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Cosmogenic radioisotopes in the Almahata Sitta ureilite

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Abstract–Asteroid 2008 TC_3 was predicted to fall in Sudan on October 7, 2008, and 2 months later, 15 meteorite fragments were recovered from the Nubian Desert. Most of these fragments were classified as polymict ureilites. In the largest ureilitic fragment #15, weighing 75 g, we have measured six gamma emitting radionuclides (^{46}Sc, ^{57}Co, ^{54}Mn, ^{22}Na, ^{60}Co, and ^{26}Al) by nondestructive whole rock counting using a sensitive gamma-ray spectrometer. The activities of ^{60}Co, produced mainly by neutron capture in cobalt, and ^{26}Al indicate that fragment #15 was located at a depth of 41 ± 14 cm inside the 1.5–2 m radius asteroid. The activity of other radionuclides is also consistent with this shielding depth within the asteroid. The ^{22}Na/^{26}Al activity ratio is higher than expected for the average cosmic ray flux, probably due to the unusually prolonged solar minimum before the fall.

INTRODUCTION

Asteroid 2008 TC_3 was seen telescopically prior to entering the Earth's atmosphere on October 7, 2008. The entry in the Earth's atmosphere was at a grazing angle of 20° with velocity of 12.4 km s^{-1}. The asteroid fragmented at an unusually high altitude of approximately 37 km and fell in the Nubian Desert of northern Sudan. A small fraction survived in macroscopic form to reach the ground as meteorites. During the first search campaign in December of 2008, 15 stones weighing 563 g were collected (Jenniskens et al. 2009; Shaddad et al. 2010).

Based on photometry of the asteroid and the albedo of the recovered meteorites, known as Almahata Sitta (mentioned hereafter as Alma), the radial size of the asteroid was estimated to be between 1.5 and 2 m. Its bulk density is not known, but should lie between the values for the lightest (approximately 1.8 g cm^{-3}) and the densest (approximately 3.1 g cm^{-3}) recovered fragments, possible voids in the asteroid not included. Therefore, its mass ranged between 25 and 100 tons.

Based on petrographic, chemical, and oxygen isotopic analysis, Alma has been classified as an achondrite, a polymict ureilite containing a few anomalous chondritic fragments (Jenniskens et al. 2009; Rumble et al. 2010; Zolensky et al. 2010). Some Alma fragments, unlike other known ureilites, are very porous and heterogeneous, and contain variable amounts of carbonaceous aggregates, resulting in a density as low as approximately 1.8 g cm^{-3}, whereas other fragments have normal, typical ureilitic matter of higher 2.7–3.1 g cm^{-3} density (Shaddad et al. 2010; Kohout et al. 2010; Zolensky et al. 2010).

Fragment #15 (Fig. 1) was made available to us for nondestructive gamma ray counting 7 months after the fall. The 75 g fragment was one of three fragments larger than 40 g recovered in the first search campaign, and the only ureilite. The other two meteorites were fresh-looking chondrites of different types, both thought

Fig. 1. Fragment #15 of Almahata Sitta, weighing 75 g. The scale is in cm. The shape of this fragment is important for determination of the gamma acquisition efficiency, for which its mold labeled with known radioisotopes was made.

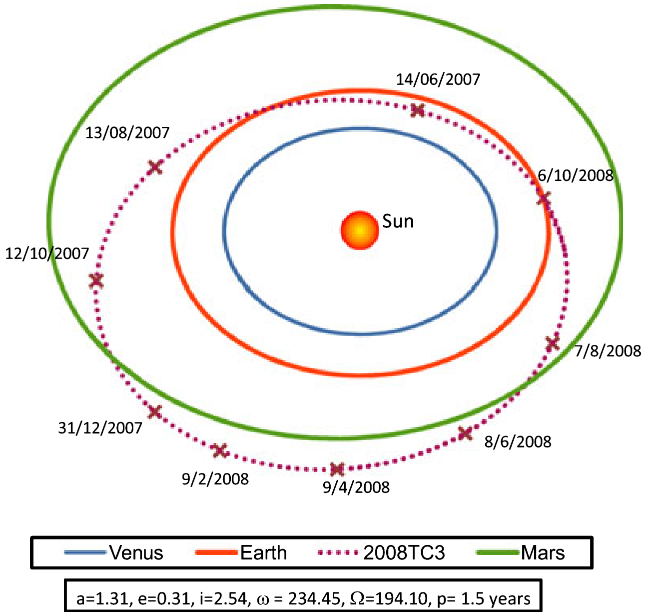

Fig. 2. The orbit of the meteoroid 2008 TC_3 calculated based on the parameters given by Jenniskens et al. (2009). The positions are marked with a cross at different dates before its fall.

to have fallen from 2008 TC_3 (Shaddad et al. 2010). The ureilite #15 had a density of 3.11 $+0.14/-0.07$ g cm^{-3} (Shaddad et al. 2010). Other Alma ureilites for which the density was measured tended to be less dense, with a mass-weighted mean density of 2.77 $+0.14/-0.11$ g cm^{-3}.

Cosmic rays (CR) produce a large number of radioactive and stable isotopes in asteroids and meteoroids while they are exposed in the interplanetary space and before they fall on the Earth where the CR irradiation becomes negligible. The orbit of 2008 TC_3 just before impact (Fig. 2) had a low inclination ($i = 2.54°$) and an aphelion in the inner asteroid belt (semi major axis $a = 1.308$ AU). Hence, before its fall it recorded the CRs in the near Earth space within about 0.9–1.7 AU from the Sun. In particular, each cosmogenic radioisotope preserved a record of the irradiation roughly over its mean life.

The solar magnetic field shields the inner solar system from cosmic rays to a variable extent. Hence, Alma could provide unique information about the cosmic ray flux at the time of the unusual prolonged solar minimum before the 24th sunspot cycle. The asteroid spent the last 2 months before its fall inside the orbit of Mars, where, for example, short-lived ^{46}Sc was produced. The asteroid impacted Earth on October 7 as it was approaching its perihelion, 45 days before it would have been at perihelion (0.899 AU from the Sun) on November 20, 2008.

Cosmogenic radionuclides can also be used to measure the depth of a given fragment within the asteroid, because some cosmogenic radionuclides, such as ^{60}Co, are produced in secondary reactions that require thermalized neutrons; the density of thermal neutrons increases with depth from the surface in the asteroid, reaches a peak value and then decreases again deep inside.

In this paper, on the basis of the radioactivity from gamma ray emitting radionuclides, we report on the shielding depth of fragment #15, give an independent estimate of the size of the meteoroid, and discuss the cosmic ray flux as it was during the recent solar minimum.

EXPERIMENTAL PROCEDURE

The counting system used is a large volume high-efficiency Ge-NaI(Tl) gamma ray spectrometer, located in the underground Laboratory of Monte dei Cappuccini (IFSI, INAF) in Torino (Italy). This system consists of a hyperpure Ge detector (3 kg, 147% relative efficiency), operating within an umbrella of NaI(Tl) scintillator (90 kg). In order to achieve very low background, the system is located in a 20 cm thick low-activity lead shield, having an additional 5 cm thick OFHC copper-cadmium graded shield, under the Monte dei Cappuccini giving an effective overhead shielding equivalent to 70 m water (m.e.w.). With this system a rock sample of up to 1 kg can be measured. The cavity where the sample is placed is continuously flushed with nitrogen to minimize contribution of the ambient radon

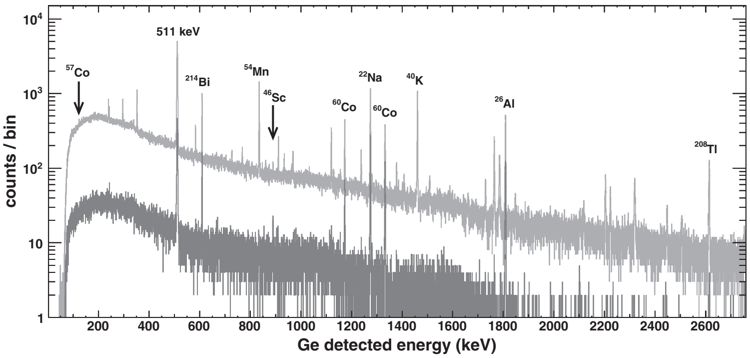

Fig. 3. Gamma ray spectra of Almahata Sitta meteorite #15 measured in normal (light gray) and in coincidence (dark gray) modes. The counting period is 65,197 min (approximately 45 days). A number of peaks discussed in the text are marked.

and its daughters. The Ge detector operates in normal, coincidence and anticoincidence modes with the NaI(Tl) scintillator. Details of the system are given in Bonino et al. (1992) and Taricco et al. (2006, 2007) where measurements of over 20 chondrite falls have been reported. Recently, we have developed and installed a multiparametric acquisition system (Colombetti et al. 2008), which allows more flexibility in selecting optimal energy channels and allows reliable measurement of low levels of activity of some radioisotopes in meteorites.

The spectrometer can operate in coincidence and anticoincidence modes to match decay scheme of a particular radionuclide and is specially suited for measurement of positron emitters. Generally, interferences due to naturally occurring uranium and thorium daughters present in the meteorites and in the laboratory environment are significant. The strongest contribution to background and interference in many energy regions of interest for measurement of cosmogenic radionuclides come from ^{214}Bi and its daughter nuclides, which emit a large number of gamma rays throughout the region of interest. The contribution from ^{214}Bi and its daughter nuclides can be reduced by an appropriate selection of the counting mode.

In order to determine the counting efficiency of the detector for various modes and different energies, we made an identical mold of the meteorite filled with labeled sediment having known amounts of ^{60}Co, ^{40}K, ^{137}Cs, mixed with iron to match the density of the meteorite. In addition, standards of ^{26}Al, ^{22}Na (obtained from National Bureau of Standards, USA, and New England Nuclear, UK, respectively) and ^{40}K (KCl) were also counted. The mold and the standards allowed us to determine the efficiency at different energies for various gamma emitters and positron emitters. Efficiencies at other energies of interest (corresponding to other radioisotopes) were derived by interpolation.

RESULTS

By the time of counting (July to October 2009), radionuclides with half-life less than a few months had decayed, but activity due to six gamma-emitting radioisotopes ^{46}Sc (half-life 83.79 days), ^{57}Co (271.74 days), ^{54}Mn (312.05 days), ^{22}Na (2.60 yr), ^{60}Co (5.27 yr), and ^{26}Al (0.717 million years) could be measured. During the counting period, the energy calibration of the system remained within 0.5 keV, indicating a high stability of the detector.

Figure 3 shows the gamma ray spectra of Alma obtained in normal (light gray) and in coincidence (dark gray) modes up to 2.8 MeV. In the same way, Fig. 4 shows the background spectra in normal and coincidence modes. By counting for a long time (approximately 65,200 min), we were able to reach a good signal-to-noise on many lines, even for a relatively small sample. The spectrum shows well-developed peaks of cosmogenic ^{22}Na, ^{26}Al, and ^{60}Co. The coincidence between Ge and NaI detectors is tuned to select gammas from β^+ decay, i.e., from ^{22}Na and ^{26}Al. The 122 keV ^{57}Co and 889 keV ^{46}Sc peaks are considerably less intense than the others and are therefore not visible on the scale plotted in Fig. 3. These are reproduced in Fig. 5 at a larger scale. The other peaks in the spectra are due to the background of naturally occurring potassium, uranium, and thorium nuclides and their gamma emitting decay products. ^{214}Bi and ^{208}Tl come from ^{238}U and ^{232}Th decay chains, respectively. The 511 keV peak is from positron annihilations.

Table 1 gives the activity of the radionuclides, corrected to the time of fall, their peak gamma ray energies and counting rate (cpm, counts per minute) together with statistical (1σ) errors. For all the radionuclides, the errors are of the order of 1–2%, except for ^{57}Co and ^{46}Sc for which they are large, because of a lower number of counts. Due to the uncertainty in the

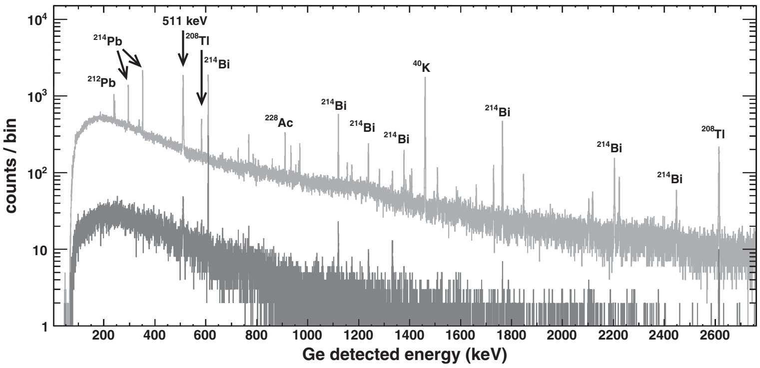

Fig. 4. Gamma ray background spectra (64 days) measured in normal (light gray) and in coincidence (dark gray) modes.

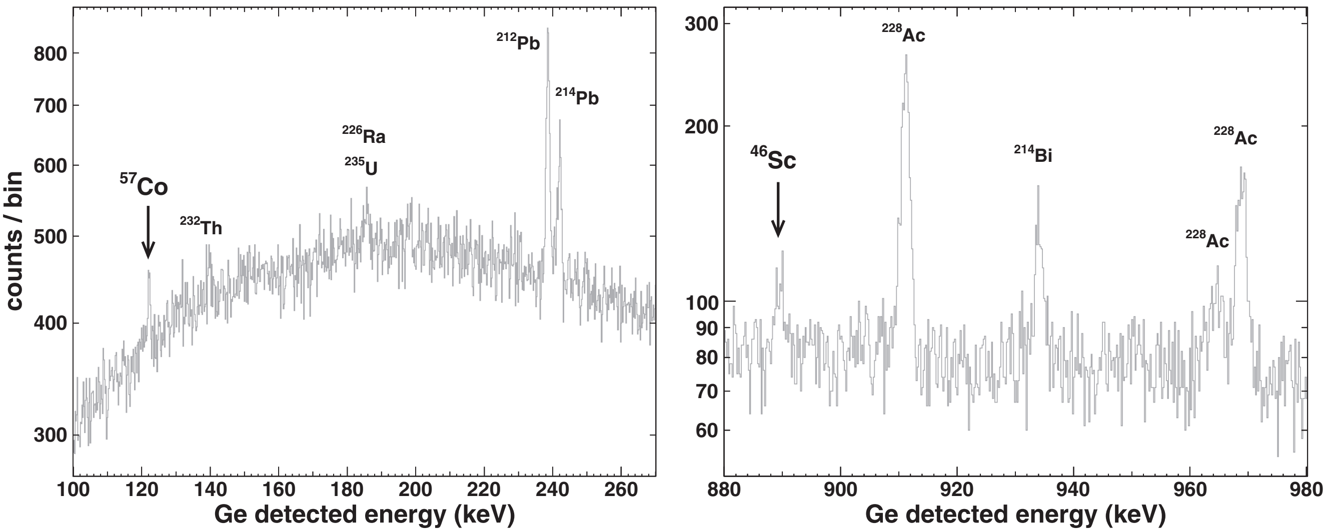

Fig. 5. Detail of Fig. 3, showing counts in normal mode in the two energy intervals containing the cosmogenic ^{57}Co and ^{46}Sc.

activity in standards used for calibrations, a systematic error of about 5% must be added.

DISCUSSION

The activities of various radionuclides measured in Almahata Sitta (fall, 2008) are given in Table 1. In this table we also give the activities of these radionuclides measured in the Torino (H6 chondrite), which fell in 1988 (Bhandari et al. 1989; Wieler et al. 1996), 20 yr earlier. Torino has been chosen for comparison with Alma for two reasons: firstly, both Torino and Alma fell at a similar phase of solar activity, at the beginning of the sunspot cycle 22 and 24, respectively. Therefore, the modulation of cosmic rays during the production of various radionuclides are expected to be similar. Secondly, both were measured shortly after their fall by the same technique in our laboratory and therefore no systematic errors due to counting procedures should be present. We first discuss the ^{60}Co and ^{26}Al activities and their implications to shielding of the measured fragment, then the effect of solar modulation on the cosmic ray flux.

^{60}Co Activity and Shielding Depth of the Fragment

^{60}Co is mainly produced by thermal neutron capture in stable ^{59}Co, while a negligible amount (<1 dpm kg^{-1}) is expected to be produced from spallation of nickel by cosmic ray nucleons. The measured ^{60}Co activity in Alma is 27.7 ± 0.8 dpm kg^{-1} meteorite. As can be seen from Table 1, this is about 10 times the value of 2.8 ± 0.3 dpm kg^{-1} meteorite measured in the Torino meteorite.

To assess the effect of a different cobalt concentration in the two meteorites, its concentration in various fragments of Alma and Torino is listed in Table 2. Considering that the measurements in Alma were made in small (approximately few mg) aliquots (Friedrich et al. 2010), too small to be representative of

Table 1. Activity levels of the cosmogenic radioisotopes measured in the Almahata Sitta ureilite fragment #15 and, for comparison, in the Torino H6 chondrite (from Bhandari et al. 1989).

			Almahata Sitta		Torino
Nuclide	Half-life	Energy, KeV	cpm	dpm kg^{-1}	dpm kg^{-1}
Co-57	271.74 days	122.06	0.0045 ± 0.0006	3.4 ± 0.5	16.3 ± 1
Mn-54	312.05 days	834.85	0.186 ± 0.002	83.5 ± 0.9	121 ± 2
Sc-46	83.79 days	889.28	0.0037 ± 0.0005	7.1 ± 1.0	10.4 ± 2.0
Co-60	5.2711 yr	1332.49	0.0598 ± 0.002	27.7 ± 0.8	2.8 ± 0.3
Na-22	2.6027 yr	1274.54	0.188 ± 0.002	105.4 ± 1.0	80 ± 1
Al-26	0.717 10^6 yr	1808.65	0.101 ± 0.001	62.1 ± 0.8	54 ± 1

Table 2. Composition of Almahata Sitta nonporous samples #15, #4, and #47, as well as porous sample #7 (from Friedrich et al. 2010; estimated values of bulk Si in italics from Welten et al. 2010) and of the Torino meteorite (from Bhandari et al. 1989).

		Almahata Sitta				
Element	Unit	(#15)	(#4)	(#47)	(#7)	Torino fragment A
Na	μg g^{-1}	760	260	260	1,600	5,500
Mg	wt%	20.9	24.5	21.1	34.5	11.3
Al	wt%	0.477	0.262	0.148	0.502	0.94
Si	wt%	*20.3*	*21.8*	*20.6*	–	a
Mn	μg g^{-1}	3,660	3,720	2,700	3,060	2,100
Fe	wt%	9.99	10.7	16.3	31.4	26.1
Co	μg g^{-1}	55	35	150	240	690
Ni	μg g^{-1}	828	604	1,890	4,750	1,160,000

a = Not measured, assumed to be 21%, the average value for chondrites.

the whole fragment, and the measurements show a high variability, we adopt a cobalt concentration of 120 μg g^{-1}, the mean value of all four Almahata Sitta ureilites measured. The activity of ^{60}Co, normalized to the cobalt concentration in Alma is 233 dpm g^{-1} cobalt, about 58 times higher than the value of 4 dpm g^{-1} cobalt measured in Torino. We therefore conclude that the high ^{60}Co activity in Alma is not related to the target element concentrations.

The high value of ^{60}Co activity in Alma is not only due to an enhanced flux of primary cosmic rays resulting from lower solar modulation. To assess the enhancement in cosmic ray flux due to the prolonged low solar activity before the fall of Alma, we follow the procedure of Bhandari et al. (1994) and estimate that the ^{60}Co production would be about 10% higher due to a higher flux of cosmic rays before the fall of Alma. Therefore, instead of the measured value of 27.8 dpm kg^{-1}, the ^{60}Co activity in the case of an average cosmic ray flux would have been 25 dpm kg^{-1}. This value is still about nine times more than in Torino.

This leaves us with only the third option, concluding that the high concentration of ^{60}Co in Alma is mainly due to a higher shielding depth. The flux of slow neutrons in large meteoroids increases rapidly with depth, giving rise to a higher production of neutron capture nuclides like ^{60}Co. The ^{60}Co production rates in chondrites calculated by Spergel et al. (1986) provide the expected production rates for Alma, after scaling for the concentration of cobalt (120 μg g^{-1}). These production rate curves for the Alma parent body 2008 TC$_3$, assuming different radii, are shown in Fig. 6. Using the curves for 1.5–2 m radius, the value of about 25 dpm kg^{-1} of ^{60}Co corresponds to a shielding depth of approximately 90 g cm^{-2} (which corresponds to approximately 30 cm, for a density 3.1 g cm^{-3}, and to approximately 50 cm, for a density 1.8 g cm^{-3}). Greater shielding depths in the case of 3.1 g cm^{-3} are excluded by the measured ^{26}Al activity when compared with the ^{26}Al depth profiles given in Fig. 7, as discussed in the next section. Taking into account the uncertainty on the measured ^{60}Co activity and the density range 1.8–3.1 g cm^{-3}, we obtain that the shielding depth should be between 27 cm and 55 cm.

Finally, our measurements of ^{60}Co (Fig. 6) and ^{26}Al (Fig. 7) can provide an independent constraint on the asteroid's radius between 0.5 m and 2.5 m. The large uncertainty arises due to the large variation in density of the asteroid.

^{26}Al Activity and Shielding Depth of the Fragment

The radionuclide ^{26}Al is mainly produced by cosmic ray interactions with Mg, Al, and Si present in the

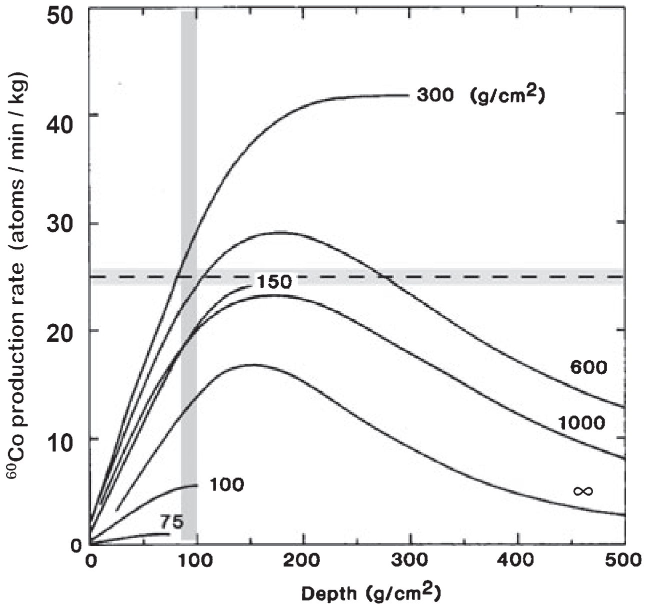

Fig. 6. Calculated ^{60}Co production rates expected in the Almahata Sitta ureilite, for cobalt concentration of 120 μg g^{-1}, based on the computations of Spergel et al. (1986) as a function of depth (expressed in g cm^{-2}) for different radii of a spherical asteroid. The radii and depths in cm can be determined by dividing the values indicated on the curves by the assumed asteroid density value. As discussed in the text, we considered a density range of 1.8–3.1 g cm^{-3}, deduced from the measurements of the available samples. The measured production value (25 ± 0.7 dpm kg^{-1}) is reported (horizontal bar). The deduced depth range is represented by the vertical bar, also reported in Fig. 7.

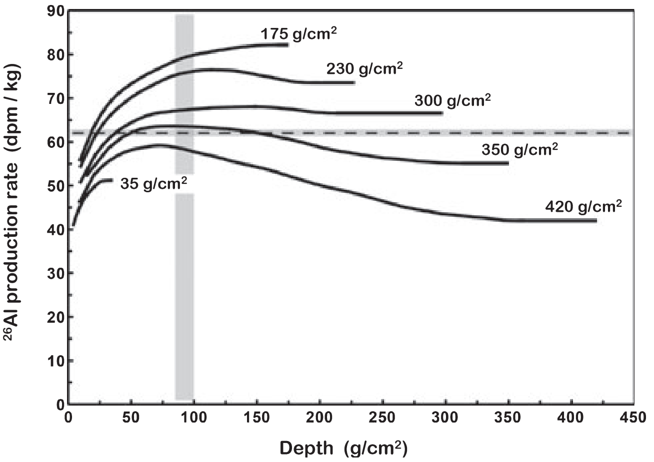

Fig. 7. ^{26}Al production rate as a function of depth, expressed in g cm^{-2}, expected for different radii of 2008 TC$_3$ with a composition measured from Almahata Sitta (Table 2), calculated using the model of Michel et al. (1991). The measured production value (62.1 ± 0.8 dpm kg^{-1}) is reported (horizontal bar). The depth range is represented by the vertical bar.

meteorite. Using the average concentrations of these elements (Table 2) and the calculation model of Michel et al. (1991) based on high energy particle transport code, we obtain the production rates of ^{26}Al in Alma shown in Fig. 7 (Bhandari et al. 1993). As can be seen from this figure, for a 1.5–2 m radius asteroid, the shielding depth range 27–55 cm, deduced from ^{60}Co, is compatible with the measured ^{26}Al activity of 62.1 dpm kg^{-1}. It may be noted that the measured value of ^{26}Al is not consistent with a high density 2 m radius meteoroid.

Thus, the activity of the two radionuclides produced in different types of nuclear reactions, the neutron capture ^{60}Co and spallation produced ^{26}Al, suggests a shielding depth of 41 ± 14 cm. The large uncertainty is mainly due to the uncertain bulk density of the asteroid.

Short Lived Radionuclides and Solar Cycle Modulation of the Cosmic Ray Flux

Unlike usual meteorite falls, the orbit of Alma is well known (Fig. 2) from the telescopically determined parameters before impact given by Jenniskens et al. (2009). The production of radionuclides such as ^{22}Na and ^{26}Al (with life time $\tau \geq$ orbital period of the meteoroid) reflects exposure over the whole orbital space of the meteoroid. ^{22}Na (with a mean life of about 4 yr) is sensitive to cosmic ray variations over the 11 yr Schwabe cycle whereas the long lived ^{26}Al is integrated over many cycles over its mean life of a million years and is insensitive to Schwabe cycle variation in galactic CR modulation. The shorter lived nuclides such as ^{46}Sc ($\tau <$ orbital period of the meteoroid), on the other hand, are produced in the orbital segment covered by the meteorite for one or two mean lives before their fall on Earth. According to Fig. 2, the 2008 TC$_3$ was within the orbit of Mars when most of the 83.79 day half-life ^{46}Sc was produced.

The reasonably good agreement of the measured activity of various short and long lived radionuclides indicates that the intensity of cosmic rays inside and outside the orbit of Mars was similar, even when the solar cycle was going through an unusually long quiet period before cycle 24.

The isotope production rate varies due to the modulation of galactic CR by the solar cycle. The activity ratio of ^{22}Na/^{26}Al is nearly independent of chemical composition and shielding parameters, because ^{22}Na and ^{26}Al are produced in similar nuclear reactions (nucleons of similar energy on similar target elements, i.e., Mg, Al, Si) within stony meteorites and therefore their production depth profiles are similar (Evans et al. 1982; Wacker 1993). Furthermore, since ^{26}Al activity is not influenced by the 11 yr Schwabe cycle, the ratio ^{22}Na/^{26}Al is a good measure of CR variations over a

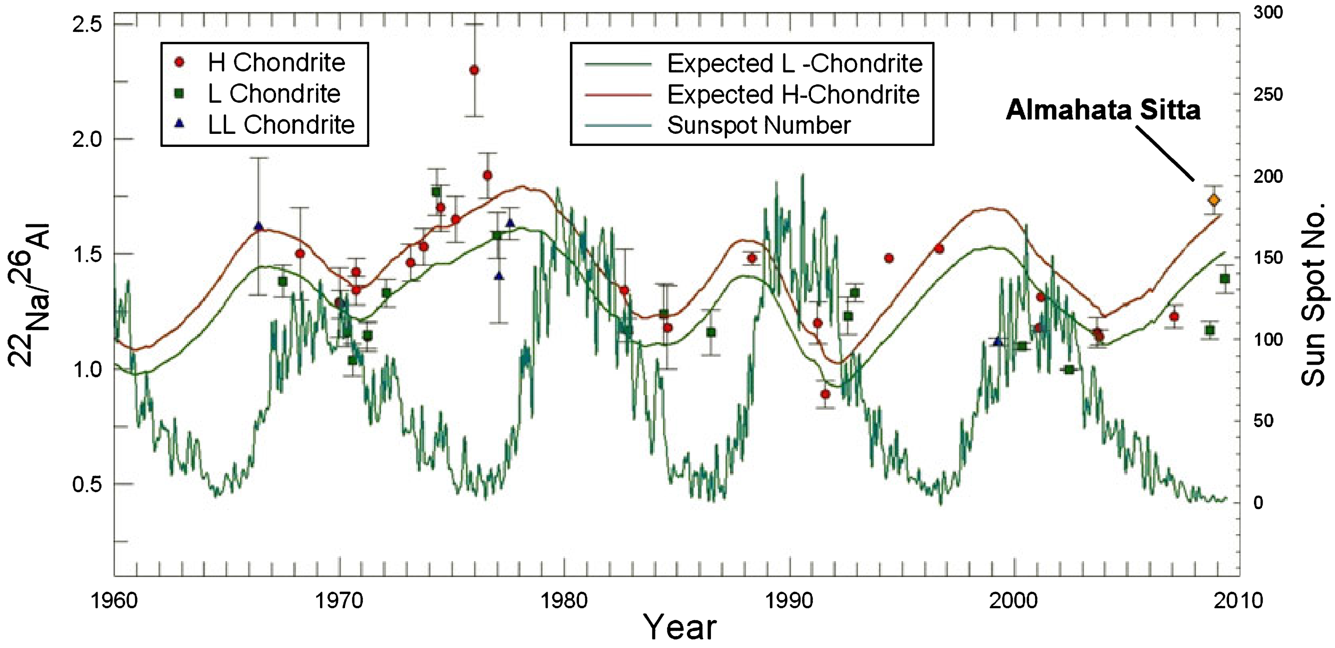

Fig. 8. The ^{22}Na/^{26}Al activity ratio in Almahata Sitta, together with those measured in meteorites which fell during the last four solar cycles. The data are taken from Bhandari et al. (1994), Dhingra et al. (2004), Shukla et al. (2005) and later measurements carried out at the Physical Research Laboratory, India. Calculated activity ratios expected for L and H chondrites are shown by a solid line. For comparison, the sunspot number series is also shown, which indicates a phase difference of 1 to 2 yr between sunspot minimum and ^{22}Na peak.

decadal scale. On the basis of these records in stony meteorites which fell during the last four solar cycles (19–23), it was found that cosmic ray intensity typically decreased by nearly 20% from solar minima to solar maxima. In Fig. 8 we show the ^{22}Na/^{26}Al activity ratio (1.70 ± 0.03) deduced for Alma, together with those measured in the past in H, L, and LL chondrites. The sunspot number superimposed on these measurements reveals the expected phase shift of about 1 or 2 yr between solar activity and ^{22}Na/^{26}Al variations.

The solar activity was low and anomalously prolonged during the 7 yr period (2001–2008) before the fall of Alma and the expected rise in solar activity around 2006–2007 was delayed (Ahluwalia et al. 2010 and references therein). A lower solar activity causes a higher cosmic ray flux at Earth. The high value of the ^{22}Na/^{26}Al activity ratio thus reflects higher cosmic ray flux during the unusually prolonged solar minimum in the years before the fall.

The relatively high value of ^{22}Na in Alma reflects this relatively higher cosmic ray flux, resulting in a higher ^{22}Na/^{26}Al of 1.7. The activities of ^{54}Mn and ^{46}Sc are lower in Alma as compared to Torino (Table 1), as would be expected for the lower concentration of target elements and for the deeper shielding. ^{57}Co, however, is significantly lower in Alma compared to the Torino meteorite because of a low abundance of iron and nickel (Table 2), which are the main target elements for its production.

CONCLUSIONS

On the basis of both ^{60}Co and ^{26}Al activity, it is estimated that the fragment #15 was located at a depth of 41 ± 14 cm in asteroid 2008 TC$_3$. The low ^{57}Co activity is due to a low abundance of target elements Fe and Ni. The high ^{22}Na activity, as well as the activity ratio ^{22}Na/^{26}Al of 1.7, is consistent with the trend expected from cosmic ray modulation due to the unusually long sunspot minimum before the fall of Almahata Sitta. The prolonged solar minimum during 2001–2008, however, did not result in an unusually large cosmic ray flux in the near Earth space sampled by the Alma ureilite compared to that during previous solar minima.

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