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Bhawad LL6 chondrite: Chemistry, petrology, noble gases, nuclear tracks, and cosmogenic radionuclides

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Abstract–Chemical and mineral analysis of the Bhawad chondrite, which fell in Rajasthan in 2002, suggest that this stone belongs to LL6 group of chondrites. Based on helium, neon, and argon isotopes, it has a cosmic ray exposure age of 16.3 Ma. The track density in the olivines shows a narrow range of 1.7–6.8 × 10^6/cm^2. The ^{22}Na/^{26}Al ratio of 1.13 is about 25% lower than the solar cycle average value of about 1.5, but is consistent with irradiation of the meteoroid to modulated galactic cosmic ray fluxes as expected for a fall around the solar maximum. The cosmogenic records indicate a pre-atmospheric radius of about 7.5 cm. Based on U/Th-^{4}He and K-^{40}Ar, the gas retention ages are low (about 1.1 Ga), indicating a major thermal event or shock event that lead to the complete loss of radiogenic ^{4}He and ^{40}Ar and the partial loss of radiogenic ^{129}Xe and fission Xe from ^{244}Pu.

INTRODUCTION

A small, fully crusted stone weighing about 678 g fell at Bhawad village (26°30′30″N, 73°06′55″E) in the district of Jodhpur, Rajasthan, India on June 6, 2002, at 18:00 h IST. The fall, which was witnessed by one woman, was described by Paliwal et al. (2002). Petrographic studies carried out by Paliwal et al. (2002) indicate that the meteorite belongs to metamorphic grade 6. To classify the meteorite, they carried out Mössbauer studies, but these results are ambiguous, since they concluded that it belongs to either L or LL class. We have therefore carried out a detailed chemical analysis of this meteorite, analyzing it for cosmogenic effects, e.g., radionuclides, tracks, and rare gases.

MACROSCOPIC AND MICROSCOPIC STUDIES

The stone has a well-developed fusion crust and regmaglypts formed due to atmospheric transit (Fig. 1). The fusion crust is dull black with sub-millimeter thickness. One corner of the stone has a broken appearance, and a thin fusion crust on this face suggests that the stone might have broken in the atmosphere shortly before its fall (Fig. 1). The meteorite was examined for its texture and mineralogy using optical and scanning electron microscopes (Fig. 2a). A variety of large (500 to 1000 μm) chondrules are present, but are rare and poorly preserved with ill-defined rims, sometimes recrystallized and partially replaced by matrix, as shown in Fig. 2. The meteorite shows a higher class of metamorphism from the melt flow patterns of feldspathic composition.

Chondrules, made up of mostly pyroxene, olivine, and troilite, have relict texture, corroded boundaries that are occasionally merged with the matrix (Fig. 2b), indicating the high degree of metamorphism suffered by the meteorite. A large feldspathic chondrule with degraded rim is shown in Fig. 2c. One of the chondrules shows the presence of plagioclase feldspar and has refractory inclusions such as spinel and calcium-aluminum rich phases (Fig. 2d). In one such inclusion, the energy dispersive X-ray analysis showed the presence of Cr, Al, Fe, Ti, Mg, and Ca, in decreasing order of abundances. All these observations suggest that the Bhawad meteorite belongs to petrologic class 6.

MINERAL CHEMISTRY

The olivine and pyroxene grains were analyzed in the polished thin section using the electron probe microscopy analyzer (EPMA) at the National Geophysical Research Institute (NGRI), Hyderabad, India. The results are given in Table 1. The olivine contains ~28 mol% fayalite and the

Fig. 1. The Bhawad meteorite, showing mild regmaglypts in thin fusion crust.

orthopyroxene has a ferrosilite (Fs) content of ~23 mol%. These compositions are in agreement with the chondrite class of LL.

CHEMICAL ANALYSIS AND CLASSIFICATION

The chemical composition of Bhawad chondrite was determined using instrumental neutron activation analysis (INAA), X-ray fluorescence (XRF), and inductively coupled plasma mass spectrometry (ICPMS) techniques following standard procedures. The crust and the rusted part of the meteorite were removed and the sample was cleaned with acetone, powdered, and dried at 60 °C for 3 hr. About 3 g of a meteorite chip were powdered for INAA analysis while chips of ~1 g from different locations of the meteorite were used for XRF, ICPMS, and other studies. Chemical composition of major elements was determined by XRF using a PHILIPS analytical system. The Dhajala (H3) chondrite was used as a standard. Typical uncertainty in measurement is 0.01 wt%. The mean composition, based on three independent analyses of two sets of samples, is given in Table 2. The carbon and sulfur content was measured using a C-H-N-O-S analyzer (ELEMENTER-VARIO EL III). These values are given in Table 2. The trace element composition was determined using a PERKIN ELMER ICPMS system on two aliquots of the sample. About 50 mg of the samples, as well as standards, were dissolved using microwave acid digestion; the solution was appropriately diluted and replicate analyses were made. The typical relative standard deviation of these measurements is 7%.

Five aliquots of powder (80–120 mg each) were used for INAA in two separate irradiations. The irradiated samples were counted on a high purity Ge detector (148 cm^3) housed in a 10-cm-thick lead shield, following standard procedures (e.g., Laul 1979). Columbia River basalt (BCR) and the Allende (CV) meteorite were used as INAA standards. Fe, Ni, Co, Cr, Ir, Os, Au, Sc, and Eu were measured using INAA procedures. Elemental concentrations, given in Table 2, are weighted averages. Typical errors of measurements and reproducibility were within ~5%, except for Os, where the error is ~20%. There is some systematic difference between measurements made using XRF and ICPMS for Fe, Co, and Ni, which are higher than those measured using INAA, and which may partly be due to sample inhomogeneity, since the samples for XRF/ICPMS and INAA were not taken from the same aliquot. The weighted average of the various Fe values of Bhawad is 18.5 wt%, similar to LL chondrites. The concentration of various other elements also lies in the range observed for LL chondrites (Kallemeyn et al. 1989).

The above-mentioned chemical data, as well as the mineral chemistry discussed above, suggest that Bhawad belongs to the LL group of chondrites of petrologic grade 6.

NOBLE GASES

A clean chip of the meteorite was taken for noble gas studies and a part of it was used for chemical analysis. The sample was wrapped in aluminum foil and loaded into the extraction system of the noble gas mass spectrometer. All noble gases were analyzed by stepwise pyrolysis, after an initial combustion at 400 °C in 2 torr O_2, using standard procedures described earlier (Murty 1997; Murty et al. 1998). The data reported here have been corrected for blanks, interferences, and instrumental mass discrimination. Blanks at all temperatures are <5% of the signal and have near-atmospheric isotopic composition within errors. The results of the measurements of He, Ne, and Ar are given in Table 3a, while Kr and Xe data are compiled in Tables 3b and 3c. ^{78}Kr data are not reported due to large background contribution at mass 78. Kr and Xe are at blank level in 400 °C fraction.

He and Ne consist of almost pure cosmogenic and radiogenic (^{4}He) components, while Ar, Kr, and Xe are a mixture of trapped, cosmogenic, and radiogenic (and fissiogenic) components. Using the end member

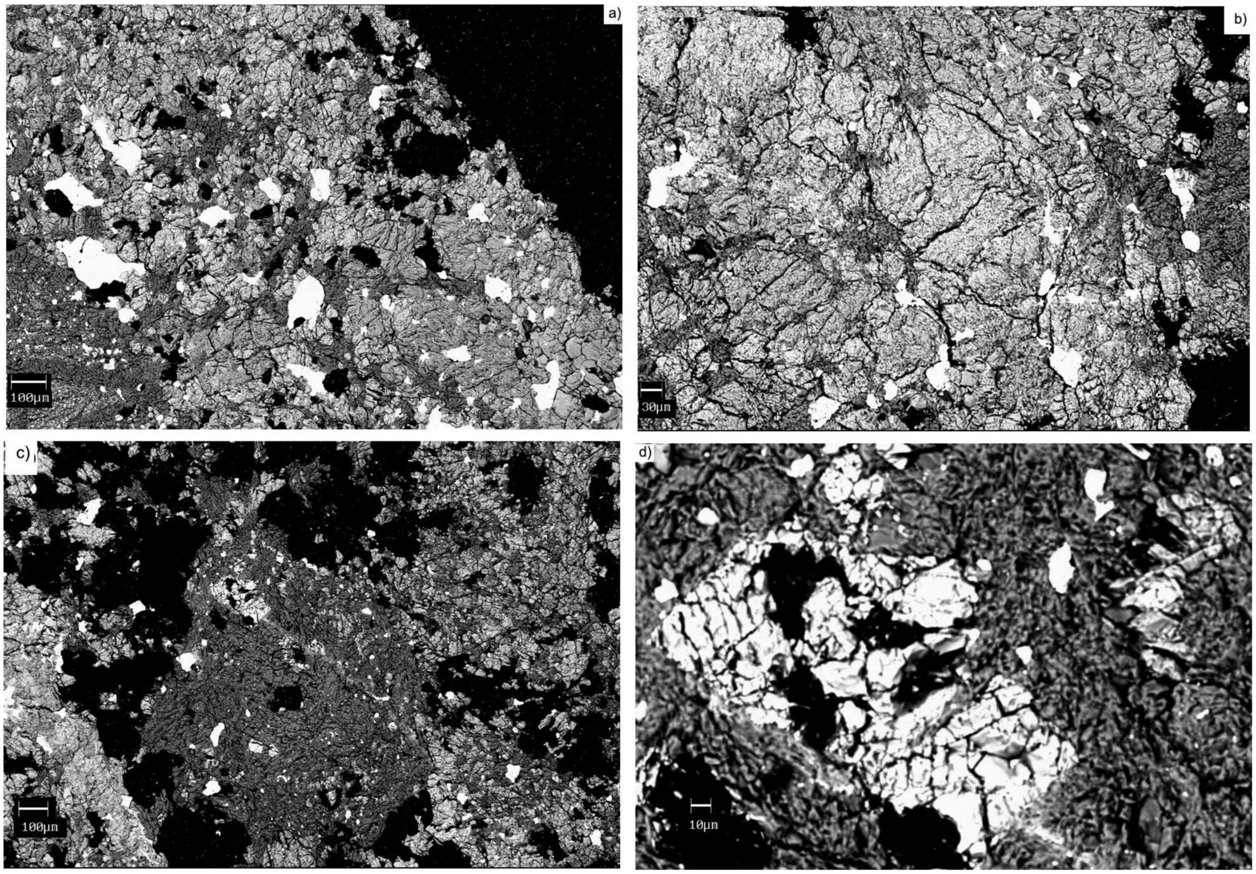

Fig. 2. a) The backscattered electron image of a thin section showing the general texture that suggests a higher petrologic type. The dark band is of feldspathic composition, which might be a signature of possible melting and thus classify this meteorite in a higher metamorphic grade, i.e., type 6. The other minerals are troilite, pyroxenes, and olivines. b) A large chondrule whose boundary can be marked by the thick development of the rim that can be identified by spherical fracture. The rim of the chondrule seems to be merged within the matrix, which is a signature of high petrologic class. c) A feldspathic chondrule with degraded rims. d) An enlarged view of the interior of a chondrule in which feldspar and a refractory grain have Cr, Mg, Al, Ca, and Ti composition.

compositions suggested by Eugster (1988) for trapped and cosmogenic components in ordinary chondrites, we have derived cosmogenic ^{3}He, ^{21}Ne, ^{38}Ar, radiogenic (^{4}He, ^{40}Ar, ^{129}Xe), and fission (^{136}Xe) components. These are given in Table 4a.

Cosmogenic Components and Exposure Ages

Cosmogenic (^{22}Ne /^{21}Ne)$_c$ has a value of 1.210 ± 0.002, indicating shallow depth in the sample analyzed for noble gases. For the chemical composition of Bhawad and the shielding parameter as given by (^{22}Ne/^{21}Ne)$_c$, production rates are calculated for ^{3}He and ^{21}Ne following the procedure suggested by Eugster (1988). In the case of ^{38}Ar, the modified procedure of Marti and Graf (1992) has been used. The exposure ages obtained for various noble gas isotopes (Table 4b) are (in Ma) T_3 = 16.7, T_{21} = 18.5, and T_{38} = 14.7. All these ages are comparable within the uncertainties of ±15%, and we take the mean of these 16.3 ± 2.5 Ma as the exposure age of Bhawad.

Radiogenic Components and Gas Retention Ages

From the radiogenic ^{4}He and ^{40}Ar (Table 4a) and the measured U (18 ppb), Th (42 ppb), and K (900 ppm) contents of Bhawad (Table 2), we derive nominal U, Th-^{4}He (T_4), and K-Ar (T_{40}) ages (Table 4b) of 1.0 and 1.2 Ga respectively. Both of these ages are in agreement within error limits and suggest that there has been a severe thermal event or shock event that lead to the complete loss of radiogenic ^{4}He and ^{40}Ar about 1 Ga ago. The measured ratios ^{129}Xe/^{132}Xe, ^{134}Xe/^{132}Xe, ^{136}Xe/^{132}Xe, and ^{86}Kr/^{84}Kr, which are higher than trapped chondritic values, indicate the presence of ^{129}Xe* (from the decay of ^{129}I) and fission contributions to ^{134}Xe and ^{136}Xe and ^{86}Kr. The radiogenic ^{129}Xe* (from ^{129}I decay), fission ^{136}Xe*, and fission ^{86}Kr* have been calculated by first correcting the measured ratios of Kr and Xe for cosmogenic contributions, using the spallation spectra of chondritic Xe (Hohenberg et al. 1981) and Kr (Lavielle and Marti 1988), and then using the corrected ratios for ^{129}Xe/^{130}Xe, ^{136}Xe/^{130}Xe, and ^{86}Kr/^{82}Kr to calculate the excess over the

Table 1. The chemical composition of olivines and pyroxenes in the Bhawad chondrite.

	Olivine			Orthopyroxene	
SiO_2 (%)	37.4	37.7	37.4	55.0	55.4
Al_2O_3	0.04	0.04	0.02	0.16	0.19
TiO_2	0.02	0.02	0.03	0.07	0.17
FeO	25.7	24.1	25.3	14.9	15.3
MnO	0.38	0.42	0.45	0.45	0.42
MgO	37.0	38.0	37.3	29.0	28.3
CaO	0.02	0.04	0.06	0.54	0.42
Na_2O	–	–	–	0.02	0.01
Cr_2O_3	–	0.06	0.04	0.13	0.15
	Fa: 28.4 mol%	Fa: 27 mol%	Fa: 28 mol%	Fs: 22.6 mol%	Fs: 23.5 mol%

Table 2. The chemical composition of the Bhawad chondrite.

Element	XRF/ICPMS	INAA	Element	XRF/ICPMS	INAA
Si (wt%)	18.5		Cs	0.15	
Al	1.29		Ba	4.24	
Ti	0.07		La	0.33	
Fe	21.5	17.4	Ce	0.82	
Mn	0.26		Pr	0.13	
Mg	15.1		Nd	0.65	
Ca	1.36	1.35	Sm	0.20	
Na	0.70	0.70	Eu	0.08	0.071
K	0.09		Gd	0.29	
P	0.13		Tb	0.05	
S	2.18		Dy	0.36	
Sc (ppm)	8.30	7.92	Ho	0.08	
V	76.5		Er	0.24	
Cr	3500/3678	3582	Tm	0.04	
Co	500/460	374	Yb	0.23	
Ni	11500/12456	6700	Lu	0.04	
Cu	92		Hf	0.17	
Zn	55	55.5	Ta	0.02	
Se		6.62	Pb	0.02	
Ga	5.3		Th	0.04	
Rb	2.0		C	<50 ppm	
Sr	13.5		Os (ppb)		331
Y	2.2		Ir		390
Zr	7.38		Au		96.7
Nb	0.33				

Errors: For XRF, the typical uncertainty in measurement is 0.01 wt%, and for ICPMS, the typical relative standard deviation is 7%. For INAA, the typical errors of measurements and reproducibility are within ~5%, except for Os, where the error is ~20%.

chondritic trapped ratios of Q composition (Busemann et al. 2000) to obtain (in 10^{-12} cm^3STP/g) the $^{129}Xe^*$ (30.7), $^{136}Xe^*$(3.53), and $^{86}Kr^*$(0.144). For the U content of 18 ppb, spontaneous fission will only produce 0.063×10^{-12} cm^3STP/g of ^{136}Xe (at 3.5×10^{-15} cm^3STP/g per ppb U), indicating that almost all of the $^{136}Xe^*$ is due to ^{244}Pu fission. The small amount of $^{86}Kr^*$ further supports this finding, as the ratio ($^{136}Xe^*/^{86}Kr^* = 25$) for Bhawad is much higher than expected for ^{238}U spontaneous fission (6.6) and is closer to ^{244}Pu fission (51) (Ozima and Podosek 2002). The ^{129}I-^{244}Pu-Xe age and the ^{244}Pu-Xe age of Bhawad can be calculated from I and Nd concentrations. We do not have the I measurement, but the Nd value is 0.65 ppm. Lugmair and Marti (1977) have shown that ^{244}Pu is similar to LREEs in its geochemical behavior and has developed a relative dating procedure with respect to the achondrite Angra dos Reis, which has an absolute Pb-Pb age of 4557.8 ± 0.4 Ma (Lugmair and Galer 1992). The relative age (ΔT) is given by the relation:

$$\Delta T = \lambda_{244}^{-1} \ln\left\{\left({}^{244}Pu/{}^{150}Nd\right)_i / \left({}^{244}Pu/{}^{150}Nd\right)_{iADOR}\right\} Ma \quad (1)$$

For Bhawad $(^{244}Pu/^{150}Nd)_i = 9.15 \times 10^{-6}$ and for ADOR it is 1.6×10^{-3} (Lugmair and Marti 1977). Taking the half-life of ^{244}Pu = 82 Ma, we get ΔT = −611 Ma. This value is unusually large as compared to the range of values [±100 Ma] found in type 5/6 ordinary chondrites (Eugster et al. 1993) and implies that Xe retention started 611 Ma after

Table 3a. He, Ne, and Ar data for the Bhawad (507.667 mg) chondrite.

Temp. (°C)	^{4}He	^{22}Ne (10^{-8}cm^{3}STP/g)	^{36}Ar	^{3}He/^{4}He	^{20}Ne/^{22}Ne	^{21}Ne/^{22}Ne	^{38}Ar/^{36}Ar	^{40}Ar/^{36}Ar
400	94.0	0.056	0.011	0.0355	2.842	0.6621	0.7408	8219
				±0.0030	0.009	0.0007	0.0247	61
1000	387.7	1.67	0.103	0.0568	1.026	0.8101	1.329	3954
				±0.0048	0.001	0.0002	0.002	37
1600	18.8	3.57	0.471	0.0427	0.8121	0.8212	0.8961	180.6
				±0.0036	0.0020	0.0005	0.0010	1.7
Total	500.5	5.29	0.585	0.0523	0.9020	0.8160	0.9691	999.2
				±0.0044	0.0018	0.0004	0.0016	9.1

Errors in concentrations are ±10%. Errors in isotopic composition represent 95% C. L.

Table 3b. Kr isotopes for the Bhawad chondrite (10^{-12}cm^{3}STP/g).

Temp. (°C)	^{84}Kr	^{80}Kr	^{82}Kr	^{83}Kr	^{86}Kr ^{84}Kr ≡ 100
1000	9.29	13.33	33.91	38.12	28.85
		±0.22	0.07	0.19	0.26
1600	27.2	6.401	23.41	24.32	30.36
		0.082	0.06	0.31	0.06
Total	36.5	8.166	26.09	27.84	29.98
		0.117	0.06	0.28	0.11

Table 3c. Xe isotopes for the Bhawad chondrite (10^{-12}cm^{3}STP/g).

Temp. (°C)	^{132}Xe	^{124}Xe	^{126}Xe	^{128}Xe	^{129}Xe	^{130}Xe ^{132}Xe ≡ 100	^{131}Xe	^{134}Xe	^{136}Xe
1000	8.18	1.396	1.711	9.969	225.2	17.12	82.18	39.65	34.49
		±0.054	0.016	0.079	1.1	0.21	0.13	0.48	0.28
1600	40.0	0.7741	0.6711	8.764	155.6	16.74	81.98	39.11	32.27
		0.0235	0.0255	0.093	0.8	0.08	0.44	0.08	0.15
Total	48.2	0.8798	0.8478	8.969	167.4	16.81	82.01	39.20	32.65
		0.0286	0.0239	0.091	0.8	0.10	0.39	0.15	0.17

Table 4a. Cosmogenic, radiogenic, fissiogenic, and trapped components (cm^{3}STP/g) in the Bhawad chondrite.

Cosmogenic			Radiogenic			Fissiogenic	Trapped		
^{3}He	^{21}Ne	^{38}Ar	^{4}He	^{40}Ar	^{129}Xe	^{136}Xe	^{36}Ar	^{84}Kr	^{132}Xe
10^{-8}	10^{-8}	10^{-8}	10^{-8}	10^{-8}	10^{-12}	10^{-12}	10^{-8}	10^{-12}	10^{-12}
26.2	4.29	0.522	364	585	31	3.53	0.237	34.6	48

Table 4b. Cosmic ray exposure ages (Ma) and gas retention ages (Ga) of the Bhawad chondrite (Errors in ages are ±15%).

Cosmic ray exposure ages			Gas retention ages	
T_3	T_{21}	T_{38}	T_4	T_{40}
16.7	18.5	14.7	1.0	1.2

ADOR formation. In such a case, no trace of ^{129}Xe* is expected since the half-life of ^{129}I is 15.7 Ma and therefore, the retention age is not realistic. This number should be taken to imply that partial loss of fission Xe occurred in a thermal/shock event late during the history of Bhawad, as is indicated by very low values of T_4 and T_{40}.

Trapped Component

Trapped He and Ne in Bhawad are negligible, while 40% of ^{36}Ar, 95% of ^{84}Kr, and 99% of ^{132}Xe are of trapped origin (Table 4b), implying that the carrier of trapped noble gases mostly contains only Ar, Kr, and Xe and no He and Ne. Phase Q fits this description well (Busemann et al. 2000). Trapped ^{84}Kr and ^{132}Xe fall in the range of values expected for petrologic type 6 (Schultz et al. 1990) and are similar to the values found in Sabrum, another LL6 chondrite (Ghosh et al. 2002). The elemental ratios (^{36}Ar/^{132}Xe) = 49.4 and (^{84}Kr/^{132}Xe) = 0.72 fall toward the lower end of the range observed for ordinary chondrites, which suggests partial loss of trapped gases and is consistent with the partial loss of radiogenic and fission gases.

Table 5. Nuclear tracks in surface samples of the Bhawad chondrite.

Sample no.	Track density tracks/cm² (no. of tracks)	Average value	Track production rate/Ma	Ablation ΔX cm
A	5.7×10^6 (500)	6.8×10^6	0.91×10^6	2.5
	7.8×10^6 (642)			
B	6.9×10^6 (280)	6.1×10^6	0.82×10^6	3.0
	6.4×10^6 (396)			
C	2.1×10^6 (203)	1.7×10^6	0.23×10^6	6.5
	1.5×10^6 (142)			
D	5.4×10^6 (271)	5.4×10^6	0.74×10^6	3.2
E	3.4×10^6 (251)	3.4×10^6	0.45×10^6	4.5

The olivine track density is converted to the pyroxene track density by multiplying with a factor of 2.2 (Bhattacharya et al. 1973).

Table 6. Cosmogenic radionuclides in the Bhawad chondrite at the time of fall.

Isotope	Half-life	γ-energy (keV)	Bhawad (LL6) Fell on June 6, 2002 Count rate (cpm)	dpm/kg
^{7}Be	53.3 d	477.56	0.119 ± 0.016	50.4 ± 6.8
^{58}Co	70.78 d	810.75	0.042 ± 0.009	2.30 ± 0.50
^{56}Co	78.8 d	846.75	0.157 ± 0.009	8.81 ± 0.50
^{46}Sc	83.9 d	889.26	0.043 ± 0.008	2.44 ± 0.46
^{57}Co	271.35 d	122.07	0.089 ± 0.009	3.56 ± 0.35
^{54}Mn	312.2 d	834.8	0.506 ± 0.008	27.8 ± 0.48
^{22}Na	2.6 y	1274.54	0.536 ± 0.007	43.1 ± 0.62
^{60}Co	5.27 y	1173.23		
		1332.51	0.003 ± 0.004	<0.25 ± 0.37
^{26}Al	7.3×10^5 y	1809.6	0.360 ± 0.005	38.2 ± 0.58
^{40}K			1.976 ± 0.012	
^{22}Na/^{26}Al				1.13 ± 0.02

PARTICLE TRACKS AND COSMOGENIC RADIONUCLIDES

Heavy nuclei tracks were studied in olivine separated from the five spot samples that were taken from different locations of the meteorite surface, following the procedure of Bhandari et al. (1980). The olivine grains were etched in WN solution for 6 hr to reveal the tracks. The track density is found to vary within a narrow range of 1.7–6.8×10^6 per cm^2 (Table 5). Taking the exposure age of 16.3 Ma and using the cosmic-ray-produced track-depth profile of Bhattacharya et al. (1973), the average shielding depth is found to be 4 cm, yielding a pre-atmospheric radius of ~7.5 cm. The mass ablation of the meteoroid is found to be 89% and it appears to belong to ablation class II, wherein the ablated thickness is comparable to the recovered radius (Bhandari et al. 1980).

The cosmogenic radioisotopes ^{7}Be, ^{58}Co, ^{56}Co, ^{46}Sc, ^{57}Co, ^{54}Mn, ^{60}Co, ^{22}Na, and ^{26}Al were measured in the Bhawad meteorite by gamma ray spectrometry. The measurements were carried out using a low-level, large (400 cm^3) hyperpure germanium detector, housed in a 20-cm-thick lead shield, described in detail in Shukla et al. (2001). The activities of the various nuclides have been estimated following the procedure of Bhandari et al. (1989), based on the assumption that potassium is homogeneously distributed within the meteorite. The results are given in Table 6.

^{60}Co is produced mainly by thermal neutrons in ^{59}Co (n, γ) reaction, and since neutrons get thermalized in large bodies, its activity depends on the size of the meteoroid in space. The very low concentration of ^{60}Co (<0.6 dpm/kg) in Bhawad (LL) indicates that the pre-atmospheric size of Bhawad was small. The ^{26}Al activity (38.2 ± 0.6 dpm/kg) for a 7.5 cm meteoroid is found to be in agreement for a shielding depth of 4 cm (Leya et al. 2000).

The activity levels of shorter-lived isotopes depend on solar modulation of galactic cosmic rays. Bhawad fell close to the solar maximum of cycle 24 and hence the activity levels of ^{22}Na, ^{54}Mn, ^{57}Co, and so on (Table 6) are small, which is consistent with the small size of the meteoroid and the expected decrease of cosmic rays due to large heliospheric magnetic field. The ^{22}Na/^{26}Al ratio of 1.13, which is relatively independent of the size of the meteoroid, is also close to the expected level calculated from the sunspot number (Bhandari et al. 1989).

In summary, the Bhawad meteorite belongs to the LL6 group of chondrites. The cosmogenic effects such as track density, ^{60}Co activity and $(^{22}Ne/^{21}Ne)_c$ of 1.210 ± 0.002 indicate a small body in space with a pre-atmospheric radius of about 7.5 cm. The gas retention ages, based on U/Th-^{4}He and K-^{40}Ar are low, about 1.1 Ga, which indicates a major thermal event or shock event that lead to the complete loss of radiogenic ^{4}He and ^{40}Ar.

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REFERENCES

Bhandari N., Lal D., Rajan R. S., Arnold J. R., Marti K., and Moore C. B. 1980. Atmospheric ablation in meteorites: A study based on cosmic ray tracks and neon isotopes. *Nuclear Tracks* 4: 213–262.

Bhandari N., Bonino G., Callegari E., Cini Castagnoli G., Mathew K. J., Padia J. T., and Queirazza G. 1989. The Torino, H6 meteorite shower. *Meteoritics* 24:29–34.

Bhattacharya S. K., Goswami J. N., and Lal D. 1973. Semiempirical rates of formation of cosmic ray tracks in spherical objects exposed in space: Pre-atmospheric and post-atmospheric depth profiles. *Journal of Geophysical Research* 78:8356–8363.

Busemann H., Baur H., and Wieler R. 2000. Primordial noble gases in "phase Q" in carbonaceous and ordinary chondrites studied by closed system stepped etching. *Meteoritics & Planetary Science* 35:949–973.

Eugster O. 1988. Cosmic ray production rates for ^{3}He, ^{21}Ne, ^{38}Ar, ^{82}Kr, and ^{126}Xe in chondrites based on ^{81}Kr-Kr exposure ages. *Geochimica et Cosmochimica Acta* 52:1649–1662.

Eugster O., Michel T., Nidermann S., Wang D., and Yi W. 1993. The record of cosmogenic, radiogenic, fissiogenic, and trapped noble gases in recently recovered Chinese and other chondrites. *Geochimica et Cosmochimica Acta* 57:1115–1142.

Ghosh S., Murty S. V. S., Pant N. C., Ghosh J. B., Shome S., Shukla A. D., Mahajan R. R., Shukla P. N., and Bhandari N. 2002. Fall, classification, and cosmogenic records of the Sabrum (LL6) chondrite. *Meteoritics & Planetary Science* 37:439–448.

Hohenberg C. M., Hudson B., Kennedy B. M., and Podosek F. A. 1981. Xenon spallation systematics in Angra dos Reis. *Geochimica et Cosmochimica Acta* 45:1909–1915.

Kallemeyn G. W., Rubin A. E., Wang D., and Wasson J. T. 1989. Ordinary chondrites—Bulk composition, classification, lithophile-element fractionations, and composition-petrographic type relationships. *Geochimica et Cosmochimica Acta* 53:2747–2767.

Laul J. C. 1979. Neutron activation analysis of geological materials. *Atomic Energy Review* 17:603–695.

Lavielle B. and Marti K. 1988. Cosmic ray produced Kr in St. Severin core AIII. Proceedings, 8th Lunar Science Conference. pp. 565–572.

Leya I., Lange H.-J., Neumann S., Wieler R., and Michel R. 2000. The production of cosmogenic nuclides in stony meteoroids by galactic cosmic ray particles. *Meteoritics & Planetary Science* 35:259–286.

Lugmair G. W. and Galer S. J. G. 1992. Age and isotopic relationships among the angrites Lewis Cliff 86010 and Angra dos Reis. *Geochimica et Cosmochimica Acta* 56:1673–1694.

Lugmair G. W. and Marti K.1977. Sm-Nd-Pu timepieces in the Angra dos Reis meteorite. *Earth and Planetary Sciences Letters* 35: 273–284.

Marti K. and Graf T. 1992. Cosmic ray exposure history of ordinary chondrites. *Annual Review of Earth and Planetary Sciences* 20: 221–243.

Murty S. V. S. 1997. Noble gases and nitrogen in Muong Nong tektites. *Meteoritics* 32:687–691.

Murty S. V. S., Bhandari N., Suthar K. M., Clement C. J., Bonino G., and Castagnoli G. C. 1998. Cosmogenic effects in Mbale, L5/6 chondrite. *Meteoritics & Planetary Science* 33:1311–1316.

Ozima M. and Podosek F. A. 2002. *Noble gas geochemistry,* 2nd ed. Cambridge: Cambridge University Press. 286 p.

Paliwal B. S., Sisodia M. S., Trpathi R. P. 2002. Bhawad L(LL)6 chondrite: Petrography and Mössbauer study. *Current Science* 83:1071–1072.

Schultz L., Weber H. W., and Begemann F. 1990. Planetary noble gases in H3- and H4- chondrite falls. *Meteoritics* 25:405.

Shukla A. D., Adhyaru P., and Bhandari N. 2001. Highly sensitive γ-γ coincidence/anticoincidence spectrometer for measurement of low radioactivity in meteorites (abstract). Proceedings, Symposium on Nuclear Analytical and Radiochemistry. pp. 554–555.