Anthropic selection of a solar system with a high Al/Al ratio; implications and a possible mechanism

J.D. Gilmour, C.A. Middleton

► To cite this version:

J.D. Gilmour, C.A. Middleton. Anthropic selection of a solar system with a high Al/Al ratio; implications and a possible mechanism. *Icarus*, 2009, 201 (2), pp.821. 10.1016/j.icarus.2009.03.013 . hal-00533510

HAL Id: hal-00533510

<https://hal.science/hal-00533510>

Submitted on 7 Nov 2010

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.

Accepted Manuscript

Anthropic selection of a solar system with a high $^{26}\text{Al}/^{27}\text{Al}$ ratio; implications and a possible mechanism

J.D. Gilmour, C.A. Middleton

PII: S0019-1035(09)00123-7
DOI: [10.1016/j.icarus.2009.03.013](https://doi.org/10.1016/j.icarus.2009.03.013)
Reference: YICAR 8967

To appear in: *Icarus*

Received date: 9 December 2008
Revised date: 27 February 2009
Accepted date: 10 March 2009

Please cite this article as: J.D. Gilmour, C.A. Middleton, Anthropic selection of a solar system with a high $^{26}\text{Al}/^{27}\text{Al}$ ratio; implications and a possible mechanism, *Icarus* (2009), doi: 10.1016/j.icarus.2009.03.013

This is a PDF file of an unedited manuscript that has been accepted for publication. As a service to our customers we are providing this early version of the manuscript. The manuscript will undergo copyediting, typesetting, and review of the resulting proof before it is published in its final form. Please note that during the production process errors may be discovered which could affect the content, and all legal disclaimers that apply to the journal pertain.

Anthropic selection of a solar system with a high $^{26}\text{Al}/^{27}\text{Al}$ ratio; implications and a possible mechanism.

J. D. Gilmour^{1*} and C. A. Middleton²

¹School of Earth, Atmospheric and Environmental Sciences, University of Manchester, Manchester
M13 9PL

Tel: 44 161 275 3681

Fax: 44 161 275 3947

Email: jamie.gilmour@manchester.ac.uk

²Department of Earth Sciences, University College London, Gower Street, WC1E 6BT.

Tel, Fax: n/a

Email: ceri.middleton@ucl.ac.uk

Pages: 14 (of which abstract, text and references take up 10).

Figures: 1

Tables: 0

Anthropic selection of an elevated $^{26}\text{Al}/^{27}\text{Al}$ ratio.

Correspondence Author

Jamie Gilmour

School of Earth, Atmospheric and Environmental Sciences, University of Manchester, Manchester
M13 9PL

Tel: 44 161 275 3681

Fax: 44 161 275 3947

Email: jamie.gilmour@manchester.ac.uk

Anthropic selection of an elevated $^{26}\text{Al}/^{27}\text{Al}$ ratio.

Abstract

Since our technological civilization depends on our planet's properties, anthropic selection can explain the close match between the high $^{26}\text{Al}/^{27}\text{Al}$ ratios in the earliest solar system solids, which are difficult to produce in models of star-formation, and the limiting value required to cause (the widely observed) thermal processing of planetesimals. We suggest that volatile loss on heating of planetesimals favours future development of technological civilizations in solar systems with elevated concentrations of ^{26}Al .

Keywords

Planetary formation

Meteorites

Cosmochemistry

Terrestrial Planets

Astrobiology

Anthropic selection of an elevated $^{26}\text{Al}/^{27}\text{Al}$ ratio.

1. Introduction

Chondrites consist of an intimate mixture of silicate and metallic (Fe/Ni) material that has been affected to varying extents by aqueous and thermal processes. Other meteorites (basaltic achondrites, pallasites and iron meteorites) are samples of differentiated bodies. Our current understanding is that the solar system progressed from the formation of the first solids – metal grains, chondrule precursors and calcium-aluminium-rich inclusions (CAIs) – to accretion of planetesimals, some of which differentiated. The meteorite record shows that some degree of thermal processing was ubiquitous at this planetesimal stage of solar system development.

The extinct radioisotope ^{26}Al has long been recognised as a possible heat source (Urey, 1955). However, adopting the parameters tabulated by Sahijpal et al. (2007) and approximating the specific heat capacity of chondritic material as $750 \text{ J kg}^{-1} \text{ K}^{-1}$ in the relevant temperature range (Ghosh and McSween, 1999), $1.2 \times 10^6 \text{ J kg}^{-1}$ is required to generate 40% melting of the silicate component, a criterion adopted as allowing the onset of differentiation (Sahijpal et al., 2007). For chondrites that are 1.2% Al by mass (Jarosewich, 1990), this corresponds to $^{26}\text{Al}/^{27}\text{Al} \approx 9 \times 10^{-6}$ on accretion. Reported $^{26}\text{Al}/^{27}\text{Al}$ ratios in chondrules are close to this limiting value (Mostefaoui et al., 2002) so, if chondrules predated planetesimal formation and if those in chondrites are representative of those in the precursor bodies of differentiated planetesimals, it is unclear whether ^{26}Al decay provided sufficient energy to cause differentiation. Conductive heat loss and extended periods of accretion with consequent loss of energy from the interior (Ghosh et al., 2003) exacerbate the problem.

Partly for this reason other heat sources have been proposed; they are summarised by Hewins & Newsom (1988). Recent work on the Hf-W system, however, has demonstrated that the magmatic iron meteorites (samples of the cores of small planetesimals that had differentiated) underwent melt separation earlier than had been thought, at a time contemporaneous with the formation of CAIs and chondrules (Markowski et al., 2007; Schersten et al., 2006). Thus when these planetesimals formed

Anthropic selection of an elevated $^{26}\text{Al}/^{27}\text{Al}$ ratio.

there was sufficient ^{26}Al to cause differentiation. Our picture is thus of planetesimal accretion as the $^{26}\text{Al}/^{27}\text{Al}$ ratio varied over time from that associated with CAIs – 5.25×10^{-5} (Jacobsen et al., 2008) – to that associated with chondrules from primitive meteorites ($\approx 10^{-5}$). Some of the variation may be attributable to isotopic heterogeneity across the presolar nebula, but the concordance of the intervals between CAI and chondrule formation measured in the Al-Mg and Pb-Pb systems (Amelin et al., 2002) argues against this.

The question of whether ^{26}Al provided the heat source responsible for processing material on planetesimals appears to have been resolved. However, the question arose because the concentration of ^{26}Al recorded by the solar system's earliest solids was close to the value necessary for differentiation. This observation of a close match between the required and observed values suggests an underlying mechanism, and seems worthy of an explanation.

2. Possible Explanations

Excluding coincidence we identify two possible mechanisms: erasure, and anthropic selection.

2.1 Erasure

The concentration of ^{26}Al in the early solar system was sufficient to melt the first planetesimals, so the concentration that would have been present had planetesimals formed earlier would have allowed even higher temperatures to be achieved. According to the model of Weidenschilling (1977), solids the size of chondrules and CAIs in the protoplanetary disk must accrete to planetesimals with radii >10 km or be lost to the sun on timescales of ~ 1 million years, so it is conceivable that a record of a higher $^{26}\text{Al}/^{27}\text{Al}$ ratio was erased by subsequent heating on planetesimals. This can explain the observation of $^{26}\text{Al}/^{27}\text{Al}$ ratios close to the limiting ratio – previous generations of material accreted to planetesimals that differentiated and destroyed this record.

However, the presence of presolar grains in primitive meteorites (Lodders and Amari, 2005) demonstrates that the record of events preceding the limiting ^{26}Al concentration has not been

Anthropic selection of an elevated $^{26}\text{Al}/^{27}\text{Al}$ ratio.

completely erased, while modelling suggests outward transport that could preserve material without requiring its accretion to a planetesimal (Ciesla, 2007). Also, complete erasure of the isotopic record may not be possible. The Al-Mg system records the time when material that had been heated cooled through a mineral's closure temperature. However, the Hf-W system dates the time at which metallic and silicate melts ceased equilibrating, which occurred as the melts separated during differentiation or when accretion ceased contributing metallic material that could flux a silicate mantle and transport radiogenic tungsten to the core. These events presumably occurred during heating, rather than cooling. Erasure may be possible if vigorous convection of chondritic melts prevents separation of metal from silicate and subsequent core formation, but we are unaware of evidence for this.

2.2 Anthropic ^{26}Al

The observation could be accounted for if some consequence of the presence of ^{26}Al at such levels in a solar system favoured the development of habitats capable of sustaining technological civilizations. This is plausible since the effects of heating by ^{26}Al decay are ubiquitous in our meteorite collection.

As an example, devolatilization of early formed planetesimals is a consequence of early heating by decay of short-lived radioisotopes that would clearly be expected to have a significant effect on the subsequent evolution of planetary bodies capable of sustaining life. Simple models of solar system formation invoke a “snow line”, where the volatile (ice) content of planetesimals is controlled by distance from the young sun. Heating by ^{26}Al imposes a “snow moment” – planetesimals forming earlier than this will be dehydrated as they are heated by the decay of ^{26}Al .

In Figure 1 we explore the location of the snow moment compared to the limiting time for differentiation as a function of ice/rock ratio (by mass) and time relative to the canonical $^{26}\text{Al}/^{27}\text{Al}$ ratio. For simplicity, we assume instantaneous accretion of planetesimals sufficiently large that loss of heat produced by radioactive decay can be neglected – vastly more sophisticated models of icy bodies are available (e.g. Prialnik and Merk, 2008), but are not necessary for this simple illustration. In

Anthropic selection of an elevated $^{26}\text{Al}/^{27}\text{Al}$ ratio.

In addition to the parameters of our previous calculation we adopt 12 kcal mol^{-1} as the latent heat of sublimation of ice (Delval et al., 2003). The $^{26}\text{Al}/^{27}\text{Al}$ ratios required on accretion to subsequently differentiate chondritic planetesimals and those required to dehydrate planetesimals that are initially ~60% ice by mass – assuming only water ice condenses (Lodders, 2003) – are similar, suggesting that the cases where dehydration or differentiation cause anthropic selection have similar limiting $^{26}\text{Al}/^{27}\text{Al}$ ratios. Devolatilization can thus be the basis of an anthropic explanation for the observation of an initial aluminium ratio close to that required to power differentiation.

We speculate that such dehydration may have many consequences for the subsequent evolution of the solar system. If core accretion is the mechanism by which the gas giants formed, then a core of 5-10 Earth masses has to accrete within the lifetime of the protoplanetary disk in order to retain a gaseous envelope (Desch, 2007; Mizuno, 1980; Pollack et al., 1996). Before the snow moment the amount of material available for core formation is decreased by two thirds, inhibiting the formation of gas giant planets and limiting their ultimate size. The presence of gas giants has been suggested to improve the stability of the terrestrial region, as impactors from the outer solar system are “swept up” by gas giants (Wetherill, 1994), although recent work suggests Jupiter in its current orbit provides little protection (Laakso et al., 2006). The position of gas giants in the solar system is also important; gas giants within 2.5 A.U. are thought to inhibit formation of terrestrial planets within the habitable zone (Raymond, 2006), and the inward migration through the solar system will have also have affected this formation (Mandell et al., 2007). If the solar system had a lower ^{26}Al concentration, giant planets may have formed more quickly, so migration (Papaloizou and Terquem, 2006) would have occurred sooner, at a different stage in terrestrial planetary formation.

Alternatively, recent work has suggested that the problem with accounting for the volatile abundances of the terrestrial planets lies in explaining their low abundance rather than accounting for their presence (Nuth, 2008). Early, abundant ^{26}Al leads to planetesimals that are relatively volatile

Anthropic selection of an elevated $^{26}\text{Al}/^{27}\text{Al}$ ratio.

poor, reducing the volatile content both of the terrestrial planets on accretion and of the planetesimals that contributed any “late veneer” of volatiles invoked to account for the terrestrial inventory (Javoy, 1997). Simulations of terrestrial planet evolution that take no account of devolatilization of planetesimals as a result of heating by ^{26}Al decay result in planets with several times the Earth’s current water budget (Mandell et al., 2007; Raymond et al., 2007). It is plausible that technological civilization is hard to develop on a planet that is covered by ocean.

3. Coincidence, Erasure, or Anthropic Selection?

Assuming that the time that elapsed between isolation of the solar system’s parent material and the formation of the solar system’s first solids was controlled by the timescale of ambipolar diffusion – 10^6 - 10^7 years (Lada and Shu, 1990), the initial $^{26}\text{Al}/^{27}\text{Al}$ ratio was greater than 1.3×10^{-4} . Since the average $^{26}\text{Al}/^{27}\text{Al}$ ratio of interstellar matter in the galaxy is 8.4×10^{-6} (Diehl et al., 2006), this corresponds to (probably much) less than 6% material sufficiently enriched in ^{26}Al as to correspond to solar system precursor material. In fact, detailed modelling shows that the probability of a solar system forming with concentrations of short-lived radioisotopes as high as those in ours is $<3 \times 10^{-3}$ (Gounelle and Meibom, 2008) if the source is a nearby supernova. It seems clear that the problem lies in accounting for an unusually high $^{26}\text{Al}/^{27}\text{Al}$ ratio in the early solar system, suggesting that anthropic selection is a plausible explanation while erasure and coincidence are not. Rather than seeing the low probability of a solar system emerging with $^{26}\text{Al}/^{27}\text{Al}$ as high as that observed in ours as a problem for models of solar system formation, we argue that the low probability of a solar system’s forming with an elevated ^{26}Al concentration is immaterial if such a concentration drastically increases the probability of the subsequent formation of an environment capable of supporting a civilization like ours. Based on our rough estimates of the probability of formation of a solar system with a sufficiently high concentration of ^{26}Al , we suggest that formulations of the Drake equation that neglect the effect of ^{26}Al

Anthropic selection of an elevated $^{26}\text{Al}/^{27}\text{Al}$ ratio.

on our solar system's evolution will overestimate the frequency of technological civilizations by factors of 100 or more.

It is reasonable to ask what predictions we might make based on this proposal. Reduced to its essentials, our argument is that the presence of ^{26}Al led to widespread effects in the first planetesimals, that these necessarily affected the properties of the terrestrial planets that eventually formed, that our emergence as technologically equipped observers was strongly dependent on a terrestrial planet with a particular set of properties, and that as a consequence anthropic selection can account for an $^{26}\text{Al}/^{27}\text{Al}$ ratio in our solar system close to the limiting value required to power processing on planetesimals, even though such ratios are rare among solar systems in general. We have explored the role of ^{26}Al in heating planetesimals and causing loss of volatiles and concluded that it is a potential mechanism; whether it is the responsible mechanism or not, volatile loss from planetesimals seems an inevitable consequence of a high $^{26}\text{Al}/^{27}\text{Al}$ ratio, so we would expect that most terrestrial extrasolar planets would be more volatile rich than those in our solar system. If, as we speculate, loss of ice from planetesimals delays the formation of cores from which giant planets can develop, we would expect the giant planets in our solar system to be at the low end of the mass spectrum, a hypothesis that can be tested as the observational bias to large gas giants is eroded by improved techniques. In contrast, it is not clear to us that the delay in formation we speculate may be caused by high ^{26}Al concentrations, and the consequent delayed migration due to the presence of ^{26}Al , would have left a signature in our solar system distinguishable from the configuration of extrasolar planetary systems.

Anthropic selection of an elevated $^{26}\text{Al}/^{27}\text{Al}$ ratio.

References

- Amelin, Y., et al., 2002. Lead isotopic ages of chondrules and calcium-aluminum-rich inclusions. *Science*. 297, 1678-1683.
- Ciesla, F. J., 2007. Outward transport of high-temperature materials around the midplane of the solar nebula. *Science*. 318, 613-615.
- Delval, C., et al., 2003. The rate of water vapor evaporation from ice substrates in the presence of HCl and HBr: Implications for the lifetime of atmospheric ice particles. *Atmospheric Chemistry and Physics*. 3, 1131-1145.
- Desch, S. J., 2007. Mass distribution and planet formation in the solar nebula. *Astrophysical Journal*. 671, 878-893.
- Desch S. J. and Leshin 2004 Making Water Worlds: The Role Of Al 26. *Lunar and Planetary Science Conference XXXV*, abstract #1987.
- Diehl, R., et al., 2006. Radioactive Al-26 from massive stars in the galaxy. *Nature*. 439, 45-47.
- Ghosh, A., McSween, H. Y., 1999. Temperature dependence of specific heat capacity and its effect on asteroid thermal models. *Meteoritics & Planetary Science*. 34, 121-127.
- Ghosh, A., et al., 2003. Importance of the accretion process in asteroid thermal evolution: 6 Hebe as an example. *Meteoritics & Planetary Science*. 38, 711-724.
- Gounelle, M., Meibom, A., 2008. The origin of short-lived radionuclides and the astrophysical environment of solar system formation. *Astrophysical Journal*. 680, 781-792.
- Hewins, R. H., Newsom, H. E., Igneous activity in the early solar system. In: J. F. Kerridge, M. S. Matthews, Eds.), *Meteorites and the Early Solar System*. The University of Arizona Press, 1988, pp. 73-101.

Anthropic selection of an elevated $^{26}\text{Al}/^{27}\text{Al}$ ratio.

- Jacobsen, B., et al., 2008. Al-26-Mg-26 and Pb-207-Pb-206 systematics of Allende CAIs: Canonical solar initial Al-26/Al-27 ratio reinstated. *Earth and Planetary Science Letters*. 272, 353-364.
- Jarosewich, E., 1990. Chemical-analyses of meteorites - a compilation of stony and iron meteorite analyses. *Meteoritics*. 25, 323-337.
- Javoy, M., 1997. The major volatile elements of the Earth: Their origin, behavior, and fate. *Geophysical Research Letters*. 24, 177-180.
- Laakso, T., et al., 2006. Gravitational scattering by giant planets. *Astronomy & Astrophysics*. 456, 373-378.
- Lada, C. J., Shu, F. H., 1990. The formation of sunlike stars. *Science*. 248, 564-572.
- Lodders, K., 2003. Solar system abundances and condensation temperatures of the elements. *Astrophysical Journal*. 591, 1220-1247.
- Lodders, K., Amari, S., 2005. Presolar grains from meteorites: Remnants from the early times of the solar system. *Chemie Der Erde-Geochemistry*. 65, 93-166.
- Mandell, A. M., et al., 2007. Formation of Earth-like planets during and after giant planet migration. *Astrophysical Journal*. 660, 823-844.
- Markowski, A., et al., 2007. Hafnium-tungsten chronometry of angrites and the earliest evolution of planetary objects. *Earth and Planetary Science Letters*. 262, 214-229.
- Mizuno, H., 1980. Formation of the giant planets. *Progress of Theoretical Physics*. 64, 544-557.
- Mostefaoui, S., et al., 2002. The relative formation ages of ferromagnesian chondrules inferred from their initial aluminum-26/aluminum-27 ratios. *Meteoritics & Planetary Science*. 37, 421-438.
- Nuth, J. A., 2008. What was the volatile composition of the planetesimals that formed the Earth? *Earth Moon and Planets*. 102, 435-445.
- Papaloizou, J. C. B., Terquem, C., 2006. Planet formation and migration. *Reports on Progress in Physics*. 69, 119-180.

Anthropic selection of an elevated $^{26}\text{Al}/^{27}\text{Al}$ ratio.

- Pollack, J. B., et al., 1996. Formation of the giant planets by concurrent accretion of solids and gas. *Icarus*. 124, 62-85.
- Prialnik, D., Merk, R., 2008. Growth and evolution of small porous icy bodies with an adaptive-grid thermal evolution code - i. Application to Kuiper belt objects and Enceladus. *Icarus*. 197, 211-220.
- Raymond, S. N., 2006. The search for other Earths: Limits on the giant planet orbits that allow habitable terrestrial planets to form. *Astrophysical Journal*. 643, L131-L134.
- Raymond, S. N., et al., 2007. High-resolution simulations of the final assembly of Earth-like planets. 2. Water delivery and planetary habitability. *Astrobiology*. 7, 66-84.
- Sahijpal, S., et al., 2007. Numerical simulations of the differentiation of accreting planetesimals with Al-26 and Fe-60 as the heat sources. *Meteoritics & Planetary Science*. 42, 1529-1548.
- Schersten, A., et al., 2006. Hf-W evidence for rapid differentiation of iron meteorite parent bodies. *Earth and Planetary Science Letters*. 241, 530-542.
- Urey, H. C., 1955. The cosmic abundances of potassium, uranium, and thorium and the heat balances of the Earth, the Moon, and Mars. *Proceedings of the National Academy of Sciences of the United States of America*. 41, 127-144.
- Weidenschilling, S. J., 1977. Aerodynamics of solid bodies in solar nebula. *Monthly Notices of the Royal Astronomical Society*. 180, 57-70.
- Wetherill, G. W., 1994. Possible consequences of absence of Jupiter in planetary systems. *Astrophysics and Space Science*. 212, 23-32.

Figure Caption

Figure 1. Dependence of planetesimal evolution on the fraction of ice present and the time dependent $^{26}\text{Al}/^{27}\text{Al}$ ratio when it accretes (relative to the time at which $^{26}\text{Al}/^{27}\text{Al} = 5 \times 10^{-5}$). There is insufficient energy density in planetesimals with ice fraction and accretion time combinations lying above and to the right of the broken and solid lines to cause dehydration and differentiation respectively, a conclusion similar to that reached by Desch and Leshin (2004). To the left of the lines, dehydration and differentiation are possible provided heat loss is small. In each case the upper line assumes all heat generated from ^{26}Al decay goes to planetesimal processing, while the lower line assumes that only the heat generated in the first 1 million years after accretion is available (to mimic the effect of conductive cooling due to planetesimals having finite size). The limiting times for differentiation of planetesimals and for dehydration of planetesimals with significant ice fractions overlap, showing that the limitations that are imposed on the initial $^{26}\text{Al}/^{27}\text{Al}$ ratios of the solar system by requiring these processes to occur are similar. The broken horizontal line indicates the maximum ice fraction assuming all available water condenses.

Anthropic selection of an elevated $^{26}\text{Al}/^{27}\text{Al}$ ratio.