EXTINCT RADIOACTIVITIES IN THE EARLY SOLAR SYSTEM AND THE MEAN AGE OF THE GALAXY. Q.-Z Yin[1] [1]Department of Geology, University of California at Davis, One Shields Avenue, Davis, CA 95616 (qyin@ucdavis.edu)

Introduction: Lodders and Cameron [1] noted that the abundances of extinct radioactivities relative to a stable reference nuclide in the early Solar System are proportional to the square of their mean lives (referred to as *Lodders line* in the following text). The slope on the log-log diagram of Lodders line is ~2. I expand Lodders line a step further by including ^{235}U (mean life τ =1.02X10^{9}y), which is an almost-extinct radionuclide. I further discuss the derivation of Lodders line alternative to that of [2]. From the linear extrapolation of Fig. 1 and 2, I derive the mean age of the Galaxy T_G = 12.3±3.6 Ga. Compared to other existing methods of calculating the mean age of Galaxy, this one is completely independent of the production ratios from nucleo-syntheses models.

Data: I have collected all the published records for extinct radioactivities in early solar system materials. The references are too numerous to list them all in this short abstract. Although some published data may still be missing from this summary, I believe all basic features are captured in the present representation. Calcium-aluminum-rich inclusions (CAI) data are not plotted in Fig. 1 and 2, in accordance with the observation [1] that most of the CAI data are above Lodders line (see Fig. 3).

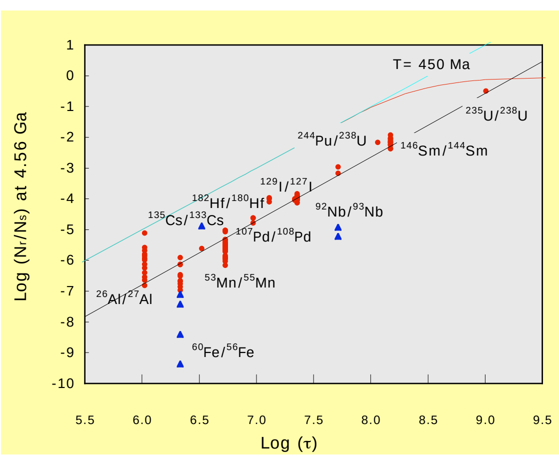

Fig. 1 Extinct radioactive nuclides in the early Solar System normalized to a stable nuclide *vs.* their corresponding mean lives on log scale. Blue triangles are excluded from the linear regression. Contour for T=450 Ma is shown in light blue ($N_r/N_s=2(\tau/T)^2$ [1,2]) and in red (without T>>τ approximation). Both lines fail to describe the data.

Lodders line predicts that the ^{92}Nb/^{93}Nb ratio in the early solar system to be ~10^{-3}, which is observed by Yin et al. [3]. If samples are young or disturbed, it is expected that the observed abundances of radioactive nuclides are low, and therefore plot below Lodders line. This is the case for ^{92}Nb as extensively argued for in [4,5], ^{60}Fe [6,7] shown in blue triangles and some ^{53}Mn data. The significance of ^{135}Cs in Bearsley (H5) is not clear, which plots above Lodders line while the datum for Zag (H3-6) plots on the line [8]. Most ^{26}Al data (eucrites or chondrules from primitive chondrites) plot above Lodders line, suggesting a different source of production is required. The validity of moving ^{92}Nb/^{93}Nb from 10^{-5} to 10^{-3} to fit onto Lodders line by assuming that 1% of ^{93}Nb is made of p-process [2] and the validity of changing ratios from ^{60}Fe/^{56}Fe to ^{60}Fe/^{58}Fe to achieve an apparent fit for old eucrite data [2] remains to be demonstrated.

Alternative Derivation: Cameron and Lodders [2] derived the $N_r/N_{tot}=2(\tau/T)^2$ relation assuming $dN/dt=ate^{-t/\tau}$, where a is a proportionality constant, τ is the mean-life of an individual radioactive nuclide, and T is the duration of nucleosyntheses. Derivation of Lodders line from $dN/dt=ate^{-t/\tau}$ is not unique, however, as it could also be derived by assuming $dN/dt=aN^{1/2}e^{-t/\tau}$, producing $N_r/N_{tot}=(\tau/T)^2$. Compared to $N_r/N_{tot}=2(\tau/T)^2$ in [2], I note that the coefficient 2 makes little difference for the intercept of a Log(N_r/N_s) *vs.* Log(τ) plot, given the scatter of the data and that T is a large number. The regressed uncertainty of the intercept is larger than log(2).

The choice between $dN/dt=ate^{-t/\tau}$ and $dN/dt=aN^{1/2}e^{-t/\tau}$ depends on our ability to assign a more reasonable physical meaning to one of them. It was postulated by [2] that $dN/dt=ate^{-t/\tau}$ implies that materials injected into the solar nebula-to-be increased in proportion to the elapsed time. The elapsed timescale T is estimated to be about 450 Ma [2], which is considered long by [2] relative to the mean life of ^{146}Sm (τ =1.49X10^{8}y). The 450 Ma timescale is related to the duration of a galactic year, for the solar nebula-to-be passing through the galactic arms of density waves with enhanced star formation. However, as shown in Fig. 1a and 1b, ^{235}U plots on Lodders line perfectly. Using T=450Ma leads to a poor approximation to the data (Fig. 1a). The T has to be >3 Ga for ^{235}U to plot on the line. The fact that ^{235}U/^{238}U plots on Lodders line implies that this line must reflect the entire cumulative Galactic nucleosynthetic history.

Mean Age of the Galaxy: Roughly 10^9 supernovae contributed to the galactic heavy elements, of which 10^5 contributed to the solar system (D. Clayton, personal communication). It is obvious from the intercept of Fig. 2 one can obtain the duration of the Galactic nucleosyntheses *T* that had contributed matter to the birth of our solar system. Fig. 2 only includes those nuclides with mean-lives longer than 9 Ma, as nuclides with shorter mean-lives show more scatter (Fig. 1). Linear regression of Fig. 1 leads to the same results, with somewhat larger uncertainty. Given that these are our solar system's records at 4.56 Ga ago, the age of the Galaxy is derived from T_G=T+4.56 =12.3±3.6 Ga.

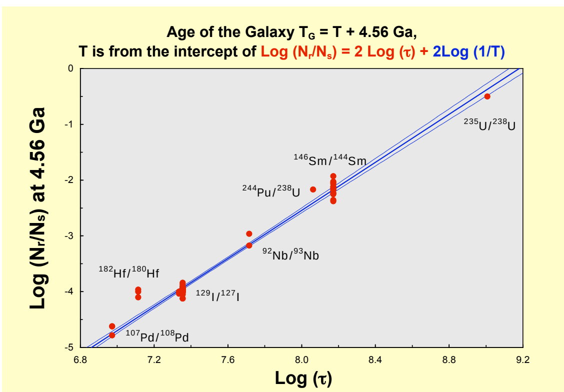

Fig. 2 Linear regression of the nuclides with mean-lives longer than 9 Ma. From its intercept, the mean age of the Galaxy is derived.

The derived age for the Galaxy is also a minimum age for the Universe. Although with large uncertainty, it is entirely consistent with the estimates from the Hubble constant, WMAP result (microwave background), and globular clusters. It is also consistent with 12.5±3 Ga age results obtained from other cosmochronometers, such as the U/Th method [9], using the relation: $T_G=21.8[\log(U/Th)_0-\log(U/Th)_{obs}]$.

However, in these methods [9] an initial production ratio, such as $(U/Th)_0$ is needed as predicted by theoretical nucleosynthesis models, which depends on adopted nuclear physics, the validity of this can only be confirmed by observation. The age of the Galaxy derived here is solely based on the meteoritic data as shown in Fig. 1 and 2 and is completely model independent.

The strong correlation in Fig. 2 suggests that together with ^{235}U and ^{244}Pu, meteoritic records of ^{146}Sm, ^{92}Nb, ^{129}I, and ^{107}Pd are consistent with continuous nucleosyntheses over the Galactic history. The classical problem of ^{182}Hf "over abundance" [10,11] is obvious in Fig. 2. A factor 2 reduction in the initial abundance of ^{182}Hf in [12] does not ease the problem quite enough.

X-wind *vs.* Galactic Nucleosyntheses: By all accounts, CAIs are exotic objects whose origin is enigmatic. Most isotopic data for extinct radioactivities are obtained from CV chondrites (Allende in particular). As noted in [1,2], the deviation of CAI data from Lodders line is obvious. Given that ^{10}Be has to be made by an irradiation mechanism [13], Fig. 3 highlights a potential reconciliation that accounts for those radionuclides plotting above Lodders line as a result of their formation in an X-wind scenario [13] in the amount above the Galactic chemical evolution line.

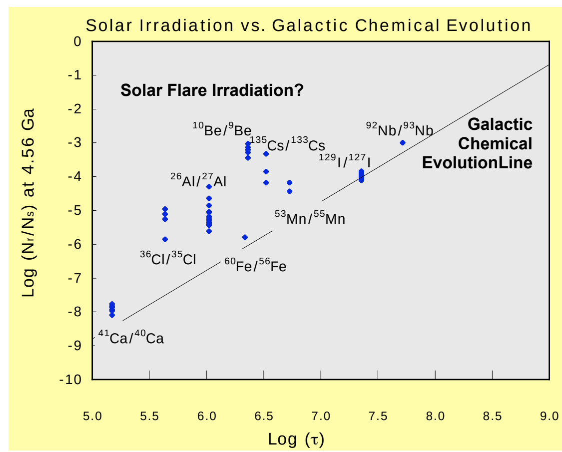

Fig. 3 Extinct radioactivities in CAIs are shown to plot above Lodders line, requiring a different source for producing these nuclides.

References: [1] Lodders K. and Cameron A. G. W. (2004) *LPS XXXV*, Abstract #1186. [2] Cameron A. G. W. (2004) *LPS XXXV* Abstract #1181. [3] Yin et al. (2000) *ApJL, 536,* L49-53. [4] Yin Q.-Z. and Jacobsen S. B. (2002) *MAPS 37,* A152. [5] Schönbächler et al (2001) *Science, 295,* 1705-1708. [6] Shukolyukov, A. and Lugmair, G.W. (1993a) *Science, 259*, 1138-1142. [7] Shukolyukov, A. and Lugmair, G.W. (1993b) *EPSL 119,* 159-166. [8] Hidaka H. et al. (2001) *EPSL 193*, 459-466. [9] Cayrel R. et al. (2001) *Nature, 409,* 691-692. [10] Wasserburg G. J. et al. (1996) *ApJL, 466*, L109-113. [11] Meyer B. S. and Clayton D. D. (2000) *Space Sci. Rev. 92*, 133-152. [12] Yin Q. et al. (2002) *Nature 418*, 949-952. [13] Shu F. et al. (1997) *Science 277,* 1475-1479.