BEREYLLIUM-10 AND CAI ORIGIN. E. Jacquet¹, IMPMC, MNHN & CNRS, UMR 7590, CP52 57 rue Cuvier, 75005 Paris, France. (Emmanuel.jacquet@mnhn.fr).

Introduction: Refractory inclusions, in particular Calcium-Aluminum-rich Inclusions (CAIs), are the oldest solids of the Solar System. They are believed to have originally formed the beginning of a condensation sequence out of a solar composition gas. The high temperature required (~1500-2000 K) have long suggested an origin at the very inner edge of the solar protoplanetary disk (at heliocentric distances R<0.1 AU), directly exposed to solar radiation. However, that inner edge may have been quite hostile to the formation and survival of solids [1], in particular because temperatures may have been raised above wholesale vaporization of disk matter by the dissipation of turbulence. This heating in fact allows CAI formation much further from the Sun, e.g. at heliocentric distances of order an AU (e.g. [2]), especially if they formed upon intermittent temperature excursions [3].

Yet evidence for the past presence of live beryllium-10 (half-life: 1.5 Ma) in CAIs may still be seen to support the inner edge origin [4]. Indeed, beryllium-10 is not significantly produced by stellar nucleosynthesis and requires a spallation origin. Although galactic cosmic rays may conceivably have produced beryllium-10 in the molecular cloud parental to the Solar System [5], the expected homogeneity in $^{10}$Be/$^{9}$Be is at variance with the observed range from $3\times10^{-4}$ in FUN CAIs [6-7] to $\sim10^{-2}$ in fine-grained group II CAIs [8]. The latter also exhibit vanadium-50 excesses which are also expected spallation products [8]. Thus, an origin local to the solar protoplanetary disk, presumably due to solar energetic particles, seems indicated. Since those energetic particles would not penetrate far into the gas, an inner edge site would indeed maximize the production rate of beryllium-10 and a few centuries there would be sufficient to reproduce the observed $^{10}$Be/$^{9}$Be ratios [8].

However, this is not the only possible site. Energetic particles arriving on the “upper” or “lower” surfaces of the disk (e.g. Fig. 1) would equally induce the formation of spallogenic beryllium-10 which could then be transported outward through the disk. I have thus set to model the associated production channels [9].

Model: The model is analytical in nature and considers a steady-state inner disk, neglecting infall there. The exact geometry of the transport of energetic solar particles is unknown and is parameterized as such in the calculations, but for numerical applications, it is assumed that they are uniformly emitted from a Sun-centered sphere of radius that the inner disk ($R_0$) and follow the field lines of a dipolar magnetic field up to a maximum heliocentric distance $R_{\text{max}}$. The total rate of emission of these particles is also not known and, as in previous work, scaled to the total X-ray luminosity using solar flares as nominal normalization values.

Two production channels were considered:

(i) Irradiation of the solar composition gas (+ dust) at the disk surface and transport.
(ii) Irradiation of already formed CAIs which intermittently reach the disk surface, with in situ production of beryllium-10.

A given CAI may have inherited the $^{10}$Be/$^{9}$Be given by (i) upon condensation (or later reequilibration with the gas) and then gained additional beryllium-10 from channel (ii). I however find that channel (ii) is generally negligible, because a refractory target has fewer suitable target nuclides (essentially O) and is enriched in stable beryllium compared to a solar gas target (see also [10]). Thus CAIs should essentially fossilize the bulk $^{10}$Be/$^{9}$Be ratio of their formation region (and epoch).

Results and discussion: In a steady-state disk, production of beryllium-10 should be balanced by loss to the Sun because of inward accretion (radioactive decay occurs on longer timescales and is here negligible). Inward accretion is counteracted by turbulent diffusion which allows some outward

Figure 1: Sketch of the model. The red hatched area features beryllium-10 production.
transport of beryllium-10. The resultant equilibrium profile of the \( ^{10}\text{Be}/^{9}\text{Be} \) ratio is a monotonic decrease with heliocentric distance (Fig. 2). This contradicts earlier claims that \(^{10}\text{Be} \) production in the gas should lead to uniform abundances [11, 12].

![Figure 2: \( ^{10}\text{Be}/^{9}\text{Be} \) ratios (in arbitrary units) as a function of heliocentric distance \( R \), for two different values of both \( R_{\text{max}} \) and the Schmidt number \( Sc_R \) which measures the inefficiency of diffusion.](image)

In terms of absolute values, the ratio is:

\[
\left( \frac{^{10}\text{Be}}{^{9}\text{Be}} \right)_{\text{final}} = 6 \times 10^{-4} \frac{K_{p,\text{disk}}}{9 \times 10^{-19} \text{ s}^{-2} \text{ m}^{-2}} \frac{(O/\text{Be})_{\text{disk}}}{2.2 \times 10^{7}} \frac{f_{\text{sum}}}{0.1} \frac{L_{10}/L_{\chi}}{6} \frac{L_{\chi}}{3 \times 10^{23} \text{ W}} \frac{10^{-7} M_{\odot}/a}{M}.
\]

(22)

with \( L_{10} \) the luminosity of \( >10 \) MeV particles, \( L_{\chi} \) the X-ray luminosity, \( M \) the mass accretion rate and other more technical parameters explained in [9] (the “\( f_{\text{sum}} \)” being roughly the \( f_{\text{eff}} \) plotted in Fig. 2). The \( ^{10}\text{Be}/^{9}\text{Be} \) ratio is comparable to the average measured in CV chondrites when setting all parameters to their nominal values. This is because the lower production rates near the disk surface (subjected to varying degrees of attenuation) compared to (inside) the inner disk edge are compensated by the long cumulative time spent there. Now, of course, the model suffers from important uncertainties mentioned in the “Model” section due to our inability to directly observe energetic particle emission in young protostars, but it does show that the beryllium-10 evidence cannot be used to decisively argue for a CAI formation at the disk inner edge. Thus, CAIs could well have formed at \( \sim 1 \) AU from the Sun which would account for their abundance which, in some carbonaceous chondrites, is comparable to the levels expected from \textit{in situ} condensation [13].

It is interesting to note that the \( ^{10}\text{Be}/^{9}\text{Be} \) ratio is inversely correlated to the mass accretion rate. Indeed, the relative importance of the surface layers prone to beryllium-10 production must decrease with increasing mass disk, that is, increasing mass accretion rate. It is thus possible that the \( ^{10}\text{Be}-\text{poorest} \) CAIs, which indeed seem to be the oldest ones [6, 7], formed when local production was so diluted that their \( ^{10}\text{Be} \) was dominated by the inheritance from the molecular cloud envisioned by [5].

\textit{Back to vanadium-50.} Although the calculations were restricted to beryllium-10, it is worth noting that the predicted effects on vanadium-50 would differ from the thin target calculations of [8]. This is because, compared to beryllium-10, the reactions producing vanadium-50 are efficient at lower energies, where attenuation (in the disk surficial layers) is strongest [14]. Thus, for a given energy power law, and a given “target” \( ^{10}\text{Be}/^{9}\text{Be} \), less vanadium-50 would be produced. (The originally predicted amount could however be restored by invoking a steeper energy spectrum [9]). Recently, [15] suggested that the vanadium-50 excesses reported by [8] were actually mostly mass-dependent kinetic effects due to condensation/evaporation, although a supporting correlation with strontium isotopic ratios was only clear for coarse-grained CAIs [15]. If the interpretation of [15] is sound, this may indicate, in the framework of the model developed here, that the power-law slope of the energy spectrum was comparable to that of present-day solar gradual flares (in \( -E^{-2.5} \)), as assumed in the nominal values of the previous equation) in contradistinction to impulsive ones (\( -E^{-4} \)).