IIE irons: Early accreted, metal-rich ordinary chondrites from a partially differentiated asteroid. Alan E. Rubin, Department of Earth, Planetary, and Space Sciences, University of California, Los Angeles, CA 90095-1567, USA (aerubin@ucla.edu).

Introduction: Ordinary chondrites (OC) are the most abundant non-carbonaceous chondrites, constituting ~80% of meteorite falls. The three established OC groups vary systematically in mineralogical, chemical and physical properties. Many of these changes result from differences in oxidation state. (1) Mean metallic Fe-Ni-Co decreases from H (17.8 wt.%) to L (8.33 wt.%) to LL (3.56 wt.%) as increasing proportions of iron change from Fe^0 to Fe^{2+}. In addition, from H to L to LL there are (2) increases in the FeO contents of olivine, low-Ca pyroxene, chromite and ilmenite, (3) increases in the Co and Ni concentrations in kamacite, (4) decreases in the kamacite/taenite modal abundance ratios (because less metallic Fe is available to produce kamacite), (5) higher olivine/low-Ca-pyroxene ratios (because in olivine, the divalent-cation/Si ratio is twice that in low-Ca pyroxene: 2:1 vs.1:1), as more divalent Fe becomes available, (6) decreases in total Fe, (7) decreases in siderophile/lithophile element ratios (e.g., Ni/Mg), (8) decreases in bulk density, consonant with deceasing proportions of metallic Fe-Ni, (9) higher refractory-siderophile/common-siderophile ratios (e.g., Ir/Ni), (10) higher refractory-siderophile/volatile-siderophile ratios (e.g., Ir/Au), (11) heavier O isotopes, and (12) increases in mean chondrule size.

Based on their W-, Mo- and Ni-isotopic compositions, Group-IIE iron meteorites are related to the noncarbonaceous chondrites [1,2]. IIE irons are structurally varied, containing coarse, medium, fine, and finest octahedrites as well as polycrystalline kamacite aggregates. All IIE irons contain kamacite and taenite, some have plessite, many have schreibersite and troilite, and a few contain chromite and phosphate.

Discussion: Unlike most iron-meteorite groups, IIE irons appear not to have formed in the metallic cores of differentiated asteroids: (1) The element-element concentration diagrams of their metal portions show slopes inconsistent with those caused by fractional crystallization [3,4]. (2) Although there are significant interelement correlations among the magmatic irons, many interelement correlations in the IIE group are weak [5]. (3) The mean kamacite bandwidths in IIE irons vary widely and are not correlated with Ni (as in most magmatic iron groups) [5]. It thus seems likely that IIE irons did not form within fully differentiated asteroids.

The initial $^{87}Sr/^{86}Sr$ ratios in the IIE irons, Colomera and Kodaikanal, are consistent with derivation from a source with a chondritic Rb/Sr ratio prior to a primordial heating episode ~4.6 Ga ago that started the radiogenic clock [6,7]. Niemeyer [8] determined that IIE silicates have moderately high abundances of primordial ^{36}Ar and ^{132}Xe, consistent with derivation from a chondritic source. Furthermore, Fischer-Gödde et al. [9] showed that IIE metal is essentially identical to ordinary chondrites in Mo and Ru isotopic composition.

Although many IIE irons contain alkali-rich silicate inclusions with non-chondritic bulk chemical compositions [e.g., 10,11], the silicate fractions of four IIE irons (Netschaëvo, Techado, Garhi Yasin, Mont Dieu) consist of highly recrystallized, petrologic-type-6, chondrule-bearing clasts [e.g., 12,13], some with plagioclase grains up to ~100 µm in size. The Netschaëvo clasts contain BO, PO, PP, POP and RP chondrules. Minerals in the clasts include olivine, low-Ca pyroxene, Ca-pyroxene, plagioclase, merrillite, chlorapatite, chromite, troilite, schreibersite, and metallic Fe-Ni. Many of the mineralogic and petrologic properties of these clasts lie along coherent, systematically varying, LL-L-H-IIE trends: mean olivine Fa (29.4, 24.7, 18.8, 14.3 mol%), mean low-Ca pyroxene Fs (24.1, 21.3, 17.2, 14.0 mol%), mean kamacite Co (77.4, 8.0, 4.7, 4.5 mg/g), and mean bulk metallic Fe-Ni (1.92, 3.19, 7.52, >10 vol.%). Chondrule-bearing clasts in other IIE irons also contain substantial metallic Fe-Ni: Techado (>10 vol.%), Garhi Yasin (5-10 vol.%) and Mont Dieu (5 vol.%) [12,13].

Mean chondrule diameter decreases from LL (550 µm) to L (500 µm) to H (450 µm). Chondrule outlines become blurred during thermal metamorphism; in many type-6 chondrites, only the largest chondrules remain discernable. It seems reasonable to accept the sizes of the smallest observable chondrules in the Netschaëvo type-6 clasts as approximations (or upper limits) of the sizes of average IIE chondrules prior to recrystallization. The smallest identifiable chondrules in Netschaëvo clasts are ~300 µm in apparent diameter [14]. If this size is representative, then Netschaëvo clasts continue the LL-L-H trend of systematically decreasing mean chondrule size.

The bulk siderophile-element concentrations of OC were measured by Kallemeyn et al. [15]. There are systematic differences among the three major OC groups in the mean ratios of these elements. IIE irons lie along systematically varying LL-L-H-IIE trends: Ir/Ni (35.4×10^{-6}, 41.6×10^{-6}, 48.5×10^{-6}, 61.5×10^{-6}), Ir/Au (2.91, 3.26, 3.63, 4.30), Au/Ni (12.2×10^{-6}, 12.8×10^{-6},

13.4×10^{-6}, 14.3×10^{-6}), and Co/Ni (48.4×10^{-3}, 48.8×10^{-3}, 51.0×10^{-3}, 53.7×10^{-3}).

The average bulk O-isotopic compositions of type 4-6 OC change systematically among the OC groups: Silicates in IIE irons lie along the LL-L-H-IIE trend: mean $\Delta^{17}O$ (1.26, 1.07, 0.73, 0.69 ‰).

All these data show that IIE irons comprise the fourth major ordinary-chondrite group.

IIE irons were derived from a separate parent asteroid than H chondrites: (1) Chondritic clasts in Netschaëvo are more reduced than those in H chondrites. (2) Netschaëvo chondrules are probably smaller, on average, than H3 chondrules. (3) IIE irons have bulk O-isotopic compositions richer in ^{16}O than H chondrites. (4) The siderophile-element concentration ratios in IIE irons are distinguishable from those in H chondrites and lie along extensions of LL-L-H trends. (5) There are no reported IIE clasts within H-chondrite breccias or H-chondrite clasts within IIE irons.

The oldest cluster of IIE Hf-W model ages is ~2-9 Ma older than Hf-W isochron ages of H-L-LL chondrites [16,17]. This is consistent with a model in which IIE irons agglomerated earlier than H-L-LL chondrites, acquired higher bulk concentrations of ^{26}Al, and were heated to the Fe,Ni-FeS eutectic temperature (~950ºC). This facilitated the separation of an FeS-rich metallic melt from unmelted silicate. Some of the melt drained into fractures and reached the gravitational center of the IIE asteroid. A dynamo was generated in this body [18], plausibly by convection currents caused by crystallization within the small core. Most IIE metal may have remained as restites within the crust/mantle region alongside chondritic clasts that had been recrystallized to petrologic type-6 levels.

It is widely accepted that most CAIs formed before most ferromagnesian chondrules. In addition, ^{26}Al-^{26}Mg chronometry shows that most Type-I chondrules formed before most Type-II chondrules [19-21]. I propose that the (Type-I)/(Type-II) chondrule modal ratio in agglomerated chondrites decreased from IIE to H to L to LL. Earlier-formed chondrules typically acquired higher proportions of refractory metal nuggets within minor amounts of CAI-fragment precursors, causing systematic decreases from IIE to H to L to LL in bulk refractory-siderophile/common-siderophile (e.g., Ir/Ni) and refractory-siderophile/volatile-siderophile (e.g, Ir/Au) ratios.

Ni is less oxidizable than Au and Co; thus, less Ni partitioned into the silicate portions of Type-I chondrules. Systematic decreases from IIE to H to L to LL in bulk Au/Ni and Co/Ni ratios were caused mainly by loss of metal-rich globules by centrifugal force from spinning, partly molten Type-I chondrules [22]. The more-reduced chondrites (with their higher proportions of Type-I chondrules) lost greater numbers of metal-rich globules. The expelled globules were not quantitatively reacquired by the whole-rocks because the globules had different aerodynamic properties than silicate chondrules; they rapidly drifted apart in the gaseous nebula [23]. This accounts, at least in part, for the metal/silicate fractionation.

Many non-chondritic IIE silicates are enriched in alkalis; some have high bulk K/Na ratios. These inclusions are compositionally similar to alkali-rich clasts in OC breccias and to melt-pocket glasses in shocked OCs [24]. All these objects are products of late-stage impact events that caused preferential melting of plagioclase (due to its low impedance to shock compression). In some cases, there was separation of (more-volatile) K from Na during vapor transport. Late-stage impacts were also responsible for quenched impact melt in some Netschaëvo clasts as well as the occurrence of the high-pressure phosphate mineral tuite and Fe-Ni-P-S melt pockets in IIE Elga [25-28].

References: [1] Burkhardt C. et al. (2011) *EPSL, 312*, 390-400. [2] Budde G. et al. (2016) *EPSL, 454*, 293-303. [3] Malvin D. et al. (1984) *GCA, 48*, 785-804. [4] Chabot N. L. and Haack H. (2006) In *Meteorites and the Early Solar System II*, pp. 747–771. [5] Scott E. R. D. and Wasson J. T. (1976) *GCA, 40*, 103-115. [6] Burnett D. S. and Wasserburg G. J. (1967) *EPSL, 2*, 137-147. [7] Sanz H. G. et al. (1970) *GCA, 34*, 1227-1240. [8] Niemeyer S. (1980) *GCA, 44*, 33-44. [9] Fischer-Gödde M. et al. (2016) *LPS, 47*, 2704 pdf. [10] Bunch T. E. et al. (1970) *CMP, 25*, 297-340. [11] Ruzicka A. (2014) *Chemie der Erde - Geochemistry* 74, 3-48. [12] McDermott K. H. et al. (2016) *GCA, 173*, 97-113. [13] Van Roosbroek N. et al. (2016) *MPS, 51*, 1-18. [14] Rubin A. E. (1990) *GCA, 54*, 1217-1232. [15] Kallemeyn G.W. et al. (1989) *GCA, 53*, 2747-2767. [16] Kruijer T. S. and Kleine T. (2019) *GCA, 262*, 92-103. [17] Hellmann J. L. et al. (2019) *GCA, 258*, 290-309. [18] Maurel C. et al. (2020) *Sci. Adv., 6*; 6: eaba1303. [19] Mostefaoui S. et al. (2002) *MPS, 37*, 421-438. [20] Tachibana S. et al. (2003) *MPS, 38*, 939-962. [21] Kurahashi E. et al. (2008) *GCA, 72*, 3865-3882. [22] Grossman J. N. and Wasson J. T. (1985) *GCA, 49*, 925-939. [23] Rubin A. E. (2011) *Icarus, 213*, 547-558. [24] Rubin A. E. et al. (1986) *EPSL, 76*, 209-226. [25] Kvasha L. G. et al. (1974) *Meteoritika, 33*, 143-147. [26] Litasov K. D. and Podgornykh N. M. (2017) *J. Raman Spectrosc., 48*, 1518-1527. [27] Khisina N. R. et al. (2017) *Geochim. Intl., 55*, 317-329. [28] Litasov K. D. et al. (2019) *Minerals, 9*, 616-626.