ISOTOPIC EVOLUTION OF THE OUTER SOLAR SYSTEM. F. Spitzer¹, C. Burkhardt¹ and T. Kleine¹,²
¹University of Münster, Institut für Planetologie, Wilhelm-Klemm-Str. 10, 48149 Münster, Germany
(fridolin.spitzer@uni-muenster.de), ²Max Planck Institute for Solar System Research, Justus-von-Liebig-Weg 3,
37077 Göttingen, Germany.

Introduction: The fundamental isotopic dichotomy between non-carbonaceous (NC) and carbonaceous (CC) meteorites reveals that the solar accretion disk can be subdivided into two distinct reservoirs, which likely represent the inner and outer solar system, respectively. It has been suggested that this dichotomy results from time-varied infall of isotopically heterogeneous molecular cloud material [1,2], and has been preserved through a dust-drift barrier in the disk [3–6]. In addition to the NC-CC dichotomy, there are isotopic variations within the NC and CC reservoirs, but the origin of these variations and how they are related to the initial formation of the NC-CC dichotomy holds important clues about the earliest history of the solar system and the dynamical processes acting in the inner and outer disk. For instance, we have recently proposed that the correlated isotope anomalies among NC meteorites reflect a rapidly changing composition of the disk during infall, where each planetesimal locks the local composition of the disk when it forms [7]. Here we aim to assess as to whether similar processes operated in the CC reservoir.

CC meteorites comprise samples from parent bodies that formed early (irons) and late (chondrites), and likely also at different locations in the disk. Isotopic variations among CC meteorites may, therefore, result from temporal and spatial variations in the composition of the outer disk. In addition, at least carbonaceous chondrites contain variable amounts of refractory inclusions such as CAI, which have large nucleosynthetic anomalies and can exert a strong control on the isotopic composition of the bulk meteorite.

To better assess any spatiotemporal heterogeneity in the isotopic composition of the outer disk, we measured the Mo isotopic composition of a comprehensive set of ungrouped CC iron meteorites and combine these data with previously reported Mo isotopic data for other CC meteorites. Molybdenum is ideally suited for identifying any compositional heterogeneity within the CC reservoir, because NC and CC meteorites display significant Mo isotope differences and because Mo isotopes can be measured to high precision in iron meteorites.

Mo isotopic variability: In a diagram of $\varepsilon^{95}\text{Mo}$ vs. $\varepsilon^{94}\text{Mo}$, most of the CC meteorites analyzed to date plot within a relatively restricted range of $\varepsilon^{94}\text{Mo}$ from $\sim1.1$ to $\sim1.8$ (Fig.1) along the CC-line as defined by a regression of bulk CC and leachate Mo isotope data by [8]. The slope of the CC-line is identical to that expected from pure $s$-process variation as deduced from the analysis of presolar mainstream SiC grains [9]. However, there is some scatter around the CC-line with a tendency of samples with $\varepsilon^{95}\text{Mo} > \sim1.3$ to plot below the CC-line. A better way to visualize this heterogeneity around the CC-line is the $\Delta^{95}\text{Mo}$ notation, which is the ppm deviation from a hypothetical $s$-process mixing line passing through the origin. As such, $\Delta^{95}\text{Mo}$ is a measure for a sample’s $r$-process excess, where the current CC-line corresponds to a $\Delta^{95}\text{Mo}_{\text{CC}} = +26 \pm 2$ [8]. However, the total variability in $\Delta^{95}\text{Mo}$ among the bulk CC meteorites is much larger and ranges from about +15 to +40.

Discussion: While some carbonaceous chondrites (CV, CM, CO, CK) contain several wt.-% CAIs, other groups contain no or only very few CAI (CI, CH, CB, CR). Simple mass balance shows that the addition of 4 wt.-% CAIs ($\Delta^{95}\text{Mo} = +115$) leads to a $\Delta^{95}\text{Mo}$ shift of about +10 ppm. This is consistent with the somewhat lower $\Delta^{95}\text{Mo}$ values about +22 for CI, CH, CB, and CR chondrites compared to values of +28 to +40 for the CAI-bearing CV, CM, CO, and CK chondrites. The new
data of this study show that iron meteorites, which represent an earlier generation of CC planetesimals, display a similar magnitude of variation in $\Delta^{95}$Mo, implying that they also contain variable amounts of CAI-like material. However, since these bodies underwent melting and differentiation, it is unknown whether they originally contained any CAIs. Instead, the $\Delta^{95}$Mo variability may also reflect the variable incorporation of disk material with a CAI-like isotopic composition.

Since the isotopic composition of the CC reservoir is intermediate between those of CAIs and the NC reservoir, it has been suggested that the isotopic composition of CAI represents that of an early disk reservoir with overall bulk chondritic chemical composition (termed IC for Inclusion-like Chondritic reservoir). Mixing between the IC and NC reservoirs then produced the composition of the CC reservoir [1,2]. Thus, for refractory elements, variable mixing between NC and IC material may produce isotope variations that resemble those produced by the physical admixture of CAI.

The fact that both early (irons) and late-formed bodies (chondrites) cover a similar range in $\Delta^{95}$Mo excludes the possibility that this variation reflects a simple temporal evolution of the isotopic composition of the CC reservoir. Instead, since the CC iron meteorite parent bodies accreted rapidly within 1 Ma after the formation of CAIs [11], their composition likely samples local heterogeneities in disk composition. Planetesimal formation in the CC reservoir is thought to have occurred at the water snowline, which provides the necessary dust pile-up to trigger the streaming instability [12–14]. Owing to the rapid migration of the water snowline in the early disk phase, the ring of planetesimals formed there extends from ~3 to ~10 au [13,14], implying that an early generation of CC planetesimals formed at different radial locations of the disk in a relatively narrow interval of time. Dynamic models of disk evolution and planetesimal accretion suggest that these planetesimals would have incorporated varying amounts of material accreted to the disk at different times [13]. Thus, provided that the isotopic composition of this material changed over time, as assumed by [1,2], this process would naturally result in variable NC-IC mixtures of the accreting planetesimals, consistent with the $\Delta^{95}$Mo variations observed among CC iron meteorites.

In summary, small Mo isotope variations of CC meteorites around the CC-line record variable relative contributions material with CAI-like isotopic compositions. For the carbonaceous chondrites this material likely is CAI themselves, but for the iron the Mo isotope variations may also reflect inherited heterogeneities related to an isotopic shift in the composition of the material accreted to the disk at early times. Either way, our results demonstrate how the isotopic variations among and between NC and CC meteorites can be linked to the dynamical evolution of the accretion disk.