

# INSPIRATION FROM STUDY OF ANTARCTIC METEORITES I: PETROGRAPHIC AND COMPOSITIONAL EVIDENCES FOR EARLY CONTINUOUS CHEMICAL FRACTIONATION OF THE SOLAR NEBULA\*

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**Abstract** Bulk concentrations of Ir, Os, Co and other siderophile elements of metal phase in chondrites increase significantly with degree of oxidation, which together with Co—content of kamacite and Fa—content of olivine, reveal a continuous variation of redox in chondrites. Intermediate groups of E/H, H/L, L/LL, and LL/C, lying between E and H, H and L, L and LL, LL and C, respectively, were proposed based on Co content in kamacite, Fa value of olivine, Fs value of low—Ca pyroxene, bulk concentrations of Ir, Os and Co of metal phase and other taxonomic parameters. The discovery of intermediate groups increases the number of chemical groups of chondrites from 9 to 13. Both variation of redox in chondrites and presence of the intermediate groups of chondrites suggest a continuous chemical fractionation in the primordial solar nebula.

**key words** chondrite, classification, solar nebula.

## Introduction

Based on whether experienced melt differentiation, meteorites were divided into differentiated and undifferentiated families. The later was also referred to chondrites after its chondrule-like components. Chondrite is one of the most primitive remains of the solar nebula, so it is a key probe to early processes in the system including condensation and physicochemical fractionation. In terms of taxonomic parameters of chondrites, most of them were classified into 9 different chemical groups, i. e. 3 groups of ordinary chondrites (H, L and LL), 4 groups of carbonaceous chondrites (CI, CM, CO and CV), 2 groups of enstatite chondrites (EH and EL). Each group differs from the others in bulk concentrations of lithophile elements (Ca, Al, Mg, Sc, Na, K), siderophile elements (Fe,

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\* Supported by State Antarctic Committee and Chinese Academy of Sciences.

Ni, Co, Au, Ir, Ge), moderately volatile elements (As, Sb, Zn, Cu) and the highly volatile elements (In, Tl, Bi, Pb), degree of oxidation, oxygen isotopic composition ( $\delta^{18}\text{O}$ ,  $\delta^{17}\text{O}$ ), petrographic and mineralogical features. The bias among different groups of chondrites implied that the nebular disc was not continuous in space. In just a few years, however, with increasing collection of meteorites (above 11000 pieces from antarctic blue ice fields and more than 300 pieces from Sahara desert), a part of unusual chondrites were recognized. These chondrites did not belong to any known chemical groups in terms of their abundance patterns, petrographic and mineralogical features, isotopic composition and noble gases. Significantly, some of the chondrites have intermediate properties of two neighbouring groups. Wang and Rubin (1989) reported that olivine fayalite (Fa) content and kamacite Co concentration of several chondrites (such as Qidong meteorite, a chondrite fell in China) dropped between L— and LL—groups. The discovery was confirmed by later study of a number of ordinary chondrites (Wang and Chen, 1991). Meanwhile, they reported chondrites with Fa—content of olivine and Co—content of kamacite lying between H— and L— groups. Recently, Yamato74063 was described to have properties between E— and H— groups (Yanai and Kojima, 1991). The discovery of intermediate properties of chondrites suggests a continuous fractionation trend of the solar nebula.

The 9 known chemical groups of chondrites display a clear increase in degree of oxidation in a sequence of  $\text{EH} < \text{EL} < \text{H} < \text{L} < \text{LL} < \text{CO} < \text{CV} < \text{CM} < \text{CI}$ . A relationship between redox state of the chondrites and the distance apart from the sun was proposed, the nearer to the sun the more reduced it is (Wasson, 1985). Hence, the redox state of chondrites is another indicator for continuity of the fractionation in space. In this paper, we discuss the redox state and other petrographic features of several unusual samples of antarctic and non—antarctic chondrites, and provide evidences for a continuous fractionation in the primordial solar nebula.

### Continuous Variation of Redox among Chondrites

#### 1. Chemical composition of Fe—Ni metal indicating redox state

Since refractory siderophile elements (Ir, Os) and common siderophile elements Co are concentrated in Fe—Ni metal in chondrites, their concentrations in the Fe—Ni metal can be calculated from the bulk compositions and metal contents of the chondrites. Table 1 gives the abundance of metal, Fa—content of olivine and calculated concentrations of Ir, Os, Co of Fe—Ni metal for several unusual chondrites. The average values of H—, L—, LL—, and CV— groups and individual E— group chondrites were also listed in the table for comparison. It should be pointed out that the abundance of Fe—Ni metal of Carlisle Lakes, ALH85151 and CV chondrites listed in Table 1 is a calculated value by assuming that sum of Ni and Co contents in Fe—Ni metal are  $\leq 100\text{wt}\%$  and all Ni are attributed to Fe—Ni metal

too. So that the calculated abundance of Fe—Ni metal represents a minimum value. In the other hand, abundance of Fe—Ni metal in these chondrites could not be significantly higher than the calculated values since they were found very rare. Using data listed in Table 1, composition of Fe—Ni metal is plotted on Fig. 1 showing relation of Ir—Os (a), and Ir—Co (b). In figure 1, it is obvious that concentrations of Ir, Os, Co of Fe—Ni metal are positively correlated with each other and increase distinctly in a sequence of E, H, L, LL and CV. Increasing concentrations of Ir, Os and Co of Fe—Ni metal reflects a stronger oxidation of the chondrites, as Fe is much easier oxidized than Ir, Os and Co. With oxidation of Fe into FeO, Ir, Os and Co become more enriched in Fe—Ni metal. The increasing trend of oxidation of chondrites indicated by concentrations of Ir, Os and Co in Fe—Ni metal is completely consistent with that suggested by other parameters (such as FeO content in silicates, bulk FeO/(FeO+MgO) ratio, abundance of metal, kamacite/taenite ratio, etc.).

Table 1. Fa value of olivine, bulk concentrations of Ir, Os and Co in Fe—Ni metal, and abundance of metal in some intermediate groups of chondrites, in comparison with the E—, H—, L—, LL— and CV—chondrites.

| Meteorites       | Fa(mole%) | Ir(ppm) | Os(ppm) | Co(mg/g) | Ni(%) | Metal(%) |
|------------------|-----------|---------|---------|----------|-------|----------|
| Qingzhen(EH3)    | <0.5      | 2.68    | 3.0     | 3.88     | 8.0   | 23.1     |
| Indarch(EH4)     | <0.5      | 3.09    | 3.9     | 4.57     | 9.40  | 17.5     |
| St. Mark's(EH5)  | <0.5      | 2.50    | 2.78    | 3.64     | 7.63  | 23.2     |
| St. Sauveur(EH5) | <0.5      | 2.26    | 2.45    | 3.41     | 7.13  | 23.7     |
| Hvittis(EL6)     | <0.5      | 2.16    | 2.43    | 2.62     | 5.10  | 24.3     |
| Khairpur(EL6)    | <0.5      | 3.17    | 3.80    | 4.22     | 8.05  | 13.3     |
| Pillistfer(EL6)  | <0.5      | 2.62    | 2.99    | 3.44     | 6.42  | 22.6     |
| Yamato74063      | 10.9      | 4.64    | 3.2     | 7.80     | 20.2  | 5.90     |
| Acapulco(a)      | 10.5      | 6.23    | 6.9     | 5.40     | 9.6   | 23.9     |
| Acapulco(b)      | 10.5      | 6.21    | 7.2     | 5.28     | 9.8   | 21.4     |
| H                | 19        | 4.49    | 4.8     | 4.72     | 9.3   | 17.6     |
| Bishunpur        | 16.6      | 4.36    | 4.8     | 6.02     | 12.7  | 7.73     |
| Krymka           | 15.5      | 5.70    | 5.8     | 7.82     | 16.7  | 5.86     |
| Tieschitz        | 19.9      | 6.68    | 7.1     | 7.36     | 14.8  | 9.91     |
| Bremerborde      | 18.6      | 4.57    | 4.85    | 5.09     | 9.93  | 14.3     |
| L                | 25        | 7.01    | 7.48    | 8.22     | 16.8  | 7.3      |
| Qidong           | 25.7      | 7.87    | 8.55    | 11.1     | 21.7  | 4.7      |
| Bjurbole         | 26.4      | 7.57    | 8.04    | 11.2     | 22.7  | 5.6      |
| Cynthiana        | 26.5      | 8.40    | 9.13    | 11.2     | 21.9  | 4.8      |
| Xi Ujimgin       | 26.4      | 6.91    | 7.3     | 7.85     | 15.1  | 8.0      |
| LL               | 29        | 15.6    | 16.8    | 21.3     | 43.9  | 2.3      |
| ALH85151         | 35        | 40.3    | 44.1    | 46.9     | 96    | 1.5      |
| Carlisle Lakes   | 38        | 43.1    | 47.3    | 48.4     | 95    | 1.5      |
| equilibrated CV  | 31        | 55.1    | 59.6    | 47.1     | 95.7  | 1.4      |

note: Fa value of olivine, abundance of metal and bulk compositions used to calculated concentrations of Ir, Os and Co in Fe—Ni metal are cited from the following references: Wang and Ouyang(1979), Wang and Chen(1991), Dodd *et al.* (1967), Keil(1968), Easton and Elliott(1977), Palme *et al.* (1981), Kellemeyn and Wasson(1981, 1986), Yanai and Kojima(1991).

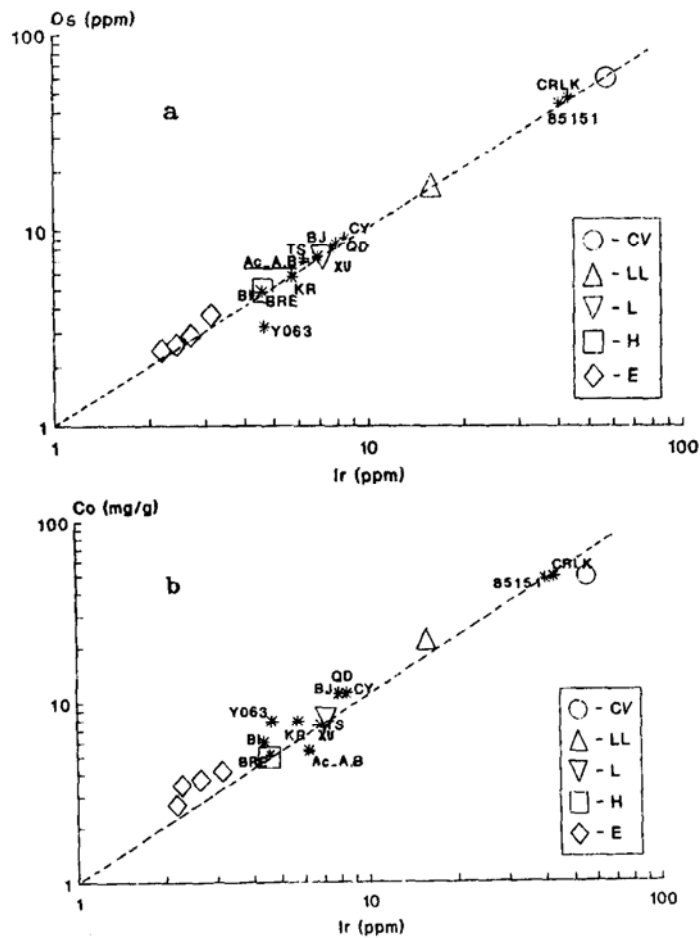


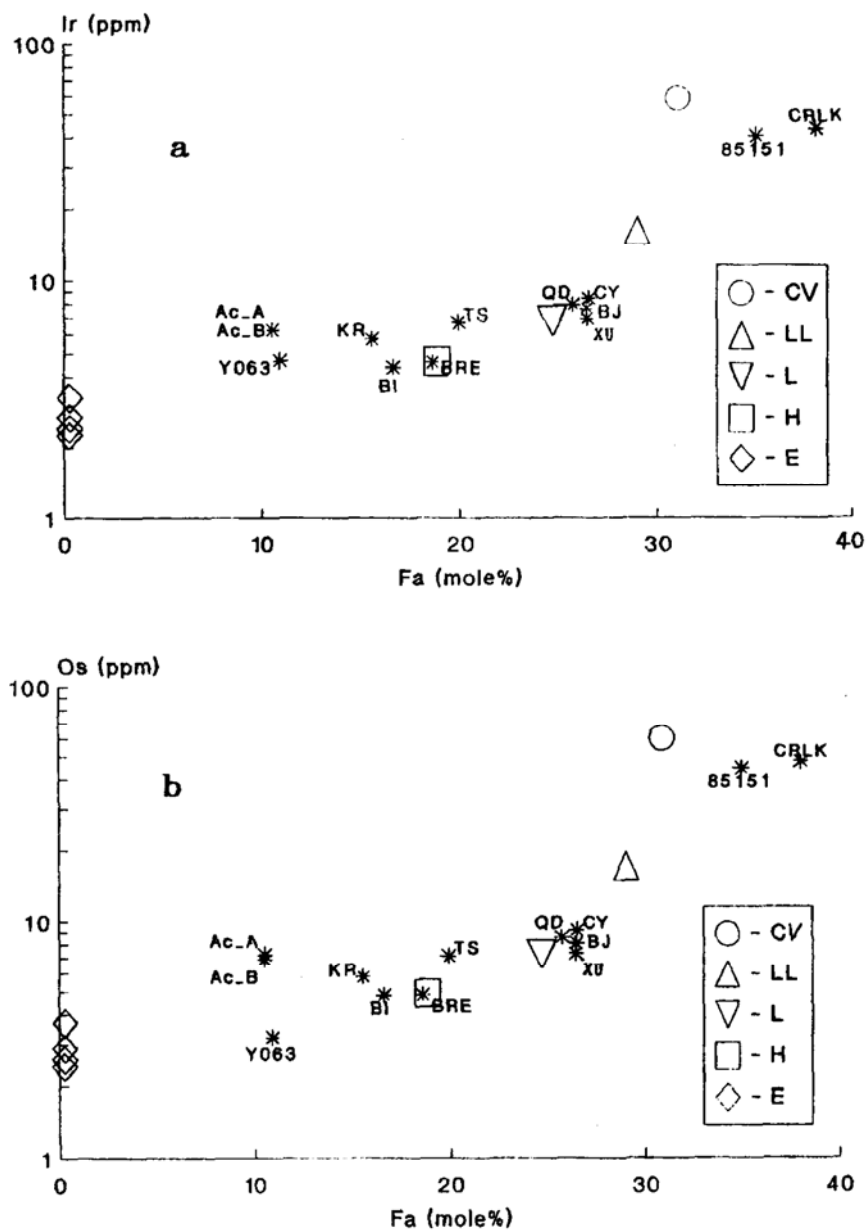
Fig. 1. Compositional diagrams of Fe-Ni metal. In Ir-Os diagram (a), except for Yamato74063 with low Os/Ir ratio, the others are very close to CI chondrites (dotted line). Furthermore, the concentrations of Ir, Os and Co of Fe-Ni metal increase significantly in a sequence of  $E < H < L < LL < CV$ , indicating a higher oxidation trend of the chondrites. The intermediate group of chondrites lies between H and L, L and LL, LL and CV, respectively. Ir-Co diagram (b) demonstrates a completely similar trend as Ir-Os. Data listed in Table 1 are used to plot. The above abbreviations are the follows: Carlisle Lakes (CRLK), ALH85151 (85151), Cynthiana (CY), Qidong (QD), Bjurbole (BJ), Tieschitz (TS), Xi Ujimgin (XU), Krymka (KR), Acapulco-A (Ac-A), Acapulco-B (Ac-B), Yamato74063 (063), Bishunpur (BI), Bremerborde (BRE).

In spite of the significant variation of Ir, Os, and Co contents in Fe-Ni metal in E, H, L, LL and CV chondrites, several unusual chondrites fall between different groups, such as Acapulco, Yamato74063 and Krymka between H and L groups, Bjurbole, Cynthiana and Qidong between L and LL groups, AHL85151 and Carlisle Lakes between LL and CV groups, respectively. This discovery makes the variation of oxidation among chondrites show a continuous trend.

## 2. Relationship of oxidation between Fe-Ni metal and silicates

The relationship of oxidation between Fe-Ni metal and silicates is demonstrated in

Fig. 2, including Fa content of olivine versus Ir (a), Os (b), and Co (3) contents in Fe—Ni metal, and Fa vs abundance of Fe—Ni metal (d) of the chondrites, respectively. It is obviously that, in Fig. 2a, b, c, degree of oxidation of Fe—Ni metal (indicated by its concentrations of Ir, Os and Co) increases well consistently with that of silicates (indicated by Fa content of olivine). However, some chondrites of intermediate groups are not in the rule. In comparison with the former—grouped chondrites, Fa content of olivine is low in Krymka and very low in Acapulco and Yamato74063, but high in Carlisle Lakes, ALH85151 and Xi Ujimgin relative to the composition of Fe—Ni metal. This deviation is confirmed in Fig. 2d by relationship between Fa of olivine and abundance of metal. Especially, Yamato74063, Krymka and Bishunpur contain considerably low Fe—Ni metal.



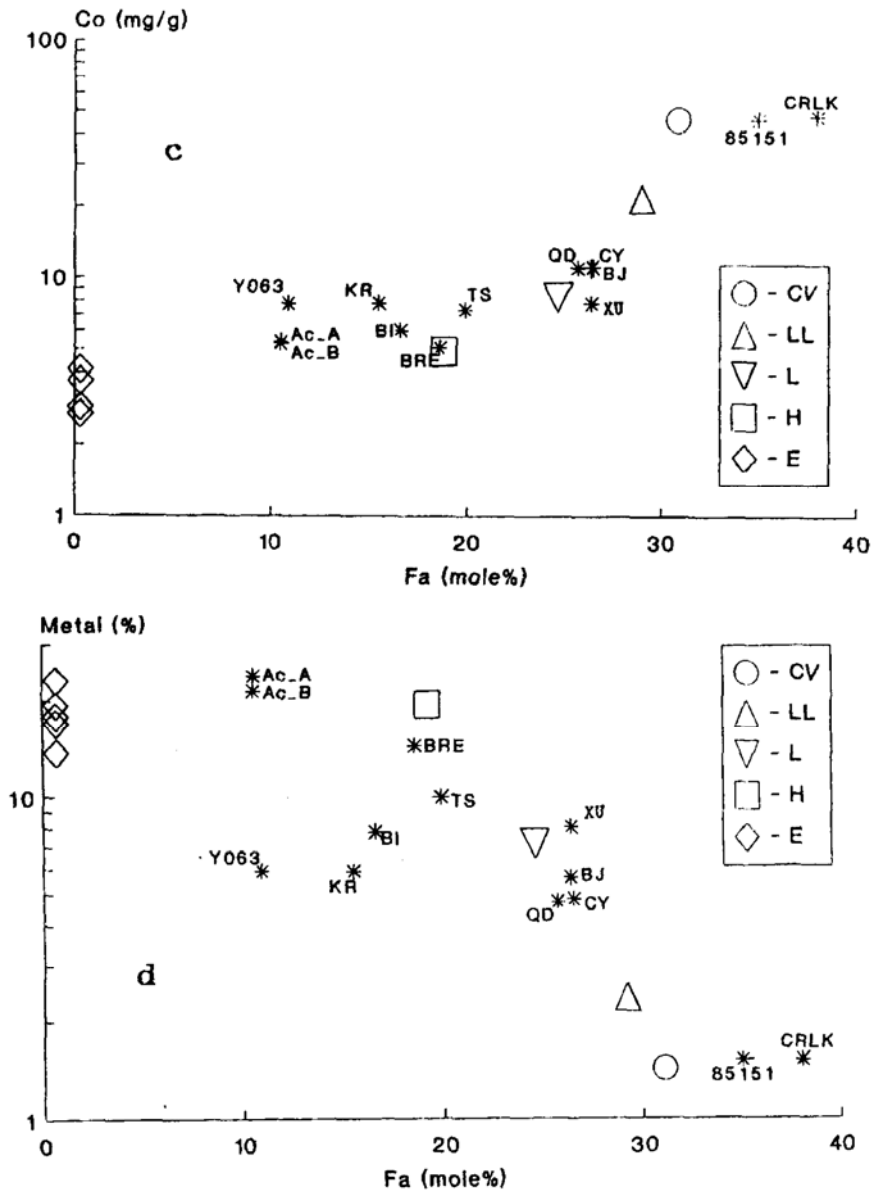


Fig. 2. Abundance of Fe—Ni metal and its bulk composition show relationship with Fa of olivine. Significantly positive relations can be found between Fa value and concentrations of Ir (a), Os (b) and Co (c), but negative relation between Fa and abundance of Fe—Ni metal. However, some intermediate groups of chondrites are not in the rule. the abbreviations and symbols are same as in Fig. 1. Data listed in Table 1 are used to plot.

Furthermore, another feature can be recognized in Fig. 2 and table 1 that composition of Fe—Ni metal has a different sensitivity to the redox state from that of Olivine. The Fa value is very sensitive to redox state of reduced chondrites and can be used to distinguish E— from H—group chondrites. However, difference in Fa values between two neighbouring groups of chondrites decreases fast as the chondrites become more oxidized. Distinguishing LL group from CV group by Fa values became rather difficult. By contraries, bias of concentrations of Ir, Os and Co of Fe—Ni metal between two neighbouring groups of

chondrites increases with oxidation. In addition, Fa of olivine is related with petrographic type of chondrites and it is too scatter to use for the unequilibrated chondrites. No relation was found between the bulk composition of Fe—Ni metal and the petrographic type of chondrites.

### Petrographic Features of the Intermediate Group Chondrites

4 intermediate groups of E/H, H/L, L/LL, and LL/C were classified based on FeO content in silicates (e. g. Fa of olivine and Fs of low—Ca pyroxene), Co content in kamacite, abundance of siderophile elements, oxygen isotopic composition and concentrations of Ir, Os and Co in Fe—Ni metal.

#### 1. *E/H intermediate group of chondrites*

Enstatite chondrites (E) formed at location most near to the sun under high reduction condition. It contains FeO—free silicates and a variety of complex assemblages of sulfides and Si—bearing metal. In term of abundances of siderophile and chalcophile elements, enstatite chondrites were classified into EH (high iron) and EL (low iron) groups (Sear et al., 1982). In just a few years, enstatite chondrites of different petrographic types (3—6) were recognized from collected Antarctic meteorites, such as Yamato69001 (EH3), Yamato74370 (EH3), ALH77295 (EH3), ALH81189 (EH3), ALH81260 (EL6), Pccora Escarp 82518 (EH3), Peckling Peak 80259 (EH5), etc.. One of the most significant discoveries was identification of Yamato74063 as an E/H intermediate group of chondrite (Yanai and Kojima, 1991). This meteorite, weights 35.41g, was collected in bare ice region in the southern Yamato Mountain by the 15th Japanese Antarctic Research Expedition on November 28, 1974. Although chondrules are poorly traced and merged into the recrystallized matrix in the thin sections, some chondrules are clearly recognized under the polarized microscope. Its recrystallized matrix has grain size larger than that in chondrites of type 6. Olivine and pyroxene are homogeneous in composition with average Fa and Fs values of 10.9 and 10.7, respectively, which fall between E and H groups of chondrites (Fig. 3). The abundance of troilite (9.39 wt%) lies between ordinary chondrites and enstatite chondrites. Abundance of Fe—Ni metal (5.90 wt%) is close to L—group (7.2 wt%) and significantly lower than E—group (13.3—29.0 wt%). Os content of Fe—Ni metal is in range of E—group and the Ir content is close to H—group, while Co content falls between H— and L—groups. In addition, clinopyroxene has an average composition of  $En_{51.0}Fs_{4.4}Wo_{44.5}$ . Recrystallized plagioclase occurs in interstice of somewhat more Ca—rich composition ( $An_{15.0}Or_{3.7}Ab_{81.3}$ ) than that in ordinary chondrites. Chromite is featured with high  $Cr_2O_3$  (59.1 wt%), MnO (1.23 wt%) and MgO (6.94 wt%), but low  $TiO_2$  (1.33 wt%) and FeO (21.9 wt%), so it is not similar to ordinary

chondrites. The bulk concentrations of Fe (19.0 wt%) and MnO (0.19 wt%) are lower than those in ordinary chondrites too. Acapulco meteorite shows texture of achondrites, however its bulk composition is in range of H-group chondrites with more enrichments of siderophile elements and metal (Palme et al., 1981). In Fig. 1 and 3, the compositions of silicates and Fe—Ni metal in Acapulco meteorite indicate a intermediate degree of oxidation between E- and H-groups.

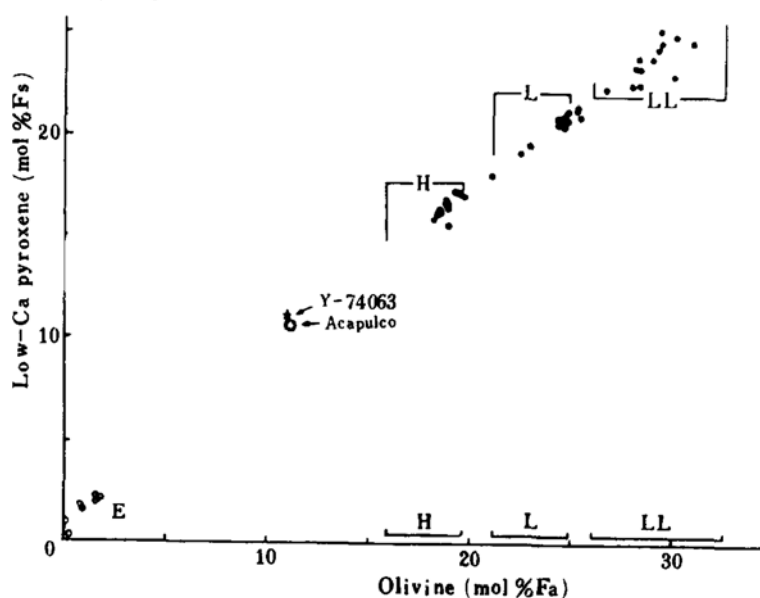


Fig. 3. Diagram of Fa versus Fs in chondrites. The Fa content of olivine and Fs content of low—Ca pyroxenes in Yamato74063 (★) and Acapulco (☆) lie between enstatite chondrites and H-group of chondrites (Yanai and Kojima, 1991).

Bulk composition of Yamato74063 analyzed by INNA is listed as below: (in wt%) Ti 0.09, Al 1.28, Fe 19.6, Ni 1.19, Mg 15.8, Ca 1.38, Na 0.705, Mn 0.263, Cr 0.270; (in ppm) Sc 9.91, V 91, La 0.35, Dy 0.52, Yb 0.24, Lu 0.045, Hf 0.23, Zn 95, As 1.73, Se 23, Co 460; (in ppb) Os 190, Ir 274, Au 168. The noble gases are composed of (in  $10^{-8}$  cm<sup>3</sup>/g) <sup>3</sup>He 8.89, <sup>4</sup>He 1530, <sup>20</sup>Ne 2.36, <sup>21</sup>Ne 1.09, <sup>22</sup>Ne 1.49, <sup>36</sup>Ar 102, <sup>38</sup>Ar 19.7, <sup>40</sup>Ar 3600, <sup>84</sup>Kr 1.33 and <sup>132</sup>Xe 3.08. The unusually high abundances of primordial Ar, Kr and Xe and depletion of primordial He and Ne suggest presence of an unknown phase preserving noble gas. Cosmic-ray exposure ages of Yamato74063 and Acapulco are about 7 Ma and 5 Ma, respectively.

## 2. H/L intermediate group of chondrites

Two ordinary chondrites were reclassified into H/L intermediate group, i. e. Bremerborde (H/L 3.9) and Tieschitz (H/L 3.6) (Wang and Chen, 1991). Composition of olivine (Fa<sub>18.6</sub>) and Co content in kamacite (4.5 mg/g) of Bremerborde is in range of H-group chondrites, but with  $\delta^{17}\text{O}$  value of 1.01‰ in range of L-group. From magnetic separation result (Chou et al., 1973), this chondrite contains 135 mg/g metal, in



comparison with 15 H-group chondrites in range of 172–222 mg/g and 3 L-group chondrites in range of 30–94 mg/g. Sears and Week (1988) reported that abundances of siderophile elements of this chondrite fall in range between H- and L-groups too, which was later confirmed by Wang and Chen (1991). Tieschitz is a chondrite of type 3.6, hence is unequilibrated. Although its average abundances of siderophile elements are lower than H-group chondrites, it is much closer to H-group relative to L-group. The Co content of kamacite (7.6 mg/g) however is in range of L-group. Both the abundance of Fe-Ni metal (9.9 wt%) and the  $\delta^{17}\text{O}$  value (0.8‰) fell between H and L groups. Krymka is a type 3.1 chondrite. Concentrations of Ir, Os, and Co of Fe-Ni metal drops between H- and L-groups. The Fa-content of olivine is about 15.5, somewhat lower than H-group (the Fa value is very scatter due to its highly unequilibration), but with its Fe-Ni metal abundance in range of L-group.

### 3. *L/LL intermediate group of chondrites*

Since recognizance of Qidong as a L/LL intermediate group of chondrite (Wang and Rubin, 1987a, b), two another chondrites former classified into L4 type (Bjurbole and Cynthiana) were members of the L/LL intermediate group as well.

Modal analysis (3928 points, 432 mm<sup>2</sup> surface area) indicates that Qidong is composed of 90.2 wt% silicates, 4.7 wt% Fe-Ni metal, 4.3 wt% troilite and 0.7 wt% chromite. The abundance of Fe-Ni metal is near lower extreme of the L-chondrites (4.4–11.7 wt%) and at middle of the LL-chondrites (3.0–6.0 wt%) (Gomes and Keil, 1980). Concentrations of Ir, Os and Co in Fe-Ni metal are plotted between L- and LL-groups, but near the former. Olivine (Fa<sub>25.7</sub>) and low-Ca pyroxene (Fs<sub>21.5</sub>Wo<sub>1.6</sub>) are homogeneous and near upper extreme of the L-chondrites with only one grain (Fa<sub>28.4</sub>) more FeO-rich. Analysis of 150 Fe-Ni metal grains using electron microprobe reveals that most Fe-Ni metal are taenite with taenite/kamacite ratio of 60. Kamacite contains an average Co content of 15 mg/g at the lower extreme of the LL-chondrites and well beyond the L-chondrites. Furthermore, metal grain of martensitic composition (75–130 mg/g Ni) are found commonly and it is also Co-rich (11 mg/g). The martensite/taenite abundance ratio is near 0.3. Concentrations of Ir, Os and Co in Fe-Ni metal, Co in kamacite (10.9 mg/g) and Fa-value of olivine (26.5 mol%) of Cynthiana fall between L- and LL-groups. Although Co content in kamacite (8.0 mg/g) and concentrations of Ir, Os and Co in Fe-Ni metal of Xi Ujimgin were in range of H-group, the olivine contains unusually high Fa content (26.4 mol%). Abundances of siderophile elements in the above all 4 L/LL intermediate groups of chondrites fall between L- and LL-groups.

In addition, Wasson and Wang (1991) reported 7 of 12 L/LL intermediate-group chondrites with U-, Th-He ages  $\geq 3.5$  Ga. The result together with compositional deviation suggests that they are different from parent bodies of L- and LL-groups of chondrites. There probably exists parent body of L/LL intermediate-group chondrites in the asteroidal belt.

#### 4. LL/C intermediate group of chondrites

Rubin and Kallemeyn (1989) classified Carlisle Lakes meteorite (found in Western Australia) and ALH85151 into a new and small chemical group on the basis of FeO-rich silicates (38 – 41 mol% Fa of olivine), isotopic anomaly of oxygen and abundant of recrystallized matrix (~35%). They suggested that redox state of these chondrites were controlled by magnetite concentrated in matrix. Yamato75302 is not typical, but could also be a member of the new group. Weisberg *et al.* (1991) classified these three chondrites as a new group as well and proposed a name of Carlisle Lake type because they were more oxidized and different in isotopic composition of oxygen from ordinary chondrites, although they are close in bulk composition and petrographic features. They suggested that the original material forming these chondrites is analogous to ordinary chondrites except for a different oxygen isotope reservoir and was more oxidized before petrogenic process. In addition, Binns and Pooley (1979) classified Carlisle Lakes as a new highly oxidized ordinary chondrites. Mason (1987) classified ALH85151 into C4 chondrite according to its high Fa of olivine (35 mol%). Table 2 gives modal compositions for Carlisle Lakes group of chondrites in comparison with H –, L –, LL – groups. Fig. 4 shows its isotopic composition of oxygen.

Table 2. Modal compositions of ALH85151, Carlisle Lakes and Yamato75302 in comparison with H –, L – and LL – group chondrites (in vol%).

|                        | H    | L    | LL   | ALH85151 |      | Carlisle lakes |      | Yamato |
|------------------------|------|------|------|----------|------|----------------|------|--------|
|                        |      |      |      | 1        | 2*   | 1              | 2**  | 75302  |
| olivine                | 40.2 | 50.2 | 60.5 | 72.2     | 56.3 | 71.2           | 58.2 | 77.7   |
| low-Ca pyroxene        | 28.7 | 24.6 | 16.7 | 6.8      | 12.8 | 2.5            | 8.7  | 3.8    |
| Ca-pyroxene            | 5.1  | 4.8  | 4.7  | 6.6      | 11.1 | 5.6            | 9.1  | 3.2    |
| plagioclase/glass      | 12.5 | 11.6 | 11.4 | 7.2      | 12.6 | 13.6           | 12.3 | 9.4    |
| chromite               | 0.4  | 0.3  | 0.3  | 1.2      | 0.2  | 0.9            | 0.4  | 0.5    |
| phosphatite            | 0.7  | 0.7  | 0.7  | 0.6      |      | 0.2            |      | 0.2    |
| troilite               | 4.0  | 3.7  | 3.7  | —        |      | —              |      | —      |
| pyrrhotine/pentlandite | —    | —    | —    | 4.9      |      | 6.0            |      | 5.2    |
| kamacite               | 7.3  | 3.1  | 0.7  | —        |      | —              |      | —      |
| taenite                | 1.1  | 1.0  | 1.3  | —        |      | —              |      | —      |
| awaruite               | —    | —    | —    | trace    |      | —              |      | —      |
| Fa(mole%)              | 19   | 25   | 29   | 38       |      | 38             |      | 38     |
| points                 |      |      | 2000 | 961      | 1000 | 1930           | 1528 |        |
| size(mm <sup>2</sup> ) |      |      |      | 96.1     | 21   | 117.3          | 173  | 64     |

note: H, L and LL from Van Schmus, 1969; 1 and Yamato 75302 from Weisberg *et al.*, 1991; 2 from Rubin and Kallemeyn, 1989.

\* low-Ni sulfides 4.3%; pentlandite 1.8%; chalcopyrite <0.1%; high-Co metal <0.1%; martensite 0.1%; taenite 0.8%.

\*\* limonite 0.4%; low-Ni sulfides 5.6%; pentlandite 5.3%.

Summarizing the data and discoveries above, we propose that Carlisle Lakes – type chondrites is not only a new but also a intermediate chemical group lying between ordinary

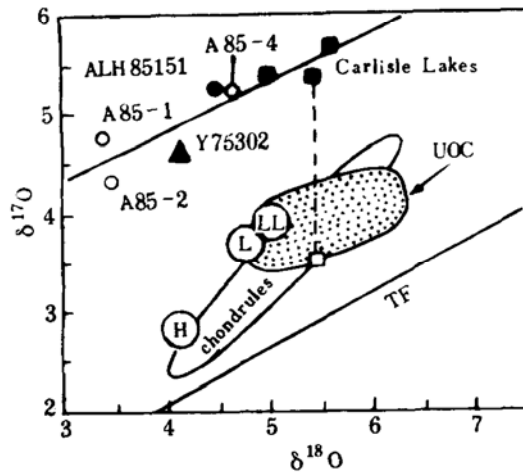


Fig. 4. Oxygen isotope diagram showing data for whole chondrites of ALH85151 (●) and Carlisle Lakes (■), their chondrules (○) and whole Yamato75302 (▲). Exception of chondrule CL-1 (□) from Carlisle Lakes which falls in a field of ordinary chondrite chondrules, the other chondrules and whole Carlisle Lake type of chondrites have higher  $\Delta^{17}\text{O}$  value than ordinary chondrites and the other known material in the solar system (Weisberg *et al.*, 1991).  $\Delta^{17}\text{O} = \delta^{17}\text{O} - \delta^{17}\text{O}_{\text{std}}$ . abbreviations: disequibrated ordinary chondrites(UOC), terrestrial fractionation line (TF).

chondrites and carbonaceous chondrites. The arguments are: (a) Concentrations of Ir, Os, and Co in Fe-Ni metal fall between LL- and CV-groups; (b) Carlisle Lakes and ALH85151 have several features of ordinary chondrites, size of chondrules ( $\sim 450 \mu\text{m}$ ) in range of ordinary chondrites ( $300-900 \mu\text{m}$ ), but larger than CO ( $159 \mu\text{m}$ ), CM ( $270 \mu\text{m}$ ), EH ( $226 \mu\text{m}$ ) and smaller than CV ( $1000 \mu\text{m}$ ). Modal abundance of fine-grained matrix ( $\sim 35 \text{ vol}\%$ ) is higher than EH3 and type-3 ordinary chondrites ( $\sim 10-15 \text{ vol}\%$ ), similar to CO3 ( $30-40 \text{ vol}\%$ ) and CV ( $40-50 \text{ vol}\%$ ). (c) Abundance of lithophile elements is in range of ordinary chondrites and siderophile elements between H- and E-groups. Normalized by CI chondrites, abundances of refractory and common siderophiles are about  $1 \times \text{CI}$ , Ga and As somewhat lower ( $0.6-0.9 \times \text{CI}$ ) and Au much lower ( $0.17 \times \text{CI}$  for Carlisle Lakes,  $0.36 \times \text{CI}$  for ALH85151) than ordinary chondrites. (d) In comparison with LL-group chondrites, the LL/C intermediate group is more oxidized ( $\text{Fa}_{39.3}$ ) and contains more olivine but less pyroxenes (Table 2). Fe-Ni metal, which occurs mainly as awaruite (Ni 64 wt%, Co 2 wt%) and coexists with sulfides (pyrrhotine and pentlandite) and magnetite, is very rare or almost absent. This is similar to the modal compositions of carbonaceous chondrites. Olivine is very homogeneous ( $\text{Fa}_{37.3}-\text{Fa}_{40.3}$ , av.  $\text{Fa}_{39.3}$ ,  $\sigma\text{Fa}_{0.62}$ ) with Fa value higher than ordinary chondrites and a part of unequilibrated carbonaceous chondrites. However, Mn and Ca contents in olivine ( $0.28-0.32 \text{ wt}\%$  and  $0.1-0.19 \text{ wt}\%$ , respectively) are just similar to type-3 ordinary chondrites. The low-Ca pyroxene, augite, diopside and plagioclase ( $\text{Ab}_{22}\text{Or}_4$ ) are close to ordinary chondrites in composition too. (e) In diagram of oxygen isotope (Fig. 4), chondrites of the group were plotted near ordinary chondrites, but with higher  $\Delta^{17}\text{O}$  value ( $2.47-2.91\%$ ). Such high  $\Delta^{17}\text{O}$  value was also reported in cristobalite-pyroxene

inclusion of ALH76003 (LL6) ( $\Delta^{17}\text{O} = 1.9\text{‰}$ , Olsen et al., 1981), magnetite of Orgueil (C1) ( $\Delta^{17}\text{O} = 1.7\text{‰}$ , Rowe et al., 1989) and plagioclase-like glass of Mezo-Madaras ( $\Delta^{17}\text{O} = 1.8\text{‰}$ , Mayeda et al., 1989). The feature of oxygen isotopes in these meteorites is  $^{16}\text{O}$ -poor, high  $\Delta^{17}\text{O}$  and dropped above L- and LL-group chondrites. They are far apart from enstatite chondrites, carbonaceous chondrites, silicate inclusions of IAB and IIE iron meteorites.

## Discussion

### 1. Mechanism of chemical fractionation in the solar nebula

Both existence of different chemical groups of chondrites and significantly different compositions of the planets (indicated by their average specific gravities, surface chemical compositions, etc.) in the solar system suggest that chemical fractionation, which caused the system to develop from homogeneous into heterogeneous, took place in its early history. Based on modern theories about evolution of the solar system and astronomical observation, the primitive nebula was probably a homogeneous mixture consisting of dust and gases which was cool and rotated slowly. As the primitive solar nebula attracted and contracted, due to itself gravitation, the temperature increased and rotation speeded up. Finally, with ignition of the H-combustion, the proto-sun was born in the core. The outer rim formed a disc which accreted into the planets and parent bodies of meteorites (Huang et al., 1983). In term of the temperature variation in the solar disc, two models of evolution of the solar nebula were proposed to explain the chemical fractionation: (a) Low-temperature accretion model and (b) high-temperature condensation model. In the first case, the solar disc stayed at a relatively low temperature in its whole history, hence it was mainly composed of solid dust, which accreted into planets and parent bodies of meteorites. As it became near to the sun, accreting temperature of the planets and parent bodies of meteorites increased. This caused fractionation of elements with different volatiles. Furthermore, dispellation of the strong solar wind in the early history was also attributed to loss of volatile elements in planets and parent bodies of meteorites. The nearer to the sun lost its more volatiles. Although the above processes was consistent with most physical models about evolution of the solar system, it met with great difficulty to explain a number of important chemical features, such as distribution of refractory Ca-, Al-rich inclusions, systematic redox change, different modal compositions of chondrites (especially for refractory phases), and fractionation of lithophile and siderophile elements in different groups of chondrites.

In the second case, assuming the solar disc experienced a heating stage in which the temperature has risen so high that most dust was evaporated ( $\sim 1500 - 1800\text{K}$ ), and followed by a cooling stage. Both experimental study of refractory Ca-, Al-rich inclusions in chondrites and theoretic calculation of condensation in the solar nebula (Grossman, 1972) suggested that there really existed a high-temperature stage in history of the solar nebula. Causes related with heating the solar nebula could include strong irradiation of the sun when passed thorough Taurun-star stage and fast contraction of the solar disc itself (Huang et

al., 1983). Then the sun reached a stable stage and the contraction of the disc came to cease. The disc would become more transparent due to evaporation of the dust. All of these effects caused temperature of the solar disc to decrease and then a cooling stage started. According to thermodynamic calculation, redox state of the solar nebula was controlled by its C/O ratio, hence fractionation of C and O is very important for the condensation (Larimer and Bartholomay, 1979). Under the initial condition ( $T \leq 100\text{K}$ ,  $P = 10 - 10^3$  Pa), oxygen exists mainly in ice form ( $\text{H}_2\text{O}$ ) and carbon in gaseous  $\text{CH}_4$  form. In the heating stage, with temperature increasing from the inner toward outer part of the disc, ice has evaporated first in the inner part and transferred in gaseous  $\text{H}_2\text{O}$  form outward by probable diffusion and turbulence. This would rise the C/O ratio toward the sun in the solar disc. After evaporation of all ice, the fractionation of C and O tended to stop. With further increasing temperature, dusts of silicates and oxides were also evaporated and transferred outward, and hence resulted in fractionation of other elements in radial direction of the disc. In the cooling stage, gaseous components started to recondense first from the outer. In contrast with the heating stage, the condensation caused the disc to be more refractory in its outer part. A very important result is that the fractionation of C and O in the disc during heating stage controlled systematic variation of redox at the locations, which determined association of mineral phases thorough condensation. The model well explained differences found in chemical and modal compositions, redox state among various chondrites.

## 2. Deviation of taxonomic parameters in some intermediate groups of chondrites

The parameters used to classify chondrites (i. g. abundance patterns of siderophile, lithophile, and chalcophile elements, isotopic composition of oxygen, bulk  $\text{FeO}/[\text{FeO} + \text{MgO}]$  ratio, relation between bulk reduced Fe content and oxidized Fe content, Fa value of olivine, Fs value of low-Ca pyroxene and Co content in kamacite, etc.) and the bulk composition of Fe-Ni metal proposed in this paper can definitively distinguish among enstatite chondrites (EH, EL), ordinary chondrites (H, L, LL) and carbonaceous chondrites (CI, CM, CO, CV). However, there is deviation for some intermediate group of chondrites, which usually behave a deviation between metal and silicates, such as Yamato74063 and Acapulco are E/H intermediate-group chondrites and contain olivine and low-Ca pyroxene lying between E- and H-groups in composition, but the bulk composition of Fe-Ni metal falls near H-group or between H- and L-groups and abundance of Fe-Ni metal of Yamato74063 is in range of L-group. Concentrations of Ir, Os and Co in Fe-Ni metal of Krymka meteorite fall between H- and L-groups, while Fa value of olivine lies between E- and H-group. The deviations above probable reflect different evolutions and histories of silicates and Fe-Ni metal of these chondrites. According to modern evolution theories of the solar system, there existed turbulence controlling effectively distribution of angular momentum in the solar system (Sears, 1988). The turbulence probably caused transportation of materials along radial direction in the disc. The different properties between silicates and metal could result in separation of them during transportation by the turbulence and, in addition, by dust dropping from higher latitude

onto equatorial surface of the solar nebula disc. The above processes could also make silicates and metal, which probably formed at different locations, accreted to a same parent body.

### Conclusions

(1) Concentrations of Ir, Os and Co in Fe—Ni metal are the sensitive indicators for redox state of chondrites. With more oxidation of chondrites, the concentrations of Ir, Os and Co in Fe—Ni metal increase consistently. It can be used to distinguish E—, H—, L—, LL— and C—group chondrites.

(2) Bulk composition of Fe—Ni metal, Fa value of olivine and Fs of low—Ca pyroxene indicated a continuous variation of the redox among different groups of chondrites, implying continuity of fractionation of the solar nebula.

(3) In terms of Co content in kamacite, Fa value of olivine, Fs of low—Ca pyroxene, concentrations of Ir, Os and Co in Fe—Ni metal and other parameters, E/H, H/L, L/LL and LL/C intermediate groups of chondrites were recognized, which increase the number of chemical groups of chondrites from 9 to 13. Discovery of the intermediate groups of chondrites also suggests a continuous fractionation of the solar nebula.

(4) The deviation of redox state indicated by silicates and metal suggests a fractionation and probably different histories of them. Silicates and metal of different origins could finally accrete to a same parent body by mechanic transportation.

**Acknowledgments** We are most grateful to Prof. Z. Y. Ouyang for many useful discussions and considerably critical review of the paper.

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