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Almahata Sitta meteorite: γ-activity measurements at Monte dei Cappuccini Laboratory in Torino

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Abstract The asteroid 2008 TC_3 was telescopically seen prior to entering Earth's atmosphere and was predicted to fall in Sudan on October 7, 2008, as it actually happened. Subsequently, many fragments were collected from the Nubian desert. At Monte dei Cappuccini Laboratory (IFSI, INAF) in Torino, using a selective gamma spectrometer we measured gamma rays from fragment #15, one of the largest retrieved, a ureilite of mass 75 g. Six cosmogenic radionuclides have been measured (^{46}Sc, ^{57}Co, ^{54}Mn, ^{22}Na, ^{60}Co and ^{26}Al). ^{60}Co and ^{26}Al activities allowed us to deduce that the fragment was located at a depth of 41±14 cm inside the 1.5–2 m radius asteroid. Moreover, ^{22}Na activity is slightly greater than expected on the basis of the average cosmic ray flux and this could be ascribed to the prolonged solar minimum preceding the meteorite fall.

Key words. Meteoroids – Cosmic rays – Sun: activity – Sun: magnetic fields – Techniques: gamma spectroscopy – Sunspots – Interplanetary medium – Solar-terrestrial relations

1. Introduction

The solar magnetic field shields the inner solar system from cosmic rays (CR) to a variable extent. CR produce a large number of radioactive and stable isotopes in meteoroids while they are exposed in the interplanetary space and before they fall on the Earth where the CR irradiation becomes negligible. Each radioisotope preserves past record of the CR flux over its mean life. Cosmogenic radionuclides produced in Almahata Sitta meteorite provided unique information about the cosmic ray flux at the time of the unusual prolonged solar minimum before the 24th sunspot cycle.

Asteroid 2008 TC_3 was seen telescopically prior to entering the Earth's atmosphere on 7 October 2008. As reported in Jenniskens et al. (2009), subsequently at JPL (Pasadena, California) time and position of the expected impact area were calculated. The orbital positions of 2008TC$_3$ have been reported in Taricco et al. (2010).

The asteroid fragmented at an unusually high altitude of ~37 km and fell in the Nubian Desert of northern Sudan. During the first search campaign in December of 2008, 15 stones weighing 563 g were collected (Jenniskens et al. 2009; Shaddad et al. 2010) and named *Almahata Sitta* meteorites (mentioned hereafter as Alma). The radial size of the asteroid was estimated to be between 1.5 to 2 meters; the density should lie between the values for the lightest (~1.8 g/cm^3) and the densest (~3.1 g/cm^3) recovered fragments. Therefore the preatmospheric mass should lie between 25 and 100 tons. Alma has been classified as an achondrite, a polymict ureilite containing 20–30 percent of anomalous chondritic fragments (Jenniskens et al. 2009; Zolensky et al. 2010; Rumble et al. 2010).

Fragment #15 (75 g) is a ureilite and was made available to us for non-destructive γ-ray counting 7 months after the fall. It has a density of 3.11 +0.14/-0.07 g cm^{-3} (Shaddad et al. 2010).

2. Experimental procedure

In order to reveal γ activity of the Alma fragment, we used a large volume high-efficiency HPGe-NaI(Tl) γ-ray spectrometer, located in the underground (70 m.e.w., meter equivalent water) Laboratory of Monte dei Cappuccini (IFSI-INAF, 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) and is housed in a thick Pb-Cd-Cu passive shield. Both detector signals are digitized to allow coincidence and anti-Compton spectroscopic analyses. Figure 1 shows the 2-dimensional spectrum of Alma in the ^{26}Al 1808.65 keV region. The spectrometer is described in greater detail in Bonino et al. (1992), Taricco et al. (2006, 2007) and Colombetti et al. (2008).

The counting γ-efficiency of Alma has been determined by making an identical mould of the meteorite filled with labelled sediment having known amounts of ^{60}Co, ^{40}K, ^{137}Cs, mixed with iron to match the density of the meteorite.

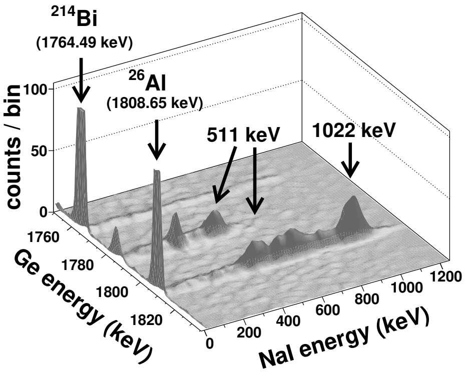

Figure 1. HPGe–NaI(Tl) γ-ray spectrum of Almahata Sitta fragment #15 between 1750 and 1835 keV Ge energies. Various peaks observed due to ^{214}Bi, ^{22}Na (in the middle) and ^{26}Al are marked.

3. Results

We identified six cosmogenic radioisotopes ^{46}Sc (half life 83.79 d), ^{57}Co (271.74 d), ^{54}Mn (312.05 d), ^{22}Na (2.6027 y), ^{60}Co (5.2711 y) and ^{26}Al (0.717 My) by measuring Alma from July to October 2009. Figure 2 shows the γ-ray spectrum of Alma obtained in normal mode (Ge signal acquired without gating). The peaks of cosmogenic radioisotopes are marked in the spectrum and magnified in Fig. 3. The results show that it is possible to obtain a good signal-to-noise with this spectrometer, even for this relatively small sample.

Table 1 gives the activity of the radionuclides, corrected to the time of fall, and the γ-ray energies of the measured peaks. Due to the uncertainty in the activity of standards used for calibrations, a systematic error of about 5% must be added.

4. Discussion and conclusions

The production of a cosmogenic radionuclide in a meteoroid depends on the concentration of

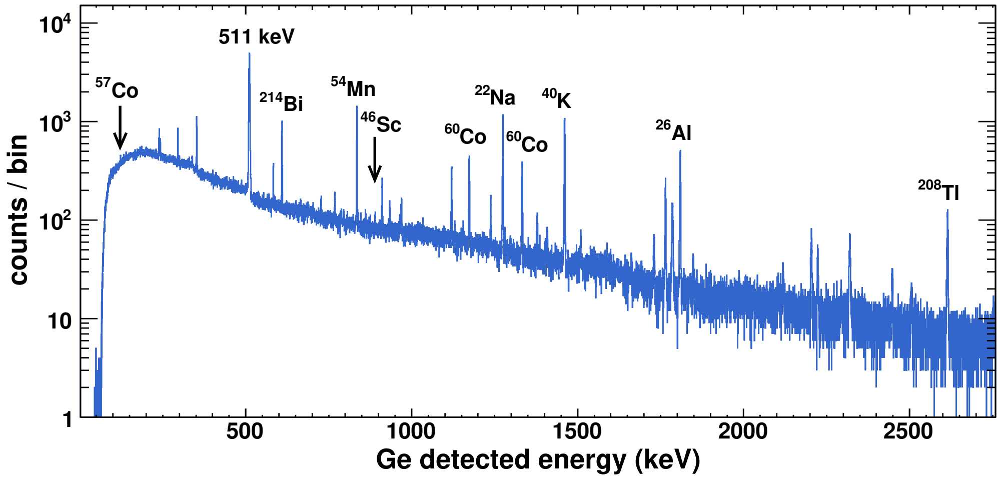

Figure 2. γ- ray spectrum of Almahata Sitta fragment #15 measured in normal mode (without gating). The counting period is 65,197 minutes (~45 days). Peaks of cosmogenic radionuclides are marked. The 511 keV peak is from β^{+} annihilations and other peaks are due to the background of naturally occurring potassium, uranium, thorium and their γ-emitting decay products. ^{214}Bi and ^{208}Tl come from ^{238}U and ^{232}Th respectively.

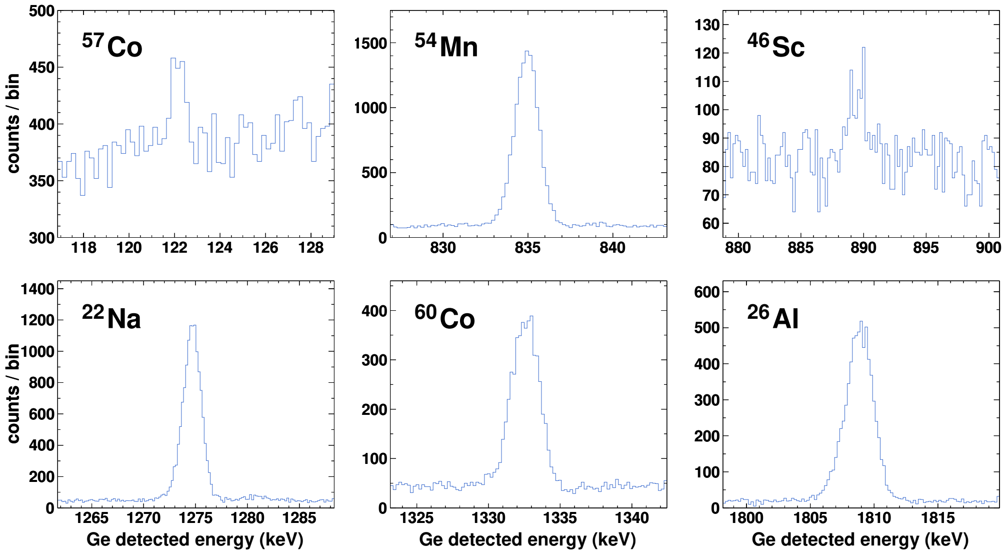

Figure 3. Regions of interest of the normal mode spectrum shown in Fig 2, corresponding to the measured peaks of the six cosmogenic radioisotopes.

target elements in it, the primary cosmic ray flux, and the shielding of the sample.

The ^{60}Co and ^{26}Al activity measurements together offer the opportunity to deduce information on the shielding depth of fragment #15 inside 2008 TC$_3$. Cosmogenic ^{60}Co is mainly produced by thermal neutron capture in stable ^{59}Co, while a negligible amount ($\ll$1 dpm/kg) is expected to be produced from spallation of nickel by cosmic ray nucleons. ^{26}Al is mainly

Table 1. Cosmogenic radioisotope activities of Almahata Sitta fragment #15.

nuclide	half life	energy, keV	dpm/kg
^{57}Co	271.74 d	122.06	3.4 ± 0.5
^{54}Mn	312.05 d	834.85	83.5 ± 0.9
^{46}Sc	83.79 d	889.28	7.1 ± 1.0
^{60}Co	5.2711 y	1332.49	27.7 ± 0.8
^{22}Na	2.6027 y	1274.54	105.4 ± 1.0
^{26}Al	0.717 My	1808.65	62.1± 0.8

produced by cosmic ray interactions with Mg, Al and Si present in the meteorite.

The measured ^{60}Co activity in Alma is 27.7 ± 0.8 dpm/kg, about 10 times the value measured in our laboratory for the Torino meteorite, which fell in 1988, in a similar phase of the solar cycle (details of the Torino-Alma comparison are given in Taricco et al. (2010)). Using the production rate curves calculated by Spergel et al. (1986) for 1.5–2 m radius and for a Co concentration of 120 μg/g, we concluded that the high concentration of ^{60}Co is mainly due to a higher shielding depth, which should be between 27 and 55 cm. This value is compatible with that deduced from ^{26}Al activity. The large uncertainty is due to the uncertain bulk density of 2008 TC$_3$.

^{22}Na (half life 2.6027 y) is sensitive to cosmic ray variations over the 11 year Schwabe cycle whereas the long lived ^{26}Al (half life 0.717 My) is insensitive to such variations.

The activity ratio ^{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 (Evans et al. 1982; Wacker 1993). Thus, the ratio ^{22}Na/^{26}Al is a good measure of CR variations over a decadal scale. In Alma this activity ratio is 1.70 ± 0.03; as discussed in Taricco et al. (2010), this high value reflects the high cosmic ray flux during the unusually prolonged solar minimum in the years before the fall. This, period, however, did not result in an unusually large cosmic ray flux in the near Earth space sampled by Alma compared to that during the previous solar minima.

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References

Bonino, G., Castagnoli, G. C., & Bhandari, N. 1992, Il Nuovo Cimento C, 15, 99

Colombetti, P., et al. 2008, in IEEE Nuclear Science Symposium Conference Record, 2008. NSS'08, 1802–1805

Evans, J. C., Reeves, J. H., Rancitelli, L. A., & Bogard, D. D. 1982, Journal of Geophysical Research, 87, 5577

Jenniskens, P., et al. 2009, Nature, 458, 485

Rumble, D., et al. 2010, Meteoritics & Planetary Science, in press

Shaddad, M. H., et al. 2010, Meteoritics & Planetary Science, in press

Spergel, M. S., et al. 1986, Journal of Geophysical Research, 91, 483

Taricco, C., et al. 2006, Journal of Geophysical Research (Space Physics), 111, A08102

Taricco, C., et al. 2010, Meteoritics and Planetary Science, in press

Taricco, C., et al. 2007, Nuclear Instruments and Methods in Physics Research A, 572, 241

Wacker, J. F. 1993, in Lunar and Planetary Institute Science Conference Abstracts, Vol. 24, Lunar and Planetary Institute Science Conference Abstracts, 1471–1472

Zolensky, M. E., et al. 2010, Meteoritics & Planetary Science, in press