

Bulk compositions of metallic Fe-Ni of chondrites: Constraints on fractionation of siderophile and chalcophile elements

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Abstract Bulk compositions of metallic Fe-Ni from two equilibrated ordinary chondrites, Jilin (H5) and Anlong (H5), and two unequilibrated ones, GRV 9919 (L3) and GRV 021603 (H3), were analyzed by inductively coupled plasma mass spectrometry (ICP-MS). The CI-, Co-normalized abundances of siderophile and chalcophile elements of metallic Fe-Ni from the unequilibrated ordinary chondrites correlate with 50% condensation temperatures (i.e., volatility) of the elements. The refractory siderophile elements (i.e., platinum group elements, Re), Au, Ni and Co show a flat pattern (1.01×CI Co-normalized), while moderate elements (As, Cu, Ag, Ga, Ge, Zn) decrease with volatility from 0.63×CI (Co-normalized, As) to 0.05×CI (Co-normalized, Zn). Cr and Mn show deficit relative to the trend, probably due to their main partition in silicates and sulfides (nonmagnetic). Metallic Fe-Ni from the equilibrated ordinary chondrites shows similar patterns, except for strong deficit of Cr, Mn, Ag and Zn. It is indicated that these elements were almost all partitioned into silicates and/or sulfides during thermal metamorphism. The similar deficit of Cr, Mn, Ag and Zn was also found in iron meteorites.

Our analyses demonstrate similar behaviors of W and Mo as refractory siderophile elements during condensation of the solar nebula, except for slight depletion of Mo in the L3 and H5 chondrites. The Mo-depletion of metallic Fe-Ni from GRV 9919 (L3) relative to GRV 021603 (H3) could be due to a more oxidizing condition of the former than the latter in the solar nebula. In contrast, the Mo-depletion of the metallic Fe-Ni from the H5 chondrites may reflect partition of Mo from metal to silicates and/or sulfides during thermal metamorphism in the asteroidal body.

Key words ICP-MS; metal; meteorite; siderophile element; platinum group elements

1 Introduction

Chondrites were formed directly from the condensation and accretion of solar nebula. They did not experience later fractionation, and hence have recorded the important information about the formation and evolution of solar nebula during the early stages of solar system evolution. Furthermore, the most primitive chondrites also contain materials from stars, such as supernova, nova and red giant star prior to the formation of the solar system (Anders and Zinner, 1993; Zinner, 1998a). Ordinary chondrites are the most common type of meteorites on the basis of the proportion of free nickel-iron metal and total metal they contain, they are divided into three chemical groups (H, L and LL) that at least represent three different types of meteorite parent bodies, respectively

(Kallemeyn et al., 1989). The contents of siderophile elements in ordinary chondrites tend to decrease (Torres-Ruiz et al., 2003) while their oxidation degree tends to increase from H, L to LL gradually (Brearley and Jones, 1998), both having a reverse correlation. Different groups of chondrites would experience varying-degree thermal metamorphism at different stages during the formation of their parent bodies. According to the intensity of thermal metamorphism, they are divided into different petrologic types from type 3 to type 6, and the type 3 is the most primitive type, having not experienced thermal metamorphism. In addition, the type 7 is regarded as an expansion from type 4 to type 6, and there is no exact classification standard.

The siderophile elements, especially the highly siderophile elements (HSE), are very important for us to understand the distribution of the siderophile elements, the fractionation of metal and silicates, and the

formation of core-mantle during the process of condensation of the solar nebula. So, it is particularly important to get a complete set of data in this aspect. In the past, the INAA and RNAA techniques were employed to analyze the bulk compositions of siderophile elements in extraterrestrial materials (Rambaldi, 1977; Sears and Weeks, 1986; Kallemeyn et al., 1989; Kong et al., 1995; Kong and Ebihara, 1996, 1997; Kong and Palme, 1999). Now, ICP-MS is more and more employed to analyze the metallic Fe-Ni of extraterrestrial materials. In this paper, ICP-MS is used to determine the bulk compositions of metallic Fe-Ni in chondrites. For the feasibility of such analysis, refer to Xu Lin et al. (2007).

Four chondrite samples and four iron meteorite samples were analyzed in this work, including 2 equilibrated chondrites, Anlong (H5) and Jilin (H5), and 2 unequilibrated GRV 99019 (L3) and GRV 021603 (H3) from the Grove Mountains of the Antarctica and 4 iron meteorites. Because of the limit of time, we did not analyze in detail the petrological, mineralogical, chemical and bulk compositions of the four ordinary chondrites. However, the Anlong and Jilin chondrites have been well documented. For their petrology, mineralogy and bulk composition data, please refer to the literature, though the data are less available. Xie Xiande and Wang Daode (1992) analyzed the metal grains differing in size and mode of occurrence in the Jilin chondrite, with an attempt to study the behavior of Fe-Ni metals during thermal metamorphism. The two Antarctic meteorites had not been studied by previous researchers, so no reference data were available. Therefore, in this paper we did not discuss the relations between metallic Fe-Ni and the bulk compositions of the two Antarctic meteorites. Instead, we preliminarily described the distribution characteristics of siderophile elements in different chemical groups and petrologic types, and in chondrites and iron meteorites, and preliminarily discussed the variations of siderophile elements in the process of condensation of nebula and metamorphism of asteroids.

2 Samples and experimental procedures

The Anlong chondrite fell in Anlong County, Guizhou Province on May 2, 1971. It belongs to the H5 type with $Fa_{19.2}$ (mol%), and the Co contents of kamacite are 4.7 mg/g. Due to slight weathering, approximately more than 50% of silicates were rusted, and some metals were oxidized. The Jilin chondrite fell in Jilin Province on March 8, 1976. It belongs to the H5 type with $Fa_{19.4}$ (mol%), and the Co contents of kamacite are 4.7 mg/g. The chondrite has no sign of being weathered on the surface, but has undergone more extensive thermal metamorphism and two stages

of collision (Xie Xiande and Huang Wankang, 1991). The two Antarctic chondrites, GRV 99019 (H3) and GRV 021603 (L3), belong to two different chemical groups, respectively, but to the same petrologic type. The iron meteorites include the Nandan, Mundrabilla, Wulasitai and Armanty. The four iron meteorite samples, occurring as sawdust in form, were analyzed, which had been taken from four different surface areas of the Armanty, respectively.

The four chondrite samples were strictly cleaned before they were ground. Analytically pure acetone and 18 M Ω /cm water were used to clean the samples, which were placed in an ultrasonic instrument to be shaken over four times, each run lasted for two minutes in order to eliminate the purities and possible existing oxides. The chondrite samples were ground as fine as about 100 mesh and the metals were separated from silicates by means of a piece of magnet, and then the remainder was continuously ground for further separation of tiny metal grains from the silicates (As the metal grains in unequilibrated chondrites are too small and usually enclosed by silicates, they are hard to separate). The separated metal grains from the chondrites and sawdust of iron meteorites were cleaned in accordance with the following procedure: they were cleaned with acetone-alcohol-highly pure water, and then dried and weighed. About 100 mg of each sample was analyzed. In this work, these magnetic fractions separated from the meteorites were divided into two groups according to their magnetic intensities, one is strongly magnetic (almost consisting of metallic Fe-Ni, which refers to as magnetic fractions in the following text) and the other is weakly magnetic (almost containing no metal grain, which refers to as silicate fractions).

Table 1. Operating parameters of ICP-MS

Parameter	Value
Instrument	VG Plasma Quad ExCell
Forward power	1300 W
Reflected power	<5 W
Argon flow rate	13 L/min
Auxiliary gas (Ar)	0.75 L/min
Nebulizer gas (Ar)	0.85 L/min
Detector mode	Pulse counting
Resolution	0.8 amu
Number of scan sweep	100
Sampling cone (Ni)	1.0 mm
Skimmer cone (Ni)	0.7 mm

The detection limits were calculated from six times the square root of the blank solution counts divided by the sensitivity of standard solutions, which are much lower than their concentrations. In this work, the contents of the major and trace elements were determined respectively by Thermo elemental IRIS Advantages ICP-AES and VG Plasma-Quad ExCell ICP-MS, at the National Research Centre for Geological Analysis, Chinese Academy of Geological

Sciences (the instrument operating parameters are listed in Table 1). Multi-element solutions (20 ng/g) were used as standards. The sample solutions were diluted in 10 mL of 3% HNO₃ for ICP-AES and ICP-MS determination.

In consideration of the possible interference of Cl⁺ in HCl, the samples to be analyzed were divided into two aliquots, each being about 50 mg. One of the aliquots was dissolved in ~1 mL *aqua regia* for analysis of PGEs, Re, Au, Mo and W, and the other was dissolved in ~2 mL of 6 M HNO₃ for analysis of P, Ni, Co, Cr, Mn, Cu, Zn, Ga, Ge and As. The analytical method was described by D'Orazio and Folco (2003). The HNO₃ and HCl were purified via sub-boiling distillation, and water used in the experiment was obtained from the 18 MΩ/cm grade millipore purification system.

The results of isotope interference and correction are listed in Table 2. The main interference elements are Ga, Ge and As. The interference of ⁵⁸Ni¹⁶O¹H⁺ on ⁷⁵As was calculated from the ratio of nickel hydroxide to nickel oxide (0.23) and ⁵⁸Ni¹⁶O⁺ derived from the intensities of peaks 70, 72, 73 and 74. The correction factors are about 0.8 for Ge and As and 0.95 for Ga. A blank sample for HNO₃ solution and the other one for *aqua regia* solution were prepared in the same way as the samples. The results showed that the blank levels of most elements are negligible, except for As, Zn and Re.

Table 2. Analyzed isotopes and corrected interferences of ICP-MS analysis

Isotope	Corrected interference	Determination limit (μg/g)
⁵² Cr		0.084
⁵⁵ Mn		0.033
⁵⁹ Co		0.107
⁶⁵ Cu		0.057
⁶⁶ Zn		0.234
⁷¹ Ga	⁵⁴ Fe ¹⁶ O ¹ H ⁺	0.008
⁷⁴ Ge	⁵⁷ Fe ¹⁶ O ¹ H ⁺ , ⁵⁸ Fe ¹⁶ O ⁺ , ⁵⁸ Ni ¹⁶ O ⁺	0.015
⁷⁵ As	⁵⁸ Fe ¹⁶ O ¹ H ⁺ , ⁵⁸ Ni ¹⁶ O ¹ H ⁺	0.076
⁹⁵ Mo		0.025
¹⁸² W		0.010
¹⁰¹ Ru		0.006
¹⁰³ Rh		0.004
¹⁰⁵ Pd		0.008
¹⁸⁵ Re		0.007
¹⁹³ Ir		0.001
¹⁹⁵ Pt		0.003
¹⁹⁷ Au		0.042

In the process of instrumental analysis, we measured the standard solutions 5 times to monitor the stability of counting, and the bulk variation was less than 1%. Relative standard deviations (RSD) of counting (2σ) are less than 2% for Cr, Mn, Co and Cu, <7% for Zn, Ga, Ge, As and Mo (17% and 8% for As and Mo in the silicate fraction separated from the Jilin, respectively), <9% for PGEs (6%–22% for the silicate frac-

tion from the Jilin), 5%–19% for Re (24% for Re in the silicate fraction from the Jilin), and <6% for W except GRV 99019 (12%), respectively.

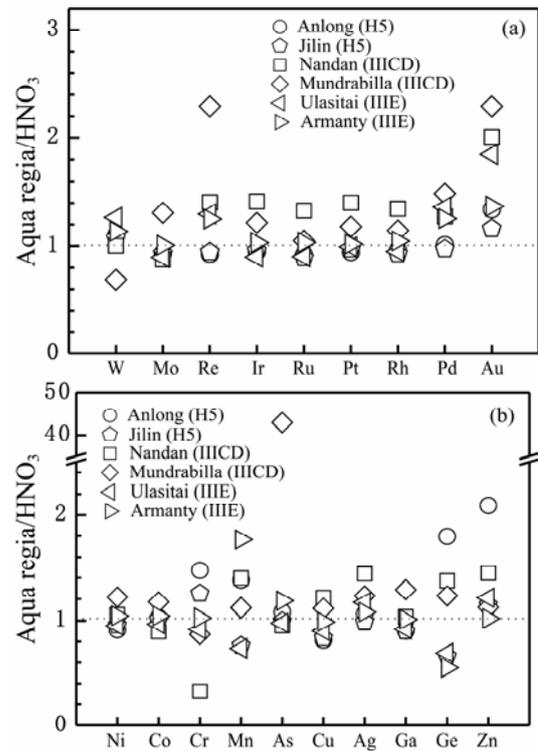


Fig. 1. Comparison of the results of analysis for the samples dissolved with *aqua regia* and HNO₃, respectively (For the data of Ulasitai iron meteorite, refer to Xu Lin et al., 2008). Note: Because of the incorporation of some silicates in the samples of GRV 99019 and GRV 021603, the siderophile element distribution patterns of their metallic Fe-Ni cannot fully represent their actual distribution characteristics. So, no comparison of the analysis results for metallic Fe-Ni in these two meteorites was made.

3 Results

The elements are taken as the x-coordinate, and the ratio of *aqua regia*/HNO₃ is taken as the y-coordinate. As shown in Fig. 1, the contents of PGEs, Re and Au in the samples dissolved with *aqua regia* are much higher than those with HNO₃, especially the contents of Re and Au in the Mundrabilla iron and Au in the Nandan and Ulasitai irons. The contents of other elements in the samples dissolved either with *aqua regia* or with HNO₃ are of little variation, but a few elements are relatively scattered (Fig. 1b), such as As in the Mundrabilla iron meteorite, Ge and Zn in the Anlong chondrite, Mn and Ge in the Armanty iron meteorite, and Cr in the Nandan iron meteorite. The results of analysis for the samples dissolved with *aqua regia* and HNO₃ are listed in Tables 3 and 4. The results of comparison between the samples dissolved with *aqua regia* and those with HNO₃ showed that most metallic Fe-Ni in chondrite samples

shows a deviation of up to 13%–56%, except for the Anlong with little variation (1%–9%), and 4% for Rh of GRV 021603. In contrast, the two different acidic solutions have little influence on the contents of PGEs in iron meteorites (1%–12%), even no variation, for

example, in some parts of the Armanty iron meteorite. The contents of Re and Au of metallic Fe-Ni in chondrites or iron meteorites show a large range of variations, even up to 60%. Of the siderophile elements, Ge varies over the largest range, even by a factor of 4.

Table 3. Measurements of the bulk samples dissolved in HNO₃

Sample	Weight (mg)	P (%)	Ni (%)	Co (%)	Cr (μg/g)	Mn (μg/g)	Cu (μg/g)	Zn (μg/g)	Ga (μg/g)	Ge (μg/g)	As (μg/g)
Metal phase in chondrites											
GRV9919 (L3)	50.4	0.11	1.26	0.07	910.5	1224	80.1	32.22	0.66	1.28	1.74
GRV021603 (H3)	52.2	0.08	1.99	0.09	711.9	580.4	88.6	9.52	3.16	1.67	1.98
Anlong (H5)	53.1	0.0003	9.47	0.41	47.5	78.4	352.8	1.4	12.9	19.2	10.9
Jilin (H5)	51.3	0.09	7.37	0.43	189.7	189.2	185	3.1	9.0	18.8	9.3
Jilin_Sil	53.5	0.09	0.08	0.002	293.4	1349.7	27.8	17.73	0.49	0.27	0.01
Iron meteorites											
Nandan	51.2	0.14	7.37	0.48	7.0	1.1	137.1	13.7	81.1	309.2	9.6
Mundrabilla	53.1	0.37	8.12	0.50	28.8	4.5	112.6	12.7	55.2	168.0	12.0
Armanty: L1	50.7	0.35	10.59	0.54	37.6	14.9	186.4	24.6	15.6	25.2	11.3
: L16	52.8	0.54	10.40	0.55	23.1	9.0	90.6	1.9	15.7	26.7	11.4
: L17	51.6	0.28	10.88	0.56	31.7	38.6	101.5	6.0	15.8	26.0	13.6

Table 4. Measurements of the bulk samples dissolved in aqua regia

Sample	Weight (mg)	Ru (μg/g)	Rh (μg/g)	Pd (μg/g)	Re (μg/g)	Ir (μg/g)	Pt (μg/g)	Au (μg/g)	Mo (μg/g)	W (μg/g)
Metal phase in chondrites										
GRV9919 (L3)	50.9	0.79	0.15	0.86	0.04	0.56	1.03	0.21	0.57	0.08
GRV021603 (H3)	52.3	1.68	0.24	1.44	0.09	1.16	1.72	0.25	2.45	0.33
Anlong (H5)	51.1	5.07	1.00	4.36	0.259	3.07	6.45	1.17	3.70	0.84
Jilin (H5)	50.7	4.85	0.95	4.01	0.256	0.03	6.22	1.11	3.61	0.74
Jilin_Sil	53.3	0.18	0.03	0.11	0.011	0.16	0.19	0.02	0.39	0.02
Iron meteorites										
Nandan	51.2	5.12	1.31	3.82	0.126	1.77	5.39	1.55	6.49	1.14
Mundrabilla	51.6	3.32	0.92	4.37	0.071	1.00	3.60	1.63	6.26	1.23
Armanty: L1	51.5	1.61	1.08	5.90	0.016	0.25	1.93	1.96	8.90	0.41
: L16	51.0	1.59	1.00	5.62	0.013	0.25	1.86	1.93	7.66	0.37
: L17	52.3	1.72	1.14	6.26	0.018	0.27	2.10	2.12	7.78	0.29

In consideration of the fact that Co is a minor element in the metallic Fe-Ni of chondrites and iron meteorites, and it is also distributed homogeneously in the metallic Fe-Ni of the same meteorite, so we normalized the analysis data with CI and Co, in order to eliminate the possible influences of some incorporated silicates in metal grains on the determination, and make the results more representative so as to reflect the fractionation characteristics of siderophile elements during the process of solar nebula and melt crystallization of meteorites. As can be seen in Table 3, the contents of Ni in the silicate fraction from the Jilin chondrite only account for 1% of those for the magnetic fraction from the same meteorite, suggesting that the incorporated metallic Fe-Ni in the silicate fraction is $\leq 1\%$. The contents of Ni in the magnetic fractions from two H5-type chondrites are 9.47% and 7.37%, respectively, approaching to and exceeding the contents of Ni in iron meteorites. This is consistent with the fact that there exists minor Ni-rich taenite in the H-group chondrites, suggesting that the magnetic fraction is almost composed of pure metallic Fe-Ni. However, the lower contents of Ni in the H3 and L3 types suggested that a considerable amount of incorporated silicates was not separated from metallic

Fe-Ni due to being fine in grain size and usually enclosed in silicates in unequilibrated chondrites.

As shown in Fig. 2a, the magnetic fraction from the Jilin chondrite is very similar in siderophile element distribution pattern to that from the Anlong chondrite. This is consistent with the situation of the H5 chemical group. Except for Mo which showed a little anomaly, the other refractory siderophile elements in the metallic Fe-Ni of chondrites show a smooth distribution pattern, while the moderately and highly volatile elements tend to be depleted with increasing volatility (or with decreasing condensation temperature by 50%), but Ag and Zn are abnormally low. Significant differences were noticed in distribution patterns between weakly and strongly magnetic fractions, and the refractory siderophile elements and the volatile elements Cr, Mn Cu and Ag of the former are high relative to Ni. The refractory siderophile element distribution patterns in the magnetic fraction from the H5 group are similar to those of the unequilibrated chondrite GRV 021603 (H3), though no Mo anomaly was observed; Ag and Zn also did not show abnormal depletion. The magnetic fraction from GRV 99019 (L3) shows negative anomalies, and the contents of W are lower than those of the H3 group. In

addition, the Ge contents of the two equilibrated Antarctic meteorites GRV 99019 and GRV 021603 are of no difference, both being lower than those of two equilibrated H5 group meteorites, but obviously higher than those of the silicate fraction from the Jilin chondrite. As compared with iron meteorites (Fig. 2b), the refractory siderophile elements in the metallic Fe-Ni of chondrites show a smooth distribution pattern, while the volatile elements tend to become depleted with increasing volatility, and Cr, Mn, Ag and Zn are abnormally low. As shown in Fig. 2b, the refractory siderophile elements of the two iron meteorites which belong to two different chemical groups experienced obvious fractionation, especially the refractory siderophile elements of the Ulasitai iron meteorite (IIIE) experienced more obvious fractionation than those of the Nandan iron meteorite (IIICD), with abnormally low Re, Ir, Ru and Pd.

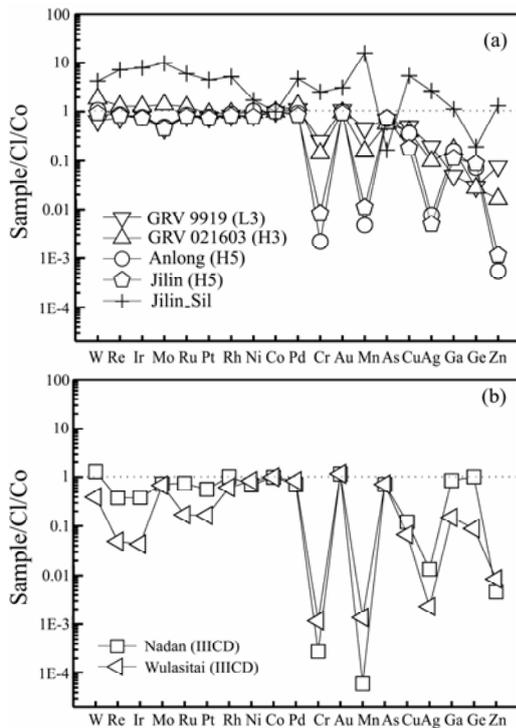


Fig. 2. Cl-, Co-normalized abundance patterns of siderophile and chalcophile elements of the magnetic fractions from the chondrites and iron meteorites. The elements are arranged with increasing volatility from left to right. (a) The magnetic fractions of chondrites; (b) metallic Fe-Ni of two iron meteorites.

The contents of siderophile elements in the magnetic fractions from the Jilin and Anlong chondrites were compared with the whole-rock data reported by previous researchers (Fig. 3). The contents of siderophile elements in the magnetic fraction are much higher than those of the whole-rock samples, close to those of moderately volatile elements (such as Ga and Zn), and the contents of Cr and Mn in the magnetic

fraction are obviously lower than those of the whole-rock samples.

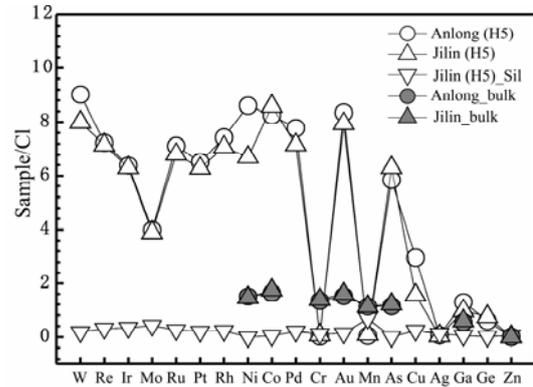


Fig. 3. Chemical compositions of the bulk rocks and metallic Fe-Ni of the Jilin and Anlong chondrites (For the bulk composition, refer to Wang Daode and Chen Youheng, 1991).

4 Discussion

4.1 Comparison of the analyses of metallic Fe-Ni dissolved with HNO₃ and aqua regia solutions, respectively

The analysis results for the samples digested by two different acidic solutions showed that the contents of PGEs in aqua regia solution are higher than those in HNO₃ solution, especially Re and Au. Although the data of some samples (such as the magnetic fractions from the Jilin chondrite and the iron meteorites of IIIE group) show great similarities when dissolved with two different acidic solutions, but the data of other samples digested by aqua regia are higher than those by HNO₃, especially Re and Au. As viewed from the above comparison, aqua regia solution should be preferentially used to decompose the samples for the determination of Re and Au, and PGEs in the metallic Fe-Ni.

The contents of other elements in the parallel samples are significantly different when the samples were dissolved with aqua regia and HNO₃, respectively, and the results showed that in case the samples were digested by aqua regia, the contents would be high in general. The contents of Cr, Mn, As, Ge and Zn in the samples digested by aqua regia are higher than by HNO₃, which is possibly related to the interference of Cl⁺ ionic groups or polyatomic group ions resultant from Cl⁺ or Cl and other elements, for example, the interference of ³⁷Cl³⁷Cl⁺ on ⁷⁴Ge, that of ³⁵Cl¹⁶O¹H⁺ on ⁵²Cr⁺ and that of ⁴⁰Ar³⁵Cl⁺ on ⁷⁵As, and that of ³⁷Cl¹⁸O⁺ on ⁵⁵Mn and ⁵⁵Zn. But the Cr contents of one sample and the Mn contents of three samples digested by aqua regia are obviously lower than by HNO₃. As Cr and Mn are usually distributed in silicates and sulfides, and these minerals usually occur as

inclusions in iron meteorites, so the above results are possibly attributed to the inhomogeneity of the samples themselves.

4.2 Abundance patterns of siderophile and chalcophile elements in metallic Fe-Ni from different petrologic types and chemical groups of chondrites

Shown in Fig. 2 are the siderophile element distribution patterns of metallic Fe-Ni in chondrites, which are related mainly to the volatility of the elements, and the refractory siderophile elements in the metallic Fe-Ni of chondrites show a smooth distribution pattern, while the moderately and highly volatile elements tend to become depleted with increasing volatility. It is suggested that the volatility of the elements is the main factor controlling the composition of metallic Fe-Ni in chondrites. Furthermore, except for Zn in the 5-type chondrites, which is obviously depleted as compared with the unequilibrated 3-type meteorites, possibly due to thermal metamorphism of parent bodies; other moderately volatile elements showed no significant difference between 5-type and 3-type, and, therefore, as viewed from the siderophile element distribution patterns of metallic Fe-Ni in the chondrites mentioned above, the elements may have formed at the stage of condensation and accretion of solar nebulae. And thermal metamorphism of the parent bodies did not play a decisive role in this aspect. The metals Cr and Mn are obviously depleted in the metallic Fe-Ni of two H5 group meteorites and lower than in the 3-type chondrites, possibly due to their frequent occurrence in silicates of ordinary chondrites. As mentioned above, the Ni contents of magnetic fractions separated from the 3-type chondrites are relatively low, because the metal grains are too small and enclosed by some silicates, so it is hard to acquire pure metal grains. Therefore, the contents of Cr and Mn are higher in magnetic fraction of the 3-type chondrites.

The elements W and Mo are two refractory elements with special behavior. They are distributed between metals and silicates in different proportions along with the variation in oxidation-reduction degree of the system. W and Mo are lithophile at the oxidation condition, and siderophile at the reduction condition. Compared with the H group, the L group would be formed at the more oxidizing condition in solar nebula, which could be the factor leading to Mo anomaly and lower W in the magnetic fraction of the L3 group. Compared with the other refractory siderophile elements, the Mo contents of metallic Fe-Ni in the H3 group are of no depletion, but the two L3 group chondrites and two H5 group chondrites show remarkable negative anomalies. The Mo contents of metallic Fe-Ni in the L3 group are relatively

low, which is consistent with the fact that meteorites of this group were formed at the more oxidizing condition than the H group, thus Mo appears to be more lithophile and was incorporated in large amounts into silicates. In contrast, differences in Mo contents of metal grains between the H5 and H3 groups may reflect the transfer of Mo from metallic Fe-Ni to silicates in the process of thermal metamorphism of asteroids. The W contents show a little variation in the metallic Fe-Ni analyzed in this work, only a slight increase in Mo content was observed in the H3-type chondrites, which is consistent with the variation characteristics of W content.

The element distribution patterns of the silicate fraction are significantly different from those of the magnetic fraction separated from the Jilin meteorite (Fig. 2a). Relative to the minor elements Ni and Co, the other siderophile elements are obviously high, and the moderately volatile elements, except for As and Ge, show no decrease in volatility as encountered in the magnetic fraction. The contents of W and Mo in the magnetic fraction are far lower than in the silicates of chondrites (Fig. 3), indicating that these two metals mostly exist in the metallic Fe-Ni. So, we can not exclude the possibility that a minor amount of metallic Fe-Ni was incorporated into the silicates, but the distribution patterns of siderophile elements in the silicates do truly reflect their own characteristics, independent of Fe-Ni metals. The refractory siderophile elements in the silicates are enriched relative to Ni, which is possibly due to earlier separation of the refractory siderophile elements than Fe-Ni metals from solar nebula in the form of particulates during the process of nebular condensation. Some refractory siderophile elements were enclosed in the aggregates of earlier crystallized refractory oxides and silicates (e.g. the noble metal particulates in Ca, Al-rich inclusions), thereby, the siderophile elements are enriched relative to Ni. The moderately volatile elements are correspondingly higher in the silicates, which may be attributed to the preferential enrichment of these elements in sulfides.

4.3 Abundance patterns of siderophile and chalcophile elements in metallic Fe-Ni from iron meteorites in comparison with those of chondrites

As is shown in Fig. 2, the comparison of distribution patterns between iron meteorites and the metallic Fe-Ni of chondrites demonstrates that Re, Ir, Ru and Pt in the Wulaitai iron meteorite (IIIE) resultant from magma fractional crystallization are distinctly low relative to the siderophile elements. For comparison, the depletion degree of the elements mentioned above is not obvious in the Nandan iron meteorite (IIICD) of impact melting origin. This is consistent

with the low degree of fractional crystallization of iron meteorites of impact melting origin. Although these two iron meteorites belong to two different chemical groups and genetic types, their Mo contents are not so low, different from the metallic Fe-Ni of ordinary chondrites. It would be implied that the parents of the two iron meteorites were formed under more reductive conditions. The depletion model of moderately volatile elements in the Wulaitai iron meteorite is generally consistent with that of the metallic Fe-Ni in ordinary chondrites, but the contents of Ga and Ge in the Nandan iron meteorite are higher than those in the metallic Fe-Ni of ordinary chondrites, which may reflect that the initial materials contained a lot of moderately volatile elements.

5 Conclusions

The contents of trace elements in the metallic Fe-Ni of meteorites dissolved with *aqua regia* and HNO₃ respectively were determined by ICP-MS. Although the results for some samples dissolved by the two acidic solutions are considerably consistent to each other, the contents of PGEs, Re and Au are slightly low in these samples dissolved with HNO₃; the contents of other siderophile elements and chalcophile elements are slightly high in the samples dissolved with *aqua regia*. This may be due to the interference of ionic groups derived from the combination of Cl⁺ with other elements. Therefore, *aqua regia* should be adopted to dissolve the samples for the analysis of PGEs, Re and Au, while HNO₃ may be used to digest the samples for the ICP-MS analysis of other elements.

We analyzed the metallic Fe-Ni in chondrites for the siderophile elements, and preliminarily discussed the variation trend of siderophile elements in the process of nebular condensation and thermal metamorphism of asteroids. In general, the refractory siderophile elements show a smooth distribution pattern, and the moderately and highly volatile elements tend to become depleted with increasing volatility (or with a decrease in condensation temperature by 50%). As mentioned above, comparisons of the W and Mo distribution patterns in the magnetic fractions separated from chondrites of different chemical groups (H and L groups) and different petrologic types reflected the influence of oxidation-reduction conditions on the W and Mo partitioning between metals and silicates during condensation of the solar nebula. In other words, more W and Mo existed in silicates. At the same time, comparisons of the element compositions of magnetic fractions separated from different petrologic types of chondrites revealed the influence of thermal metamorphism of asteroids on the trace element composition of the metal phase in chondrites.

Zinc in the metallic Fe-Ni was obviously lost because of thermal metamorphism, but the depletion patterns of other moderately volatile elements would more reflect the characteristics of condensation of solar nebula. In addition, the elements W and Mo showed a tendency of being transferred into silicates as a result of thermal metamorphism of asteroids. The refractory siderophile elements in the silicates separated from ordinary chondrites are obviously enriched relative to Ni, suggesting that it is not the result of incorporation of a minor amount of metals. More possibly, the silicates contained a trace amount of refractory metal alloy separated early from solar nebula.

Comparisons of the siderophile element distribution patterns of chondrites with those of iron meteorites showed that the two types of iron meteorites of different origins, (the IIICD group of impact melting origin relative to the IIIE group of magma fractional crystallization origin) are different in fractional crystallization degree, i.e., the former's is lower than the latter's. But the contents of their refractory siderophile elements are higher than those of the metallic Fe-Ni in chondrites, with no Mo depletion. This case is not true for ordinary chondrites.

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