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Noble gases, nitrogen and cosmic ray exposure age of the Sulagiri chondrite

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ABSTRACT

The Sulagiri meteorite fell in India on 12 September 2008, LL6 chondrite class is the largest among all the Indian meteorites. Isotopic compositions of noble gases (He, Ne, Ar, Kr and Xe) and nitrogen in the Sulagiri meteorite and cosmic ray exposure history are discussed. Low cosmogenic $(^{22}Ne/^{21}Ne)_c$ ratio is consistent with irradiation in a large body. Cosmogenic noble gases indicate that Sulagiri has a 4π cosmic-ray exposure (CRE) age of 27.9 ± 3.4 Ma and is a member of the peak of CRE age distribution of LL chondrites. Radiogenic ^{4}He and ^{40}Ar concentrations in Sulagiri yields the radiogenic ages as 2.29 and 4.56 Ga, indicating the loss of He from the meteorite. Xenon and krypton are mixture of Q and spallogenic components.

1. Introduction

Meteorites are important sources for understanding the origin and evolution of solar system, and various processes occurred in early solar system. Every year several meteorites fall on Earth. More than 25,000 fragments of meteorites are recovered from hot and cold deserts (Meteoritical society data base), however, they are subject to weathering and contaminations (Lee and Bland, 2004) during stay on open conditions after fall, until recovery and careful preservation afterwards. To get a fresh piece of meteorite is therefore important and hence the recovery of meteorites immediately after the fall. During last three decades, 22 meteorites felled in India, of various sizes and chemical classes, Didwana-Rajod (H5), Lohawat (Howardite), Itawa Bhoji (L3-5), Sabrum (LL6), Kendrapara (H5), Bhawad (LL6), Kavarpura (Iron), Bhuka (Iron), Piplia-Kalan (Eucrite), Jodiya (L5), Devari-khera (L6), Mahadevpur (H4/5), Kasauli (H4), Dergaon (H3), Devgaon (H5), Vissannapeta (Eucrite), Kaprada (L5/6), Katol (L6-7), Jalangi, Karimatti (L/LL), Nathdwara (H6) and Sulagiri (LL6), most of them were recovered immediately, with one find Aradki (L5). Some general information on recent Indian meteorites (fall/find after 1990) with their weight and date of fall etc. is given in Table 1. A 110 kg meteorite fell at Sulagiri in Krishnagari district of state Tamil Nadu, India on 12 Sept. 2008 around 8.30 h local time and is the largest meteorite among all the Indian meteorites (around 130 so far) and classified as LL6 chondrite (Murty et al., 2009a). Ordinary chondrites are more common in these falls during last three decades.

The petrological investigation shows that Sulagiri is composed of orthopyroxene and olivine (Murty et al., 2009a), presence of varying textures and sizes chondrule, with poorly defined boundaries. Cosmogenic radionuclide indicates the pre-atmospheric radius ∼40 cm against recovered size ∼20 cm indicates 90% mass loss (Murty et al., 2009a). In this paper noble gases and nitrogen composition in Sulagiri chondrite are reported to understand the cosmic ray exposure history and trapped noble gas and nitrogen components. The CRE history of Sulagiri meteorite is investigated based on production rates of noble gases and concentrations of cosmogenic noble gases.

2. Experimental procedures

Noble gases and nitrogen analyses were performed at Physical Research Laboratory, Ahmedabad, India, using VG1200 (VG micromass, U.K.) mass spectrometer, by stepwise heating. The exact

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Table 1
List of Indian meteorites fall/find during last three decades.

Meteorite	Fall/find	Year of fall/find	Weight (kg)	Fragments	Type	Reference
Aradki	Find	2001	4.460	Single	L5	Bhandari et al. (2008)
Bhawad	Fall	6 June 2002	0.678	Single	LL6	Bhandari et al. (2005)
Bhuka	Fall	25 June 2005	2.5	Single	Iron	Shrivastava et al. (2005)
Dergaon	Fall	2 March 2001	13	Several	H5	Shukla et al. (2005)
Devgaon	Fall	12 Feb. 2001	12.0	Single	H3	Murty et al. (2004)
Didwana-Rajod	Fall	12 Aug. 1991	1	Single	H5	Paliwal et al. (2001)
Devari-khera	Fall	30 Oct. 1994	1.14	Six	L6	Murty et al. (2010)
Itawa Bhoji	Fall	30 May 2000	1	Single	L(3–5)	Bhandari et al. (2002)
Jalangi	Fall	8 July 2012	2	–	–	GSI website
Jodiya	Fall	31 July 2006	0.1	Shower	L5	Murty et al. (2009b)
Kaprada	Fall	28 Oct 2004	1.6	Single	L(5/6)	Bhandari et al. (2009)
Karimatti	Fall	28 May 2009	1	Single	L/LL	Layek and Verma (2009)
Kasauli	Fall	2 Nov. 2003	16.82	Single	H4	Chattopadhyay et al. (2005)
Katol	Fall	22 May 2012	13	Shower	L6–7	Suresh et al. (2013)
Kavarpura	Fall	29 Aug 2006	6.8	Single	Iron	Murty et al. (2008)
Kendrapara	Fall	27 Sept. 2003	~6	Six	H5	Dhingra et al. (2004)
Lohawat	Fall	30 Oct. 1994	6.245	Several	Howardite	Sisodia et al. (2001)
Mahadevpur	Fall	21 Feb. 2007	70	Several	H(4/5)	Murty et al. (2009b)
Nathdwara	Fall	25 Dec. 2012	1.5	Single	H6	Agarwal et al. (2014)
Piplia-Kalan	Fall	20 June 1996	30	Shower	Eucrite	Vaya et al. (1996)
Sabrum	Fall	30 April 1999	1.5	Single	LL6	Ghosh et al. (2002)
Sulagiri	Fall	12 Sept. 2008	110	Seven	LL6	Murty et al. (2009a)
Vissannapeta	Fall	13 Dec. 1997	1.304	Single	Eucrite	Mahajan et al. (2000)

location of the sample analysed in the meteorite recovered used for this study is not known. A 465.22 mg sample was wrapped in Al foil and loaded into the glass extraction system. The sample was heated at 150 °C for two days to drive off atmospheric gases adsorbed on the surface. Blanks were measured before and after the analysis of sample. The gas extraction at 400 °C is by combustion and at higher temperature, 800 °C and 1600 °C by pyrolysis. Extracted gas was divided into two parts, one for nitrogen analysis and other for noble gas analysis. Split fraction for nitrogen analyses was cleaned by generating oxygen from CuO (at 2 torr pressure) and then collecting the volatiles in cold finger with external liquid nitrogen trap. Noble gas fraction was cleaned by exposing the gas to Ti-Zr getter at 750 °C. Heavy noble gases (Ar-Kr-Xe) were collected on a charcoal trap by liquid nitrogen and the He-Ne in gas was measured. Liquid nitrogen trap was maintained during He-Ne measurements to remove background gases and interfering species. Typical blanks in cm^3 STP unit are $^4He = 6.1 \times 10^{-7}$, $^{22}Ne = 9.4 \times 10^{-10}$, $^{36}Ar = 2.1 \times 10^{-11}$, $^{84}Kr = 2.5 \times 10^{-13}$, $^{132}Xe = 1.8 \times 10^{-13}$ and for nitrogen (in μg) 0.0015 at 1600 °C temperature. The mass spectrometer was calibrated for sensitivity using air noble gas from reservoir. The measured noble gas concentrations in Sulagiri, as listed in Table 2, are accurate to ~10%. Data reported are corrected for blanks, interference and mass discrimination. Errors reported include uncertainties derived from all corrections including volume calibration (experimental details and calibration and other details are given elsewhere Murty, 1997).

3. Results on noble gases and nitrogen

The isotopic ratios and concentrations of noble gases (He, Ne, Ar and Kr), nitrogen and Xe are given in Tables 2 and 3 respectively. Statistical 1σ errors are given for the isotopic ratios. The measured $^{38}Ar/^{36}Ar$ and $^{40}Ar/^{36}Ar$ ratios during the step-heating gas extraction vary from 0.60 to 0.77 and 11,892 to 1319 respectively, indicating the mixing of cosmogenic, radiogenic and trapped argon components. Major concentration of the ^{22}Ne (94%), ^{36}Ar (89%), ^{84}Kr (100%) and ^{132}Xe (100%) is released at 1600 °C, but helium-4, major which released at low temperatures (64%). 54% of total ^{14}N is released at 1600 °C. The trapped noble gas abundances in Sulagiri, $^{20}Ne = 0.84 \times 10^{-8}$, $^{36}Ar = 1.23 \times 10^{-8}$, $^{84}Kr = 1.0 \times 10^{-10}$ and $^{132}Xe = 76.2 \times 10^{-12}$ cm^3 STP/g are within the range of other LL chondritic bulk measurements (Alaerts et al., 1979).

In a three-isotope plot of $^{20}Ne/^{22}Ne$ versus $^{21}Ne/^{22}Ne$ for the individual temperature steps (Fig. 1) the neon isotope data of Sulagiri data is shown. A fit of the data yields a trapped $(^{20}Ne/^{22}Ne)_{tr}$ ratio of 10.36 ± 0.65 for $^{21}Ne/^{22}Ne = 0.03$. The trapped $(^{20}Ne/^{36}Ar)_{tr}$ ratio is 0.68, indicating the trapped gases in this meteorite is planetary noble gases, as is also evident from trapped $(^{84}Kr/^{132}Xe)_{tr}$ ratio as 1.33.

The krypton and xenon isotopes indicate that it is a complex mixture of various components. The results cannot be explained by a simple binary mixture of Q and spallogenic components, indicating the existence of additional components such as ^{244}Pu-fission produced xenon. As shown in $^{131}Xe/^{132}Xe$ vs. $^{128}Xe/^{132}Xe$ plot (Fig. 2) the data falls in triangle between spallogenic, Q and ^{244}Pu-fission xenon.

The cosmogenic $(^{20}Ne/^{22}Ne)_c = 1.094$ is calculated based on the model of Leya and Masarik (2009) and using the chemical composition of Sulagiri (Aarthy et al., 2012). The cosmogenic ration $(^{20}Ne/^{22}Ne)_c$, 1.094 indicates a shallow depth of the sample analysed. The recovered mass, 110 kg confirms it. For cosmogenic corrections $(^{38}Ar/^{36}Ar)_c = 1.53$ (Wieler, 2002) are used to obtain $^{36}Ar_{tr}$ and concentrations of ^{40}Ar and ^4He are assumed to be entirely radiogenic. For calculation of cosmogenic, trapped Ne was used from best fit line ($^{20}Ne/^{22}Ne = 10.36$), trapped Ar was assumed to be air like and trapped Kr and Xe isotopic composition is used for chondrites given by Marti (1967). Cosmogenic, trapped and elemental concentrations of noble gases are given in Table 4.

Cosmic ray exposure (CRE) ages of cosmogenic ^{21}Ne (T_{21}) and ^{38}Ar (T_{38}) are calculated from the cosmogenic noble gas concentrations, the production rates derived from Dalcher et al. (2013). The production rates calculated for Sulagiri composition are, $P(^{21}Ne_c) = 0.402 \times 10^{-8}$ and $P(^{38}Ar_c) = 0.0477 \times 10^{-8}$ cm^3 STP/g/Ma. The 4π CRE ages are, $T_{21} = 26.3 \pm 2.9$, and $T_{38} = 29.5 \pm 1.5$ Ma. The average CRE age obtained from $^{21}Ne_c$ and $^{38}Ar_c$ is 27.9 ± 3.4 Ma and adopted as the exposure age for Sulagiri chondrite. For calculation of CRE age using cosmogenic ^3He_c, Eugster (1988) production method is used. The CRE age derived from cosmogenic