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Spectacular fall of the Kendrapara H5 chondrite

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Abstract–An extremely bright fireball was seen for over 250 km near the eastern coast of India in the evening sky on September 27, 2003. In a rare observation, the fireball was seen by two airline pilots, providing direction of the trail with reasonable accuracy, consistent with ground-based observations. A few fragments of the meteorite were subsequently recovered along the end of the trail in different parts of Kendrapara district (20°30′ N; 86°26′ E) of Orissa. Based on petrography and chemical composition, the meteorite is classified as H5 chondrite. The cosmogenic radionuclides ^{54}Mn, ^{22}Na, ^{60}Co, and ^{26}Al and tracks have been studied in this stony meteorite. Two of the fragments show an unusually high activity of ^{60}Co (~160 dpm/kg) indicating a meteoroid radius of 50–150 cm. Assuming that less than 10% (by weight) of the fragments could be recovered because of difficult terrain, an atmospheric mass ablation of >95% is estimated. Based on the observations of the trail and the estimated mass ablation, orbital parameters of the meteoroid have been calculated. The aphelion is found to lie in the asteroidal belt (1.8–2.4 AU), but the inclination of the orbit is large (22°–26°) with respect to the ecliptic. Noble gases have been analysed in two samples of this meteorite. He and Ne are dominantly cosmogenic. Using production rates based on the sample depth derived from ^{60}Co content, ^{21}Ne-based exposure age of 4.50 ± 0.45 Ma is derived for Kendrapara. One of the samples, known to be more deeply shielded based on high ^{60}Co activity, shows the presence of ^{80}Kr, ^{82}Kr, and ^{128}Xe produced by (n, γ) reaction on ^{79}Br, ^{81}Br, and ^{127}I, respectively. The $(^{80}\mathrm{Kr}/^{82}\mathrm{Kr})_n$ ratio of 3.5 ± 0.9 is consistent with neutrons being mostly thermal. Trapped ^{84}Kr and ^{132}Xe are in the expected range for metamorphic grade H5.

THE FIREBALL

A big fireball was seen over the eastern coast of India on September 27, 2003 at about 1830 IST, covering over 250 km, starting in the north at Digha in West Bengal to Angul in Central Orissa, developing into a bright blue-white trail, and traveling all the way south to Chilika Lake, covering Mayurbhanj, Balasore, Bhadrak, Jajpur, Khurda, Cuttack, Bhubaneswar, Kendrapara, and Jagatsinghpur. The event lasted several seconds and was accompanied by many detonating sounds. Subsequently, ~6 stony meteoritic fragments weighing from 50 g to about 6 kg were recovered from a number of places in the Kendrapara district of coastal Orissa. Locations of two of them are shown in Fig. 1a. These include the remote villages of Benakanda and Paschim Suniti in the Mahakalpada block that first reported the recovery of the meteorite fragments. The large fragments are preserved with the Geological Survey of India and the local authorities of the Orissa government. From the field survey, it appears that many more fragments may have fallen, and only a small fraction (~10%) could be recovered because of heavy raining during the week of the fall. Further, standing paddy crops in the fields made it difficult to identify and recover the fragments.

In a rare observation, two airline pilots flying toward Kolkata saw the trail in its full glory. Captain A. Ranganathan, commander of the Air Sahara flight from Bangalore to Kolkata, flying at an altitude of 11.3 km, described it in the following way:

"I saw what appeared like a normal shooting star from the north. What appeared like a whitish streak started becoming

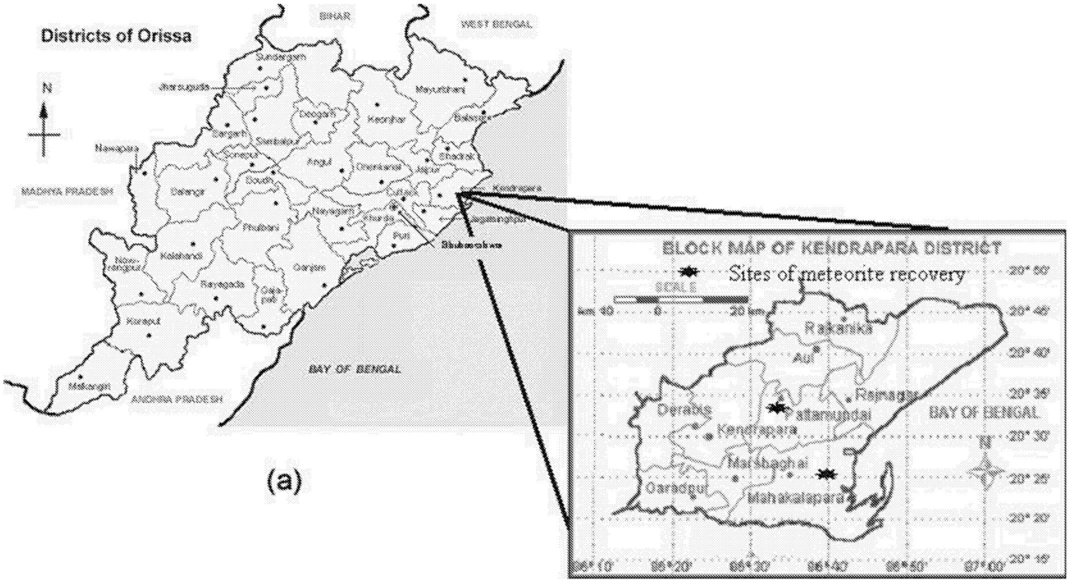


Fig. 1a. The map of Orissa showing the sites of meteorite recovery.

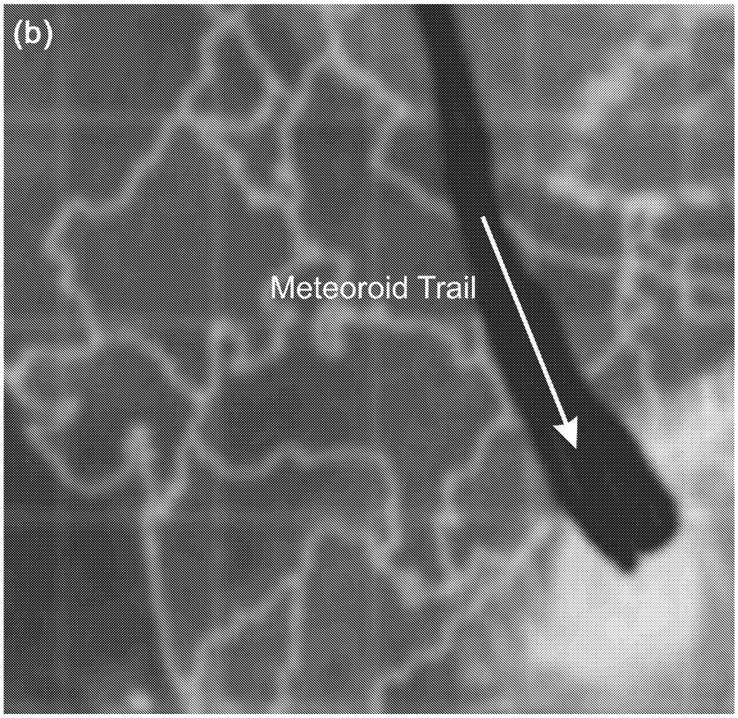


Fig. 1b. Observation of the fireball trail by an Air Sahara pilot.

red and growing bigger until it became an absolutely brilliant bluish green fireball. The sight was stunning. The size of the fireball was enormous, filling our front windshield completely, hurtling straight at us.

"Just when I thought that we were going to be blown out of the sky, the whole sky turned into an incandescent blue green light, almost as brilliant as mid-day sun. The fireball burnt out just in front of our eyes!!! It was an amazing but frightening sight.

"After we had covered another 21 nautical miles along our track, I could see whisps of smoke drifting across the sky above us. The smoke layer was about 1500 to 3000 m above our altitude of about 11.3 km. I think the fireball exploded around that altitude (13 to 14.5 km) above mean sea level."

Captain Ranganathan estimates the angle of elevation of the trail as 60° with an azimuth of 345 ± 5°. The direction of the trail as given by the pilot is shown in Fig. 1b. Subsequently, we recorded the observations of several

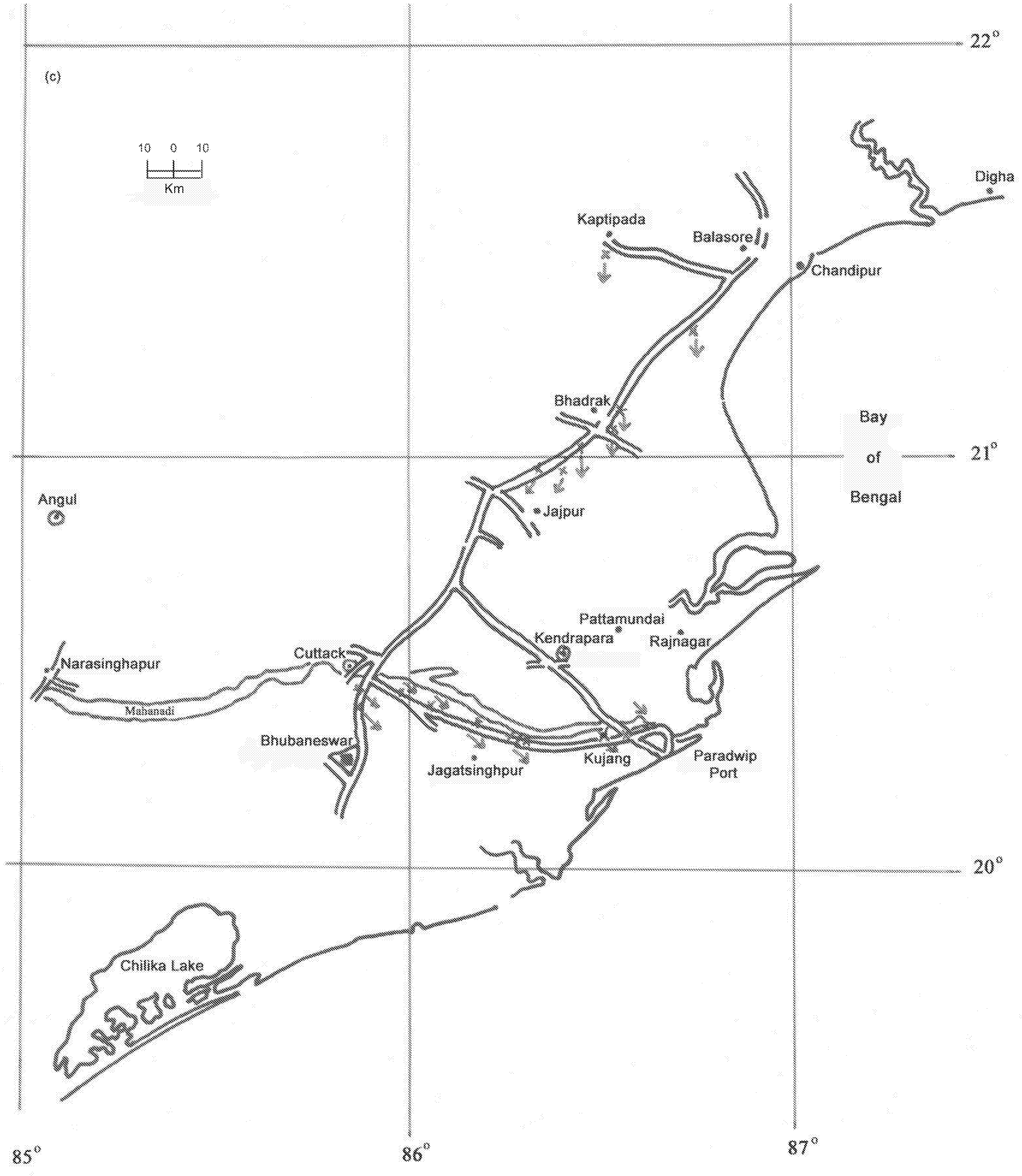


Fig. 1c. Direction of trail (marked by arrows) as inferred from the eyewitness accounts.

eyewitnesses during our ground survey that covered a distance of more than 300 km between October 3–4, 2003. Figure 1c shows the direction of the meteoroid trail as inferred from the eyewitness accounts. In spite of the inaccuracies involved in such estimates by unqualified observers, it appears that the fireball was traveling from north to south, or slightly northwest to southeast for the most part. But then, toward the end of the trail, it turned eastward. Such a change in direction is only possible after the fragments slow down and become small enough to be drifted easily by the local wind currents.

The event was extensively reported by the media, sometimes based on heresay, without verifying its authenticity. There were reports that as many as 11 curious onlookers became unconscious after witnessing the event. One of them, Sukadeb Singh (75), died in SCB Medical College in Cuttack one day after the event took place. Other reports could not be confirmed. Likewise, there were reports that two huts caught fire because of the hot meteorite fragments that fell on them. On enquiry, one report turned out to be false. When we visited the other site at Sudusudia village, the thatched roof of the hut had indeed burnt from the top, as would be expected by a hot body falling from the sky. However, no meteorite fragments were recovered from the ashes collected from the hut. Some metallic objects (mm to 2 cm in size) with white luster looked unusual, but their physical examination and absence of any cosmogenic radioactivity in the largest piece indicated that they were not fragments of the meteorite. Since, during the monsoon season, the roof is usually wet and since no meteorite fragment was recovered, it is difficult to comment on whether or not the roof caught fire because of the meteorite.

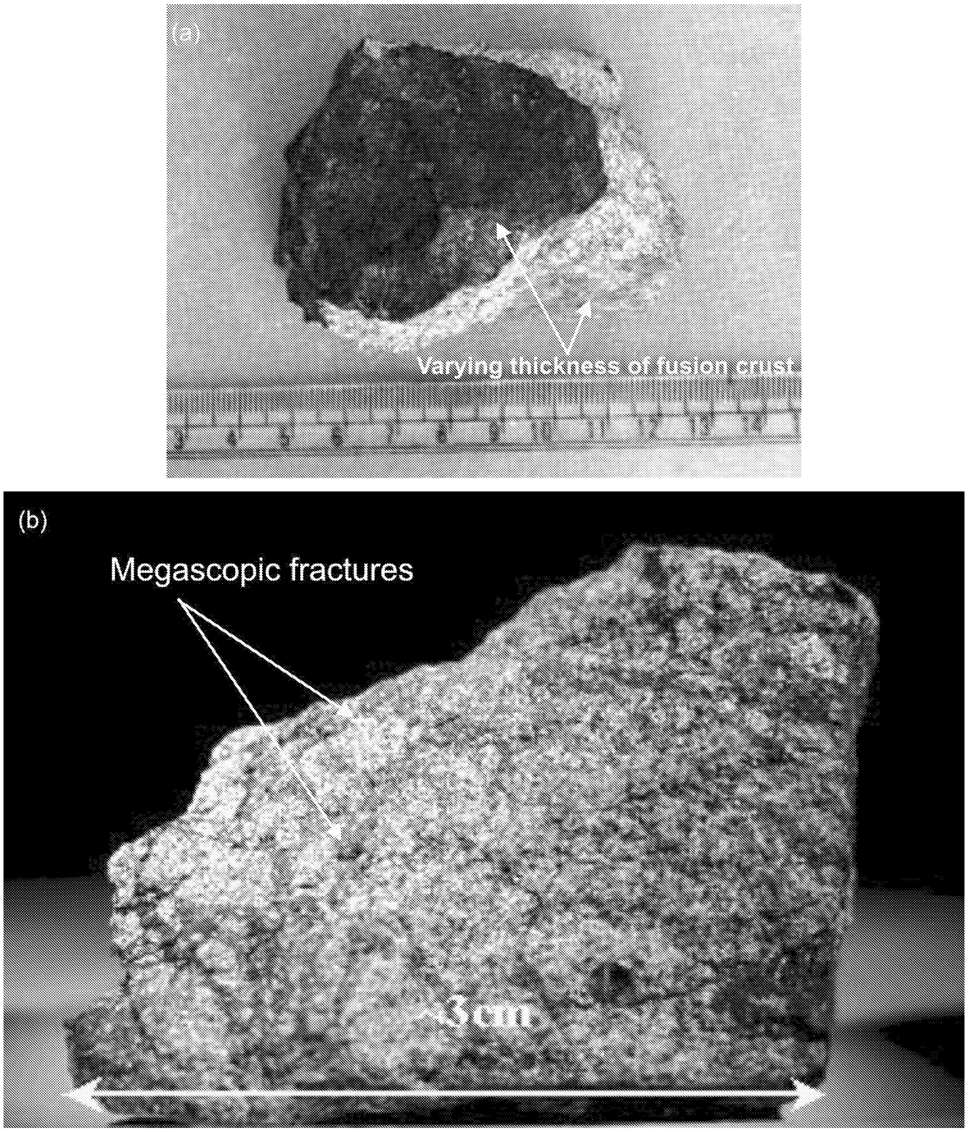
MACROSCOPIC EXAMINATION OF THE FRAGMENTS

Physical examination of the stones showed that most of the fragments have a thick mature fusion crust with regmaglypts, typical of meteorites. Figures 2a and 2b show some of the recovered fragments. On some surfaces, the fusion crust is extremely thin and barely recognizable, indicating fragmentation just before slowing down. Several generations of the crust indicate multiple fragmentation events, one being at about 14 km, as observed by the airline pilot. Figure 2c shows a pothole created by one of the falling stones in a field in the Mahakalpada block.

Dark metallic veins filling up the fractured planes in the meteorite are easily seen, indicating a high degree of metamorphism. Chondrules are rare, although one as big as 3 mm in diameter was seen Fig. 2d.

PETROGRAPHY, CHEMICAL COMPOSITION, AND CLASSIFICATION

Thin section studies show that the meteorite is heavily shocked, having fractured grains. Some photomicrographs of the thin sections are shown in Fig. 3, exhibiting chondrules at various stages of degradation and minerals like olivine and



Figs. 2a and 2b. Some fragments of the recovered meteorite.

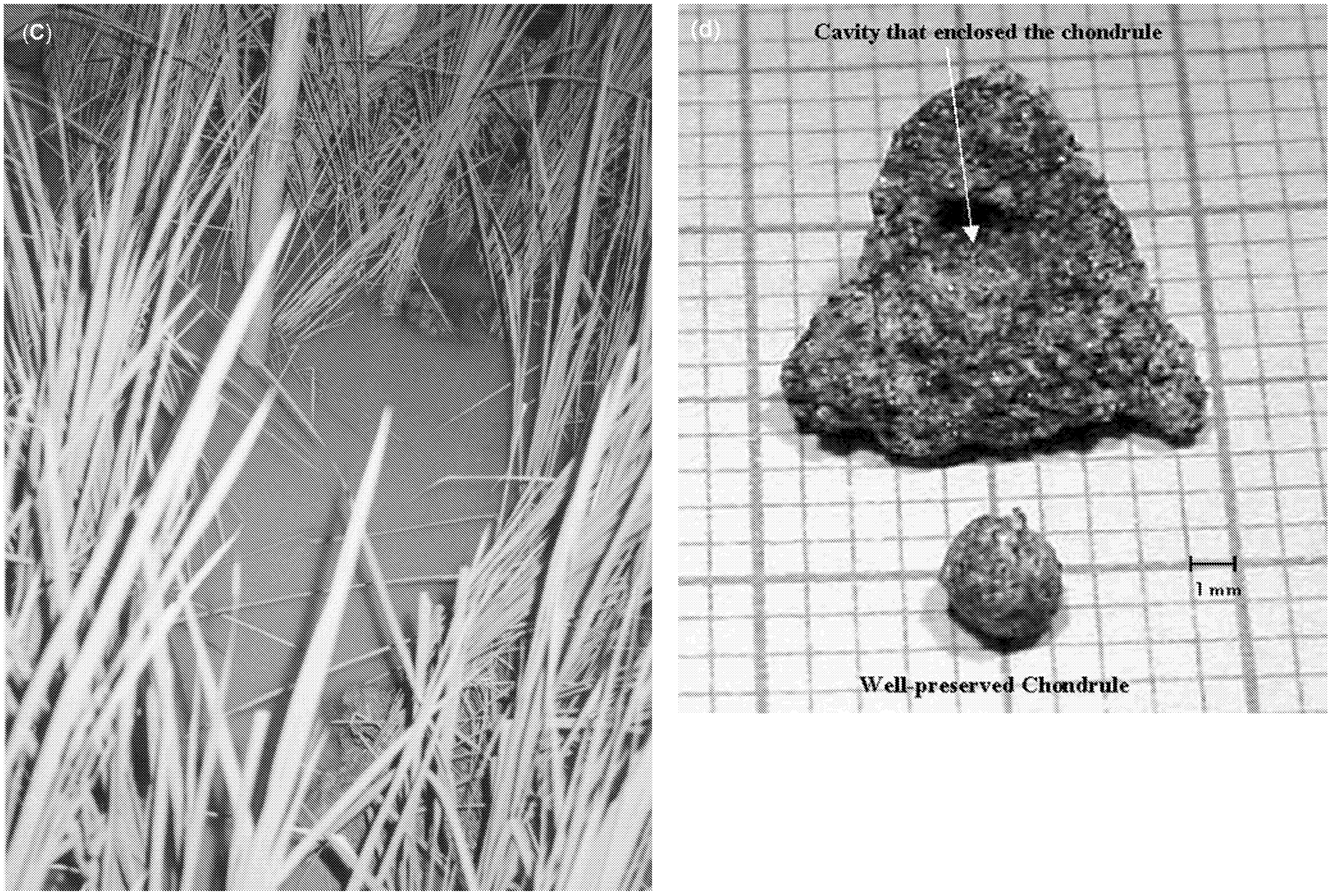


Fig. 2. c) One of the largest fragments was recovered from a paddy field. The falling stone formed a big pothole; d) a large chondrule recovered from one of the meteorite fragments. The grid is 1 mm across.

opaques. Based on these studies, the meteorite is classified as belonging to grade 2 of Stöffler et al. (1991) and grade 5 of Van Schmus and Wood (1967).

The chemical composition of the major elements was determined by X-ray fluorescence (XRF). For XRF, we used a PHILIPS analytical system at the National Geophysical Research Institute, Hyderabad. The crust and rusted part of the meteorite was removed, the sample was cleaned with acetone, powdered, and dried at 60° C for three hours. 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 on two sets of samples is given in Table 1a. The carbon, hydrogen, nitrogen, and sulfur content was measured using a C-H-N-O-S Analyzer (ELEMENTER—VARIO EL III). These values are given in Table 1a except for nitrogen because of the possibility of contamination during processing. The trace element composition was determined using a PERKIN ELMER ICP-MS system on two aliquots of the sample. About 50 mg of the samples and the standards were dissolved using the microwave acid-digestion technique following the procedure described by Balaram and Gnaneshwar Rao (2003). The solution was appropriately diluted, and replicate analyses were made. The typical relative standard deviation in these measurements is 7%. The results are given in Table 1b. The K concentration of 813 ± 27 ppm was measured with better accuracy by gamma ray spectrometry (Table 2) rather than XRF measurements (Table 1). The content of Fe (27.7%) and the values of Mg/Si = 0.83, Al/Si = 0.073, and Fe/Si = 1.62 match with the values of H-group chondrites (Krot et al. 2003), and hence, we classify the stone as belonging to the H5 group. The concentrations of other elements (Table 1) matches reasonably well with mean H-group concentrations.

COSMOGENIC RADIONUCLIDES AND TRACKS

Cosmogenic radioisotopes ^{56,57,58,60}Co, ^{54}Mn, ^{22}Na, and ^{26}Al were measured in three small fragments (A, B, and C) weighing 37 to 274 g by gamma ray spectrometry. Since larger fragments were not made available to us quickly enough, the opportunity of measuring the short-lived radioisotopes was lost. The measurements were carried out with a low level, large (400 cm^3) hyper-pure germanium detector, located in a 20 cm-thick lead shield described in detail elsewhere (Shukla et al. 2001). ^{40}K (as well as ^{60}Co,

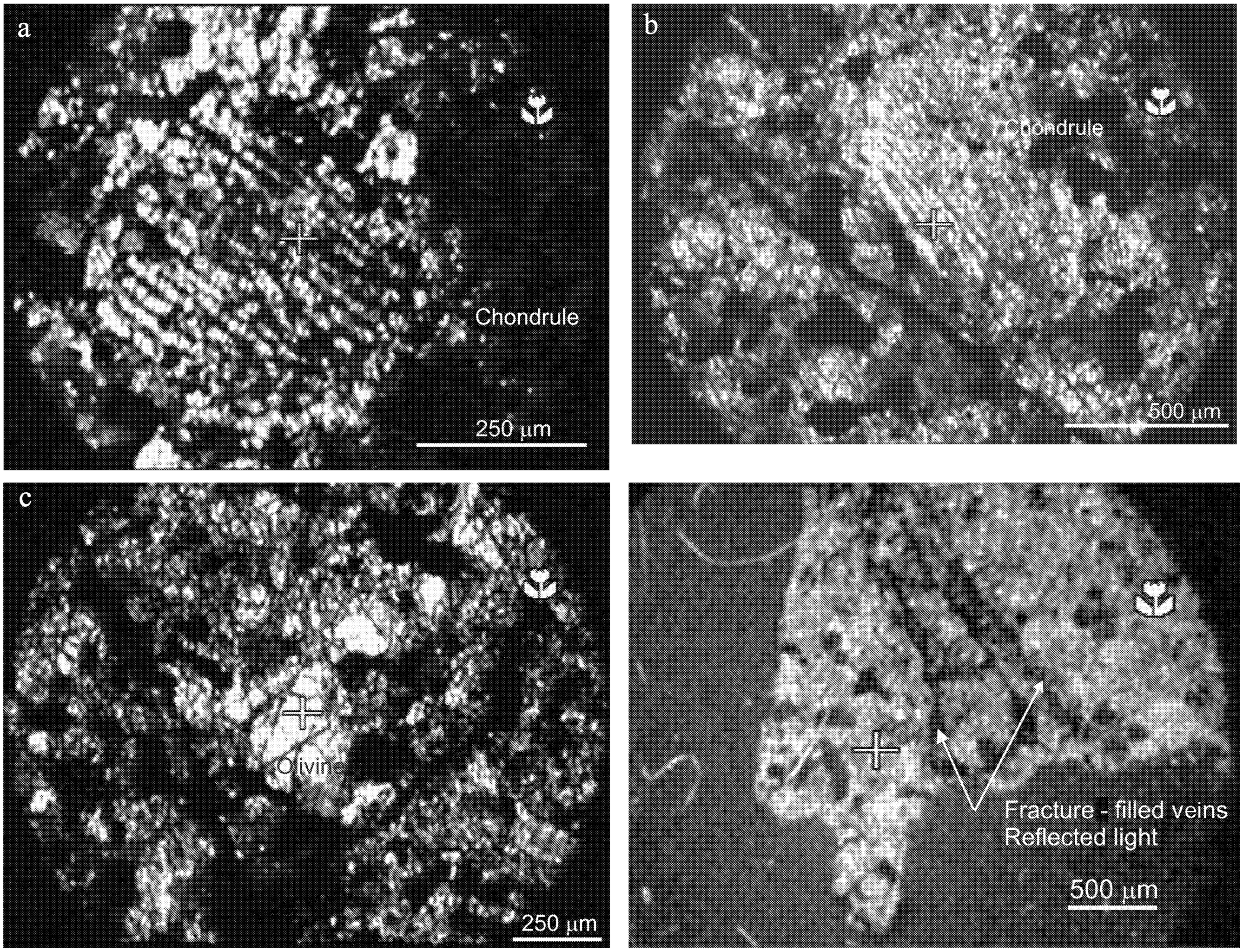


Fig. 3. Photomicrographs of thin sections showing degraded chondrules, olivine, opaque minerals, and metal filled veins.

^{54}Mn, ^{22}Na, and ^{26}Al) was measured in a 54.95 g sample of fragment A in a standard geometry, and the K content was found to be 813 ± 27 ppm. This value was used for determining the counting efficiency and geometry corrections of various fragments following the procedure of Bhandari et al. (1989). The results are given in Table 2.

We have also carried out a study of heavy nuclei tracks in olivine separated from the three fragments following the procedure of Bhandari et al. (1980). The olivine grains were etched in a WN solution for six hours to reveal the tracks. In only one fragment (A), the tracks show measurable density of 7×10^4/cm^2. The density of the tracks was too low to be measured in other fragments ($<10^4$/cm^2). The track density indicates a shielding depth of 9 cm in sample A and >12 cm in other samples (including sample B used for noble gas studies, as discussed later).

The production rates of the radioisotopes depend on the flux of galactic cosmic rays, which, for isotopes with a half-life shorter than a few years (e.g., $^{56, 57, 58}$Co, ^{54}Mn, ^{22}Na), depend on modulation due to the 11 yr sunspot cycle. The cosmogenic radioisotopes, particularly radionuclide ^{60}Co, produced by the neutron capture (n, γ) reaction on stable ^{59}Co, and tracks are useful in estimating the pre-atmospheric size of the meteoroid. The activity of ^{60}Co varies by a factor of three in the three fragments—from 45 to 162 dpm/kg. The value of 162 dpm/kg is among the highest values observed in ordinary chondrites; it is only slightly less than the maximum value found in Jilin, which is known to be part of a large body in space (Heusser et al. 1985). Comparing these values with the expected profiles calculated for cobalt concentration of 850 ppm in this meteorite (Eberhardt et al. 1963; Spergel et al. 1986; Potdar et al. 1986), we estimate the pre-atmospheric radius of the Kendrapara meteoroid to be between 50–150 cm, corresponding to the meteoroid weight of 2 to ~50 tons before it entered Earth's atmosphere. It is difficult to estimate the total weight of fragments that fell due to this meteorite shower. Under the best of conditions, e.g., in the case of Dhajala, the recovery efficiency was only about 60–70%. But, considering the unfavorable field conditions, the recovery efficiency for the

Table 1a. Major and some trace element composition of the Kendrapara meteorite based on the XRF and C-H-N-O-S analyzer.

Element	Concentration (wt %)
Si	17.0
Mg	14.11
Ca	1.29
Al	1.22
Fe	27.7
Ni	1.77
Co	0.085
Cr	0.33
Mn	0.265
K	0.08
P	0.15
Na	0.61
Ti	0.065
S	1.93
H	0.22
C	0.17

Table 1b. Trace element composition of the Kendrapara meteorite.

Elements	Concentration (ppm)
Sc	8.49
V	73.9
Cr	3685
Co	850
Ni	17450
Cu	89.5
Zn	46.6
Ga	2.7
Rb	3.69
Sr	9.17
Y	2.14
Zr	6.12
Nb	0.66
Cs	0.089
Ba	5.60
La	0.34
Ce	0.756
Pr	0.126
Nd	0.556
Sm	0.219
Eu	0.085
Gd	0.295
Tb	0.054
Dy	0.342
Ho	0.076
Er	0.235
Tm	0.0446
Yb	0.225
Lu	0.037
Hf	0.170
Ta	0.0253
Pb	0.23
Th	0.043
U	0.017

Kendrapara shower should be no more than 10% (by weight), i.e., the amount of material that fell must be around 200 kg or less. Using this estimate, the mass ablation is estimated to lie in the range of 90% to 99.5%. Ablation depends on the geocentric velocity, and according to the models of Baldwin and Scheaffer (1971) and the calculations given by Potdar (1981), such high ablation is typical of meteoroids with geocentric velocity ≥18 km/s. Any reasonable error in estimating the ablation, because of uncertainty in the recovery, does not significantly change the estimated velocity of the meteoroid.

MODULATION OF COSMIC RAYS

The meteorite fell at the time of the descending phase of solar cycle 23, when the cosmic ray intensity was gradually increasing. The radioisotopes with a half-life of a few years (like ^{54}Mn and ^{22}Na) represent the average galactic cosmic ray flux during the past 1 to 3 years. The activity of both of these radioisotopes is low (Table 2) compared with the average production rate estimated from the model of Michel et al. (1991) but are consistent with the expected values during the phase of the solar cycle (Bhandari et al. 1993, 1994; Bonino and Castagnoli 1997) when the meteorite fell. The observed mean activity of ^{54}Mn in the three fragments (115 dpm/kg) is consistent with the activity expected at the time of fall, calculated using the sun spot numbers (Fig. 4b), and the variation (102 to 125 dpm/kg) in different fragments can be understood in terms of different shielding of the samples to cosmic rays, consistent with track density variation.

^{22}Na and ^{26}Al are produced in similar nuclear reactions in various targets present in the meteorite, and therefore, the size and shielding effects are nearly similar for them. Therefore, we use the ratio of ^{22}Na/^{26}Al to estimate the solar modulation. The data are shown in Fig. 4 for all the chondrite falls since 1965 where the values are available. A good agreement is seen for the observed and calculated ^{22}Na/^{26}Al, indicating a simple one-stage exposure history of the meteorite for the past 1 or 2 million years.

NOBLE GASES

About a half gram sample from two fragments, Kendrapara-A and -B, having significantly different shielding depths as determined from ^{60}Co, were used for noble gas measurements. The procedure has been described in detail earlier (Murty 1997; Murty et al. 1998). Briefly, the samples were wrapped in Al foils and loaded into the extraction system of a noble gas mass spectrometer (VG 1200). The results reported here have been corrected for blanks (≤5% of the signal for all gases and for air composition within errors), instrumental mass discrimination, and interferences, and the associated errors have been propagated. The data for He, Ne,

Table 2. Cosmogenic radioactivity and track data

		Fragment A (54. 95 g)	Fragment B (37.6 g)	Fragment C (50.3 g)
Radioisotope	Half-life	dpm/kg at time of fall		
^{54}Mn	312 d	102.5	125	119
^{22}Na	2.6 yr	60.6	48.4	47
^{26}Al	7.3×10^5	49.4	46.3	52.5
^{60}Co	5.27 yr	44.7	145	162
^{22}Na/^{26}Al		1.23	1.05	0.9
Track density		7×10^4/cm^2	$<10^4$	$<10^4$
		K = 813 ± 27 ppm		

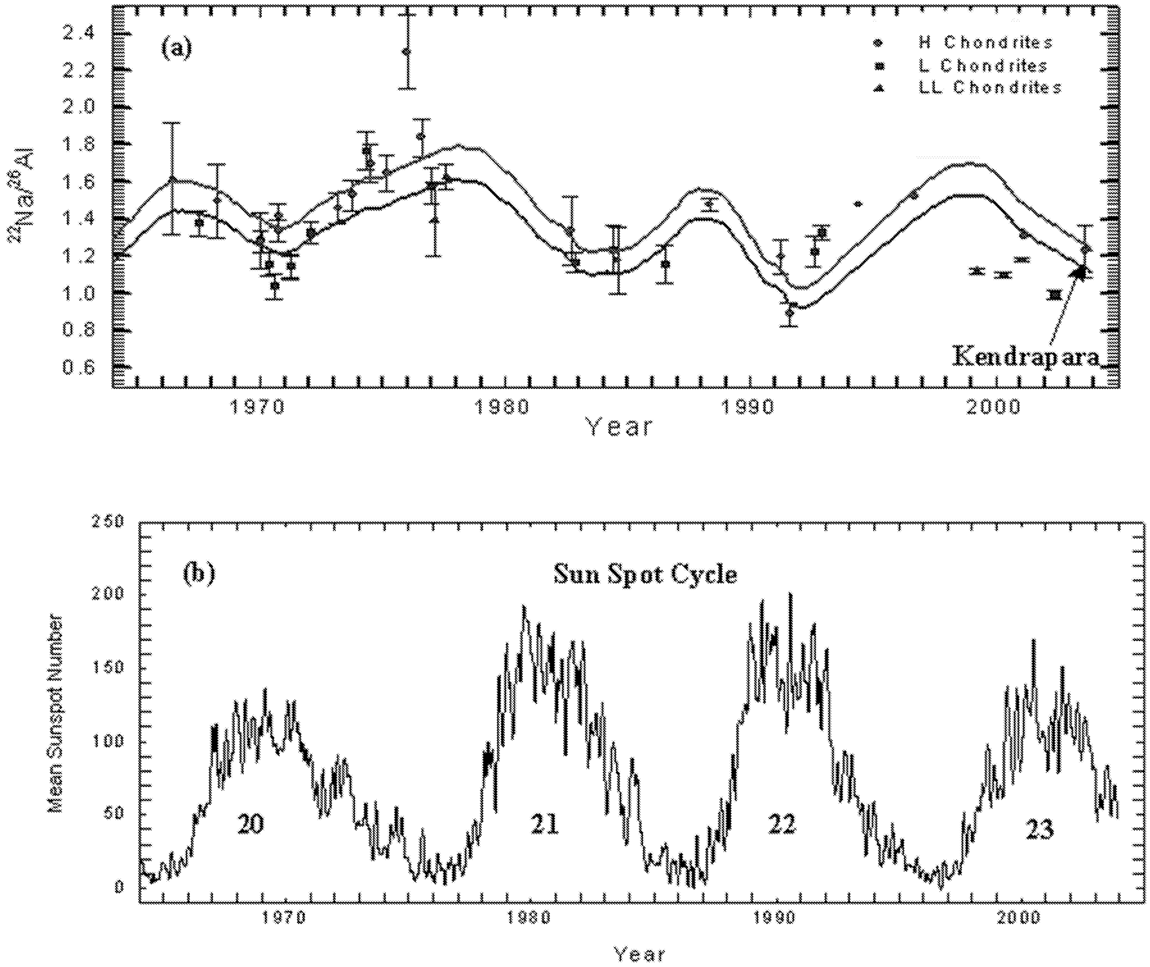


Fig. 4. a) Solar cycle variation of ^{22}Na/^{26}Al in H, L, and LL chondrite falls after Bhandari et al. (1994). The Kendrapara point is marked. The solid curves have been calculated from the Sun spot numbers as a function of time shown in (b).

and Ar are compiled in Table 3, while the data for Kr and Xe are given in Tables 4 and 5, respectively. The errors in concentration are ±10% (He, Ne, Ar) and ±15% (Kr, Xe), while the errors in the isotopic ratio correspond to 95% confidence limits.

Light Noble Gases

He is a mixture of radiogenic (^{4}He) and cosmogenic components. All measured ^{3}He is considered to be cosmogenic, and the radiogenic ^{4}He is calculated by correcting the measured ^{4}He for cosmogenic contribution using (^{3}He/^{4}He)$_c$ = 0.2 (Eugster 1988). There is a small amount of trapped Ne in both samples. We derive the cosmogenic ratio (^{22}Ne/^{21}Ne)$_c$ of 1.069 ± 0.005 and 1.046 ± 0.003 for samples A and B, respectively. These values are low in general and indicate that they come from deeply shielded locations, consistent with track and ^{60}Co data. The ratio (^{22}Ne/^{21}Ne)$_c$ is generally used as a shielding parameter to derive shielding dependent production rates (Eugster 1988; Graf and Marti 1992). However, this ratio is not a reliable

Table 3. Isotopic composition of He, Ne, and Ar in Kendrapara samples.

	^{4}He	^{22}Ne	^{36}Ar					
Temp. (°C)	10^{-8} cm^3 STP/g			^{3}He/^{4}He (10^{-4})	^{20}Ne/^{22}Ne	^{21}Ne/^{22}Ne	^{38}Ar/^{36}Ar	^{40}Ar/^{36}Ar
Kendrapara-A (511.783 mg)								
400	17.5	0.020	0.01	388.2 ± 32.8	3.730 ± .050	0.5218 ± .0082	0.4587 ± .0168	5728 ± 43
1000	481	0.497	0.05	78.8 ± 6.7	1.047 ± .010	0.9122 ± .0032	0.6721 ± .0060	58132 ± 553
1200	49.6	0.422	0.097	28.9 ± 2.4	1.277 ± .020	0.8868 ± .0062	0.4757 ± .0002	2160 ± 21
1600	16.6	0.451	0.402	14.0 ± 1.2	1.122 ± .003	0.9111 ± .0035	0.2867 ± .0001	468 ± 4
Total	565	1.39	0.557	82.1 ± 7.0	1.179 ± .011	0.8987 ± .0042	0.3569 ± .0015	6021 ± 57
Kendrapara-B (515.195 mg)								
400	157	0.041	0.080	74.3 ± 6.3	1.955 ± .032	0.6579 ± .0095	0.2869 ± .0017	13335 ± 124
1000	658	0.572	0.047	49.5 ± 4.2	0.9325 ± .0089	0.9264 ± .0022	0.5474 ± .0030	77970 ± 741
1200	37.0	0.411	0.128	36.1 ± 3.1	1.095 ± .012	0.9416 ± .0014	0.4156 ± .0007	1626 ± 16
1600	13.5	0.468	0.421	24.8 ± 2.1	0.9880 ± .0056	0.9600 ± .0044	0.2973 ± .0001	487 ± 5
Total	866	1.49	0.677	53.1 ± 4.5	1.023 ± .009	0.9338 ± .0026	0.3360 ± .0006	7632 ± 72

Table 4. Isotopic composition of krypton.

	^{84}Kr	^{80}Kr	^{82}Kr	^{83}Kr	^{86}Kr
Sample	10^{-12} cm^3 STP/g	^{84}Kr ≡ 100			
Kendrapara-A	67.1	5.004 ± .112	21.554 ± .184	21.993 ± .143	30.806 ± .141
Kendrapara-B	131.6	8.653 ± .161	22.080 ± .161	21.267 ± .169	31.169 ± .156

Table 5. Isotopic composition of xenon.

	^{132}Xe	^{124}Xe	^{126}Xe	^{128}Xe	^{129}Xe	^{130}Xe	^{131}Xe	^{134}Xe	^{136}Xe
Sample	10^{-12} cm^3 STP/g	^{132}Xe ≡ 100							
Kendrapara-A	88.7	0.6206 ± .0296	0.6767 ± 0.409	8.577 ± .057	113.5 ± .5	16.14 ± .08	81.82 ± .16	38.17 ± .09	32.46 ± .23
Kendrapara-B	120	0.6792 ± .0453	0.6387 ± .0194	8.760 ± .072	127.4 ± .3	16.49 ± .11	81.99 ± .26	38 46 ± .10	32.53 ± .16

depth indicator when $(^{22}Ne/^{21}Ne)_c$ ≤1.08, (Masarik et al. 2001; Leya et al. 2001).

Therefore, we use the measured track density and ^{60}Co activity of the samples as depth indicator to derive production rates. Track density gives a shielding depth of 9 cm for sample A, and their absence in sample B gives a lower limit of 12 cm as discussed earlier. To get a better estimate of the shielding depth of sample B, we compare the ^{60}Co activity of Kendrapara with the Jilin (H5) chondrite (Heusser et al. 1985), which gives a shielding depth of 30 cm for sample B. Using these depths of 9 and 30 cm, we have computed the production rates for ^{3}He and ^{21}Ne using the chemical composition of Kendrapara and the obtained exposure ages T_3 and T_{21} for sample A (3.35 and 4.40 Ma) and for sample B (3.38 and 4.63 Ma) as given in Table 6a. Realizing the possible presence of nucleogenic $^{36}Ar_n$ from a ^{35}Cl (n, γ) reaction and its effect on T_{38} (Bogard et al. 1995; Wieler et al. 1996; Bhandari et al. 2002; Murty et al. 2004), we did not use $^{38}Ar_c$ for exposure age calculation. Both samples, thus, give consistent ages, with T_3 being about 25% lower. This may be due to partial loss of ^{3}He (in the form of ^{3}H from metal), which is more prominently observed in metal-rich H chondrites (Hintenberger et al. 1966). We take the average of the two ^{21}Ne-based ages for sample A and B of 4.50 ± 0.45 Ma as the exposure age of Kendrapara.

Radiogenic Components and Gas Retention Ages

The radiogenic components for samples A and B and the gas retention ages (calculated using measured U, Th, and K contents and the radiogenic gas components) T_4 and T_{40} are given in Table 6b. K-Ar ages are higher as compared to U-Th-^{4}He ages, suggesting diffusive loss of ^{4}He. Also, sample A has lower K-Ar as well as U-Th-^{4}He ages, suggesting greater gas loss for sample A. Considering the fact that both samples give closely matching exposure ages based on ^{3}He, it is clear that any differential loss of ^{4}He (and, hence, of ^{40}Ar) are signatures of event(s) that pre-date the break-up event that initiated the cosmic ray exposure of the meteoroid 4.5 Ma ago. This gas loss event could be inferred to either coincide or predate the minimum age given by T_4 (i.e., 1.5 Ga for sample A) and might indicate a large impact on the parent asteroid of Kendrapara at about 1.5 Ga.

Kr and Xe

Kr and Xe isotopic data for the totals suggest excesses at ^{80}Kr, ^{82}Kr, and ^{128}Xe over and above what is expected by usual spallation. We first calculate the excesses over the trapped composition (taken to be Q-Xe and Q-Kr; Busemann et al. 2000). From these excesses, the expected spallation contributions have been subtracted, taking excesses of ^{83}Kr and ^{126}Xe to be due purely to spallation and using the spallation spectra of Kr (Leoville and Marti 1988) and Xe

Table 6a. Cosmogenic components, production rates[a] (10^{-8} cm^3 STP/gMa), and exposure ages (Ma).

	^{3}He	^{21}Ne					
Sample	10^{-8} cm^3 STP/g		$(^{22}Ne/^{21}Ne)_c$	P_{21}	P_3	T_3	T_{21}
Kendrapara-A	4.64	1.25	1.069 ± .005	0.283	1.386	3.35 ± .33	4.40 ± .44
Kendrapara-B	4.60	1.39	1.046 ± .003	0.300	1.36	3.38 ± .34	4.63 ± .46

[a] P_{21} from Leya et al. (2000); P_3 from Leya et al. (2004).

Table 6b. Radiogenic and nucleogenic components (in cm^3 STP/g units) and gas retention ages (Ga).

	^{4}He	^{40}Ar	^{129}Xe	^{80}Kr	^{82}Kr	^{128}Xe			
Sample	10^{-6}		10^{-12}				$(^{80}Kr/^{82}Kr)_n$	T_4	T_{40}
Kendrapara-A	5.42 ± .54	33.6 ± 3.4	9.4 ± 1.5	0.135 ± .147	0.049 ± .145	~0	–	1.47 ± .15	3.48 ± .35
Kendrapara-B	8.42 ± .84	51.7 ± 5.2	29.3 ± 4.4	6.00 ± .93	1.71 ± .36	0.167 ± .094	3.51 ± .92	2.13 ± .21	4.16 ± .42

Table 7. Calculated orbital elements of the Kendrapara meteoroid for various geocentric velocities based on deduced coordinates of the radiant (RA: 279.76°; Dec: 49.86°).

Geocentric velocity (km/s)	16	17	18	20	22
a (AU)	1.45	1.61	1.81	2.41	3.7
e	0.31	0.38	0.44	0.58	0.73
i	19.3	21.05	22.65	25.49	27.97
Node (deg)	183.98	183.98	183.98	193.98	183.98
Longitude of perihelion (deg)	186.58	186.26	186.04	185.75	185.57
q (AU)	1	1	1	1	1

(Hohenberg et al. 1981). These excesses are thus attributed to (n, γ) reactions on the halogen isotopes ^{79}Br, ^{81}Br, and ^{127}I and can be expected on the basis of high ^{60}Co activities. These neutron-produced components are compiled in Table 6b. They roughly correlate with the ^{60}Co activity, being high in sample B and marginal in sample A. The reason for their not scaling like ^{60}Co may be due to heterogeneity in the halogen contents of samples A and B. The radiogenic ^{129}Xe in sample B is about three times larger and would indicate three times higher abundances of I (and, hence, of other halogens). The ratio of activities of ^{60}Co in both these samples (B/A) is ~3.2, while that of $^{82}Kr_n$ ~10 (taking upper limit values for both samples), but if halogen contents that are higher by factor of three in sample B are taken into consideration, this ratio, $(^{82}Kr_n)_B/(^{82}Kr_n)_A$ ~3.3, is in agreement with the ^{60}Co activity ratio. Also, the ratio $(^{80}Kr/^{82}Kr)_n = 3.5 \pm 0.9$ will be closer to the value expected for predominantly thermal neutrons (Marti et al. 1966). The trapped gas amounts of ^{84}Kr and ^{132}Xe fall in the expected range for the metamorphic grade H5 (Schultz et al. 1990).

ORBIT OF THE METEOROID

The radiant of the trail was estimated from the observations made by the airline pilot, which allowed us to estimate the values of RA: 279.76° and Dec: 49.86°. Using these values and a range of geocentric velocities (16 to 22 km/s), we have calculated the probable orbit of the meteoroid, following the procedure of Porter (1952) used earlier by Ballabh et al. (1978) in the case of the Dhajala chondrite. The probable orbital elements are given in Table 7, which indicate that the aphelion lies in the asteroidal belt, "a" being in the range of 1.45 to 3.7 AU, e = 0.3 to 0.73, but the inclination is high (19 to 28°). There are very few asteroidal streams at this high heliolatitude. Within the given uncertainties, the closest match is obtained with the Hungaria group of asteroids (a = 1.8 to 2 AU; i = 18–20°) if v is taken to be 18 km/s.

The Dhajala (H3) meteorite also had a high inclination (27.6°). It fell in 1976 at the time of solar minimum between sunspot cycles 20 and 21. High ^{22}Na (73–135 dpm/kg) and ^{54}Mn (123–144dpm/kg) in Dhajala were interpreted as being due to higher flux of galactic cosmic rays at high heliolatitudes (Bhandari et al. 1978; Potdar et al. 1986). In contrast, Kendrapara, with a high inclination, fell just after the solar maximum of cycle 23. It will be interesting to compare the flux of cosmic rays at solar maximum and solar minimum, at high heliolatitudes. Such studies are in progress and will be discussed separately.

Soon after the fall of the meteorite, the Lowell observatory reported a small asteroid going past the Earth at an altitude of about 90,000 km at 27.94 UT. The asteroid is one of the closest ever seen, probably the third nearest observed so far in the Earth-crossing orbit. This asteroid, which was observed between September 27 and 29, 2003, has been named SQ_{222}. It had a large magnitude (H = 29.986). From its magnitude, its size has been estimated to be about 8 m. In view of the timing and the closeness of the orbit to the Earth, it was speculated that the Kendrapara meteorite might be a fragment of SQ_{222}. However, the orbital parameter of SQ_{222}, estimated from the telescopic observations (a = 1.505 AU, e = 0.5187, i = 3.562°), and Kendrapara (Table 7) do not match, indicating that these bodies are not related.

SUMMARY

The fireball associated with this meteorite was one of the brightest observed during the past decade, with a trail extending over 250 km. Chemical and petrological studies suggest it to be an ordinary chondrite belonging to the H5 class. High ^{60}Co activity in various fragments suggests a large pre-atmospheric radius (50–150 cm) of the meteoroid. During its passage through the Earth's atmosphere, it underwent significant (>95%) ablation. Activities of various cosmogenic radionuclides (^{26}Al, ^{22}Na, etc.) are consistent with the solar modulation during the descending phase of the solar cycle 23. The rare gas exposure age is found to be 4.5 Ma, and one of the fragments show large activity of ^{60}Co and neutron capture components in Kr and Xe isotopes, indicating the large size of the meteoroid.

The orbital parameters of this meteorite were calculated using the radiant determined by the airline pilot who observed the trail during flight and plausible values of geocentric velocity (18–20 km/s) estimated from ablation models. The aphelion lies in the asteroidal belt ($a = 1.8$ to 2.4 AU, $e = 0.44$ to 0.58), but the inclination is high (22 to 26°), making it an interesting object to estimate the cosmic ray fluxes at high heliolatitudes.

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