EPISODIC HETEROGENEOUS ACCRETION OF THE SOLAR NEBULA. John T. Wasson, Institute of Geophysics and Planetary Physics, University of California, Los Angeles, CA 90095-1567, USA

Introduction. The Sun and the solar nebula formed together with other stars from a molecular cloud. Because of common injections of new materials from AGB stars and rare injections of supernova materials, molecular clouds are probably not homogeneous in composition. Typical lifetimes of moderate-size (30 pc, 10^4 $M_\odot$) molecular clouds are estimated to be ~10 Ma whereas mixing times calculated by dividing cloud diameters by estimated turbulent velocities are 10 Ma or longer (but not well constrained). Even small (1 pc, 300 $M_\odot$) clouds have estimated mixing times of ~3 Ma (e.g., [1]). It is thus reasonable to expect that the properties of chondritic meteorites may reflect incomplete mixing of the molecular cloud.

The inefficiency of star formation in molecular clouds is believed to result from turbulence that prevents the formation of self-gravitating regions; instead, parcels of matter were continuously colliding, merging, and dispersing. It therefore seems likely that the formation of the protosun and the solar nebula was chaotic, not the symmetrical, organized process commonly modeled. Parcels originating in different parts of the cloud were probably accreting to the solar nebula throughout its chondrite-forming history, commonly estimated to be ~2 Ma on the basis of $^{26}Al/^{26}Mg$ systematics.

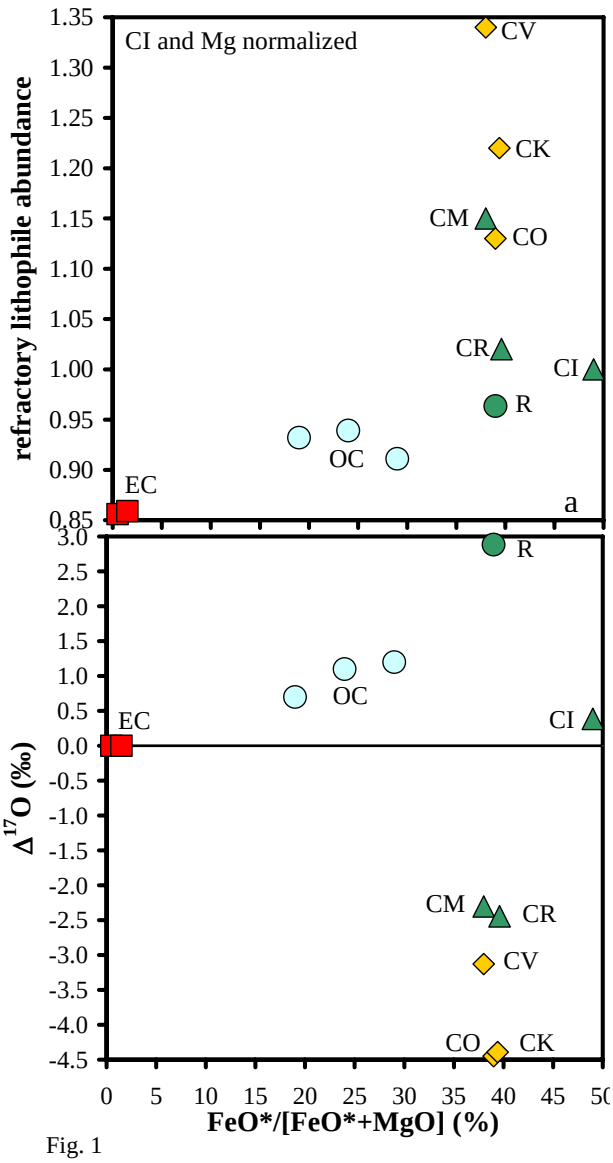

Fig. 1

FU-Orionis-style increases in luminosity and turbulence within the forming and evolving solar nebula could have mixed and homogenized the formation locations of the chondritic groups. On the other hand, drag forces may have resulted in the transport of chondrule-size solids into the Sun on a scale of 100 ka, leaving open the possibility of the replacement of chondrite-forming materials on this time scale. Thus repeated homogenization was required to keep the inner nebula homogenous, and still leaves open the possibility of a gradual compositional drift as new parcels of matter accreted.

Compositional hiatus in chondrite compositions. Chondrites preserve the compositions of kilometer-size planetesimals, and probably the composition of nebular materials agglomerating during small ranges in time and distances from the Sun. The first chondritic compositional features implying heterogeneous and episodic accretion were the large ranges in refractory lithophile element abundances and degree of oxidation indicated by the fraction of oxidized Fe (Fig. 1a). The compositions do not form a continuum; in most but not all cases there are hiatus between chondrite-group compositions.

The quantized nature of the data distribution is inconsistent with a continuous variation of formation processes throughout the lifetime of the nebula. Although sampling errors are important, these have been alleviated by the large sets of small meteorites recently recovered from cold and hot deserts. My preferred alternative is that chondrites formed during episodes of low nebular turbulence and could not form when turbulence hindered the settling of solids to the midplane.

More important is the large range in O-isotopic compositions, best represented by $\Delta^{17}O$ ($\delta^{17}O$ - 0.52•$\delta^{18}O$). Most models attempt to explain these variations in terms of two O-isotopic reservoirs formed by unmixing an initially well-mixed reservoir [e.g.,2]. The large compositional gaps on plots of $\Delta^{17}O$ vs. refractory lithophile abundance suggest that an equally plausible alternative is heterogeneous accretion of the nebula [2].

Recent studies support the view that the solar nebula formed by heterogeneous accretion. Trinquier et al. [4] report $\varepsilon^{54}Cr$ and Bizzarro et al. [5] and Regelous et al. [6] $\varepsilon^{62}Ni$ data. These two isotopes are formed by neutron capture in the same stellar regions. A plot of $\varepsilon^{54}Cr$ vs. $\Delta^{17}O$ (Fig.2a) shows that, with a couple of exceptions, chondrite groups are so well resolved that, like $\Delta^{17}O$, $\varepsilon^{54}Cr$ can be used as a taxonomic parameter. Although the ^{62}Ni anomalies measured by [6] (pale yellow points) are smaller than those reported by [5] (darker points), both sets are positively correlated with $\varepsilon^{54}Cr$ (Fig. 2b). Noteworthy is the fact that enstatite chondrites (EC) are closely

similar to the Earth in terms of $\Delta^{17}O$, $\varepsilon^{54}Cr$ and $\varepsilon^{62}Ni$, implying that EC are the main building blocks of our home planet.

Although it may be tempting to argue that the tiny ranges observed in $\varepsilon^{54}Cr$ (2ε) and $\varepsilon^{62}Ni$ (0.7ε) are so small that they can be neglected, this is not the case. The size of the effect depends on the magnitude of the original ratios produced in stellar (or, for O-isotopes, possibly also molecular-cloud) processes. The range of $^{17}O/^{16}O$ and $^{18}O/^{16}O$ ratios in ejecta from a single supernova can be huge (>>100) because the ^{17}O and ^{18}O are burned in deep layers that are efficient at producing ^{16}O. In contrast, the neutron-capture processes that produce ^{54}Cr and ^{62}Ni also produce the adjacent isotopes; thus enhancements of these two isotopes are modest, factors of 2 or less), even in fresh ejecta.

Because each stellar source will generate a different isotopic mix, there is no reason to expect that anomalies correlate linearly. What is significant for a heterogeneous accretion model is that anomalies should be ubiquitous. They should be similar within each group but varying among different groups, as seems to be the case.

Summary. The simplest explanation of most isotopic and some chemical variations among the chondrite groups is that these are inherited from the molecular cloud. The magnitudes of the variations were reduced by mixing within the convecting solar nebula, and dust/solid fractionations within the nebula may also have played a role in producing the chemical variations. The continuing infall of new parcels created the turbulence that delayed planet formation and played the major role in establishing the isotopic differences observed in bulk chondrites.

References: [1] Xie T. et al. (1995) Astrophys J. **440**, 674; [2] Lyons J. and Young E. D. (2005) Nature **435**,317; [3] Wasson J. T. (2000) Rev. Geophys. **38,** 491;[4] Trinquier A et al. (2007) Astrophys. J. **655**, 1179; [5] Bizzarro M. et al. (2007) Science **326**,1178; [6] Regelous M. et al. (2008) EPSL, submitted. [

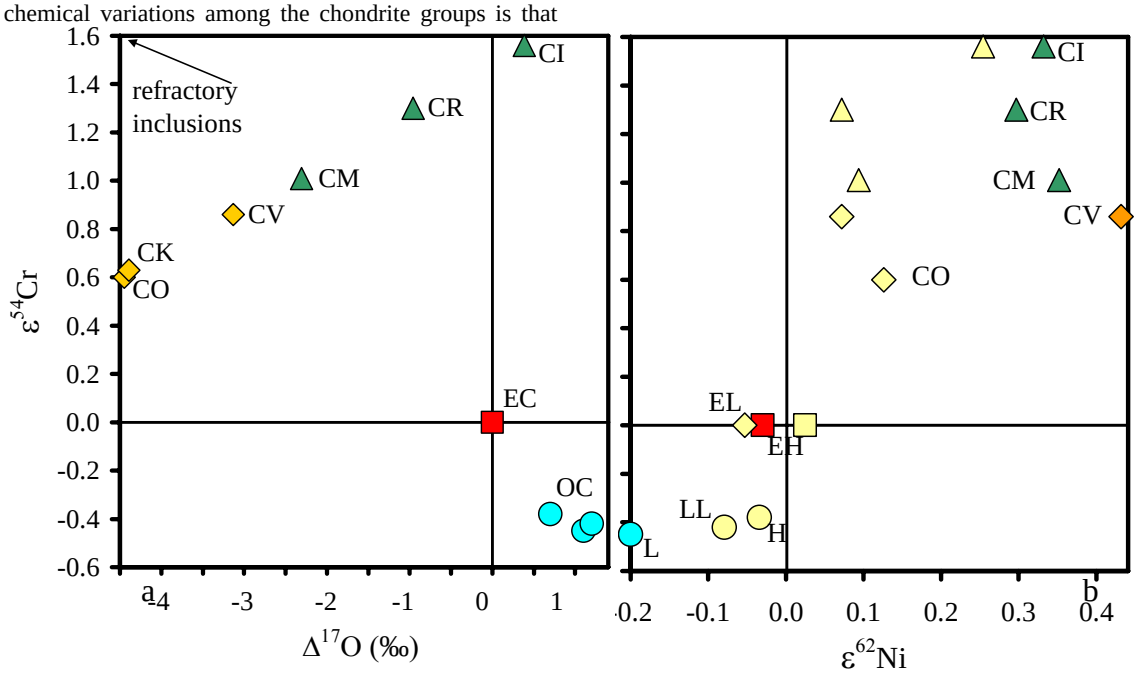

Fig 2