

^{57}Fe Mössbauer study of the chainpur meteorite

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Abstract The Chainpur meteorite is one of 23 ordinary chondrites classified as LL3-type (low-Fe & low-metal). It was observed as a shower of stones falling on May 9, 1907 in Uttar Pradesh, India. We report here the characterization of the Fe-bearing phases in this chondrite using ^{57}Fe Mössbauer spectroscopy carried out at 298 K, 120 K, 50 K and 13 K. The paramagnetic doublets of olivine and pyroxene dominate the room temperature spectrum, accounting for around 70 % of the spectral area. Moreover, a doublet present with a spectral area of 5 % and assigned to a superparamagnetic Fe^{3+} phase is a consequence of terrestrial weathering. On the basis of the measured ^{57}Fe electric quadrupole splitting of the olivine component at room temperature we estimate the mean Fe:Mg ratio in this meteoritic olivine to be around 35:65 % although there is clearly a wide range of composition. The effects of magnetic ordering of the major components olivine and pyroxene are observed at 13 K.

Keywords Mössbauer spectroscopy · Olivine · Meteorites

1 Introduction

Nearly all meteorites are considered fragments of planetary asteroids. Meteorites can be divided into two types: those modified by melting from the parent body, known as achondrites, or those that did not experience melting, known as chondrites. The latter are the dominant type of meteorites hitting the Earth, particularly the ‘ordinary chondrites’ that account for about 80 % of all falls on Earth [1]. It has been suggested that ordinary chon-

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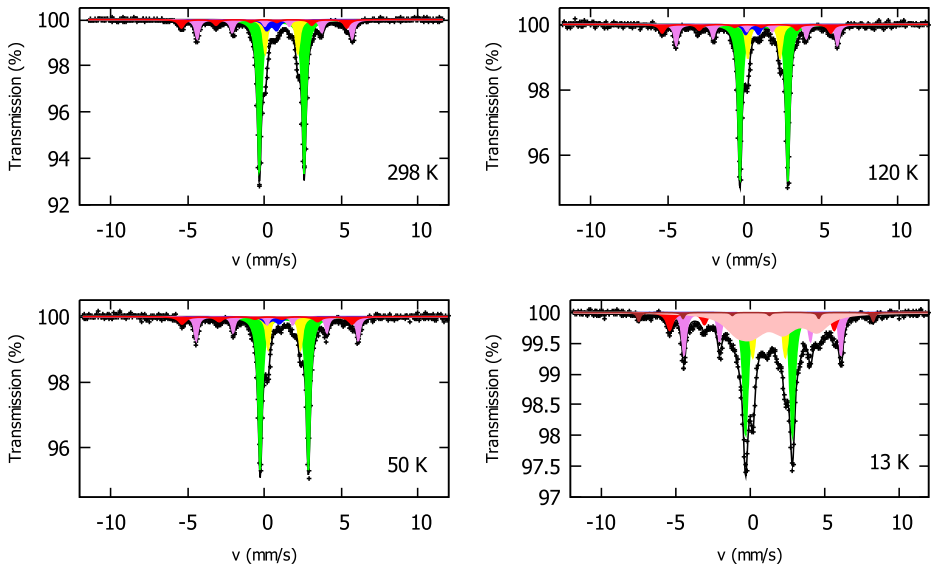


Fig. 1 The ^{57}Fe Mössbauer spectra of Chainpur collected at 298 K, 120 K, 50 K and 13 K. The colour coding is: olivine = green; pyroxene = yellow; paramagnetic ferric component = blue; troilite = violet; Fe-Ni alloy = red; magnetic olivine component = pink and nanocrystalline ferric phase = brown

drites are fragments of S-type asteroids [2]. ^{57}Fe Mössbauer Spectroscopy is useful in studying ordinary chondrites as these meteorites contain significant amounts of iron-bearing phases such as olivine, pyroxene, troilite (FeS) and FeNi metal (e.g. kamacite and taenite), as well as weathering products in the form of ferric compounds (e.g. [3–5]). In this paper, we study the Chainpur meteorite which fell in 1907 in the Uttar Pradesh region of India at coordinates (25° 51' N / 83° 29' E) [6]. Chainpur is classified as an LL3.4-type (low-Fe and low metal) ordinary chondrite considered as the least altered by aqueous conditions. The aim of our study is to identify the iron-bearing phases in the Chainpur meteorite and study their behaviour over a wide range of temperatures. Additionally, we observed the effect of magnetic ordering of the olivine and pyroxene components.

2 Experimental methods

Approximately 60 mg of the Chainpur meteorite were ground to make a Mössbauer absorber of diameter 1.5 cm. ^{57}Fe Mössbauer spectroscopy was carried out in standard transmission mode with a $^{57}\text{CoRh}$ source. All Mössbauer spectra were least-squares fitted using the RECOIL software [7] and all isomer shifts quoted hereafter are relative to the metallic α -iron calibration spectrum acquired at room temperature. For the purposes of the Mössbauer fitting the paramagnetic doublets of the olivine and pyroxene components were constrained to be symmetric, despite the fact that both phases have two sites available to the Fe. Resolution of the two sites in both olivine or pyroxene at room temperature is far from straightforward, given the similarities in their hyperfine parameters and the presence of other overlapping spectral contributions. The use of a symmetric doublet for each of these phases has proven to be a good approximation at room temperature in numerous studies of

Table 1 ^{57}Fe Mössbauer parameters: Isomer Shift (δ), Quadrupole Splitting ($|\Delta|$) or Quadrupole Shift (2ϵ), Hyperfine Field (B_{hf}) and relative areas obtained from the Chainpur spectra

Component	δ (mm/s)	$ \Delta : 2\epsilon$ (mm/s)	B_{hf} (T)	Area (%)	Phase
T = 298 K					
Doublet 1	1.13(1)	2.92(1)		57.8(4)	Olivine
Doublet 2	1.12(1)	2.12(1)		12.7(3)	Pyroxene
Doublet 3	0.47(2)	0.65(1)		5.2(5)	para Fe^{3+}
Sextet 1	0.75(1)	-0.16(1)	31.3(1)	15.8(5)	Troilite
Sextet 2	-0.02(1)	0.01*	33.4(1)	8.6(6)	<u>Fe</u> Ni
T = 120 K					
Doublet 1	1.27(1)	3.12(4)		58.0(5)	Olivine
Doublet 2	1.28(1)	2.11(2)		12.9(7)	Pyroxene
Doublet 3	0.49(4)	0.85(8)		4.8(8)	para Fe^{3+}
Sextet 1	0.90(1)	-0.19(2)	32.6(1)	15.8(6)	Troilite
Sextet 2	0.19(3)	-0.10*	34.1(2)	8.5(3)	<u>Fe</u> Ni
T = 50 K					
Doublet 1	1.29(1)	3.14(1)		57.5(6)	Olivine
Doublet 2	1.30(1)	2.11(2)		12.2(9)	Pyroxene
Doublet 3	0.54(7)	0.86(13)		4.3(7)	para Fe^{3+}
Sextet 1	0.93(1)	-0.18(2)	32.7(1)	16.5(8)	Troilite
Sextet 2	0.21(4)	-0.08*	34.3(3)	9.5(3)	<u>Fe</u> Ni
T = 13 K					
Doublet 1	1.28(1)	3.16(1)		26.9(9)	Olivine
Doublet 2	1.29(1)	2.19(1)		10.2(8)	Pyroxene
Doublet 3	0.69(4)	0.93(9)		2.1(6)	para Fe^{3+}
Sextet 1	0.91(1)	-0.20(1)	32.8(1)	15.8(8)	Troilite
Sextet 2	0.13(2)	-0.08*	34.3(1)	9.3(4)	<u>Fe</u> Ni
Sextet 3	1.49(5)	3.78(10)	7.0(3)	31.5(4)	mag.-Olivine
Sextet 4	0.27(3)	0.29(9)	48.7(2)	4.3(9)	n-Ferric oxide

The symbol * represents parameters that were ‘fixed’ during the fitting process

similar spectra. In the case of magnetic sextets, the line intensities of the outer, middle and inner pairs were constrained to the ‘powder’ ratio 3:2:1.

3 Results and discussion

The Mössbauer spectra of Chainpur over the temperature range 13–298 K are shown in Fig. 1 and the Mössbauer parameters derived from the fits to these spectra are given in Table 1. It is clear that the Chainpur spectra show the characteristic Fe-bearing phases of an ordinary chondrite. At 298 K, the silicates olivine and pyroxene dominate the spectrum with their combined quadrupole doublets accounting for $\sim 70\%$ of the total spectral area. The olivine quadrupole splitting of 2.92(1) mm/s allows us to estimate the fayalite composition to be $\sim 35(5)\%$ mol %, using data from Menzies et al. [8] but we consider this an average value as it was reported that the olivine in Chainpur is found over a range of molar ratios

[9], as we clearly observe in our low temperatures spectra. Furthermore, the spectra show the magnetic signatures of troilite and FeNi metal with relative spectral areas of 15.8(5) % and 8.6(6) %, respectively, at room temperature. The room temperature Mössbauer parameters of the FeNi metal, viz. hyperfine magnetic field of 33.4(1) T with nearly zero isomer shift and quadrupole splitting, suggest that the nickel content in the metal matrix is around 5–6 wt.% [10], indicative of kamacite. In addition to these fingerprint phases, additional unidentified peaks, initially discussed by Sprenkel-Segel [11], appeared and were assigned on the basis of their Mössbauer parameters to another paramagnetic Fe³⁺ phase with an absorption area of around 5 %. The small relative spectral contribution of the ferric phases is consistent with the short terrestrial age (109 years) of this meteorite.

The ratio of the sub-spectral absorption area of olivine to that of the pyroxene can be used to differentiate between the L/LL chondrites, using the classification work by Verma et al. [12–14]. Chainpur has a rather large olivine:pyroxene area ratio of 4.55(14) which is consistent with its LL3.4 classification.

Upon lowering the temperature to 50 K, no new magnetic ordering effects were detected. However, at 13 K magnetic spectral components appear. At 13 K, an obvious decrease in the olivine doublet spectral area from 57.8(4) % to 26.9(9) % was observed, as reported in Table 1. Additionally, the pyroxene doublet shows a small decrease in absorption area from 12.7(3) % to 10.2(8) %. These changes were accompanied by the appearance of a magnetic subspectrum with a relative absorption area of 31.5(4) % (the pink component in Fig. 1), indicating the magnetic ordering of some of the olivine and pyroxene. The coexistence in the 13 K spectrum of a greatly reduced paramagnetic olivine doublet and a substantial magnetic component reflects a large range of olivine (and pyroxene) composition. Our assignment of the new magnetic subspectrum to magnetically ordered olivine is consistent with our estimate of the Fe:Mg composition in this meteoritic olivine and the magnetic ordering temperatures of ferro-magnesian olivines reported by Hoye and O'Reilly [15] and Belley et al. [16]. At this point, the Mössbauer parameters used to 'fit' the magnetically ordered olivine component should be considered *ad hoc* since, to our knowledge, there is as yet no definitive fit to the Mössbauer spectra of magnetically ordered mixed Fe:Mg composition olivine.

Finally, at 13 K we also detect another magnetic phase with a small absorption area of 4.3 % and a hyperfine magnetic field of 48.7(2) T, likely arising from a 'blocked' ferric oxide or oxyhydroxide. The appearance of this magnetic component in the Mössbauer spectrum at 13 K suggests a low blocking temperature, consistent with akaganéite (β -FeOOH) [17, 18], and is accompanied by a decrease in the superparamagnetic ferric doublet spectral area from 5.2 % at room temperature to 2.1 % at 13 K.

4 Conclusion

The iron-bearing phases in the Chainpur chondrite meteorite were identified and studied over a wide temperature range. This meteorite shows all the characteristic Mössbauer signatures of a weathered ordinary chondrite i.e. olivine, pyroxene, troilite, FeNi metal and a superparamagnetic Fe³⁺ component. On the basis of our silicate absorption areas, we confirm the LL classification of Chainpur. The effects of the magnetic ordering of the olivine were observed in the 13 K spectrum and the coexistence at 13 K of magnetically ordered and paramagnetic olivine spectral components attests to the wide range of Fe:Mg composition of this meteoritic olivine.

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