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RESEARCH ARTICLE

SYSTEMATICS OF MÖSSBAUER ABSORPTION AREAS AND THEIR RATIO IN ORDINARY CHONDRITES AND APPLICATION TO A FALLEN METEORITE IN NATHDWARA, INDIA

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ABSTRACT

Mössbauer absorption areas corresponding to ^{57}Fe in olivine, pyroxene, troilite, and the metallic phase in ordinary chondrites exhibit certain systematic behavior. H chondrites occupy distinct regions on the plot of metallic phase absorption area versus silicate absorption area. While L/LL chondrites fall in separate region. The absorption area ratio of (olivine to troilite+kamacite) also show characteristic range in which H,L and LL chondrites fall. Based on these systematic, a fallen meteorite near Nathdwara, Rajasthan, India is suggested to be an L chondrite.

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INTRODUCTION

Chondritic meteorites, known as chondrites, are divided into three classes, viz., ordinary, carbonaceous and enstatite. Depending on their chemistry and mineralogy Ordinary chondrites (OCs) are further divided into three groups viz., H group, L group and LL group. Among these three, H group meteorites contain highest (above 20%) weight percentage of iron with an appreciable amount in metallic Fe (Fe^0) state. LL group meteorite has lowest weight percentage of total Fe and hence of metallic Fe. Recently, Agarwal *et al*., (2014) have reported mineralogy and classification of a meteorite (Nathdwara meteorite) which fell as a single stone at Dhyal ki Chappar (24°58'N, 73°48'27"E), near the well known holy town of Nathdwara in Rajsamand district of Rajasthan (India) on 25th Dec 2012 at 18:20 hrs (local time). Location map of the fallen meteorite is given in the reference (Agarwal *et al*. 2014). The stone was fully covered with fusion crust and had well rounded edges and well developed regmaglypts (thumb print like impression) on its surface, formed by ablation of material during the course of meteor passing through the Earth's atmosphere. The meteorite sample initially weighed about 1.5 kg which was hammered in several small pieces out of curiosity by the villagers; one small piece was made available to us by Professor V. Agarwal, Department of Geology, Mohan Lal Sukhadia University, Udaipur, Rajasthan (India) for Mössbauer spectroscopic study. In the present investigation for the first time we have shown that the absorption area ratio of (olivine to troilite+kamacite) also show characteristic range in which H, L and LL chondrites fall. Based on these systematic Nathdwara meteorite, Rajasthan, India is suggested to be an L chondrite.

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Mössbauer spectroscopy and classification of ordinary chondrites

Iron bearing minerals form an important component of all meteorites. The study of composition of such minerals, impurity inclusions, their relative abundance, gives useful information about the pre terrestrial history of the meteorite and is useful in the classification of the meteorite Dodd (1981) and Rubin (1997). ^{57}Fe Mössbauer spectroscopy is a powerful technique for characterization of iron-bearing minerals. In a single run one gets information about various iron bearing minerals present in a given sample. Our group has conducted extensive Mössbauer spectroscopic studies concerning classification of different meteorites Verma *et al.,* (2002), Verma *et al.,* (2003), Verma *et al.,* (2004), Verma *et al.,* (2008), (Tripathi *et al* 2000), and (Paliwal *et al.,* 2000). Different classes of meteorites exhibit characteristic Mössbauer parameters and shapes so that a "fingerprint" Mössbauer analysis can be quickly made to obtain a broad classification. As an example it is worth noting that Didwana meteorite which was initially identified as enstatite chondrite, was later on in a Mössbauer spectroscopic study shown to be an ordinary H-chondrite (Paliwal *et al* 2000). Subsequent study using conventional techniques, reported by (Paliwal *et al.,* 2001) on this meteorite confirmed this classification.

Experimental

About 500 mg of Nathdwara meteorite was ground to fine powder, and about 70 mg of this powder was used to prepare absorber for Mössbauer study. Mössbauer spectrum of this powdered sample was recorded at 300 K using a conventional constant acceleration Mössbauer spectrometer with a ^{57}Co in Rh matrix as the gamma ray source. Calibration spectra with pure α-iron sample were recorded before and after experimental run to ensure electronic stability during the experiment. Spectrum was computer fitted using a least square routine (NORMOS) and assuming spectrum to be a sum of Lorentzian functions. During the curve fitting, the width and the intensity of the two halves of a quadrupole doublet were constrained to be equal. In the case of a sextet,(the areas of 1^{st} and 6^{th} peaks, areas of middle. 2^{nd} and 5^{th} peaks and inner pairs3^{rd} and 4^{th} peaks were constrained to be equal) .Width of all the six peaks were also constrained to be equal. Quality of fit was judged from the value of χ2, which was close to 1.0 per degree of freedom. The isomer shift (IS) is reported with respect to α-iron. The reported values of IS and quadrupole splitting (QS) have an accuracy of about 0.02 mms^{-1}, while that hyperfine magnetic field B has an accuracy of about 0.2 T. It is worth mentioning that Mössbauer facility for present work was provided by UGC-DAE consortium for scientific research, Indore (India)

RESULTS AND DISCUSSION

Mössbauer spectroscopic investigations reported out on large number of unweathered ordinary chondrite samples e.g (Verma *et al.*2004) clearly exhibit that most of the ordinary chondrites form a class of meteorites which have essentially four kinds of iron-bearing minerals, viz., olivine, pyroxene, troilite and Fe-Ni alloy (kamacite/taenite). The first two are silicate minerals having the chemical formulae $(Fe, Mg)_2SiO_4$ and $(Fe, Mg)SiO_3$, respectively, and result in quadrupole doublets. QS (qudrupole splitting) value for olivines are centered around 3.0 mms^{-1} while QS value for pyroxenes are centered around 2.2 mms^{-1} . Troilite (FeS) is a magnetically ordered mineral and shows a six-line component in the Mössbauer spectrum having a hyperfine magnetic field of about 31.6 T and isomer shift of about 0.75 mms^{-1}Kamacite and taenite also referred to as metallic Fe(in the meteorite research community) are Fe-Ni alloys with nickel abundance around 5–15 wt%, each giving a six-line Mössbauer spectral component. Hyperfine magnetic field for kamacite varies slightly with the Ni content but remains close to the pure iron value of 33.0 T. For taenite, the hyperfine magnetic field is around 31.1 T. When the content of taenite is small in ordinary chondrites it does not get resolved from kamacite in the Mössbauer spectrum. Relative distribution of these minerals varies depending on the class of meteorite in OCs. Mössbauer parameters of the olivine, pyroxene, troilite and Fe-Ni alloy (kamacite/taenite) are characteristically different so that they can easily be identified in a Mössbauer spectrum. Mössbauer spectrum collected for Nathdwara meteorite under present study is displayed in Fig. 1. For sake of comparison, Mössbauer spectra of two well classified H chondrites Dergaon (Shukla *et al.,* 2005) and Devgaon (Murthy *et al.,* 2004) are displayed in Fig 2, and Mössbauer spectra of L/LL type chondrites Itawa Bhopji, Jodhpur (Bhandari *et al.,* 2002) (Bhawad), Ararki (Bhandari, *et al.,* 2008) are displayed in Fig 3. Mössbauer parameters of Nathdwara meteorite and the other meteorites are given in Table 1. In Table 2 we have provided brief description of meteorites (for which Mössbauer parameters are given in Table 1) and source of their classification. It can be seen from Table 1 that all H chondrites (Didwana, Dergaon, Devgaon) show an intense sextet corresponding to Kamacite. On the other hand only weak sextet is observed for L/LL type ordinary chondrites. Similar observation is observed for many other meteorites also .c.f. (Verma *et al.,* 2003).

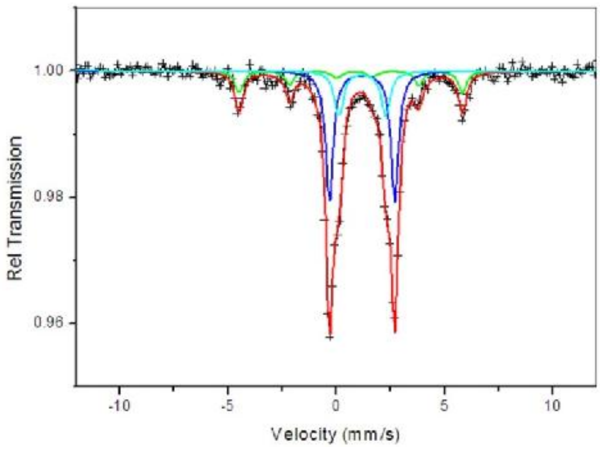

Fig. 1. Mössbauer spectra of Nathdwara meteorite at room temperature

It is well known that H chondrites are highly reduced meteorites. Hence fresh (unweathered) samples of such meteorites, should exhibit adequate presence of iron in metallic phase (dominantly Kamacite) meteorites also (c.f. Verma *et al.*2003). It can be seen from Table 1 that metallic phase is practically absent in the Mössbauer spectrum of Nathdwara meteorite and iron is dominantly distributed in silicate phases. This conclusively ruled out H-type classification of Nathdwara chondrite. Further, (Verma *et al.,* 2003) have given a plot of Mössbauer absorption area for the metallic phase versus that for silicate phases for 24 ordinary chondrites. This systematic is shown in Fig.4 in which H and L/LL chondrites fall in different regions. Only there is a small region where there is a overlap of H and L chondrites. Arrow shows the position of Nathdwara meteorite on this plot (Fig. 4).

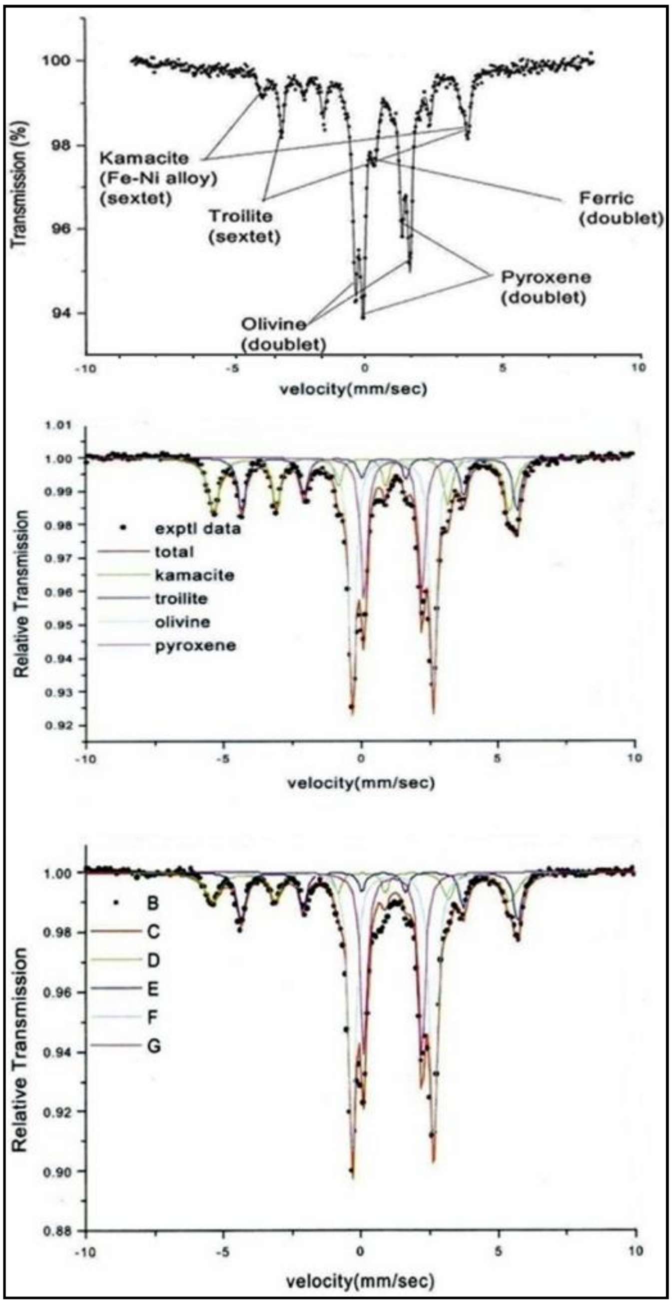

Fig. 3. Mössbauer spectra of (a) Itawa- Bhopji (b) Jodhpur (c) Ararki meteorites at room Temperature

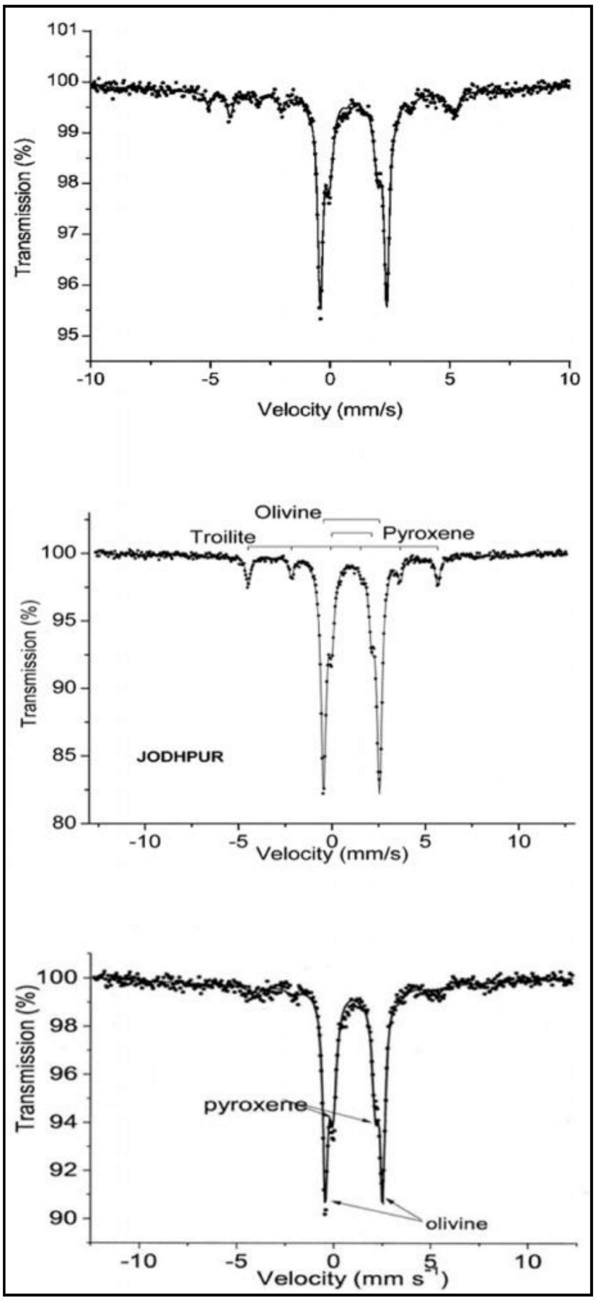

Fig.4 Location of Nathdwara meteorite

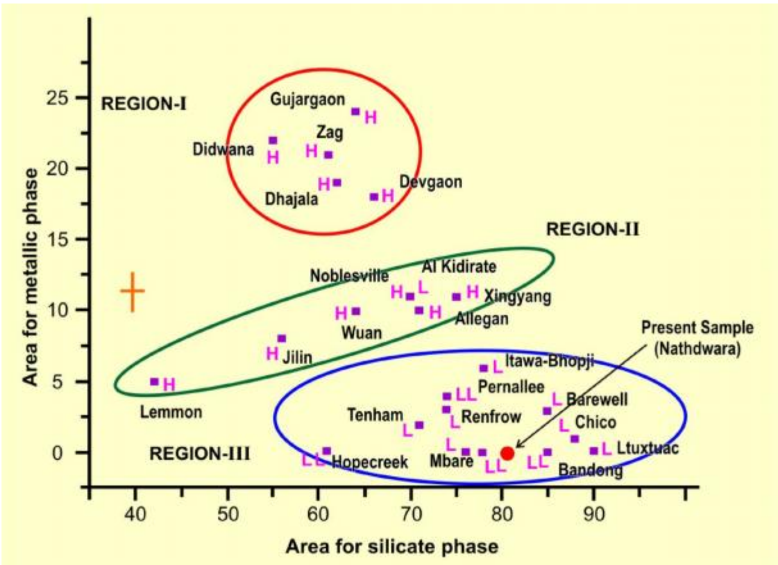

Fig. 5. Plot showing Olivine / Opaque mineral ratio for the meteorites studied by Verma *et al*. (Dodd, 1981) and the meteorite under study

Table 1. Mössbauer parameters of the meteorites

Meteorites	Spectrum	IS (mms^{-1})	QS (mms^{-1})	MHF (kOe)	Area (%)	Assigned Mineral	O/K+T Minerals ratio
Nathdwara	Sextet	0.75	0.16	32.02	19.7	Troilite	2.79
	Doublet	1.19	3.02	–	55.1	Olivine	
	Doublet	1.19	2.16	–	25.2	Pyroxene	
Deedwana	Sextet 1	0	0	33.8	17	Kamacite	0.87
	Sextet 2	0.87	0.17	31.7	23	Troilite	
	Doublet	1.17	2.96		35	Olivine	
	Doublet	1.14	2.1		25	Pyroxene	
Devgaon	Doublet 1	1.15	2.95	–	39.3	Olivine	1.14
	Doublet 1	1.14	2.08	–	26.2	Pyroxene	
	Sextet 1	0.78	-0.07	312	16.9	Troilite	
	Sextet 2	0.02	-0.02	335	17.6	Kamacite	
Dergaon	Doublet 1	1.15	2.95	–	34.7	Olivine	0.79
	Doublet 1	1.14	2.08	–	21.1	Pyroxene	
	Sextet 1	0.78	-0.07	312	18.8	Troilite	
	Sextet 2	0.02	-0.02	335	25.4	Kamacite	
Itawa-Bhopji	Sextet 1	0.04	0	33.2	6	Fe–Ni	2.9
	Sextet 2	0.73	-0.03	31.3	16	Troilite	
	Doublet 1	1.12	2.95		58	Olivine	
	Doublet 1	1.12	2.09		20	Pyroxene	
					0	Fe–Ni	
Jodhpur		0.73	-0.15	31	15	Troilite	4.27
	Doublet 1	1.11	2.95	0	64	Olivine	
	Doublet 1	1.13	2.11	0	21	Pyroxene	
Ararki	Doublet 1	1.14	2.98	–	48.57	Olivine	3.1
	Doublet 1	1.14	2.14	–	35.62	Pyroxene	
	Sextet 1	0.57	-0.16	287	11.43	Troilite Altered	
	Sextet 2	0.69	-0.19	313	4.3	Pure Troilite	

Table 2. Description of the meteorites studied

Sample	Fall Date	Description	Reference	Place
Nathdwara	2012 fall	Present study	Present study	Rajasthan, India
Deedwana	1991 fall	H chondrite	Paliwal *et al.*	Rajasthan, India
Dergaon	2001 fall	H5 chondrite	Shukla *et al.*	Assam, India
Devgaon	2001 fall	H3 chondrite	Murty *et al.*	Chhattisgarh, India
Itawa-Bhopji	2000 fall	L chondrite	Bhandari *et al.*	Rajasthan, India
Jodhpur	2002 fall	LL chondrite	Verma *et al.*	Rajasthan, India
Ararki	2001 fall	L5 chondrite	Bhandari *et al.*	Rajasthan, India

Table 3. Olivine/Opaque minerals ratio for different class of Ordinary Chondrites studied by Verma *et al.* (Dodd, 1981)

Sample No.	H	Olivine / Kamacite+Trolite	Sample No.	L	Olivine / Kamacite+Trolite	Sample No.	LL	Olivine / Kamacite+Trolite
1.	Gujargaon	1.02	11.	Itawa-Bhoopji	2.63	17.	Tuxtuac	6.10
2.	Zag	0.92	12.	Barewell	3.80	18.	Richfield	5.18
3.	Didwana#	0.68	13.	Tenham	3.26	19.	Bandong	4.57
4.	Noblesville	1.60	14.	Renfrow	3.18	20.	Jodhpur	4.27
5.	Xingyang	1.76	15.	Mbale	2.94			
6.	Allegan	1.31	16.	Ararki	>3.2o<3,3			
7.	Wuan	1.41						
8.	Jilin	1.80						
9.	Lemmon	1.04						
10.	Al-Kidirate	1.62						
21.	Mahadevpur	0.99						
22.	Devgaon	1.14						
23.	Devgaon	0.79						
24.	Djaumine	1.84						

Average of many fragment

It is seen that Nathdwara meteorite distinctly fall outside the region of H chondrite. For having a further insight in the classification of Nathdwara meteorite, we have collected Mössbauer parameters reported for large number of meteorites (OCs) in literature. Using these data in Fig.5 we have plotted the ratio of absorption area of olivine (O) to absorption area of opaque minerals i.e.(K+T) for different unweathered meteorites. Here O,K,T represents absorption area of olivine, Kamacite and troilite respectively.

This ratio is also given Tables.1and 3. The reference from which data are taken is given in Table 3 and in Fig. 5. It can be seen from Fig.5 that range of this ratio is characteristically different for H chondrites, L chondrites and LL chondrites. For H Chondrites it is less than 2, for L chondrites it lies between 2 and 4 and for LL chondrites it is above 4. The observed characteristic range of this ratio for different class of meteorites is an interesting finding which we have noticed for the first time. In the case of Nathdwara meteorite this ratio (O/K+T) =

2.6 indicative of this meteorite being in the L-chondrite region rather than H and LL-chondrite region.

Conclusion

Absence of kamacite in Mössbauer spectrum of Nathdwara meteorite conclusively indicates that this meteorite is not an H chondrite. Further the observed Mössbauer spectral area ratio O/K+T suggestive of it being L type. Further ^{57}Fe Mössbauer spectroscopy (non destructive and phase sensitive) is finger print technique for the classification of the meteorites.

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