Did Iron Meteorites Form in the Asteroid Belt?—Evidence from Thermodynamic Models

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The major iron meteorite groups are defined essentially by their Ga, Ge, and Ni contents. It now seems clear that the differences between their abundances of Ga and Ge were produced by the process of condensation and accretion in the primordial solar nebula. The simplest interpretation of the Ni abundance, and its variations between the groups, is also that it was fixed during condensation and accretion; more particularly, it reflects the oxidation state of the nebula during condensation and accretion. The abundance patterns of 17 other trace elements have been examined and are consistent with this model. It is believed to be the simplest model published and most consistent with analogous calculations for the chondrites. If it is correct, then the iron meteorite groups formed over a very wide range of pressures, 10^{-4} to 10^{-8} atm. Such a range could only be found in a restricted region of the nebula, such as the asteroid belt, if a complex accretion sequence inside a protoplanet occurred. More likely, the iron meteorites were formed in widely dispersed regions of the nebula and only one group formed in the asteroid belt, probably group IIIAB. Groups IAB and IIAB formed nearer the Sun, and group IVA formed much further out, say, beyond the orbit of Jupiter.

INTRODUCTION

The iron meteorite groups are defined essentially on their nickel, gallium, and germanium contents. The Ga and Ge variations between the groups are very large, while within the groups they are small, making these elements ideal for classification (Scott and Wasson, 1975). The intergroup variations are generally thought to be a consequence of their condensation and accretion processes in the solar nebula. In particular, it is a result of their extreme volatility under the prevailing conditions. Most of the other trace elements show very large variations within the groups due to some secondary melting event, but averaged within the groups they are generally present in cosmic proportions. However, Scott (1972) has shown that to some extent several "moderately volatile" elements mimic Ga and Ge in showing variations between the groups and he and Wasson and

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Wai (1976) have lately argued that they are the result of differences in their condensation and accretion conditions (Scott, 1978). The intergroup variations shown by Ni are much smaller and were produced by oxidation and sulfuration of the parent body, either during accretion or subsequently (Sears, 1978a; Kelly and Larimer, 1977).

In a previous paper I presented a model in which the Ni, Ga, and Ge contents of the major groups (IAB, IIAB, IIIAB, and IVA) are explained by their accretion over a narrow temperature range (600–700°K, with IIAB 50°K or so higher), but over a very wide range of pressures (Sears, 1978a). This is consistent with these meteorites containing sulfur, which condenses at the pressure-independent temperature of 695°K, and when IAB is assumed to have formed at 10^{-4} atm—so that IIAB, IIIAB, and IVA formed at 10^{-4}, 5×10^{-6}, and 10^{-8} atm, respectively—it can also explain their highly differing contents of carbon.

In the present paper, I examine the condensation behavior of several other elements to see if they fit into the simple model
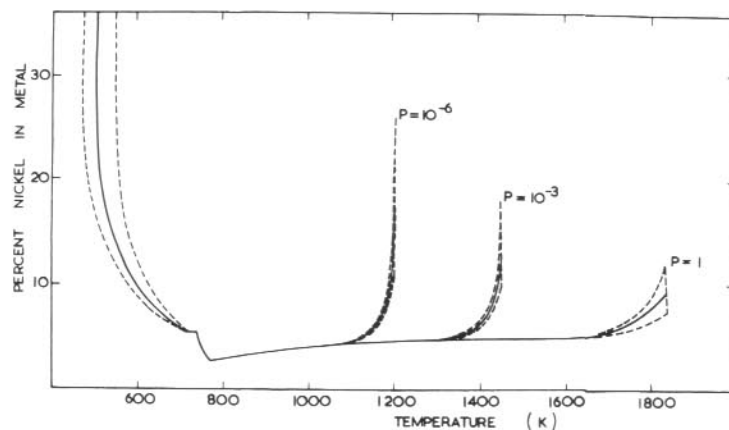
FIG. 1. Nickel content of the metal at equilibrium with the nebular gases as they cooled. The region of interest here is below 700°K and is pressure independent. (The P values refer to assumed nebula pressures.) The broken lines reflect uncertainty in the thermodynamic data. Iron meteorite Ni contents are observed between 600 and 750°K [for details see Sears (1978a)].

derived from Ni, Ga, and Ge contents. I also consider the implications the model has for the theory that iron meteorites come from the asteroid belt. It is concluded that my earlier finding—that large pressure differences were involved in the formation of the iron meteorites—is largely correct. From this I suggest that only one of the major iron meteorite groups, probably IIIAB, formed in the asteroid belt; IAB and IIAB formed much nearer the Sun, and IVA formed much further out—possibly beyond or near the orbit of Saturn.

METHOD

The techniques for carrying out the necessary calculations have been well documented by Urey (1952), Lord (1965), Larimer (1973), and Grossman (1972). Most of the calculations were performed by hand but some, especially the Ni oxidation/sulfuration curve (Fig. 1), required the use of a computer. The University of Manchester Regional Computer Center's CDC 6300-ICL 1906A joint system and the NAG Library program CO5 NAF (numerical solution of irregular polynomials by the Newton–Raphson method) were used. This was part of a larger project which will be reported elsewhere. The sources of thermodynamic data of relevance here are

listed in Table I. The cosmic abundance values were taken from Cameron (1973). The sources of analytical data are listed in Table II, along with the mean and standard deviation for each element in the four iron meteorite groups under discussion here. Wai *et al.* (1978) have suggested that, instead of taking the mean, one should calculate the original composition of the group by working the fractional crystallization equations in reverse. I have not done this because the nature of the melting event is still disputed, and because the method is critically dependent on the end member of the sequence. Data for this member, assuming its identity is known, are not always available.

RESULTS

My interpretation of the analytical data has been guided primarily by a factor analysis of iron meteorite compositions which I performed several years ago—details of this will be published elsewhere—and the order in which I present the results reflects this. Essentially, it indicated that the elements may be divided into three groups, with the inference that the members of each group were primarily affected by a different process. One involved Ni, Co, Pd, Cu, and possibly Mo, and another concerned Ga,

TABLE I

Sources of Thermodynamic Data

Species[a]	Source
Fe, Ni, Co, Pd, Mo, Cu, Ga, Ge, Zn, Sb, As	Hultgren et al. (1973)
Fe_2SiO_4, $FeSiO_3$	Robie and Waldbaum (1968); Larimer (1968)
FeS, CuS, ZnS	Robie and Waldbaum (1968)
GaO(g), GaCl(g), GaBr(g), GaH(g), GeS(g), GeO(g), $GeCl_4$(g), $GeBr_2$(g), $GeBr_4$(g), GeI_2(g), GeI_4(g), Sb(g), Sb_2(g), Sb_4(g), $SbCl_3$(g), $SbCl_5$(g), SbH_3(g), $SbBr_3$(g), As(g), As_2(g), As_4(g), As_4O_6(g), AsH_3(g), AsF_3(g), $AsCl_3$(g), $AsBr_3$(g), AsN(g)	Wagman et al. (1968)
GaOH(g)	Battat et al. (1974)
SbS(g)	Mills (1974)
ZnS, $ZnSiO_3$, Zn_2SiO_4	Robie and Waldbaum (1968); Wagman et al. (1968); Barin and Knacke (1973)

[a] Solid unless otherwise stated.

Ge, Sb, Zn, and perhaps to a small extent As. Both processes involve differences between the groups, and will be considered here. The third, commonly interpreted to be some kind of melting event, was responsible for elemental fractionations within the groups.

Ni-Like Elements

Cobalt and palladium resemble nickel in showing small intergroup variations. The elements are not volatile, but condense ahead of, or simultaneously with, iron–nickel alloy. Their variation between the groups is almost certainly due to the same processes as those for Ni; namely, sulfuration and oxidation (Kelly and Larimer, 1977; Sears, 1978a). By way of example, a plot of the Ni content of the metal as a function of temperature is given in Fig. 1. The observed Ni contents of iron meteorites are produced at high temperatures, during condensation of iron–nickel alloy, and at low temperatures (600–750°K), during oxidation and sulfuration. For the reasons elaborated earlier—mainly the implausibility of the large γ(Ge) and γ(Ga) required by a high-temperature formation and the abundance

of sulfur in iron meteorites—it is the second process which is relevant here (Sears, 1978a). It is suggested that the intergroup fractionations shown by Co, Pd, and Mo are due to the same mechanisms.

According to the factor analysis copper also belongs in this group of elements although, unlike the others, it is quite volatile in the primordial solar nebula. Its condensation curves are given in Fig. 2. In calculating them I considered both the condensation of Cu in solid solution in the metal, and the formation of CuS and its solid solution in FeS, but found that copper condensed almost entirely by the former process. At all pressures of interest here, and in the temperature region 600–750°K, it is fully condensed.

Ga- and Ge-Like Elements

Gallium and germanium were discussed at length in an earlier paper and are mentioned only briefly here.

Germanium. At all pressures and temperatures considered, GeS(g) is the stable gas phase. However, Ge does not condense as GeS in solid solution in FeS, but as Ge in the metal. The solution is very much

TABLE II

Composition of the Four Major Iron Meteorite Groups[a]

Element	IAB			IIAB			IIIAB			IVA			COSMIC[b]
	Mean	Std. dev.	No.	Mean	Std. dev.	No.	Mean	Std. dev.	No.	Mean	Std. dev.	No.	
Ni	7.69	2.14	107	5.64	0.293	61	8.29	0.79	159	8.28	0.73	41	5.47
Ga	76.6	15.1	107	58.4	3.8	61	19.7	1.4	159	2.13	0.20	41	54.7
Ge	308	87	107	172	20	61	38.8	4.3	159	0.122	0.02	41	131
Cu	161	88	23	136	28	22	155	28	43	145	25	19	615
Au	1.58	0.28	20	0.78	0.29	13	1.05	0.61	25	1.98	2.08	14	0.230
As	13.3	4.0	16	5.4	2.2	10	7.8	4.2	17	6.9	4.19	11	7.52
Sb	0.36	0.08	11	0.068	0.028	8	0.11	0.08	13	0.016	0.004	8	0.36
Zn	26	11	13	<1	—	6	3.6	2.3	12	<7.07	—	9	1417
Co	0.47	0.04	27	0.46	0.03	25	0.51	4.8	58	0.40	0.03	16	0.25
Pd	4.1	0.6	14	2.2	1.3	14	3.58	1.5	20	4.62	1.26	12	1.48
Mo	7.0	1.1	12	6.8	0.8	8	7.2	0.9	13	6.0	1.1	7	4.56

[a] Ni and Co as percentages; the others are in parts per million. References: Bauer and Schaudy (1970)—Au, Cu; Chakraburthy et al. (1964)—Pd; Cobb (1967)—Au, Cu; Crocket (1972)—Au; Fouché and Smales (1966)—Au; Goldberg et al. (1951)—Au, Co, Pd; Hara and Sandell (1960)—Mo; Herpers et al. (1969)—Cu, Co; Lewis and Moore (1971)—Co; Lovering et al. (1957)—Cu, Co; Moore et al. (1968)—Cu; Murthy (1963)—Cu; Nichiporuk and Brown (1965)—Zn, Pd, Mo; Nishimura and Sandell (1964)—Zn; Rosman and DeLaeter (1974)—Zn; Sen Gupta (1968)—Pd; Sen Gupta and Beamish (1963)—Pd; Smales et al. (1967)—Cu, As, Sb, Zn, Pd, Mo; Tanner and Ehmann (1967)—Sb; Wasson (1974)—Ni, Ga, Ge; Wetherill (1964)—Co, Mo; Wiik and Mason (1965)—Co.

[b] Defined by A(E)/(A(Fe) + A(Ni)), where A(E), A(Fe), and A(Ni) refer to the cosmic abundances given by Cameron (1973) and expressed as a percentage or in parts per million as appropriate.
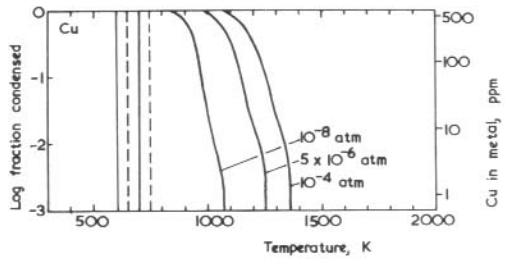
FIG. 2. Condensation curves for copper. The solid vertical lines enclose the temperature range in which IAB, IIAB, and IVA Ni contents are observed, and the broken lines enclose the temperature regions in which group IIAB formed. At all pressures of interest here, copper, like nickel, was fully condensed over this temperature range. The intergroup variations in its abundance are thought to be due to the same processes as those responsible for the Ni variations (Fig. 1).

in the cooling solar nebula. At high pressures it condenses as ZnS. If one assumes an ideal solution between ZnS and FeS, then at moderate pressures it condenses as ZnS in solid solution in FeS. A certain amount dissolves in the metal as Zn. The result is that the Zn content of the metal increases as the temperature drops, until ZnS forms. Then it drops slowly until 695°K. At this temperature FeS forms and rapidly consumes the Zn as ZnS in solid solution. The maximum levels of Zn in the metal are highest at high pressures. I have also calculated the amount of $ZnSiO_3$ which forms at low temperatures, but it never becomes significant. Wai and Wasson (1977) argued that the activity coefficient of ZnS in FeS was $10^{3\pm1}$. In this case, the Zn is present as pure ZnS and as a solid solution of

nonideal, much more gas goes into solution than Henry's law predicts and this is reflected in the activity coefficient being very much less than one. It is probably of the order of 10^{-2}, but its precise value is unimportant for the present model.

Gallium. Gallium also forms a nonideal solution; its activity coefficient is probably somewhere near 10^{-1}, but again it is unimportant. Gallium shows complex behavior in the nebula (Fig. 4b). At the time of metal condensation, GaOH(g) is the most important gas phase, while over the temperature at which I believe accretion took place it is GaCl(g). Condensation curves for Ge and Ga are shown in Figs. 3 and 4a, respectively.

Zinc. Zinc also shows complex behavior

FIG. 3. Condensation curves for germanium. The vertical lines are described in the figure caption to Fig. 2. The right-hand sacle is approximate, and has been calculated from $x = A(Ge)/(A(Ni) + A(Fe))$, where x is the fraction condensed and A is the cosmic abundance of the element in question.
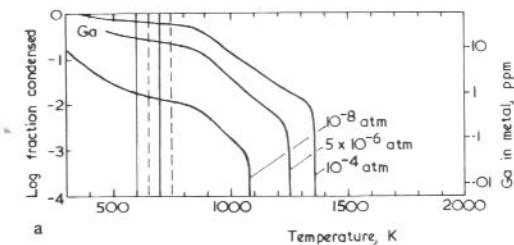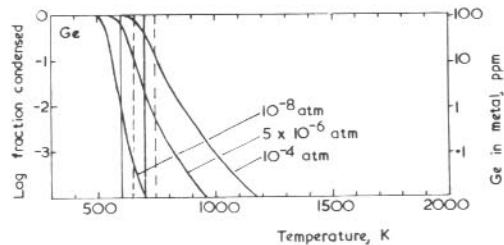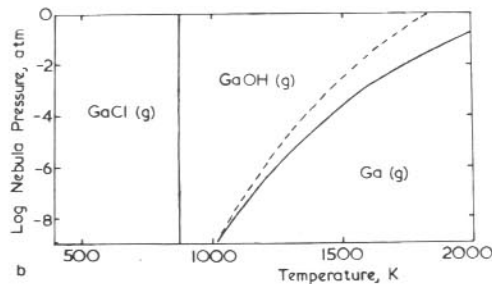

FIG. 4. (a) Condensation curves for gallium. See the figure captions for Figs. 2 and 3 for an explanation of the vertical lines and the right-hand scale. The curves have two inflections. The first is caused by a certain amount of the Ga being present in the metal when it condenses, and the second is when GaOH(g) gives way to GaCl(g) as the dominent gas species of Ga. (b) Stability fields for gallium and its compounds in the primordial solar nebula. The dotted curve indicates the condensation temperature of iron–nickel alloy.
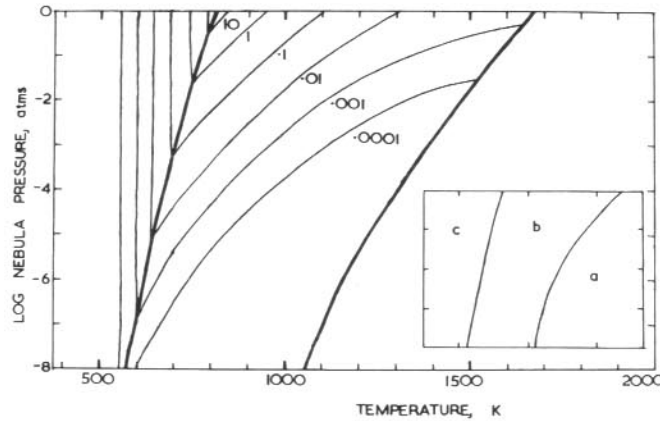
FIG. 5. Concentration of zinc in the metal (in parts per million). The pressure–temperature fields are shown in the inset figure. These are: (a) no metal condensed, (b) Zn forms solid solution in the metal, and (c) pure ZnS forms. This assumes no ZnS dissolves in FeS. Should it do so, the curves below 695°K require minor adjustment.

Zn in metal. It also spends slightly longer in the metal before reacting to form ZnS (Fig. 5).

Antimony. Antimony exists as mona-tomic, diatomic, and tetratomic species in the gas. I included data for $SbCl_3$, $SbCl_5$, $SbBr_3$, SbS, and SbO gases (Fig. 6). Wai and Wasson (1977) point out, ther-modynamic data for a number of potentially important species are not available and it may be that the condensation curves will have to be displaced to the left. I have explored the possibility that Sb may be-come lithophile or chalcophile and transfer to the silicates or FeS, but this does not seem likely.

Arsenic. Arsenic also exists in the nebula gases as the monomer, dimer, and tetramer,

depending on pressure and temperature (Fig. 7). The calculations included As_4O_6, AsH_3, AsF_3, $AsCl_3$, $AsBr_3$, and AsN gases, and again there are potentially important species which could not be included. The condensation curves are shown for an ideal solution, whereas Wai and Wasson (1977) have suggested that a value of 0.1 is more reasonable. This moves the curves to higher temperatures by about 100°K, but the con-clusion that As is fully condensed between 600 and 750°K is unchanged.

DISCUSSION

Comparison between Calculations and Observations

Factor analysis sorted the elements into four groups on the basis of their mutual cor-

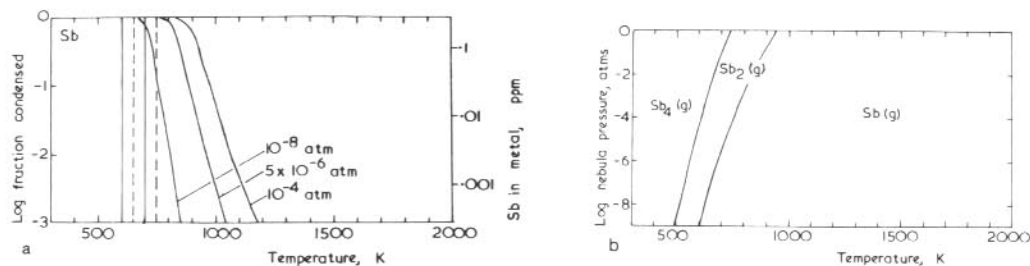
FIG. 6. (a) Condensation curves for antimony. The slight inflection is caused by $Sb_2(g)$ becoming the stable gas phase for Sb. See also the figure captions for Figs. 2 and 3. (b) Stability fields for Sb species in the primordial solar nebula.
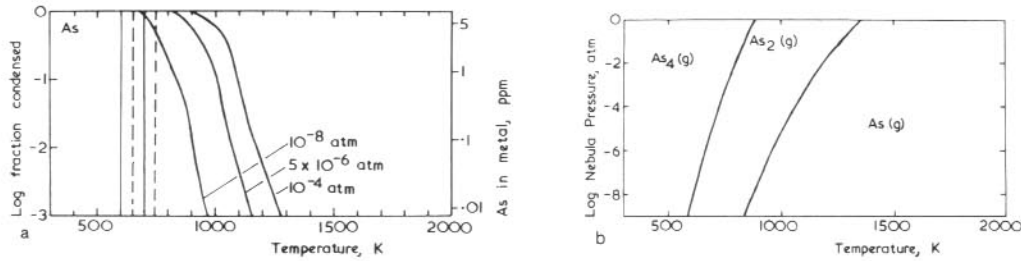
FIG. 7. (a) Condensation curves for arsenic. See also the figure captions for Figs. 2 and 3. (b) Stability fields for As species in the primordial solar nebula.

relations in abundance. These were:

Factor A: Ga, Ge, Sb, and Zn

Factor B: Ni, Pd, Co, and Cu

Factor C: Ir, Au, Os, Ru, Re, Pt, As, and Cr

Factor D: Mo

For reasons elaborated in Sears (1979)—mainly a significant correlation with Cu—Mo probably belongs with factor B elements. Of course, it would be naive to believe that each element was affected by only one process. Indeed, the factor analysis indicates that As has a small contribution from factor A and that within the groups factor C has affected virtually all elements. But it does identify the *major* process as far as each element is concerned. From the interpretations offered by Scott (1972), Kelly and Larimer (1977), Sears (1978a), and Wai *et al.* (1978), we can identify factor A with nebula condensation processes, factor B (and possibly D) with oxidation and sulfuration, and factor C with some melting event (fractional crystallization or partial melting).

The factor B elements have small intergroup variations which, in the case of Ni, have become important parameters in the classification of iron meteorites. We have shown that the appropriate Ni contents can be found by accretion between 600 and 750°K (Sears, 1978a), and, since the major process is the oxidation of Fe, similar variations are predicted for the other elements. Generally these are observed. The histogram for Co contents cannot be distinguished

from that for Ni, the only "anomaly" being that the Co/Ni ratio in IIAB irons exceeds that of the cosmic ratio by about 30%. In contrast, the Pd/Ni ratio in group IIAB is lower than that of the cosmic value by about 30%. Kelly and Larimer (1977) suggested that this was because 30% of the Ni was present in the meteorite parent body as phosphide. This would explain the high Co, but not the low Pd. In any case, below 800°K phosphide is oxidized to phosphate, unless the IIAB parent body formed in a gas of noncosmic composition. One possibility, mentioned earlier, is that the factor B elements do not oxidize at the same rates. This would explain the observations if one assumes Ni is more noble than Co, but less noble than Pd. A detailed study of the oxidation processes would seem to be required, but sufficiently good thermodynamic data for Ni_2SiO_4, Co_2SiO_4, and Pd_2SiO_4 are apparently not available.

Copper is well below its cosmic proportions in all groups. Despite this, its intergroup variations are very similar to nickel's and hence its placement with the factor B elements. I therefore interpret its variations as an oxidation–sulfuration effect. The reason for its low abundance, compard to $C1$ chondrites, is most probably a sampling effect and Wai and Wasson (1979) have suggested that its values should be raised by a factor of 3.5 to allow for this effect. (A factor of 5 would bring the IAB values to somewhere near cosmic.) Copper occurs both as metallic Cu associated with sulfides

(El Goresy, 1965) and as Cu sulfides which concentrate in macroscopic and sparsely distributed inclusions. These are difficult to sample in a representative way for chemical analysis. Nevertheless, a sufficient amount is present in microscopic form for Scott (1972) and the factor analysis to have been able to characterize the intergroup variations.

An essential feature of the present model is that oxidation and sulfuration in the manner described by Kelly and Larimer (1977) occurred in the solar nebula, simultaneously with accretion. Kelly and Larimer mentioned the possibility, without going into details, that it may have occurred in the meteorite parent body after accretion. My main reason for preferring nebular oxidation and sulfuration is that this seems to have been the case with the chondrites: ordinary chondrites show an inverse correlation between oxidation state and bulk Fe/Si ratio, while E chondrites show a correlation between sulfuration and bulk Fe/Si ratio (Table III). Variations in the Fe/Si ratio are generally assumed to have occurred in the nebula, by the separation of silicates and metal. The inverse correlation between Fe/Si and oxidation state is interpreted as being due to the change in oxidation state of the nebula during accretion (e.g., Anders, 1971; Müller et al., 1971). Similarly, the correlation between S/Si and Fe/Si in E chon-

drites is generally assumed to be the result of processes in the nebula; for example, Baedecker and Wasson (1975) suggest that some sulfide was removed with the metal, while Sears (1978b) suggested that the E chondrites accreted between 600 and 750°K—during sulfuration of the condensed iron. Since it seems that these two major chondrite classes had their present state of oxidation or sulfuration fixed in the nebula—despite subsequent metamorphic heating to perhaps 1200°C (Sears, 1978c)—it seems simplest to assume the iron meteorites did likewise.

I will now examine the abundance of the elements whose distribution we believe to have been fixed during condensation and accretion between 600 and 750°K (Ga, Ge, Zn, Sb, and perhaps As). Superimposed on the condensation curves (Figs. 2, 3, 4a, 6a, and 7a) are four vertical lines which refer to the temperature interval during which the metal has a Ni content appropriate to iron meteorites. (The solid lines correspond to IAB, IIIAB, and IVA and the broken lines to IIAB.) The width of the interval is governed by the range of Ni contents observed and the uncertainty in the thermodynamic data for the oxidation of iron. An important point is that the relative errors for IAB, IIAB, IIIAB, and IVA are much smaller, in fact $\pm 10°K$. (This amounts to saying that the shape of the curve below 700°K in Fig. 1 is better known than its position on the temperature axis. This is because it is governed by well-known thermodynamic principles.)

It has long been realized that Ga and Ge provide particularly valuable data on the genesis of iron meteorites (Goldberg et al., 1951; Lovering et al., 1957; Wasson, 1967). Different authors agree that the distribution of these elements is associated with their extreme volatility in the solar nebula, but differ over details. Kelly and Larimer (1977) propose that the low Ga and Ge groups accreted at higher temperatures than the others. This fails on closer inspection (Sears, 1978a). For example, if group IVA accreted

TABLE III

OXIDATION, SULFURATION, AND THE
METAL–SILICATE FRACTIONATION IN CHONDRITES
(Sears, 1978c)[a]

Class	Fe/Si	S/Si	Fe⁰/Si
Ordinary chondrites			
H	0.83	—	0.63
L	0.59	—	0.32
LL	0.53	—	0.08
E chondrites			
EI	1.00	0.31	—
EII	0.60	0.15	—

[a] Fe/Si reflects the extent of metal–silicate fractionation, and S/Si and Fe⁰/Si reflect the extent of sulfuration and the inverse of oxidation, respectively.

at a high enough temperature to give its Ga and Ge contents (approximately 10^{-2} and 10^{-4} times cosmic), the sulfur would not have condensed at all. According to Turkdogan et al. (1955), sulfur forms an ideal solution in iron. This being so, the calculated amount of S in solid solution in the metal does not exceed 10^{-6} mole%. This class is quite rich in sulfur; for example Gibeon contains macroscopic inclusions of FeS (see Fig. 3 in Schaudy et al., 1972). Other objections to a high-temperature origin for group IVA are as follows. (i) The same values for γ(Ge) and γ(Ga) could produce the observed Ge and Ga contents in group IVA as well as the other groups, suggesting they formed in the same temperature range. If these groups formed at the same pressure, but at different temperatures, they would require different values of one or both of γ(Ge) and γ(Ga). (ii) Unlike group IVB—which is believed to have formed from the first metal to condense—group IVA shows no refractory element enrichment and volatile element depletion.

Wai and Wasson (1979) favor the model Wasson and co-workers have developed for ordinary chondrites (Wasson and Chou, 1974; Wai and Wasson, 1977). This is based on the disputed observation that the extent of depletion for a given element in ordinary chondrites is inversely related to the temperature at which it condenses (Anders, 1977; Wasson, 1977). The model involves loss of a volatile-rich aerosol or gas–dust fractionation. At some temperature, below 700°K, the dust accreted to form the meteorite parent body. Thus group IVA suffered much gas–dust fractionation, whereas group IAB suffered none. This is the most disquieting aspect of such a model; why the extent of gas–dust fractionation—or whatever—varies between the groups. It also says nothing about the intergroup fractionation of Co, Pd, and Ni.

The model discussed by Sears (1978a) was that accretion between 600 and 750°K produces the observed Ga and Ge abundances by accretion at different pressures

(Figs. 3 and 4a). In a similar way, it explains the Zn distribution. It is well known that group IAB contains much Zn (Smales et al., 1967) and Rosman and DeLaeter (1974) pointed out that Zn and Ge had similar distributions over the groups as a whole—a conclusion borne out by the factor analysis. We see from Fig. 5 that group IAB, which we believe accreted at 10^{-4} atm, is predicted to have about 10^4 times the Zn content of a group accreting at 10^{-8} atm. We believe that group IVA was such a group. The analytical data are subject to the same difficulties as Cu, because it is also chalcophile—and again its distribution is better known that its absolute abundance. The Zn-rich IAB group has 26 ± 11 ppm Zn—one could perhaps multiply this by 85, bringing it up to cosmic proportions, to allow for the sampling problem. This compares with group IVA values which are generally less than 1 ppm. Group IIIAB are a factor of 10 lower than IAB, consistent with a pressure $\frac{1}{20}$ that required for group IAB.

The antimony and arsenic calculations are unsatisfactory because thermodynamic data for several potentially stable gas phases could not be found (Wai and Wasson, 1977). Even so, within the uncertainty of the data it also seems likely that their distribution can be explained by the same mechanism. From Fig. 6 we predict that group IVA should have 10% of the Sb content of the other groups. In fact, this group has a depletion in Sb of about 10^{-2}, whereas IIAB and IIIAB are similar at a 10^{-1} depletion and IAB has cosmic abundances. A displacement of the condensation curves 50°K or so to lower temperatures would suffice; slightly more would be required if Wai and Wasson's (1979) estimated activity coefficient of 0.2 was adopted. The small intergroup difference in As can be explained in a similar way.

To summarize this section, the model presented by Sears (1978a) is thought to be the simplest published and explains most readily the intergroup element distributions observed in iron meteorites. It considers

oxidation and sulfuration nebula processes which occurred simultaneously with accretion, and that the volatile trace element and minor element distributions are the result of very large pressure differences in the regions where the iron meteorite parent bodies accreted. These pressures were 10^{-4} atm for IAB and IIAB, 5×10^{-6} atm for group IIIAB, and 10^{-8} atm for group IVA.

Implications of the Present Model for an Origin in the Asteroid Belt

It is of considerable interest to see how this conclusion relates to existing ideas on conditions in the early solar system. Figure 8 shows how the pressure varies as a function of distance from the Sun according to the models of Cameron and Pine (1973) and Lewis (1974)—the "low" and "very low" adiabats—and Camerson (1978). The "very low" adiabat predicts that all iron meteorites formed beyond the orbit of Jupiter and, since there are data which show that at least one iron meteorite parent body formed in the asteroid belt, we can reject this adiabat. The data in question are (i) the orbital studies of Wetherill (e.g., 1976), which show that the exposure ages of iron meteorites

are comparable with the lifetime expected for Mars-crossing asteroids to reach Earth, and (ii) the reflectivity spectra reviewed by Chapman (1976), which show that some asteroids have surfaces resembling iron meteorites. The "low adiabat" and the curve of Cameron (1978) lead to broadly the same conclusions; that groups IAB formed near the orbits of Venus and Earth, that group IIIAB formed in the asteroid belt, and that group IVA formed at or beyond the orbit of Saturn. The existence of the satellites of the major planets and Pluto and the discovery of Chiron already suggest that small bodies could readily form in the outer solar system.

These arguments assume that the iron meteorite parent bodies formed by the accretion of dust, under the ambient nebula pressure—this being governed primarily by distance from the Sun. Another possibility is that they formed inside protoplanets of the kind described by Cameron (1978), at pressures governed by the size and state of evolution of the protoplanet. On the strength of existing calculations this seems an unlikely scenario. First, the protoplanet, or its planetary-sized core, would require
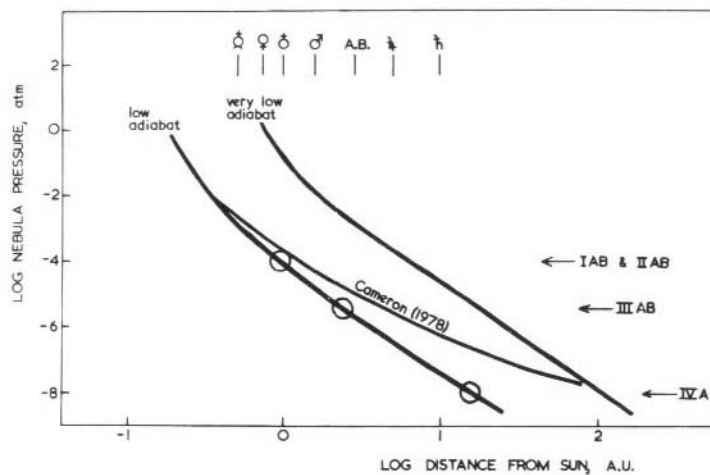

FIG. 8. Pressure–distance profiles in the primordial solar nebula calculated by Cameron (1978). and earlier versions based on the work of Cameron and Pine (1973) and Lewis (1974)—the "low" and "very low" adiatbat. The Cameron (1978) and "low" adiabat curves provide pressures suitable for the formation of group IAB and IIAB in the Venus–Earth vicinity of the solar system, group IIIAB in or near the asteroid belt, and group IVA in the outer solar system.

very large escape velocities for the meteorite parent bodies. These would correspond to an energetic event capable of causing considerable melting; one might imagine the meteorites would be converted to something resembling tektites. This means that they would have to have been ejected from the protoplanets of the terrestrial planets during the event which stripped off the gaseous envelope. Again such an event would surely lead to a major alteration of the meteorite parent bodies. There are also problems concerning the protoplanets themselves. First, tidal disruption prevents protoplanets from forming nearer the Sun than Jupiter's orbit, and second, protoplanet models do not explain the heavy metal excess in the major planets (DeCampli and Cameron, 1979). Subsequent developments may overcome these problems, but for the moment it seems more reasonable to assume that meteorite parent bodies formed by the accretion of dust as envisaged above.

CONCLUSIONS

The condensation and related calculations are most consistent with the formation of iron meteorite parent bodies at a temperature between 600 and 750°K, but over a very wide range of pressures; 10^{-4} atm for groups IAB and IIAB, 5×10^{-6} atm for group IIIAB, and 10^{-8} atm for group IVA. The pressures, and the range of pressures, required by this model are consistent with existing models for the origin of the planets, but suggest that not all iron meteorites formed in the asteroid belt.

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Note added in proof: There is an error in my Sb calculations. Below ~1000°K SbS(g) is the stable gas phase of Sb and the construction curves in Fig. 6(a) should be displaced downwards by 50–100°K [depend-

ing on the assumed γ(Sb)], bringing the predictions of my model more closely into line with the observed Sb distribution.

REFERENCES

ANDERS, E. (1971). Meteorites and the early solar system. *Ann. Rev. Astron. Astrophys.* **9**, 1–34.

ANDERS, E. (1977). Critique of "Nebular condensation of moderately volatile elements and their abundances in ordinary chondrites" by Chien M. Wai and John T. Wasson. *Earth Planet. Sci. Lett.* **36**, 14–20.

BAEDECKER, P. A., AND WASSON, J. T. (1975). Elemental fractionations among enstatite chondrites. *Geochim. Cosmochim. Acta* **39**, 735–764.

BARIN, I., AND KNACKE, O. (1973). *Thermochemical Properties of Inorganic Substances,* Springer-Verlag, New York/Berlin.

BATTAT, D., FAKTOR, M. M., GARRETT, I., AND MOSS, R. H. (1974). Modified entrainment method for measuring vapour pressures and heterogeneous equilibrium constants, 2. Equilibria in the water/gallium system. *J. Chem. Soc. Faraday* **1**, 2280–2292.

BAUER, R., AND SCHAUDY, R. (1970). Activation analytical determination of elements in meteorites, 3. Determination of manganese, sodium, gallium, germanium, copper and gold in 21 iron meteorites and 2 mesosiderites. *Chem. Geol.* **6**, 119–131.

CAMERON, A. G. W. (1973). Abundances of the elements on the solar system. *Icarus* **15**, 121–146.

CAMERON, A. G. W. (1978). Physics of the primitive solar accretion disk. *The Moon and the Planets* **18**, 5–40.

CAMERON, A. G. W., AND PINE, M. R. (1973). Numerical models of the primitive solar nebula. *Icarus* **18**, 377–406.

CHAKRABURTHY, A. K., STEVENS, C. M., RUSHING, H. G., AND ANDERS, E. (1964). Isotopic composition of silver in iron meteorites. *J. Geophys. Res.* **69**, 505–520.

CHAPMAN, C. R. (1976). Asteroids as meteorite parent-bodies: The astronomical perspective. *Geochim. Cosmochim. Acta* **40**, 701–719.

COBB, J. C. (1967). A trace element study of iron meteorites. *J. Geophys. Res.* **72**, 1329–1341.

CROCKET, J. H. (1972). Some aspects of the geochemistry of Ru, Os, Ir, and Pt in iron meteorites. *Geochim. Cosmochim. Acta* **36**, 517–535.

DeCAMPLI, W. M., AND CAMERON, A. G. W. (1979). Structure and evolution of isolated giant gaseous protoplanets. Preprint.

EL GORESY, A. (1965). Mineralbestand und Strukturen der Graphit- und Sulfideinschlüsse in Eissenmeteoriten. *Geochim. Cosmochim. Acta* **29**, 1131–1151.

FOUCHÉ, K. F., AND SMALES, A. A. (1966). The distribution of gold and rhenium in iron meteorites. *Chem. Geol.* **1**, 329–339.

GOLDBERG, E., UCHIYAMA, A., AND BROWN, H. (1951). The distribution of nickel, cobalt, gallium, palladium and gold in iron meteorites. *Geochim. Cosmochim. Acta* **2**, 1–25.

GROSSMAN, L. (1972). Condensation in the primitive solar nebula. *Geochim. Cosmochim. Acta* **36**, 597–619.

HARA, T., AND SANDELL, E. B. (1960). Meteoritic abundance of ruthenium. *Geochim. Cosmochim. Acta* **21**, 145–150.

HERPERS, U., HERR, W., AND WÖLFLE, R. (1969). Evaluation of ^{53}Mn by (n,γ) activation, ^{26}Al and special trace elements in meteorites by γ-coincidence techniques. In *Meteorite Research* (P. M. Millman, Ed.), pp 387–396. Reidel, Derdrecht.

HULTGREN, R., DESAI, P. D., HAWKINS, D. T., GLEISER, M., KELLEY, K. K., AND WAGMAN, D. D. (1973). *Selected Values of Thermodynamic Properties of the Elements.* Ameri. Soc. for Metals, Metals Park, Ohio.

KELLY, W. R., AND LARIMER, J. W. (1977). Chemical fractionations in meteorites, VIII. Iron meteorites and the cosmochemical history of the metal phase. *Geochim. Cosmochim. Acta* **41**, 93–111.

LARIMER, J. W. (1968). Experimental studies in the system Fe-MgO-SiO$_2$-O$_2$ and their bearing on the petrology of chondritic meteorites. *Geochim. Cosmochim. Acta* **32**, 1187–1207.

LARIMER, J. W. (1973). Chemical fractionations in meteorites, VII. Cosmothermometry and cosmobarometry. *Geochim. Cosmochim. Acta* **37**, 1603–1623.

LEWIS, J. S. (1974). Temperature gradient in the solar nebula. *Science* **186**, 440–443.

LEWIS, C. F., AND MOORE, C. B. (1971). Chemical analysis of thirty-eight iron meteorites. *Meteoritics* **6**, 195–206.

LORD, H. C. (1965). Molecular equilibria and condensation in a solar nebula and cool stellar atmospheres. *Icarus* **4**, 279–288.

LOVERING, J. F., NICHIPORUK, W., CHODOS, A., AND BROWN, H. (1957). The distribution of gallium, germanium, cobalt, chromium and copper in iron and stony-iron meteorites in relation to nickel content and structure. *Geochim. Cosmochim. Acta* **11**, 263–278.

MILLS, K. C. (1974). *Thermodynamic Data for Inorganic Sulphides, Selenides and Tellurides,* Butterworth, London.

MOORE, C. B., LEWIS, C. F., AND NAVA, D. (1968). Superior analyses of iron meteorites. In *Meteorite Research* (P. M. Millman, Ed.), pp. 387–396. Reidel, Dordrecht.

MÜLLER, O., BAEDECKER, P. A., AND WASSON, J. T. (1971). Relationship between siderophilic-element content and oxidation state of ordinary chrondrites. *Geochim. Cosmochim. Acta* **35**, 1121–1137.

MURTHY, V. R. (1963). Elemental and isotopic abundances of molybdenum in some meteorites. *Geochim. Cosmochim. Acta* **27**, 1171–1178.

NICHIPORUK, W., AND BROWN, H. (1965). The distribution of platinum and palladium in metal in iron meteorites and the metal phase of ordinary chondrites. *J. Geophys. Res.* **70**, 459–470.

NISHIMURA, M., AND SANDELL, E. B. (1964). Zinc in meteorites. *Geochim. Cosmochim. Acta* **28**, 1055–1079.

ROBIE, R. A., AND WALDBAUM, D. R. (1968). Thermodynamic properties of minerals and related substances at 298·15 K and one atmosphere pressure and at higher temperatures. *U.S. Geol. Surv. Bull.* 1259.

ROSMAN, K. J. R., AND DeLAETER, J. R. (1974). The abundance of cadmium and zinc in meteorites. *Geochim. Cosmochim. Acta* **38**, 1665–1677.

SCHAUDY, R., WASSON, J. T., AND BUCHWALD, V. F. (1972). The chemical classification of iron meteorites—VI. A reinvestigation of irons with Ge concentrations lower than 1 ppm. *Icarus* **17**, 174.

SCOTT, E. R. D. (1972). Chemical fractionation in iron meteorites and its interpretation. *Geochim. Cosmochim. Acta* **36**, 1205–1236.

SCOTT, E. R. D. (1978). Primary fractionation of elements among iron meteorites. *Geochim. Cosmochim. Acta* **42**, 1447–1458.

SCOTT, E. R. D., AND WASSON, J. T. (1975). Classification and properties of iron meteorites. *Rev. Geophys. Space Phys.* **13**, 527–546.

SEARS, D. W. (1978a). Condensation and the composition of iron meteorites. *Earth Planet. Sci. Lett.* **41**, 128–138.

SEARS, D. W. (1978b). Formation of E chondrites. Paper presented at the 41st Annual Meeting of the Meteoritical Society, Sudbury, Ontario.

SEARS, D. W. (1978c). *The Nature and Origin of Meteorites,* Adam Hilger, Bristol.

SEARS, D. W. (1979). Composition of iron meteorites; a study by factor analysis. *Meteoritics* **14**, (3) (in press).

SEN GUPTA, J. C. (1968). Abundances of the six platinum metals in some iron and stony meteorites: Relationships of the theories of evolution of parent bodies of meteorites and the origin of these elements. *Chem. Geol.* **3**, 293–305.

SEN GUPTA, J. G., AND BEAMISH, F. E. (1963). The determination of the platinum metals in siderite meteorites. *Amer. Mineral.* **48**, 379–389.

SMALES, A. A., MAPPER, D., AND FOUCHE, K. F. (1967). The distribution of some trace elements in iron meteorites, as determined by neutron activation. *Geochim. Cosmochim. Acta* **31**, 673–720.

TANNER, J. T., AND EHMANN, W. D. (1967). The abundances of antimony in meteorites, tektites and rocks by neutron activation analysis. *Geochim. Cosmochim. Acta* **31**, 2007–2026.

TURKDOGAN, E. T., IGNATOWTOWICZ, S., AND PEARSON, J. (1955). The solubility of sulphur in iron and iron–magnesium alloys. *J. Iron Steel Inst.* **180**, 349–354.

UREY, H. C. (1952). *The Planets,* Yale Univ. Press, New Haven, Conn.

WAGMAN, D. D., EVANS, W. H., PARKER, V. B., HALOW, I., BAILEY, S. M., AND SCHUMM, R. H. (1968). Selected values of chemical thermodynamic data properties. *Natl. Bur. Stand. Tech. Notes* 240–3, 4, 5.

WAI, C. M., AND WASSON, J. T. (1977). Nebular condensation of moderately volatile elements and their abundances in ordinary chondrites. *Earth Planet. Sci. Lett.* **36**, 1–13.

WAI, C. M., AND WASSON, J. T. (1979). Nebular condensation of moderately volatile siderophile elements and the formation of iron meteorite groups. Preprint.

WAI, C. M., WASSON, J. T., WILLIS, J., AND KRACHER, A. (1978). Nebular condensation of moderately volatile elements, their abundance in iron meteorites, and their quantization of Ge and Ga abundances. *Abstracts of papers presented at the Ninth Lunar Sci. Conf.*

WASSON, J. T. (1967). The chemical classification of iron meteorites: I. A study of iron meteorites with low concentrations of gallium and germanium. *Icarus* **31**, 161–180.

WASSON, J. T. (1974). *Meteorites—Their Classification and Properties,* Springer-Verlag, New York/Berlin.

WASSON, J. T. (1977). Reply to Edward Anders: A discussion of alternative models for explaining the distribution of moderately volatile elements in ordinary chondrites. *Earth Planet. Sci. Lett.* **36**, 21–28.

WASSON, J. T., AND CHOU, C. -L. (1974). Fractionation of moderately volatile elements in ordinary chondrites. *Meteoritics* **9**, 69–84.

WASSON, J. T., AND WAI, C. M. (1976). Explanation for the very low Ga and Ge concentrations in some iron meteorite groups. *Nature* **261**, 114–116.

WETHERILL, G. W. (1964). Isotopic composition and concentration of molybdenum in iron meteorites. *J. Geophys. Res.* **69**, 4403–4408.

WETHERILL, G. W. (1976). *Fragmentation of Asteroids and the Delivery of Fragments to Earth.* Paper presented at the I.A.U. Colloquium, Lyon, France.

WIIK, H. B., AND MASON, B. (1965). Analysis of eight iron meteorites. *Geochim. Cosmochim. Acta* **29**, 1003–1005.

ADDENDUM

The Sb calculations shown in Fig. 6 are correct using the data of Mills (1974) for SbS(g). More recent and superior data for SbS(g) have been brought to my attention by Bruce Fegley and John Wasson (Faure et al., High Temperature Science, 4, 181, 1972). These data, for an activity coefficient of 10^{-1}, yield the results shown in the revised Fig. 6.

Top panel: y-axis "Log Nebula Pressure, atm" with values 0, -2, -4, -6, -8; x-axis 400, 800, 1200, 1600. Regions labeled Sb_4, SbS, Sb.

Bottom panel: y-axis "Fraction Condensed" with values 0·1, 0·01, 0·001; x-axis "Temperature (K)" 400, 800, 1200, 1600. Curves labeled 10^{-4} atm, 5×10^{-6} atm, 10^{-8} atm.