic (graphitic or polyaromatic) carbon. These results indicate that Mukundpura meteorite is a rare type of extraterrestrial object deserving further in-depth studies.

Keywords: Carbonaceous chondrite, chemical composition, meteorite fragments, spectral analysis.

A black meteoritic stone, weighing about 2 kg, fell with a thunderous sound in the farm at Bhankrota village (26°52'52.5"; 75°39'53.7"), near Mukundpura, Jaipur, Rajasthan, India in the early morning (about 5:15 am IST) of 6 June 2017, and created an approximately half a metre diameter crater with a maximum depth of about 20 cm. One of the present authors (R.P.T.) learnt about this cosmic event around 11 am through television news. Immediately afterwards he reached the impact site, but by that time the object was already collected by the Police and Geological Survey of India (GSI). However, careful search in and around the crater showed a few black chips mixed in the soil. These chips could be easily distinguished from the local farm soil and, based on their black colour, texture, smell of sulphur, etc. were identified as part of the impactor. These chips, altogether weighing about 5 g, have been analysed using a variety of techniques to characterize the meteorite. Meanwhile GSI has reported preliminary results and conditions of fall (<https://employee.gsi.gov.in>)¹.

Stony meteorites are classified based on their mineral and chemical composition. Optical examination of the chips revealed that it may be carbonaceous chondrite. Hence it was considered necessary to characterize it, as carbonaceous chondrites are classified into various subgroups identified by their main member such as CK (Karoonda-type), CI (Ivuna), CM (Murchinson), CV (Vigarano), CR (Renazzo), CO (Ornans), CR (Renazzo), CB (Bencubbin), etc. although some carbonaceous chondrites still remain unclassified.

We have carried out quantitative studies using energy dispersive X-ray spectroscopy, Mössbauer spectroscopy and laser Raman spectroscopy to characterize and classify this meteorite. Our results, described below, establish the uniqueness of this rare carbonaceous chondrite, which is found to be similar to the Cold Bokkeveld (CM) chondrites². Based on these similarities, this meteorite is classified as belonging to CM class of carbonaceous chondrites.

As the chips available with us were lying in the soil, it was first considered necessary to confirm if they are extra-terrestrial, characterized by high Fe and Ni, and not local material. To examine morphological features and determine their elemental composition, we used energy dispersive X-ray spectrometer (Oxford-make) with Carl Zeiss scanning electron microscope (SEM). Figure 1a shows the high-resolution SEM photomicrograph along with electron image of the sample, while Figure 1b shows the Energy Dispersive X-ray (EDX) spectrum. The measured elemental abundances in wt% are: O (43.05%), Fe (22.65%), Si (13.85%), Mg (10.89%), S (3.69%), Ni (1.53%), Al (1.16%) and Ca (0.48%). Abundances of Fe, Ni, S, Mg and Al confirm that it is a carbonaceous chondrite.

Iron-bearing minerals form an important component of all meteorites and their composition is used in characterizing the meteorites^{3,4}. ⁵⁷Fe Mössbauer spectroscopy is a powerful non-destructive technique for the characterization of iron-bearing minerals⁵. The importance of Mössbauer spectra lies in the fact that (a) most of the iron-bearing minerals present in the meteorite exhibit characteristic Mössbauer parameters, based on which the meteorites can be classified; generally, it is possible to identify different iron phases in a Mössbauer spectrum recorded even at room temperature and (b) relative distribution of iron phases is representative of the class of meteorite, e.g. in ordinary chondrites, iron is mainly distributed in a set of four iron-bearing minerals: kamacite, troilite, pyroxene and olivine, but their relative distribution depends on the type of meteorite⁵. Similarly, in CV (CC) iron is mainly distributed in olivine with some iron in phyllosilicates⁶. HED meteorites also follow systematic distribution in different sites of pyroxene⁷. Burns and Fisher² have carried out systematic studies of a large number of carbonaceous chondrites like Allende, Cold Bokkeveld, Karoonda and carbonaceous achondrites

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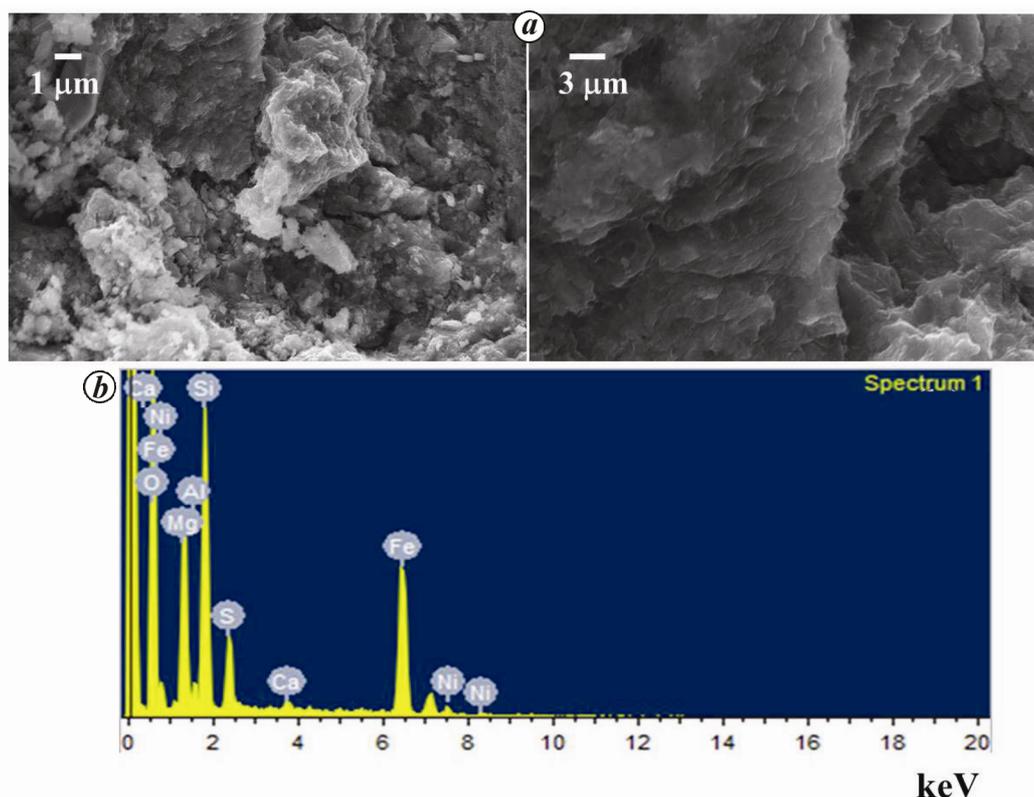


Figure 1. *a*, (Left) High-resolution scanning electron microscope photomicrographs and (right) backscatter electron image of Mukundpura meteorite illustrating the fine texture and presence of chondrule-like objects. *b*, *k*-X ray spectra showing the surface abundances of different elements in the sample.

(ureilites), and have shown that they have different characteristics depending on iron phases, hydrolization, etc. We have therefore carried out Mössbauer studies on two samples of Mukundpura meteorite.

About 100 mg of each sample (sample-1 and sample-2) was separately ground to fine powder and about 70 mg of these fractions was used to prepare absorbers for Mössbauer study. Mössbauer spectrum of these samples was recorded using a conventional constant acceleration Mössbauer spectrometer With ^{57}Co source in Rh matrix. Calibration spectra of alpha iron was recorded before and after the sample run to ensure electronic stability during the experiment. The spectrum was computer-fitted using a least square routine (NORMOS) and also assuming that it is the sum of Lorentzian functions. During curve-fitting, the width and intensity of two halves of a quadrupole doublet were constrained to be equal. Quality of fit was judged from the chi-square analysis value, which was close to 1.0 per degree of freedom. The isomer shift (IS) was reported with respect to alpha-iron. The reported values of IS and quadrupole splitting (QS) have an accuracy of 0.02 mm s^{-1} . The Mössbauer spectra of the two samples were found to be identical (Figure 2). Table 1 shows the calculated Mössbauer parameters, FWHM, IS, QS and calculated area.

The inner doublet corresponds to iron in Fe^{3+} state and the outer doublet corresponds to iron in Fe^{2+} state. It is

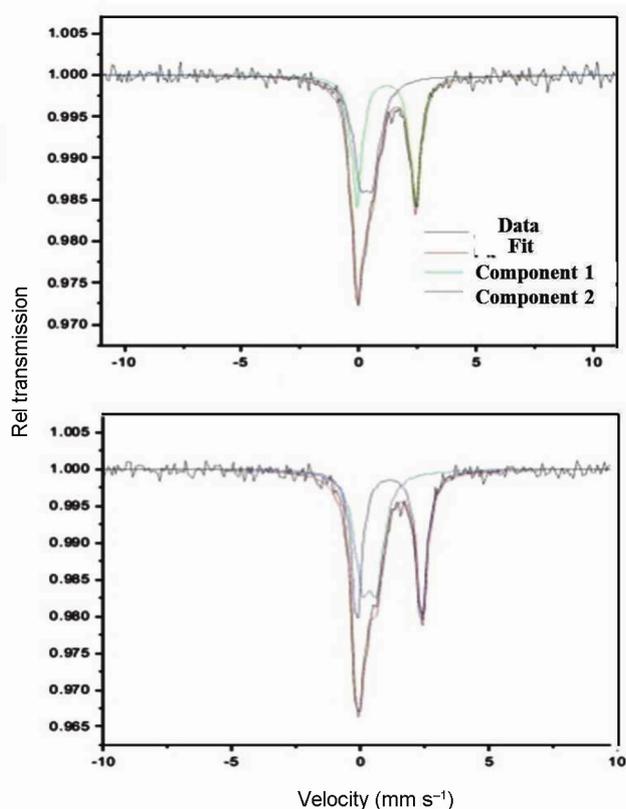
worth mentioning that doublet corresponding to iron in olivine ($\text{QS} \sim 3.0 \text{ mm s}^{-1}$ and $\text{IS} \sim 1, 2 \text{ mm s}^{-1}$) is distinctly absent in this sample. Besides, the sextet corresponding to magnetite and/or troilite is also absent. It is well known that carbonaceous chondrites exhibit Fe^{3+} doublet. The occurrence of ferric assemblage minerals, corresponding to phyllosilicates, oxy-hydroxides or magnetite indicates that this carbonaceous chondrite underwent pre-terrestrial sub-aqueous oxidation reactions. Olivine grains have undergone reactions, producing minerals of serpentine group and poorly crystalline phase such as ferrihydrite.

The Mössbauer parameters of the outer doublet correspond to Fe^{2+} in serpentine group minerals. So we assigned the outer ferrous doublet to Fe^{2+} in serpentine. Also, serpentine has been observed in some carbonaceous chondrites, but the most unusual finding is the near absence (less than 5%) of olivine. This indicates that olivines have undergone complete serpentinization and reflect the conditions prevailing on the parent body. Another unique feature of the Mukundpura meteorite is that the intensity of both the doublets is almost the same. Such a trend of distribution of iron in different carbonaceous chondrites has not been observed before. We have compared the Mössbauer spectrum of Mukundpura meteorite with the Mössbauer spectra of other groups of carbonaceous chondrites. Mössbauer spectra of CK chondrites

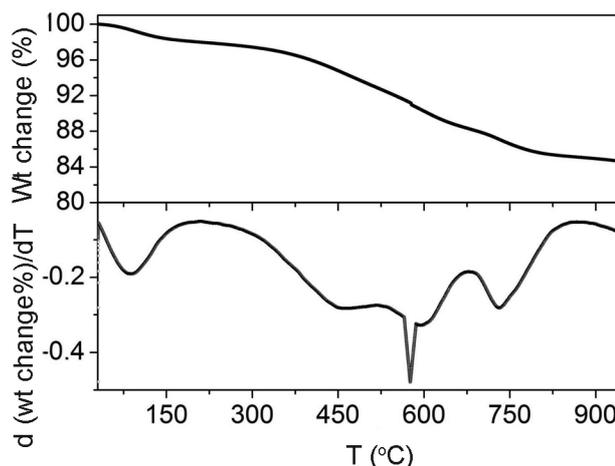
Table 1. Mössbauer parameters for Mukundpura meteorite at room temperature

Sample	FWHM* (mm s ⁻¹)	Isomer shift (mm s ⁻¹)	Quadrupole splitting (mm s ⁻¹)	Area (%)
Sample 1				
Doublet 1	0.52 ± 0.02	1.15 ± 0.01		51
Doublet 2	0.78 ± 0.05	0.33 ± 0.01	0.53 ± 0.03	49
Sample 2				
Doublet 1	0.49 ± 0.02	1.12 ± 0.01	2.53 ± 0.02	51
Doublet 2	0.71 ± 0.02	0.34 ± 0.01	0.56 ± 0.03	49

*FWHM, Full Width at Half Maximum.

**Figure 2.** Mössbauer spectra of two samples of Mukundpura meteorite taken at room temperature showing the presence of iron-bearing minerals. The spectra obtained from the two samples are identical.

always exhibit intense magnetite sextet, appreciable iron in olivine and Fe³⁺ in silicates. Further, CV carbonaceous chondrites spectra show about 80% iron in olivine and the remaining iron in Fe³⁺ state⁶. CI chondrites also show intense sextet corresponding to iron in magnetite and Fe³⁺ in silicates and serpentine. CR chondrites show presence of olivine in appreciable amounts. A comparative study of Mössbauer spectrum of Mukundpura meteorite with various types of carbonaceous chondrites shows that there is only one CM-type – Cold Bokkeveld – which exhibits a spectrum at room temperature which is almost identical to that of Mukundpura meteorite. At room temperature

**Figure 3.** Thermogravimetric analysis (weight loss) pattern as a function of temperature, from 30°C to 1000°C for Mukundpura meteorite.

Mössbauer spectrum in Cold Bokkeveld shows two peaks of comparable intensity and olivine is distinctly absent; the doublet corresponding to serpentine is distinctly present². Mössbauer spectrum of Mukundpura is nearly similar to that of Murchison meteorite. Earlier studies have established that ordinary chondrites can be classified on the basis of Mössbauer spectra³⁻⁵. Thus, in view of the similarities between Mukundpura and CM chondrites (Cold Bokkeveld and Murchison), we conclude that Mukundpura meteorite belongs to CM class.

A small sample (10 mg) of Mukundpura meteorite was subjected to thermogravimetric analysis (TGA) in nitrogen atmosphere using STA 600 Perkins Elmer Analyser. Weight loss from the sample was recorded as the sample was heated from 30°C to 1000°C at a rate of 10°C/min (Figure 3). As it can be seen from Figure 3, there is a little weight loss between 30°C and 300°C. This indicates that minerals like Fe oxyhydroxides which dehydrate at 200–300°C are absent. Low temperature Mössbauer study of Cold Bokkeveld had shown that oxyhydroxide minerals were absent². This similarity further supports our assignment of Mukundpura meteorite to CM class. It can be seen that significant mass loss for Mukundpura sample occurs between 300°C and 800°C. This is consistent with

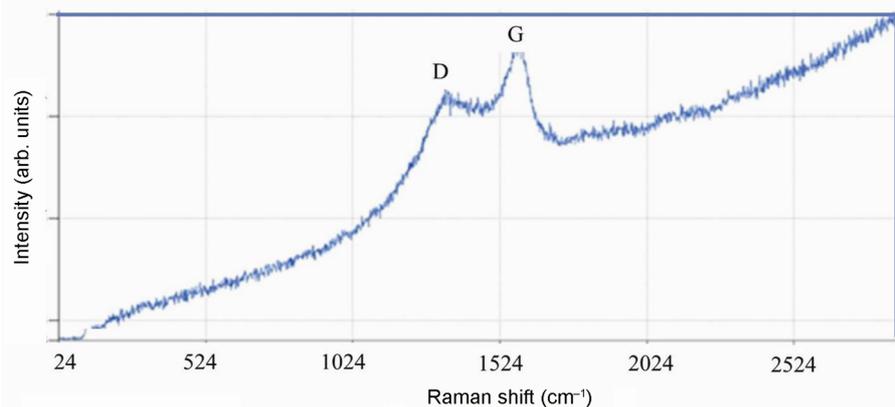


Figure 4. Typical laser Raman spectrum of Mukundpura meteorite showing D band due to disordered carbon and G band between 1200 and 1600 nm due to aromatic carbon (graphite-type or poly aromatic solid)⁹.

dehydration and dehydroxylation of abundant serpentine in the sample⁸.

We have also carried out Raman spectroscopic analysis using STR 5000 CONFOCAL micro Raman spectrometer. The excitation source was 532 nm line of DPPS laser. While collecting the spectra, precaution was taken to avoid overheating. Figure 4 shows a typical Raman spectrum obtained. Between 1200 and 1600 nm range, the spectrum exhibits two first-order Raman bands: D band on the left and G band (1600 nm) on the right of the figure. The spectrum also exhibits significant fluorescence emission, as evident by the slope and intensity of the background. Matrajt *et al.*⁹ have reported the occurrence of these two bands in most of the carbonaceous chondrites due to the presence of carbonaceous material. The D band is characteristic of disordered carbon, whereas the G band is characteristic of an aromatic carbon: graphite-type or polyaromatic solid. The D and G Raman spectral bands obtained in this study confirm the presence of highly distorted carbonaceous material in Mukundpura meteorite.

In conclusion, the Mukundpura meteorite is analogous to Cold Bokkeveld in Mössbauer and Raman spectra, and therefore is classified as carbonaceous chondrite-type CM. Thus, this is a rare type of meteorite and further studies of carbonaceous material will throw light on its origin and evolutionary history.

1. <https://employee.gsi.gov.in>

2. Burns, R. G. and Fisher, S., Pre-terrestrial oxidation products in carbonaceous meteorites identified by Mössbauer spectroscopy. Washington Reports of Planetary Geology and Geophysics Program, NASA, USA, 1990, Part 1, pp. 256–258.

3. Dodd, R. T., *Meteorites: A Petrological–Chemical Synthesis*, Cambridge University Press, Cambridge, UK, 1981.
4. Rubin, A. E., Mineralogy of meteorite groups. *Meteorit. Planet. Sci.*, 1997, **32**, 231–247.
5. Verma, H. C., Jee, K. and Tripathi, R. P., Systematics of Mössbauer absorption areas in ordinary chondrites and applications to a newly fallen meteorite in Jodhpur, India. *Meteorit. Planet. Sci.*, 2003, **38**, 963–967.
6. Hoffman, H., Seifu, D. and Oliver, F. W., Axtell and Allende: a Mössbauer spectroscopic study. *Meteorit. Planet. Sci.*, 2000, **35**, 431–434.
7. Bhatia, Beena, Patel, K. R., Tripathi, R. P., Layek, S. and Verma, H. C., Implication of Mössbauer spectra on mixing model of eucrites and diogenites (resulting in howardites). *Curr. Sci.*, 2015, **109**, 331–337.
8. Ashley, King, J., Solomon, J. R., Paul, Schofield, F. and Russell, S. S., Characterizing the CI and CI like carbonaceous chondrites using thermogravimetric analysis and infrared spectroscopy. *Earth-Planets Space Sci.*, 2015, **67**, 198–211.
9. Matrajt, G., Borg, P., Raynal, I., Djouadi, Z., d’Hendecourt, I., Flaynn, G. and Deboffe, D., FTIR and Raman analyses of the Tagish Lake meteorite: relationship with the aliphatic hydrocarbons observed in the diffuse interstellar medium. *Astron. Astrophys.*, 2004, **416**, 983–990.

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