^{26}Al DECAY: HEAT PRODUCTION AND A REVISED AGE FOR IAPETUS.

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Introduction: We revisit the decay energies that have been used for computing the heat produced by the decay of ^{26}Al in geophysical models. Its decay scheme is complex and the values that have been used have a range of about a factor of three (Table 1). This is a major issue because ^{26}Al is a primary heat source for planetary objects formed in the early solar system. Based on Schramm et al., [1] and updated with the most recent nuclear constants, we recommend a heat production value of 3.12 MeV per decay and a half-life of 0.717 My. The heat value is a factor of ~2.4 higher than used for Iapetus by Castillo-Rogez et al. [2]. The new value does not change their conclusions but does shift their time of formation of Iapetus by about 1 My, moving it (from ~2.5 - 5.0) to between ~3.4 and 5.4 My after the formation of the Ca-Al inclusions (CAIs). This range is fully consistent with the growing number of observed protoplanetary disks that have cleared lanes, indicating giant planet formation, in less than 8 My after their formation [3].

Decay Scheme: ^{26}Al decays either by positron emission or electron capture, with neutrinos carrying away some energy in either case. The daughter, ^{26}Mg, is initially in an excited state, and decays to its ground level by emitting one or two γ rays, as shown in Fig. 1. The γ rays are absorbed nearby since the attenuation coefficient is about 0.1 cm^2 g^{-1} [4]. For positron decay, the γ rays (0.511 MeV) resulting from positron-electron annihilations are also absorbed locally. The nuclear parameters that determine the heating rate are the half-life, $T_{1/2}$, and the energy released per decay, E_d. The half-life of ^{26}Al is $7.17 \pm 0.24 \times 10^5$ yrs [5]. The relevant energy for heating is the total energy of disintegration less the energy carried away by the neutrinos, which are not absorbed locally in a planetary setting [1][6][7]. Thus we obtain our recommended energy of 3.12 MeV per decay for heating in a geophysical or planetary setting. Combination of E_d and the half-life leads to a specific power production for ^{26}Al of ~0.355 W/kg. See [7A], for the detailed derivations of these values.

There are similar discrepancies in the literature for ^{60}Fe, although the dispersion in the data and the consequences for geophysical modeling are not nearly as significant as for ^{26}Al. Most studies use 3.04 to 3.06 MeV corresponding to the total disintegration energy [8][9][10]. The differences among these studies is due to not accounting for the loss of energy by neutrinos. The actual amount of energy deposited locally as heat is 2.712 MeV per decay of ^{60}Fe via ^{60}Co to ^{60}Ni [11].

Consequences For Modeling Icy Objects Such As Iapetus: Assuming that ^{26}Al dominates the heating, i.e., the initial concentration ^{60}Fe/^{56}Fe was less than 0.5×10^{-6} [12], the times of formation updated with the numbers discussed in the present paper are presented in Fig . 2 and discussed in the caption.

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References: [1] Schramm D. et al. (1970) *Earth Planet. Sci. Lett., 10*, 44-59. [2] Castillo-Rogez J. et al. (2007) *Icarus, 190,* 179-202. [3] Cieza et al. (2007) ApJ 667, 308-328. [4] Hubbell J. H. and Seltzer S. M. (2004) *Tables of X-Ray Mass Attenuation Coefficients and Mass Energy-Absorption Coefficients (version 1.4)*, http://physics.nist.gov/xaamdi. National Institute of Standards and Technology, Gaithersburg, MD. [5] Wu S.-C. and Browne E. (1997) *Comments on Evaluation* CEA ISBN 2 7272 0211 3. [6] Stepinski T. F. (1992) *Icarus, 97*, 130-140. [7] Takata T. and Stevenson D. J. (1996) *Icarus, 123*, 404-421. [7A] Castillo-Rogez et al., (2009) *Icarus,* submitted. [8] Ghosh A. and McSween H. Y. (1998) *Icarus, 134*, 187-206. [9] McCord T. B. and Sotin C. (2005) *J. Geophys. Res., 110*, E05009. [10] Ghosh, S. J. et al. (2006) *Meteorites and the Early Solar System II* (D. Lauretta et al., Eds.), Univ. of Arizona Press, 555-566. [11] Kohman T. P. and Robison M. S. (1980) LPS 11, 564. [12] Chen, J. H. et al. (2007) *LPS XXXVIII*, Abstract #1753. [13] Cohen B. A. and Coker R. F. (2000) *Icarus, 145*, 369-381. [14] Grimm R. E. and McSween Jr. H. Y. (1989) *Icarus, 82*, 244-280. [15] Travis B. J. and Schubert G. (2005) *Earth Planet. Sci. Lett., 240*, 234-250. [16] Urey H. C. (1955) *Proceed. Nat. Acad. Sci., 41*, 127-144. [17] Prialnik D. et al. (1987) *ApJ* 319, 993-1002. [18] Leliwa-Kopystyncki J. and Kossacki K. (2000) PSS 48, 727-745. [19] Choi Y.-J. et al. (2002) *Icarus* 160, 300-312. [20] Young E. D. et al. (2003) *Earth*

Planet. Sci. Lett., 213, 249-259. [21] Hevey P. J. and Sanders I. S. (2006) *Met. Planet. Sci.,* 41, 95-106. [22] Orosei, R. et al. (2001), *Advances in Space Research, 28*, 1563-1569. [23] Merk R. and Prialnik D. (2003) *EMP* 92, 359-374. [24] Merk R. and Prialnik D. (2006) *Icarus* 183, 283-295. [24] Barr A. and Canup R. (2008) *Icarus* 198, 163-177.

Table 1. Guide to ^{26}Al decay energies used in the literature. The 4.004 MeV value includes energy carried away by neutrinos and does not apply to geophysical situations.

Energy per ^{26}Al Decay (MeV	**Reference**
1.21	McCord and Sotin [9]
1.28	Castillo-Rogez et al. [2]
2	Ghosh et al. [10]
2.5	Cohen and Coker [13]
3	Grimm and McSween [14], Ghosh and McSween [8]
3.12	This study [7A]
3.16	Schramm et al. [1], Stepinski et al. [6], Takata and Stevenson [7], Travis and Schubert [15]
3.3	Urey [16], Barr and Canup [24]
4.0	Prialnik et al. [17], Leliwa-Kopystyncki and Kossacki [18], Choi et al. [19], Young et al. [20], Hevey and Sanders [21], Orosei et al. [22], Merk and Prialnik [23]

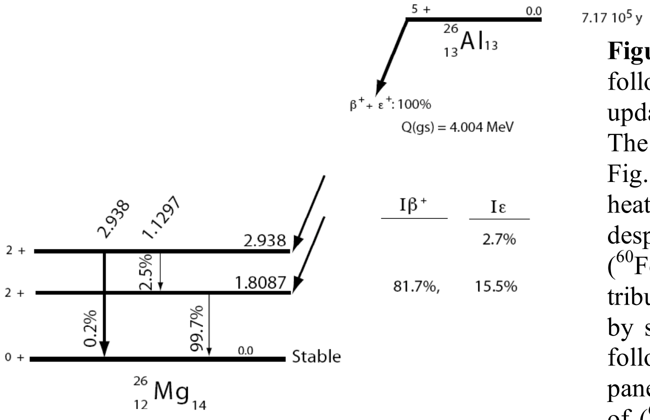

Figure 1. (Above) ^{26}Al decay scheme (modified after National Nuclear Data Center intensity and probability data). The ground state decays with half-life 7.17x10^5 y by either positron emission (β^+) or electron capture (ε), producing ^{26}Mg in one of two excited states. The upper state yields one or two γ-rays in decaying to the ground state. The intermediate state produces the strong γ-ray line at 1.809 MeV. The fraction of decays following each path is shown as a percentage. (a detailed treatment and references can be found at www.nucleide.org).

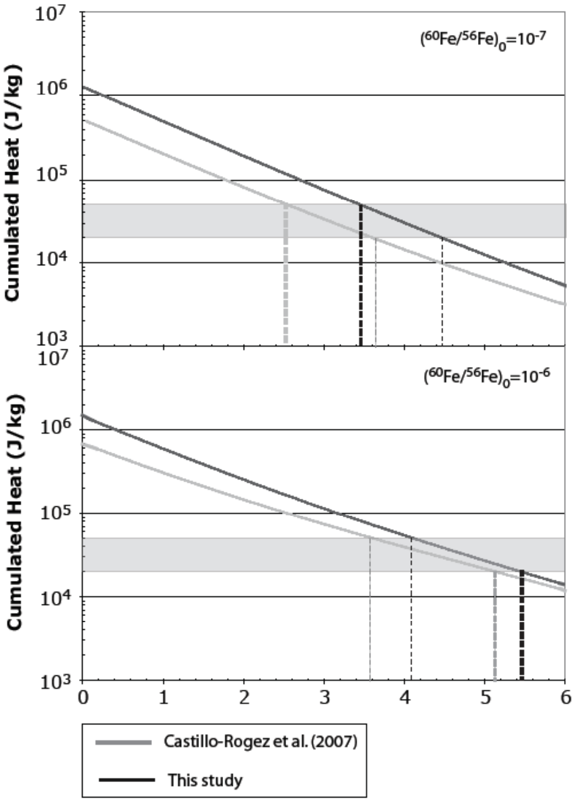

Figure 2. (Above). Times of formation of Iapetus, following the approach by Castillo-Rogez et al. (2007) updated with the recommended ^{26}Al heat production. The results are compared to the Castillo-Rogez et al. Fig. 13. The grey, horizontal, band corresponds to the heat required by models in order to explain Iapetus' despinning and non-hydrostatic shape. In the top panel (^{60}Fe/^{56}Fe)$_0$ is equal to 10^{-7}. For this value ^{60}Fe contributes only a few percent of the total heat provided by short-lived radioisotope decay in the first few My following the production of CAIs. In the bottom panel: Same calculation using an initial concentration of (^{60}Fe/^{56}Fe)$_0$ equal to 10^{-6}. Formation time interval is given by the outer bounds, ~3.4 to 5.4 My.