ONCE A CAI, ALWAYS A CAI: FLARE-UP-INDUCED EPISODIC FRACTIONATION AND MELTING IN THE EARLY SOLAR NEBULA. G. J. MacPherson. Dept. of Mineral Sciences, Museum of Natural History, Smithsonian Institution, Washington, D.C. 20560. USA. (macphers@si.edu).

The classic model [e.g. 1] for elemental fractionation in the early solar system is equilibrium condensation, in evolving monotonic cooling and crystallization of solids from a gas of solar composition. Abundant evidence supports the idea of relative element volatilities being the dominant factor during fractionation (review by [2]), but melt evaporation as well as gas condensation also played an important role [3]. Finally, the pre-solar nebula was almost certainly much more complex and violent than a simple cooling and quiescent cloud [4]. As a result the mechanism that caused the fractionations remains unclear.

Most if not all young protostars undergo collimated mass outflows from their rotational poles (commonly bi-polar), and the outflow jets (Herbig-Haro objects) commonly consist of a linear series of knots or “puffs”. In addition, most if not all young stars experience episodic flare-ups, in the form of FU-Orionis and EX-Lupi bursts [e.g. 5]. FU outbursts are larger and less frequent) (frequency ~ 10^3-10^4 yrs) than the smaller EX outbursts (frequency~ few years). The two may be differing extremes of a single process, namely non-uniform accretion of disk material onto the central protostar, with the flares indicating much higher-than-normal accretion rates. Whether outflow jets and episodic flare-ups are manifestations of the same non-linear accretion process remains a matter of debate [5]. Regardless, it is probable that our infant Sun also experienced such outbursts. There is some evidence (albeit not conclusive) to suggest this actually was is the case. Fig. 1 shows a histogram of initial ^{26}Al/^{27}Al values for normal (non-FUN) CAIs, based exclusively on internal isochrons. The data have not been filtered for isochron quality but, based on this unfiltered dataset, in addition to the usual peak at ~ 5×10^{-5} there is much-smaller second peak at 4×10^{-5}. If CAIs were continuously produced and reprocessed in the earliest solar nebula there should be a continuous histogram peak that slopes down from 5×10^{-5} to lower values. The existence of a second peak, if confirmed by more high-quality data, implies an episodicity in CAI formation and processing with a time interval on the order of 200,000 years. Data for chondrules form yet a third peak at initial ^{26}Al/^{27}Al ~0.7×10^{-5}, with the inferred chondrule–CAI time gap being on the order of 1.5 million years. Boss et al. [6] explored the ramifications of such outbursts in our solar system for mass transport within the disk.

FU-Orionis and EX-Hydra bursts are observed as significant spectral brightenings of their central protostars, but it has not been entirely clear what the thermal consequences for the disks are. Recently however, [7] used the Atacama Large Millimeter/submillimeter Array (ALMA) to measure (at λ = 1.3 mm) the effects of an FU-Orionis outburst in the ~ solar mass protostar V883 Ori, and showed that the ice line (water/snow boundary) greatly expanded out to around 40 AU, as compared with the apparent snow line in our own early solar nebula at ~ 5 AU. This begs the question: what happens to the rock line?

FU outbursts produce major short-lived (~ 100 year; [5]) thermal spikes superimposed on the quiescent background temperatures [8]. A highly schematic T *vs.* heliocentric distance graph (not based on V883 Ori) is given in Fig. 2, showing that during a period of high mass accretion (in this case, not even an FU outburst for which the effects are more extreme 8]) the temperatures in the inner nebula are greatly raised relative to those during a quiescent stage. The temperature *difference* between the two profiles at any given distance represents the suddenly-altered fractionation between solids and gas. A $T \propto r^{-1}$ dependency was chosen for the temperature profiles in Fig. 2 in order to best fit the estimated temperatures given by [8]; in reality of course the temperatures at the center (star) will not go to infinity. However, the choice of exact functional T *vs.* r dependence does not matter: it is only the difference between the two profiles that matters.

Figure 2 shows that, during such enhanced accretion onto the central star, the radial thermal profile is greatly elevated relative to that during the quiescent phase. Existing solids in the inner nebula are suddenly vaporized, those in the innermost region completely so (approximated here as above the hibonite condensation temperature) and material somewhat farther out is only partially so; melting may occur. As the flare subsides, re-condensation in the innermost region (“1” in Fig. 2) will approximate equilibrium condensation, albeit on a relatively short time scale (100 years or less). Re-condensation somewhat farther out (“1” in Fig. 2) will be fractional, from a gas out of which the most refractory components were never vaporized. Such fractional condensation may produce e.g. Group II rare earth patterns. Even farther out, less volatilization of magnesium and silicon occurs; such material, if melted, would be chondrule-like.

However, recall that this process happened more than once; judging from the extant Al-Mg isotopic data, at least three major events. The first such event, represented by initial $^{26}Al/^{27}Al = 5.2\times10^{-5}$ [8], possibly fractionated Al from Mg and homogenized ^{26}Al. Early-formed CAIs, unless completely evaporated by later outbursts, would basically have remained as CAIs and their constituent material was largely removed from the system. Some (if any) early-formed chondrules might have similarly persisted, but if so were isotopically reset by the last recorded flare-up at 1.5 my after CAIs.

Issues:

Cooling rates of CAIs and chondrules. This is a potential problem for the model that must be explored in detail. Igneous CAIs are thought to have cooled at rates of a few degrees per hour, whereas chondrules cooled much faster. But CAIs and chondrules formed at different times (and places). Specifically, CAIs formed at the very earliest stage of the nebula (Class 0 or 1 protostar) when the disk was still thick. The cooling rates of igneous CAIs would have been controlled by the cooling rate of the gas. Although FU outbursts persist for many (perhaps 100) years or more before they entirely subside, the local density of the gas likely was very heterogeneous and CAI transit times in and out of dense gas regions may have played an important role in constraining cooling rates. Chondrules formed much later than CAIs, at a stage when the disk gas was probably much thinner. In such a circumstance their cooling rates could have been much faster. But still, cooling rates may be a problem for the model.

Oxygen Isotopes and fO_2. CAIs are enriched in ^{16}O and formed in a region of very low fO_2. Chondrules are far less enriched in ^{16}O relative to CAIs and formed in a far more oxidizing environment. This (and any) model must be able to explain these fundamental facts. Qualitatively, the above model appears to succeed. CAIs formed in the innermost where they were surrounded only by other CAIs and an enveloping gas dominated by hot hydrogen and with oxygen derived from the ^{16}O-rich proto-Sun [9]. Chondrules formed later and more distally, in a ^{16}O-poor dust-rich environment with little residual nebular gas other than that produced by episodic dust evaporation. But this issue too must be explored in terms of the present model.

References: [1] Yoneda S and Grossman L (1995) *GCA* **59**: 3413–3444. [2] Davis A. M. and Richter F. M. (2014) *In Treatise on Geochemistry 2nd edition* (K. Turekian and H. Holland, eds), Ch. 1-11, 361-395. Elsevier. [3] Richter F. M. *et al.* (2002). *GCA* **66**, 521-540. [4] Boss A. P. (2004) in *Treatise on Geochemistry* (K. Turekian and H. Holland, eds), Ch. 1.04, 63-82. Elsevier. [5] Audard M *et al.* (2014) In *Protostars and Planets VI*. (eds.: H. Beuther, R. S. Klessen, C. P. Dullemond, and T. Henning), Univ. of AZ Press, Tucson. 914 pp. [6] Boss A. P., et al. (2012) *EPSL* **345-348**, 18-26. [7] Cieza L. A. *et al.* (2016) *Nature* **535**, 258-261 [8] Jacobsen, B. *et al.* (2008). *EPSL* **272**:353–364. [9] McKeegan K. D. et al. (2011) *Science* **332**, 1528. [10] Stolper E (1982) *GCA* **46**, 2159–2180.

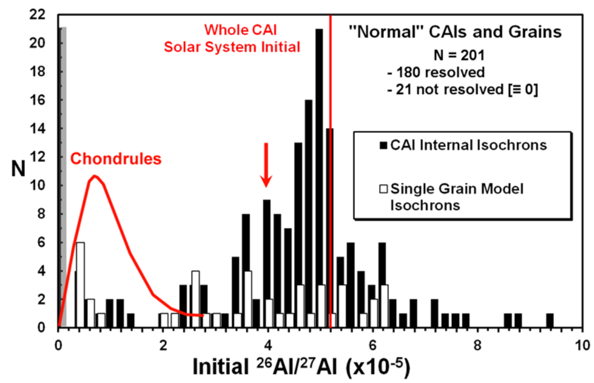

Fig. 1. Histogram of initial $^{26}Al/^{27}Al$ ratios in normal (non-FUN) CAIs and chondrules, based solely on internal isochron slopes. Note that in addition to the primary peak at $^{26}Al/^{27}Al \sim 5 \times 10^{-5}$ there is a smaller but resolved peak at $\sim 4 \times 10^{-5}$ (red arrow). Histogram includes all available data as of ~ 2015.

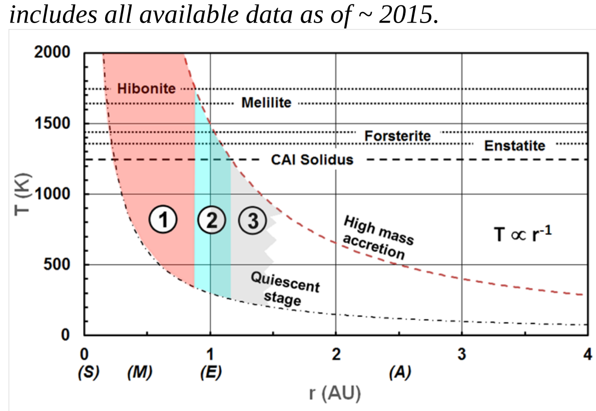

Figure 2. Temperature (T) vs. heliocentric distance (r) thermal profile for a protostellar disk during a quiescent accretion phase (lower curve) and a greatly increased accretion rate (upper curve). Shown for reference are the equilibrium condensation temperatures of several refractory minerals, as calculated by [1], and the minimum melting temperature for Type B CAIs [9]. During a high accretion stage the temperatures are greatly raised. All solids in region "1" (pink)) are completely evaporated and, upon cooling, will undergo equilibrium condensation to form (among other things) condensate CAIs. Solids in region "2" (blue) will undergo melting and partial evaporation, leading to CAI residues and fractionally-condensed solids (possibly Group II REE). The residual objects will undergo reaction with the cooling gas. The grey region "3" corresponds crudely to where chondrules could form.