ORIGIN OF THE NON-CARBONACEOUS–CARBONACEOUS METEORITE DICHOTOMY.

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Introduction: The isotopic composition of meteorites reveals a fundamental dichotomy in their genetic heritage, distinguishing between non-carbonaceous (NC) and carbonaceous (CC) meteorites [1, 2]. This dichotomy is most clearly seen in the isotopic compositions of Ti, Cr, and Mo, where the CC reservoir is characterized by enrichments in the neutron-rich isotopes ^{50}Ti, ^{54}Cr, and in Mo isotopes produced in the *r*-process [1-5]. Intriguingly, the isotope characteristics of the CC reservoir resembles those found in CAIs, the oldest dated solids of the solar system. Thus, there seems to be a genetic link between CAIs, which are commonly thought to have formed close to the Sun, and the CC reservoir, which presumably was located in the outer solar system. However, the origin of this link, and the general process by which the NC-CC dichotomy was established, are not understood.

Nickel isotopes are useful to address these issues. Bulk meteorites exhibit nucleosynthetic Ni isotope anomalies, and these anomalies seem to be distinct for NC and CC meteorites [6-10]. Further, Ni is non-refractory and therefore not enriched in CAIs, but condenses with the main component and therefore records the isotopic evolution of the main mass of the disk. Consequently, if the NC-CC dichotomy also exists for Ni, then it cannot result from transport and mixing of specific components (e.g., CAI), but must reflect a change in the isotopic composition of major parts of the disk. However, with the exception of IVB irons, no Ni isotope data for iron meteorites belonging to the CC suite have been reported. Yet, these irons are essential for assessing whether the NC-CC dichotomy holds for Ni isotopes, because they record the onset time at which the dichotomy was established.

Here, Ni isotopic data for several iron meteorite groups are presented, with emphasis on CC iron meteorite groups for which no Ni isotopic data have been previously reported. The new data are used to assess whether the NC-CC dichotomy holds for Ni isotopes, and, ultimately, to identify the processes by which the NC-CC dichotomy and the link between CAIs and the CC reservoir were established.

Methods: Nineteen iron meteorites from the chemical groups IC, IIC, IID, IIIE, IIF, IIIF, and IVA were selected. Except for the IC and IVA irons, no samples from these groups have previously been investigated for Ni isotopes. The chemical separation of Ni followed [11], and Ni isotope measurements were performed using the Neptune *Plus* MC-ICPMS at Münster. Data are reported as µ values (ppm deviations from terrestrial standard values) relative to the Ni solution standard SRM 986.

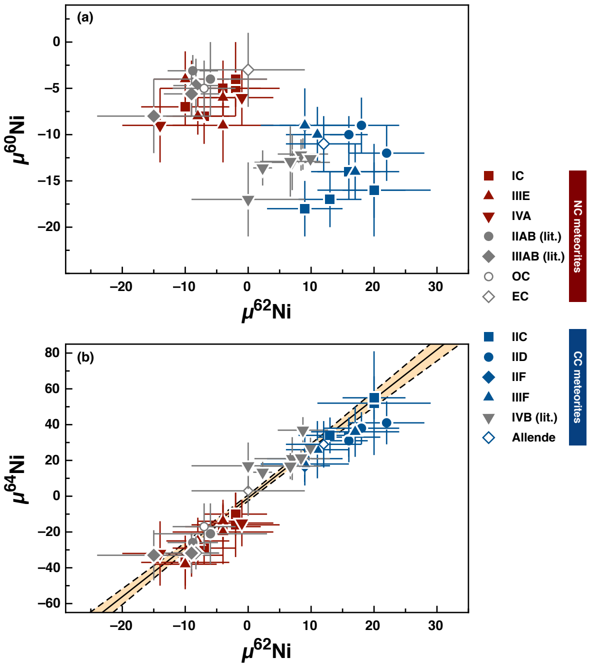

Fig. 1: Nickel isotope compositions, normalized to ^{61}Ni/^{58}Ni, for iron meteorites (filled symbols) and chondrites (open symbols). Data from this study are shown in red (NC meteorites) and blue (CC meteorites). Literature data are shown in grey.

Ni isotope dichotomy: The new Ni isotopic data are shown in Fig. 1, together with previously reported data for other meteorite groups. A key observation from the new data is that they reveal the same fundamental dichotomy as observed for Mo isotopes. That is, the same iron meteorite groups that based on their Mo isotopic signatures are genetically linked to carbonaceous chondrites (IIC, IID, IIF, IIIF, IVB), also define the carbonaceous group in Ni isotope space (Fig. 1). Likewise, the same iron meteorites with non-carbonaceous Mo isotope signatures (IC, IIAB, IIIAB, IIIE, IVA) define the non-carbonaceous group in Ni isotope space.

As in previous studies [7-10], the Ni isotopic data of the present study reveal a µ^{62}Ni-µ^{64}Ni correlation with a slope of ~3 (Fig. 1), consistent with variable anomalies on ^{58}Ni. Re-normalization of the Ni isotopic data to a fixed ^{62}Ni/^{61}Ni confirms this observation and demonstrates that the CC reservoir is characterized by a fairly homogeneous, ~60 ppm ^{58}Ni excess over the NC reservoir.

Characteristics of the NC-CC dichotomy: Our results show that in addition to excesses in ^{54}Cr, ^{50}Ti, and *r*-process Mo, the CC reservoir is also characterized by a ^{58}Ni excess. These nuclides have in common that they are produced in neutron-rich stellar environments, such as supernovae. Importantly, the NC-CC dichotomy exists for both refractory (Ti, Mo) and non-refractory (Ni, Cr) elements. As such, the dichotomy neither reflects the heterogeneous distribution of CAIs, nor thermal processing within the disk. Instead, the most straightforward interpretation is that the NC-CC dichotomy reflects the addition of *isotopically* distinct material whose bulk *chemical* composition was broadly similar to average solar system matter. As such, the NC-CC dichotomy likely reflects an isotopic change of the infalling material from the solar system's protostellar envelope.

Formation of NC-CC dichotomy during infall: As noted above, there is an obvious genetic link between CAIs—the oldest dated solids of the solar system which are commonly thought to have formed close to the Sun—and the CC reservoir, which presumably was located in the outer solar system and contains some of the latest-formed meteorite parent bodies. These seemingly contradictory observations hold important clues as to how the NC-CC dichotomy ultimately formed.

Figure 2 is a cartoon illustrating our preferred scenario for the compositional evolution of the disk during infall and the formation of the NC-CC dichotomy. In this model, CAIs formed close to the Sun during the earliest stage of infall, and were transported outwards by rapid radial expansion of the early infalling material [12, 13]. Later infalling material, which provides most of the mass of the inner disk, was isotopically distinct and, compared to the earlier infalling material, depleted in supernova-derived nuclides of elements like Cr, Ti, Ni, and Mo. As most of the material in the inner disk derives from this infall, this material likely had the composition of the NC reservoir. In the outer disk, beyond the radius at which material is infalling, the composition of the initial disk is preserved, but became diluted through mixing between inner and outer disk material. The final isotopic composition of the CC reservoir is thus intermediate between the isotopic composition of the earliest disk and the NC composition of the inner disk. The initial *isotopic* composition of the disk was therefore similar to that measured for CAIs, whereas its bulk chemical composition was broadly chondritic [14].

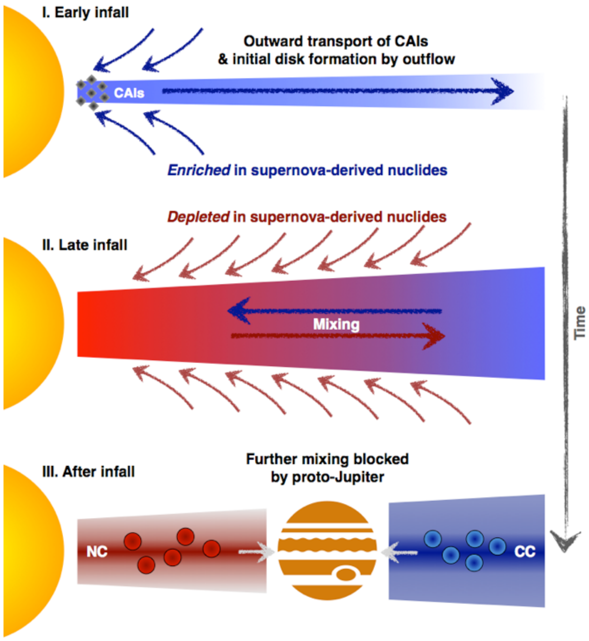

Fig. 2: Cartoon illustrating the formation of the NC-CC dichotomy by late infall of isotopically distinct material (not to scale).

After the infall of material ceased, the proto-Sun continued to accrete material from its disk, as a result of inward transport of mass and outward movement of angular momentum. Thus, to avoid complete homogenization and to maintain an isotopic difference between the CC and NC reservoirs, the inward transport of outer disk material must have been at least partially blocked before planetesimal formation in the CC reservoir had begun (i.e., prior to ~1 Ma after CAI formation). This most likely occurred when Jupiter's core grew large enough to prohibit significant material exchange between material inside (NC reservoir) and outside (CC reservoir) its orbit [5].

References: [1] Budde, G. et al. (2016) *EPSL*, *454, 293-303*. [2] Warren, P.H. (2011) *EPSL*, *311, 93-100*. [3] Poole, G.M. et al. (2017) *EPSL*, *473, 215-226*. [4] Worsham, E.A. et al. (2017) *EPSL*, *467, 157-166*. [5] Kruijer, T.S. et al. (2017) *PNAS*, *114, 6712-6716*. [6] Regelous, M. et al. (2008) *EPSL*, *272, 330-338*. [7] Steele, R.C.J. et al. (2012) *ApJ*, *758*. [8] Steele, R.C.J. et al. (2011) *GCA*, *75, 7906-7925*. [9] Tang, H. and N. Dauphas (2014) *EPSL*, *390, 264-274*. [10] Tang, H.L. and N. Dauphas (2012) *EPSL*, *359, 248-263*. [11] Chernonozhkin, S.M. et al. (2015) *JAAS*, *30, 1518-1530*. [12] Yang, L. and F.J. Ciesla (2012) *MAPS*, *47, 99-119*. [13] Hueso, R. and T. Guillot (2005) *Astron. Astrophys.*, *442, 703-725*. [14] Burkhardt, C. (2018) *Goldschmidt Abstracts*, 2018 312.