



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

C. Taricco^{1,2}, N. Bhandari³, P. Colombetti^{1,2}, A. Romero², G. Vivaldo^{1,2}, N. Sinha⁴,
P. Jenniskens⁵, and M. H. Shaddad⁶

¹ Dipartimento di Fisica Generale, University of Torino, Via Pietro Giuria 1, I-10125 Torino, Italy, e-mail: taricco@ph.unito.it

² Istituto di Fisica dello Spazio Interplanetario di Torino (IFSI-INAF), Corso Fiume 4, I-10133 Torino, Italy

³ Basic Sciences Research Institute, Navrangpura, Ahmedabad 380 009, India

⁴ Indian Institute of Astrophysics, II Block, Koramangala, Bangalore 560 034, India

⁵ SETI Institute, Carl Sagan Center, 189 Bernardo Ave, Mountain View, CA 94043, USA

⁶ Department of Physics and Astronomy, University of Khartoum, P.O. Box 321, Khartoum 11115, Sudan

Abstract The asteroid 2008 TC₃ 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 (⁴⁶Sc, ⁵⁷Co, ⁵⁴Mn, ²²Na, ⁶⁰Co and ²⁶Al). ⁶⁰Co and ²⁶Al 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, ²²Na 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 TC₃ 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 2008TC₃ 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/cm³) and the densest (~ 3.1 g/cm³) 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 $3.11 \pm 0.14 / -0.07$ 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 ²⁶Al 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

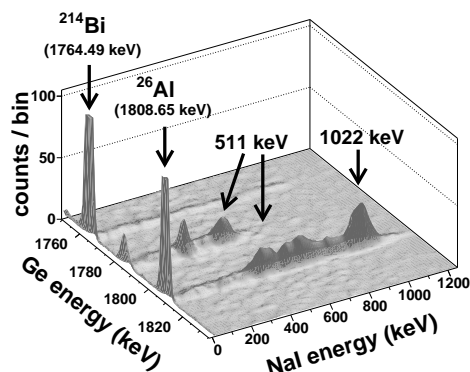


Figure 1. HPGe-NaI(Tl) γ -ray spectrum of Almahata Sitta fragment #15 between 1750 and 1835 keV Ge energies. Various peaks observed due to ²¹⁴Bi, ²²Na (in the middle) and ²⁶Al are marked.

of the meteorite filled with labelled sediment having known amounts of ⁶⁰Co, ⁴⁰K, ¹³⁷Cs, mixed with iron to match the density of the meteorite.

3. Results

We identified six cosmogenic radioisotopes ⁴⁶Sc (half life 83.79 d), ⁵⁷Co (271.74 d), ⁵⁴Mn (312.05 d), ²²Na (2.6027 y), ⁶⁰Co (5.2711 y) and ²⁶Al (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

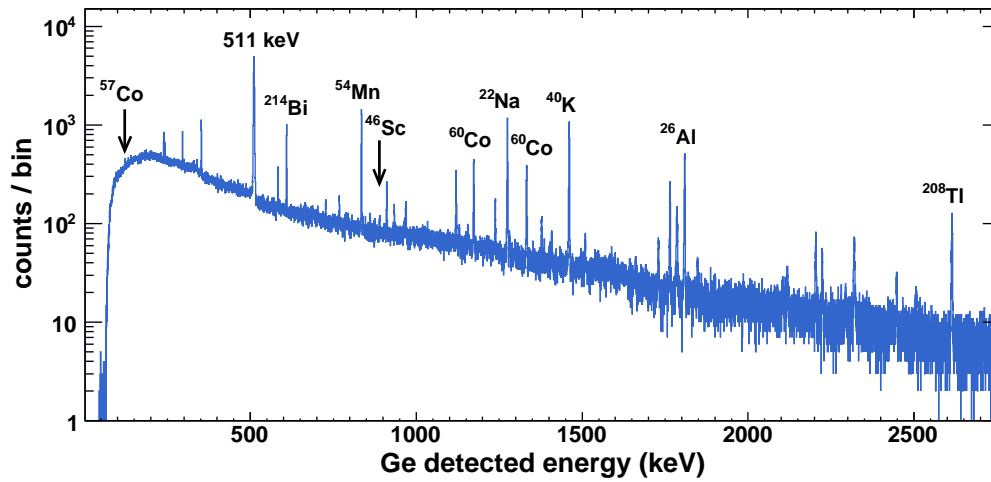


Figure 2. γ -ray spectrum of Almahata Sitta fragment #15 measured in normal mode (without gating). The counting period is 65,197 minutes (\sim 45 days). Peaks of cosmogenic radionuclides are marked. The 511 keV peak is from β^+ annihilations and other peaks are due to the background of naturally occurring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

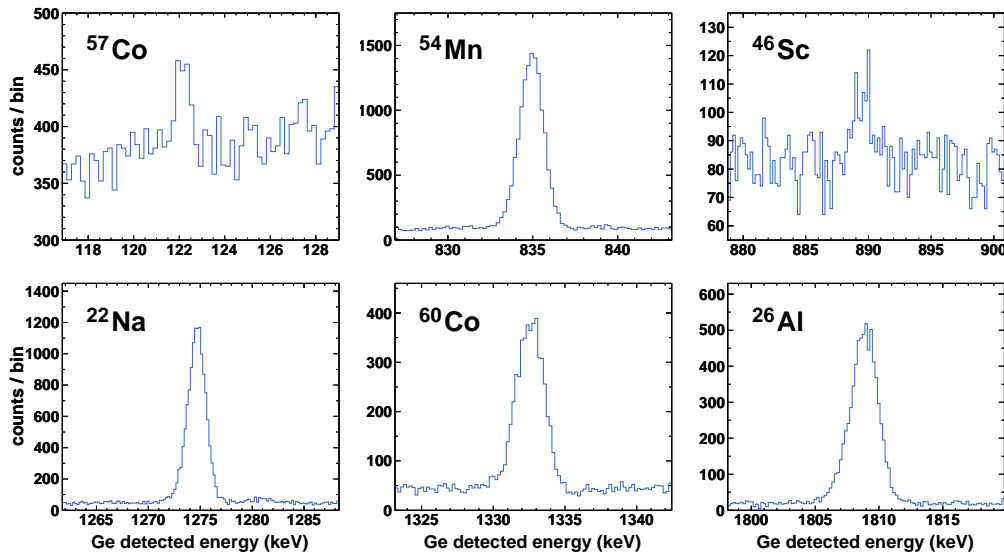


Figure 3. Regions of interest of the normal mode spectrum shown in Fig 2, corresponding to the measured peaks of the six cosmogenic radioisotopes.

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 TC₃. 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 ⁶⁰Co 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 μ g/g, we concluded that the high concentration of ⁶⁰Co is mainly due to a higher shielding depth, which should be between 27 and 55 cm. This value is compatible with that deduced from ²⁶Al activity. The large uncertainty is due to the uncertain bulk density of 2008 TC₃.

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

The activity ratio ²²Na/²⁶Al is nearly independent of chemical composition and shielding parameters, because ²²Na and ²⁶Al are produced in similar nuclear reactions (Evans et al. 1982; Wacker 1993). Thus, the ratio ²²Na/²⁶Al 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.

Acknowledgements. We are grateful to Carlo Morello, Director of Istituto di Fisica dello Spazio Interplanetario (IFSI-INAF, Torino) for support. We also thank Rolf Michel for his computer code used to calculate the production rate of ²⁶Al. We are also grateful to Sami K. Solanki (Max-Planck-Institut für Sonnensystemforschung, Katlenburg-Lindau, Germany) for financial support. We thank the students of the University of Khartoum who recovered the meteorites. PJ is supported by a grant from the NASA Planetary Astronomy program and NB acknowledges Indian National Science Academy for Honorary scientist grant. We thank also Martina Machet for the cooperation at the Laboratory of Monte dei Cappuccini.

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