STABILITY OF REFRACTORY MINERALS IN "T-TAURI" ION IMPLANTERS AROUND YOUNG SUNS.

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Introduction: Competing irradiation models have been proposed to account for the formation of short-lived isotopes, such as ^{26}Al and ^{41}Ca, in the minor component (about 5 wt.%) of refractory inclusions (CAIs) found in chondrites and micrometeorites. They involve high fluences of protons ($\geq 10^{19}$ p/cm^2), α-particles and ^{3}He nuclei with energy ≥ 1 MeV/amu, coined as SEPs here below (solar/stellar energetic particles). We just consider the models based on the fluctuating X-wind picture (see ref. 1 and 2), even though it is still challenged today (see ref. 3, p. 16 and p. 353). Indeed, this conjecture has been supported by the recent analysis of refractory phases from comet Wild 2 trapped in the aerogel of the Stardust mission. These models allow deducing the SEPs fluences from the X-rays luminosity, Lx, of impulsive X-ray flares (IXFs) detected around T-Tauri type young stellar objects (YSOs). These fluences can next be related to laboratory ions implantations as to assess how long CAIs exposed to the IXF-SEPs could have survived against ion beam "slicing", melting and vaporization.

Astrophysical setting: In the X-wind picture, these IXFs occurred in the mid-plane of the reconnection ring (X-Ring) of YSOs. This hot ring was spreading from about 0.75 Rx to Rx ~ 0.065 AU (Rx corresponds to the inner edge of the truncated solar nebula). In this zone, a fraction of the magnetic field lines of the Sun were confined in a dipolar magnetosphere (i.e., in a kind of "flat tire" geometry) extending up to Rx. Kinds of "short- circuits" between the twisted field lines did occur, right into the mid-plane of the nebula. They generated the ^{3}He-rich IXFs in close proximity to the CAIs, which were also concentrated in this plane.

This most favourable irradiation configuration minimized serious wastage problems concerning all SEPs generated outside the X-Ring, and which are associated to both the almost permanent X-ray background coined as *"characteristic"* and one other type of *"gradual"* X-rays flares. Before reaching the CAIs, these "outsiders", which are now very poor in ^{3}He, had to face the stopping power of both the dust particles and the hot nebula gas at a pressure of 10^{-3} – 10^{-4} bar, as well as a leakage into interplanetary space along open magnetic field lines. Moreover, their X-rays luminosity, Lx, has not been related, yet, to their proton luminosity, L_p, as to yield the key proton *number-flux*, Φ (p/cm^2/s).

Simulations with ion beams: Many changes occur in targets exposed to high fluences of energetic ions. For example, we investigated the accumulation of SW and SEP solar neon [4] in micrometeorites during their recent ~ 200,000 yr flight times to the Earth, when they were peeled off ~ 60 times by a high fluence of SW He (~ 2.5×10^{19} He/cm^2). This peeling belongs to a general process of micro-slicing driven by ions, which was cleverly patented in 1995 by Bruel and collaborators [5], who successfully sliced ~100 cm^2 wafers of silicon and silicon carbide with an astonishingly low fluence (~ 5×10^{16} p/cm^2) of 0.1 MeV protons.

Our simplest observations were just made with our naked eyes looking with apprehension though a window at anhydrous silicates during their proton irradiations at 1 keV (SW ions) and 1 MeV (SEPs) in the ion implanters of CSNSM. For both energies, when the beam intensity reaches a critical value, $\mathbf{I_c}$ ~ 1 µAmp/cm^2 (i.e., 5×10^{12} p/cm^2/s in the *number-flux* unit), silicates glow red within a few seconds, and the beam intensity has to be quickly reduced as to avoid melting! In this abstract, I_c will be our unit of beam intensity.

The projected range, R_p, of 1 MeV and 10 MeV protons in refractory silicates is about 12 µm and 530 µm, respectively. A beam intensity, $\mathbf{I_c}$, of 1 MeV and 10 MeV protons would deliver about 0.22 kJ/g/s and 0.05 kJ/g/s, respectively. Sanders and Taylor (see ref. 3, p. 918) estimated that the amount of energy needed to heat cold "primitive dust" from 250 K to the highest melting temperatures of CAIs of about 1850 K, and to melt the dust completely, was about Q_1 ~ 1.6 kJ/g. In this case, it would take about 7 s and 32 s of exposure to a proton beam, $I_p \sim \mathbf{I_c}$, to melt completely CAIs up to depths of about 12 µm and 530 µm, with 1 MeV and 10 MeV protons, respectively. This well fits the naked eyes observations at 1 MeV/amu.

Heating of CAIs with ≥ 10 MeV/amu SEPs: Let us consider the "median" impulsive X-Rays flare (median-IXF), which was defined for a subset of 28 solar mass YSOs of the Orion nebula cluster [6]. Its median X-rays luminosity, Lx~ 10^{31} ergs/s (see fig. 5 in ref. 3), is larger than the value of 4.5 × 10^{30} ergs/s used in previous works, and which was estimated for a broader range of stellar masses, including low mass YSOs that emit less powerful flares than solar mass YSOs, as $Lx \propto (M_☼)^3$. We use the formulation given in ref. 1 that is only valid for impulsive flares and for protons with $E_{10} \geq 10$ MeV. It yields the proton luminosity, $L_p(E \geq E_{10}) \sim \xi \times Lx$. With $\xi \sim 0.1$, one finds:

$$\Phi(E_{10}) = [(0.1\ Lx / E_{10})] \times [(q-2) / (q-1)] \times [1 / S] \times M$$

where, $\Phi(E_{10})$ is the proton *number-flux* (p/cm^2/s); S is the X-Ring area (~10^{24} cm^2); q ~ 4 the exponent of the differential energy spectrum of the SEPs protons ($dN/dE \sim E^{-q}$), and; *M*, a kind of confinement efficiency that expresses that a proton trapped in the "flat tire" confinement zone can cross the mid-plane several times. Gounelle et al [2] selected a low value of *M*~ 1.6, which corresponds to a spectacular virtual close packing of CAIs around the mid-plane.

Finally, $\Phi(E_{10}) \sim (4.5 \times 10^{10}$ p/cm^2/s$) \times M$. This value can be directly converted into a 10 MeV proton beam intensity, $I_p \sim \mathbf{I_c} / 70$, because CAIs are isotropically irradiated in the X-Ring. With this conversion, each IXF can be assimilated to a kind of T-Tauri ion implanter (TT-implanter), where CAIs would be heated up in about 2000 s, from 250 K to their liquidus temperature of ~ 1850 K, thus being melted up to a depth, R_p ~ 0.5 mm.

However, the T-Tauri conditions are less favourable to the survival of targets than the mild laboratory conditions.

First, the temperature in the mid-plane of the R-Ring is already 1400-1500 K (see ref. 3, p. 358 and 799), and not 250 K. Now, a smaller amount of energy ($Q_2 \sim 0.5$ kJ/g), would be sufficient to reach 1850 K in ~500 s. Moreover, in the polyatomic beam of IXF-SEPs, the relative abundance of ^{4}He (relatively to proton) is about 0.1 (i.e., 4 times larger than in the contemporary SEPs), the abundance of ^{3}He is about 0.3, and each He delivers about 4 times more energy than protons. The polyatomic beam of protons and He ions delivers about 2.6 times more energy per g/s than a single beam of protons. This further reduce the melting time to about 0.2 ks (200 s), whereas the durations of IXRs at peak intensity are randomly distributed between a few ks up to 100 ks. These X-rays studies would already suggest that about once every few days (i.e., the frequency of occurrence of median IXFs) all CAIs of the X-ring would have been likely ablated by successive melting steps, $R_p \sim 0.5$ mm, induced by the ≥ 10 MeV/amu SEPs.

Heating CAIs mantles with ≥ 10 MeV/amu SEPs: The "theoretical" birth of short-lived isotopes faces another difficulty, which is the overproduction of ^{41}Ca by a factor ≥ 100. To avoid this problem, theoretical CAIs are coated with virtual Ca-poor mantles with thicknesses up to ~2000 µm, as to shield ^{40}Ca, which is the progenitor nucleus of ^{41}Ca in the CAIs core. The mantle material would be made of the most refractory material that could condense from the Ca-poor residual gas, which was left over after the formation of the CAIs (i.e., forsterite and enstatite).

Lodders [7] and Scott and Krot (see ref. 2, page 19), give a scale of mineral stability above 900 K, in a solar nebula at $\sim 10^{-3}$ bar. It clearly shows that these Mg-rich silicates condense around 1350–1400 K. With a mid-plane temperature of ~ 1400–1500 K, and a partial pressure of $10^3 - 10^{-4}$ bars, a small increase in temperature would probably boil off the mantles in less than a few tens of seconds in median-IXFs (for $M \sim 1.6$). Therefore, CAIs were hardly shielded during their ≥ 10 MeV/amu SEPs irradiations and the overproduction of ^{41}Ca is still around us.

Devastating effects at ≤ 5 MeV/amu: Jean Duprat first noted the odd differential energy spectrum of the IXF-SEPs so far used, and which make them so much damaging. It has been assumed that this spectrum is similar to that measured for the contemporary Sun (i.e., $q \sim 4$). In this case, the equivalent "median" beam intensity of the 1 MeV protons, $I_p \sim \mathbf{I_c} \times 15$, would be ~ 1000 times higher than at 10 MeV. Now, CAIs should have been ablated away by successive ~ 12 µm-thick melt layers formed in less than ~ 0.2 s.

At 5 MeV/amu, $R_p \sim 160$ µm, and the melting time of each R_p–layer would still be smaller than 10 s. This fast ablation might have markedly decreased the contributions of ^{3}He to the formation of ^{26}Al and ^{41}Ca, because its major cross sections for the formation of both isotopes peak between about 1–5 MeV/amu (see fig. 3, ref. 1). The SEPs IXFs beam would look as a kind of ^{3}He-depleted beam generated by "gradual" X-rays flares, known to produce a vast overproduction of ^{10}Be and the underproduction of ^{26}Al [2].

Lucky survivors: *However, CAIs are found in a large size range, from about 1 µm (in micrometeorites) up to 2.5 cm (in CV3 chondrites)*. Therefore, efficient "rescue" processes were effective in YSOs as to decrease the beam intensity of the 10 MeV/amu and 1 MeV/amu SEPs by factors of about 10 and 1000, respectively, as to keep some safe margin against frequent melting and slicing.

We cannot be guided any longer by ion implantation experiments. Indeed, the ion beam of a T-Tauri implanter had a giant cross section in the X-ring. It probably quickly fluctuated in both intensity and energy along this cross section. This could have produced a kind of fast erratic "rastering" of the beam, which decreased its intensity on a given CAI spot, like on a TV screen. Another alternative is linked to the "canonical" partial pressure of about $10^{-3} - 10^{-4}$ bar (see ref. 3, p. 19) of a hydrogen-dominated solar nebula. This low pressure is already very high in term of SEPs deceleration. The TRIM code yielded the projected range, R_p, of protons in a nebular gas at 10^{-3} bar, of about 1 km (1 MeV) and 6 km (10 MeV). The low energy SEPs of a given IXF quickly decelerated and vanished in the nebula thus contributing to decrease their beam intensity, unless they were constantly accelerated on a scale ~ 10 km, along the X-Ring.

Anyway, the validity of the two key relationships used in X-wind irradiation models (i.e., $L_p \sim 0.1 \times Lx$, and $q \sim 4$) looks problematic. Indeed, they were estimated with detectors on spacecrafts, which were measuring X-Rays and SEPs of the modern Sun, which propagate in the high vacuum ($\sim 10^{-16}$ bar) of interplanetary space, without being noticeably absorbed and/or decelerated.

Conclusions: "Healthy" CAIs show that irradiation models bearing on the production of short-lived isotopes near the young Sun have to face the distressing conclusion that the functioning of the giant T-Tauri ion implanters, which delivered the ^{3}He enriched SEPs to the X-Ring, is not understood. Moreover, it has also been argued that the ^{3}He-rich IXFs might just be "stellar", i.e., produced outside the X-ring. In this case the X-wind model should be fully revised. X-Rays astronomy, the "theoretical" excess of either ^{41}Ca or ^{10}Be, improved estimates of Q_1 and Q_2, and laboratory ion implantations (conducted in particular to better check whether ion beam "slicing" occurs before melting) will hopefully give a few hints about the fascinating mystery of these widespread giant cosmic ion implanters.

References: [1] Lee et al (1998) *ApJ. 506*, 898-912. [2] Gounelle M. et al (2001) *ApJ. 548*, 1051-1070; [3] *Chondrites and the Protoplanetary Disks* (2005) *ASP Conf. series, vol. 341* (Eds, Krot E.N. et al); [4] Maurette M. (2006) *Micrometeorites and the Mysteries of our origins* (Springer), section 19.3; [5] Bruel M. (1996) *Nucl.Inst.Methods B108*, 313-319; [6] Wolk S.J. et al (2005) *ApJ. 160*, 423-449; [7] Lodders K. (2003) *ApJ. 591*, 1220-1247.