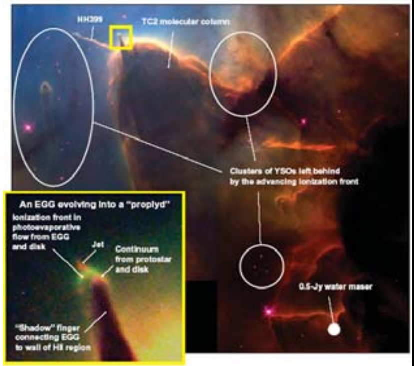
Earth Structure and Evolution



Bulk earth composition, radioactive heating, partitioning/fractionation, natural reactors

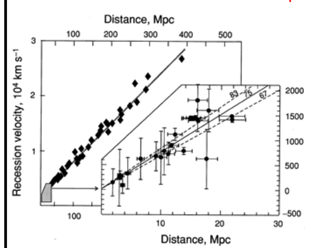
Earth Structure and Evolution

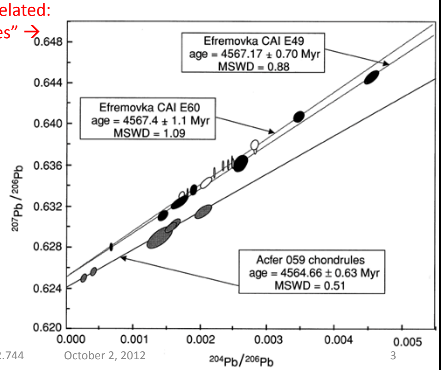
- **Fitting Isotope/Isochron Data**
- Bulk Earth Composition and Differentiation
- Radioactive Heating
- Natural Reactors

A word about dealing with "real data" for isotope-isotope relations

- All isotope data have uncertainties

Note: if errors uncorrelated: we have "error ellipses" →





Note: isotope ratio errors involve propagation of errors →

A word about dealing with "real data" for isotope-isotope relations

- All isotope data have uncertainties
- Finding "best fit" (straight) lines must account for relative uncertainties/weights → and provide uncertainties in slope/intercept
- Normal "least squares" methods account only for uncertainties (weights) in the "y-coordinate"
- When there are uncertainties in *both* x- and y-coordinates, you need to use a "Type 2 Regression"; a *non-trivial* exercise

Type 2 Regressions

- Involve "weighted distance normal to trend line"
  - Therefore are complicated & iterative in nature
  - Especially problematic when strongly correlated errors and large dynamic range
  - IsoPlot (a BSD openware app for Excel)
    - Problem: IsoPlot 3 only compatible with Excel 2003 & earlier (need IsoPlot 4 for 2007+ mutually incompatible & performance compromises)
  - See 12.747, Lecture 3 & MATLAB m-files, plus chapter 3 of Glover, D. M., W. J. Jenkins, et al. (2011). Modeling methods for marine science. Cambridge, U.K., Cambridge University Press.
- Some references (posted on web site):
  - York, D., N. M. Evensen, et al. (2004). "Unified equations for the slope, intercept and standard errors of the best straight line." American Journal of Physics **72**(3): 367-375.
  - Reed, B. C. (1992). "Linear least-squares fits with errors in both coodinates. II: Comments on parameter variances." American Journal of Physics **60**(1): 59-62.
  - Reed, B. C. (2010). "A spreadsheet for linear least-squares fitting with errors in both coordinates." Physics Education **45**(1): 93-96.

A note on terminology

- Traditionally isotope information presented in δ notation, referred to a generally accepted/available standard:

$$\delta_X = \left(\frac{R_{\text{Unknown}}}{R_{\text{Standard}}} - 1 \right) \times 1{,}000 \text{ ‰}$$

- Another notation used for some systems:

$$\varepsilon_X = \left(\frac{R_{\text{Unknown}}}{R_{\text{Standard}}} - 1 \right) \times 10{,}000$$

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Bulk Earth Composition

- We can only sample the top ~1% of the earth's material
  - Other inferences made from seismic, isotopic, mineralogical, and heat-flow information
- Speculate that earth may have formed from material similar to undifferentiated meteorites
  - Which meteorites?
    - C1 (carbonaceous chondrites) main candidate
    - Enstatite condrites

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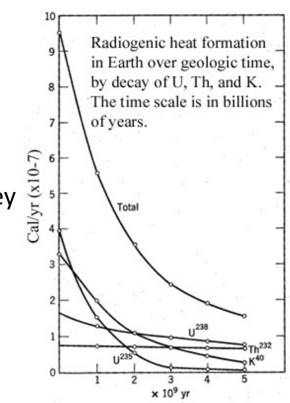
The terrestrial heat flux

- Lord Kelvin (W. Thompson) in 1863 estimated age of earth to be 20-400 Ma based on observed conductive heat flux and secular conductive cooling
  - Before radioactivity was discovered
- Early in solar system/planetesimal history gravitational energy release,
  - ^{26}Al, ^{36}Cl, ^{60}Fe, and ^{244}Pu were probably important
  - earth likely molten
- Later, it's just down to ^{40}K, ^{232}Th, ^{235}U, ^{238}U
  - All decreasing with time at their own rates

Radioactive heat generation

- Drives mantle convection, mantle plumes, plate tectonics
- Serves to slow earth cooling
- ~Half of 44 TW generated by radioactivity
  - Other half is "secular cooling"
  - Ratio radiogenic/total flux = "Urey Ratio"
    - Usage may/may not include continents
- Modeled heat production depends on bulk earth composition and differentiation/distribution



RG2007 Korenaga: UREY RATIO AND EARTH'S MANTLE RG2007

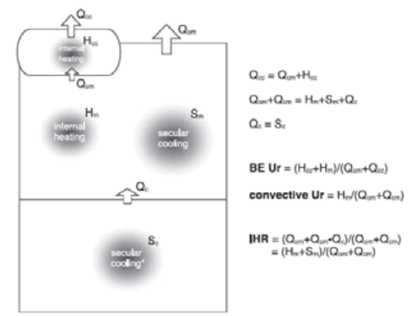


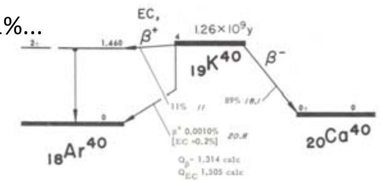
Figure 1. Schematic drawing to clarify the definitions of the bulk Earth Urey ratio (Ur), the convective Urey ratio, and the internal heating ratio (IHR). Q_{cc} is surface heat flux from continental regions, Q_{om} is surface heat flux from oceanic regions, Q_{cm} is heat flux from subcontinental mantle, H_{cc} is the heat production of continental crust, H_m is the heat production of the mantle, S_m is heat flux due to the secular cooling of the mantle, Q_c is core heat flux, and S_c is heat flux due to the secular cooling of the core (including the effect of inner core growth). The presence of heat-producing elements in the core is neglected here for simplicity.

Korenaga, J. Urey Ratio and the structure and evolution of Earth's mantle. Rev. Geophys. **46** *2007RG000241*

Lest you think neutrinos are just a curiosity…

Geoneutrinos and the K/U ratio of the earth

- Present day geothermal heat (~44 TW) partly produced by U,Th series and ^{40}K decay
- What is terrestrial K/U ratio?
  - Based on chemical/physical formation models
  - Implications regarding chemical, physical, and thermal history of earth
    - different half-lives of decay
    - Chemical differentiation
- ^{40}K produces 89% … ,11%…
- U,Th chains produce…
  - But at different energies



Geoneutrinos

- Stellar fusion produces…
- Alpha-chain and K-decay produce…
- Use "inverse neutron decay reaction"

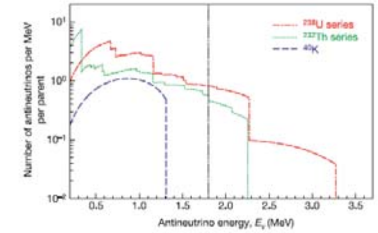


Figure 1 | The expected ^{238}U, ^{232}Th and ^{40}K decay chain electron antineutrino energy distributions. KamLAND can only detect electron antineutrinos to the right of the vertical dotted black line; hence it is insensitive to ^{40}K electron antineutrinos.

$$n \xrightarrow[2MeV]{11\min} p + e^- + \bar{\nu}_e$$

$$\bar{\nu}_e + p \rightarrow n + e^+$$

Araki et al, 2005 *Nature* **436** p 499-503

Where do geoneutrinos come from?

There are **other** sources of antineutrinos:

- Nuclear reactors (fission products)
- The crust (enriched in K, U, Th)
- The mantle (what we're *really* interested in)

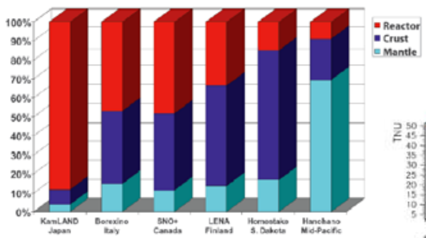
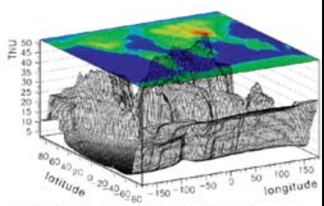


Fig. 1. Predicted antineutrino flux from nuclear reactors, crust, and mantle at project sites.

Other neutrino detector sites
Dye et al, 2008 *EOS* **89** (44) p 433-434



Progress so far…

- Surface heat flow ~47 TW
- Radiogenic heat production ~24 TW
  - But ~5 TW escapes via antineutrinos
  - Thus a large portion is secular cooling

Dye, S.T. Geoneutrinos and the radioactive power of the Earth. Rev. Geophys. **50** *2012RG000400*

Mareschal, J-C et al. Geoneutrinos and the energy budget of the Earth. J. Geodyn. **54** 43-54

12.744 October 2, 2012 16

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Natural Nuclear Reactors?

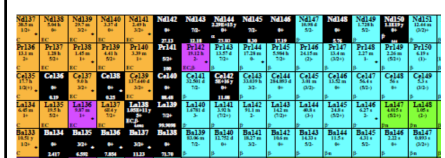
- Present global $^{235}U/^{238}U = 0.00720$
  - Extremely constant
    - small relative mass difference → less opportunity for geochemical/geological mass fractionation
  - French nuclear weapons lab noted small but significant ^{235}U deficit in Oklo U-ore
    - $^{235}U/^{238}U = 0.00717$ (δ = -4‰)
- Remember the following:
  - ^{235}U is much more fissionable than ^{238}U
    - Fission process is $n + {}^{235}U \rightarrow$ FP's + a few n
    - To have "critical mass" need ^{235}U "density" high enough so that at least 1 of the "few n" yields another fission
  - $^{235}U/^{238}U$ is decreasing with time

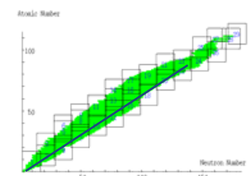
^{235}U-fission

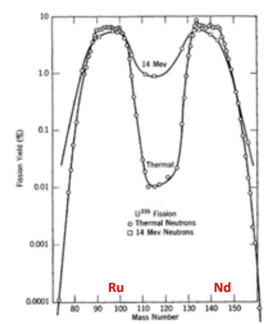
- ^{235}U much more fissile than ^{238}U
- Requires critical concentration of ^{235}U
  - ~2Ga ago $^{235}U/^{238}U$ = ???
  - Ore formation *via* redox processes in groundwater
    - U^{+6} oxic is soluble
    - U^{+4} anoxic is insoluble
- Need water to slow neutrons down by inelastic collisions (probability of n-induced fission ~ 1/v)
- Further evidence?

Tell-tale Evidence

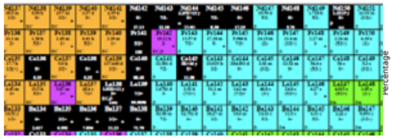
Fission products! (2 examples)

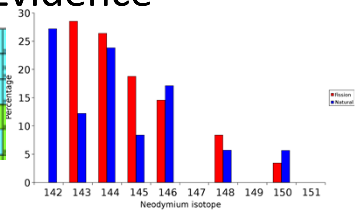


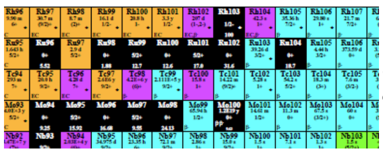


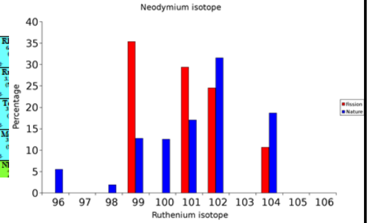


Tell-tale Evidence









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