CHEMICAL CONDENSATION SEQUENCES IN SUPERNOVA EJECTA*

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(Received in final form 19 May, 1978)

Abstract. The mineralogical composition of grains produced in supernova ejecta is explored via chemical equilibrium condensation computations. These calculations are carried out for chemical compositions characteristic of each of several supernova zones, taking into account the pressure decrease due to adiabatic expansion and condensation. The distributions of the major elements among the various gaseous species and solid phases are graphically displayed. These computations reveal that many of the major condensates from supernova ejecta are also stable against evaporation in a gas of solar composition at high temperatures. This is especially true for minerals containing the elements O, Mg, Al, Si, Ca, Fe and Ti. Grains which form in supernova ejecta are less likely to become homogenized with solar nebular gas than SN gas and are thus potential sources of exotic isotopic compositions in the early solar system. The calculated elemental distributions of supernova condensates are applied to problems concerning isotopic anomalies and large mass-dependent isotopic fractionations discovered in the meteorite Allende. The order in which the major elements become totally condensed is found to be nearly independent of the supernova zone considered, being the same as that for a solar gas. The consequence of this may be that some of the observed depletions of heavy elements in the interstellar gas are due to supernova-produced dust.

1. Introduction

The idea that one or more supernovae (SN) were the sources of some, if not all, of the isotopic anomalies discovered in Ca-rich inclusions in Allende (R. Clayton *et al.* 1973; Lee *et al.*, 1976, 1978; McCulloch and Wasserburg, 1978) and in other meteorites (Reynolds and Turner, 1964; Black, 1972) has been proposed by several authors (e.g., Black, 1972; R. Clayton *et al.*, 1973; D. Clayton, 1975; Lee *et al.*, 1976; Sabu and Manuel, 1976; Cameron and Truran, 1977; Lattimer, Schramm and Grossman, 1978 hereafter LSG)). The suggestion that incorporation of isotopically exotic presolar condensates from supernovae is responsible for the ^{16}O anomaly in Allende inclusions was first published by R. Clayton *et al.* (1973). In addition, some aspects of recent experimental studies (R. Clayton and Mayeda, 1977; Wasserburg *et al.*, 1977) suggest that anomalies in O and Mg may be due to condensation of the inclusions from a mixture of solar and isotopically different SN gas. The mineralogical composition of isotopically

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[*] Paper presented at the Conference on Protostars and Planets, held at the Planetary Science Institute, University of Arizona, Tucson, Arizona, between January 3 and 7, 1978.

The Moon and the Planets 19 (1978) 169–184.

anomalous grains depends on the chemical composition of the gas in which they form, and thus on whether these grains condensed from a pure SN gas or a mixture of solar and SN gas. A first step in sorting our the relevant processes is to investigate equilibrium condensation for compositions and pressures representative of SN ejecta, and to compare these results with those obtained for the solar nebula. Conclusions may then be drawn regarding the consistency of the SN grain hypothesis in explaining isotopic anomalies.

Lattimer *et al.* (1978) investigated in detail the condensation sequences obtained in both the solar and supernova cases. However, condensation sequences alone are insufficient for estimating quantitatively the magnitudes of chemical fractionations and mass-dependent isotopic fractionations that might occur in gases of these compositions. It is also necessary to know the distribution of the elements among the various gaseous species and solid phases. In this paper we present such information for solar and SN shell condensation sequences similar to those computed by LSG. We then discuss the application of these data to problems concerning the observed mass fractionations in Allende of Si, Mg and O, and to the strong depletions of heavy element abundances in the interstellar medium.

2. Calculations

Presupernova stars are thought to consist of concentric spherical shells, containing unburned fuel in the outermost zone and products of static, H, He, C, O and Si burning in progressively deeper interior zones. Each layer is the result of the successive burning stages in the star's history. The detonation of the supernova causes the ejection and possible explosive burning of the matter in these layers, resulting in zones that LSG referred to as the (H), (He), (C), (O), (Si) and neutron zones, respectively. For example, the static He zone becomes the explosive (C) zone in this terminology. The relative number abundances assumed by LSG for the 12 most abundant elements excluding noble gases in the solar case and of all zones but the (Si) and neutron zones are listed in Figures 1–8. The composition of the (Si) zone is listed in Table V. Because of the possibility of variable C/O ratios in the presolar nebula and in some SN zones, two C/O ratios were used in these cases. Since these sequences depend only on whether this ratio is greater or less than 1, just two values were considered. Two values of the (S + Si)/O ratio in the (O) zone were considered for similar reasons.

The major features of these assumed abundances are: the (H) and (He) abundances are similar, except for variations in the N content, and smaller variations in the He abundance. Since He is inert and N is nearly so, LSG treated these zones as identical. The major difference between these and the solar cases is the absence of H in these zones. During explosive carbon burning only elements lighter than Si are synthesized, so that heavier elements remain in solar proportion to one another. Calculations show (Pardo *et al.*, 1974) that C, O, Al, Mg and Na are the major products of explosive C burning and their abundances are thus enhanced relative to those of heavier elements relative to solar abundances. These 5 elements remain in solar proportion relative to each other. The work of Woosley *et al.* (1973) was used to find the abundances in the (O) and (Si) zones. In the former zone, elements heavier than Ca are not synthesized, while C is completely burned and Al, Mg and Na are heavily depleted relative to the (C) zone. The (Si) zone is composed predominantly of iron peak elements in roughly solar proportion to each other, but small amounts of Ca, S and Si remain. Lighter elements are not present.

The method of calculating equilibrium condensation sequences used by LSG involved solving mass balance equations for each element and mass-action equations for each gaseous species at successively lower temperatures for a given initial total pressure. At each temperature interval, solutions were checked for the appearance of solid phases, and a mass-action equation was added for each new condensate. The pressure decrease due to adiabatic expansion, molecule formation and condensation was taken into account. A $\gamma = 5/3$ expansion for each SN zone was used, while no expansion was assumed for the solar cases. LSG investigated SN sequences at initial pressures of 10^{-4} and 10^{-12} atm and showed that equilibrium sequences are not very sensitive to large pressure changes. Thus we choose an intermediate case of 10^{-8} atm for the calculations reported here.

Some minerals predicted in these sequences form solid solutions. We have considered here two of the most important ones – melilite [$Ca_2(Al_2, MgSi)SiO_7$] and a metallic Si-Fe alloy. Melitite was treated as an ideal solid solution, while the Si-Fe system was assumed to be non-ideal and was included only in the solar cases. Solutions of two components were treated as follows. When the phase condenses, mass-action equations for both end members are added to the system. For the ideal solutions, the activity for each end-member is set equal to its mole fraction in the solution. If the solution is non-ideal, the activity becomes the product of the mole fraction and an experimentally-determined activity coefficient. For the Si-Fe system, the data of Chipman and Baschwitz (1963) and Wooley and Elliott (1967) were used. Although these data actually refer to a liquid solution, the activity coefficients are close to those for solids (Baedecker and Wasson, 1975). We have taken liquid data because they appear to be much more accurate than data for solid solutions.

3. Results

Our results are displayed in Tables I–V and Figures 1–8. Each table contains three columns: the condensate, its condensation temperature and its disappearance temperature. Each figure shows the way each of 4 or 5 major elements are distributed among the various gaseous species and solid phases, as a function of temperature. Gases are indicated by the notation (*g*). For the SN cases (Figures 3–8), the pressure-temperature relation is also given. The calculations were, in general, only carried down to 700 K: the validity of chemical equilibrium becomes more tenuous as temperature decreases.

Table Ia and Figure 1 detail the normal solar sequence. Our results are nearly identical to those of Grossman (1972). Al and Ti are the most refractory elements, Al_2O_3 and $CaTiO_3$ being the first condensates. As Figure 1 shows, Al and Ti are completely condensed

TABLE I

Solar case ($P = 10^{-3}$ atm)

a. C/O = 0.55			b. C/O = 1.2		
Mineral	Condensation temperature	Dissappearance temperature	Mineral	Condensation temperature	Disappearance temperature
Al_2O_3	1743		TiC	1893	1025
$CaTiO_3$	1677	1409	SiC	1742	1154
melilite	1625	1438	C	1732	871
$MgAl_2$	1533	1391	Fe_3C	1463	1326
Fe-Si	1458		AlN	1396	1234
$CaMgSi_2O_6$	1438		CaS	1385	1040
Mg_2SiO_4	1433		Fe-Si	1326	
Ti_3O_5	1409	1274	Al_2O_3	1235	1229
$CaAl_2Si_2O_8$	1392	1068	$MgAl_2O_4$	1229	1077
$MgSiO_3$	1351		Mg_2SiO_4	1154	
Ti_4O_7	1274	1120	MgS	1131	1100
TiO_2	1120	774	$CaMgSi_2O_6$	1069	
Al_2SiO_5	1068		$CaAl_2Si_2O_8$	1057	1044
$NaAlSi_3O_8$	1028	780	$MgSiO_3$	1054	
$NaAlSi_2O_6$	780		Al_2SiO_5	1045	
$CaTiSiO_5$	774		TiN	1025	910
			$NaAlSi_3O_8$	961	780
			Ti_4O_7	910	862
			TiO_2	862	770
			$NaAlSi_2O_6$	780	
			$CaTiSiO_5$	770	

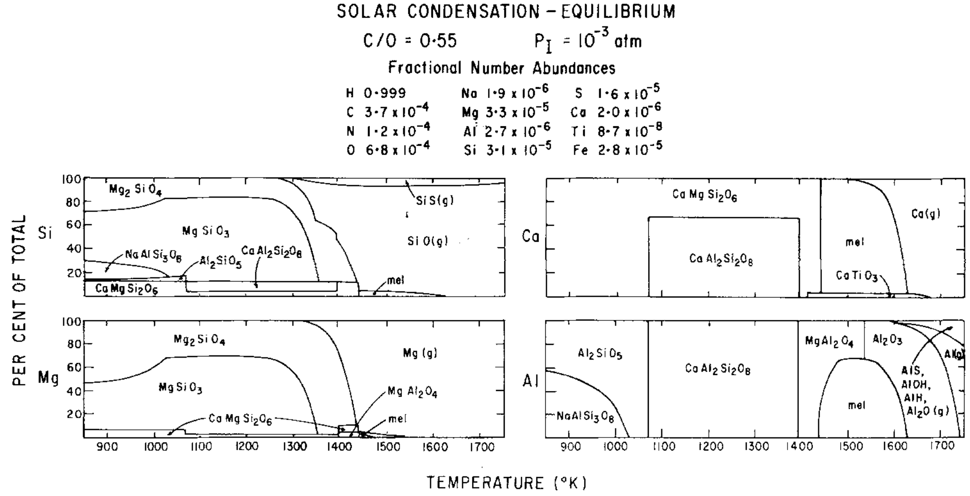

Fig. 1. The distribution of the major elements Al, Ca, Mg and Si among gaseous (*g*) and solid phases for a solar composition (C/O = 0.55) at a pressure of 10^{-3} atm. No adiabatic expansion is assumed. The fractional number abundances of the elements considered in this chemical equilibrium condensation calculation are also listed. Each graph shows the stable phases as a function of temperature. The solid solution melilite $[Ca_2(Al_2, MgSi)SiO_7]$ is indicated by 'mel'.

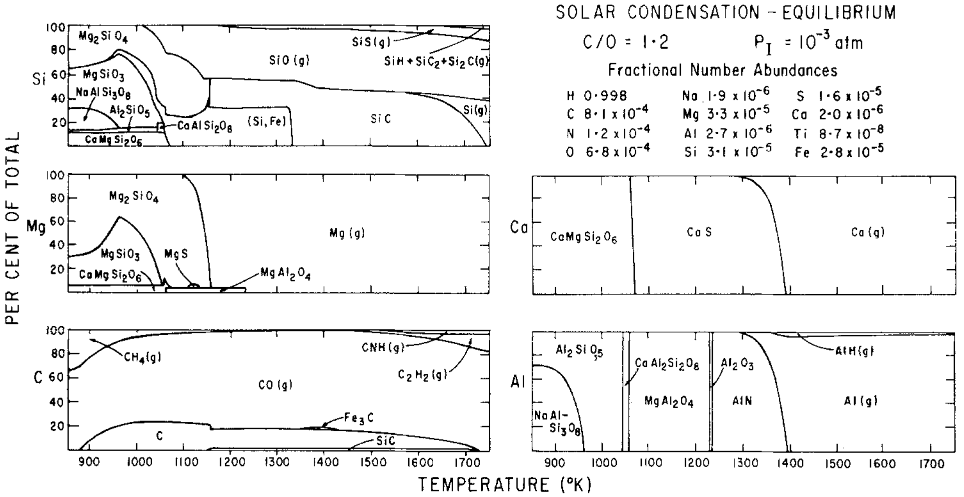

Fig. 2. Same as Figure 1 except that C/O = 1.2 and an additional graph for carbon is included.

by 1600 K. Ca, Mg, Si and Fe follow at 1500 K, 1300 K, 1250 K and 1250 K, respectively. Na and S prove to be relatively volatile, remaining largely gaseous until 800 K and 650 K, respectively. The amount of Si dissolved in Fe is negligible.

The effect of changing the C/O ratio is quite dramatic. For the solar case, our results (Table Ib) agree well with the C/O > 1 calculations of Larimer (1975). Carbides, sulfides and nitrides replace oxides and silicates as the initial condensates. Ti, C and Si are now the most refractory, but if C/O $\lesssim$ 2, Figure 2 shows that only half the Si and less than half the C condense at high temperatures. The 100% condensation temperatures of Al, Si, Ca and Mg are now decreased by 350 K, 250 K, 200 K and 200 K, respectively, relative to the C/O < 1 case. Below 900 K, a comparison of Figures 1 and 2 shows that the major elements Al, Ca, Mg, Na and Si are distributed in identical phases. The condensation temperature of the element iron is almost unaffected by changes in the C/O ratio, even though Fe_3C is the initial condensate in the C/O > 1 case. By 1300 K, all the Fe is condensed in the metallic state. If the effects of the Fe-Si solid solution are ignored (LSG), Fe_3C does not decompose to form metallic Fe until 1050 K, a much lower temperature.

A final interesting feature of low temperatures revealed by Figure 2 is that graphite is converted into methane below 1000 K and disappears at 875 K. Larger C/O ratios depress the disappearance temperature, but this effect could nevertheless have important consequences for systems such as the expanding envelopes of certain novae, for which there is evidence that graphite dust has condensed (D. Clayton and Wickramasinghe, 1976; Ney and Hatfield, 1977). This dust apparently survives to < 700 K. Depending on the C/O ratio in the ejecta, these observations could provide tests of the validity of the equilibrium hypothesis at low temperatures.

The composition of the (H) and (He) zones differ greatly from the solar case only in the H abundance. As a result, the sequences for these zones (Table II) are very similar

TABLE II

(H), (He) zones ($P_I = 10^{-8}$ atm)

a. C/O = 0.55			b. C/O = 1.5		
Mineral	Condensation temperature	Disappearance temperature	Mineral	Condensation temperature	Disappearance temperature
Al_2O_3	1597	1390	C	1950	
melilite	1467	1332	TiC	1550	747
$MgAl_2O_4$	1390	1341	SiC	1308	783
$CaTiO_3$	1370	1306	Fe	1053	
$CaAl_2Si_2O_8$	1340	1328	AlN	1035	890
$CaMgSi_2O_6$	1332		CaS	1020	610
$MgAl_2O_4$	1331	1281	Al_2O_3	890	878
Mg_2SiO_4	1320		$MgAl_2O_4$	878	766
$MgTi_2O_5$	1306	1255	Mg_2SiO_4	829	746
$CaAl_2Si_2O_8$	1281	1071	Al_2SiO_5	783	555
TiO_2	1255	1120	$MgSiO_3$	753	
$MgSiO_3$	1251		MgS	752	695
$FeTiO_3$	1120		TiN	747	650
FeO	1087		SiO_2	729	710
$Al_6Si_2O_{13}$	1071	1068	$NaAlSi_2O_6$	715	
Al_2SiO_5	1068		FeS	710	
$NaAlSi_3O_8$	807	775	Mg_2SiO_4	695	
FeS	786		Ti_4O_7	650	635
$NaAlSi_2O_6$	775		$CaTiSiO_5$	635	
			$CaMgSi_2O_6$	610	515
			$Ca_3Al_2Si_3O_{12}$	555	
			$CaSiO_3$	515	

to the solar case, as are the elemental distributions (Figures 3 and 4). The gross depressions of condensation temperatures relative to the solar case are caused by the lower pressure assumed here. The zero H abundance results in condensation of FeO rather than metallic Fe in the $C/O < 1$ case. Although the Si-Fe alloy is not included here, the oxidation state of a gas of this composition would prevent its appearance anyway. Comparison of the first four figures reveals that the H abundance has little effect on the order of either the initial condensation temperatures, or the temperatures at which complete solidification of Al, Ca, Mg, Na and Si occurs. A zero H abundance makes Ti less refractory than Al and Ca in the $C/O < 1$ case.

The (C) zone (Table III, Figs. 5 and 6) differs from the (H) and (He) zones in that the abundances of C, O, Na, Mg and Al are greatly increased at the expense of the He and N abundances relative to solar composition. First, consider the O-rich case. The larger Al/Ca ratio means that Ca-rich phases cannot dominate the high temperature portion of the Al diagram in Figure 5 as they do in Figure 3. This is not obvious from the condensation sequences alone. In fact, the Ca abundance is so small that Ca-bearing phases (melilite and anorthite) comprise only a few percent of the mass of Al-rich phases (corundum, spinel), in marked contrast to the solar and (H, He) cases in which the Al/Ca ratio is ~ 1. The larger Mg/Si ratio causes forsterite (Mg_2SiO_4) to be the major

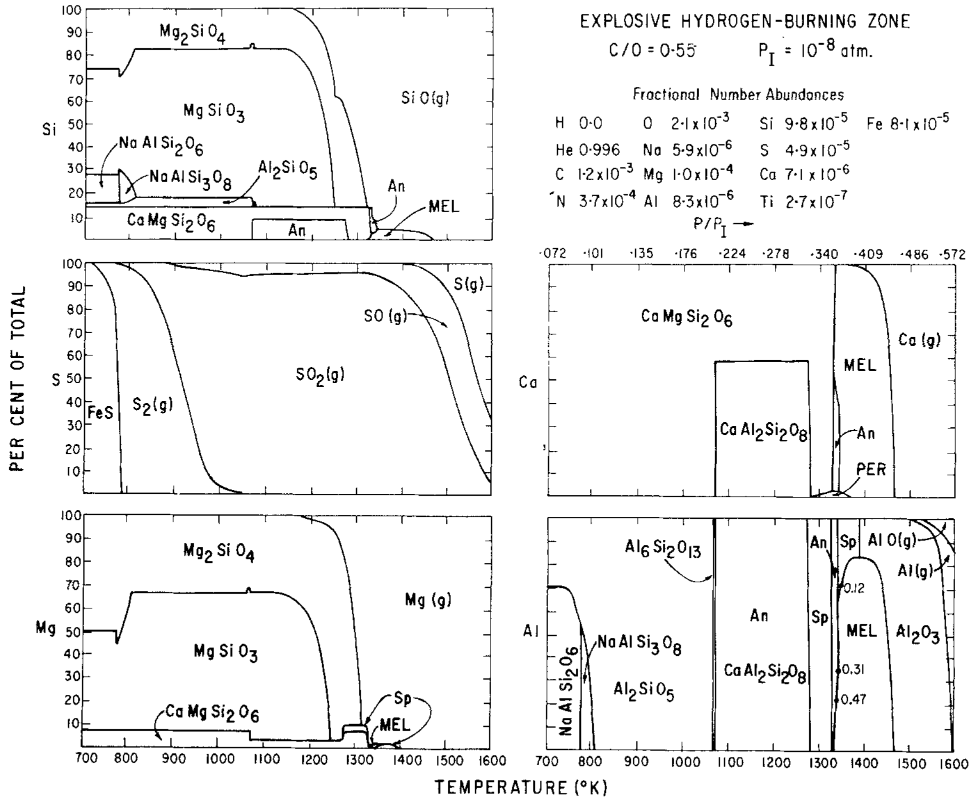

Fig. 3. The distribution of the major elements Al, Ca, Mg, S and Si among gaseous (*g*) and solid phases for the explosive hydrogen burning (H) zone with C/O = 0.55, whose fractional number abundances are also shown. As the text explains, these calculations are also appropriate for the (He) zone. The initial pressure P_I (i.e., the pressure that would attain if only monatomic gases were present at 2000 K) is 10^{-8} atm and a $\gamma = 5/3$ expansion is assumed. The actual pressure is indicated at 100 K intervals above the Ca diagram. The abbreviations MEL (melilite), An (anorthite, $CaAl_2Si_2O_8$), Sp (spinel, $MgAl_2O_4$) and PER (perovskite, $CaTiO_3$) are used.

condensate of Si at lower temperatures, instead of enstatite ($MgSiO_3$). Mg cannot be totally solidified until MgO condenses; this delay results in the total solidification of Si at higher temperatures than Mg. Also in contrast to the solar case, one sees from Fig. 5 that Ti totally condenses as $CaTiO_3$ at 1400 K, *after* Al (1750 K), Ca (1500 K) and Si (1450 K) have done so.

The C-rich case is detailed in Table IIIb and Figure 6. As in the solar and (H, He) cases, carbides (SiC, TiC, Fe_3C) and sulfides form the initial condensates, but here the lack of N prevents AlN from condensing. Nevertheless the order in which Al, Ca, Si and Mg become completely condensed remains the same as in the O-rich (C) case.

The (O) zone is characterized by large Si, S, O and Ca abundances. Because of uncertainties in the value of the (S + Si)/O ratio, two values have been utilized. The O-rich case is shown in Table IVa and Figure 7. The large Ca/Al ratio causes the preponderance

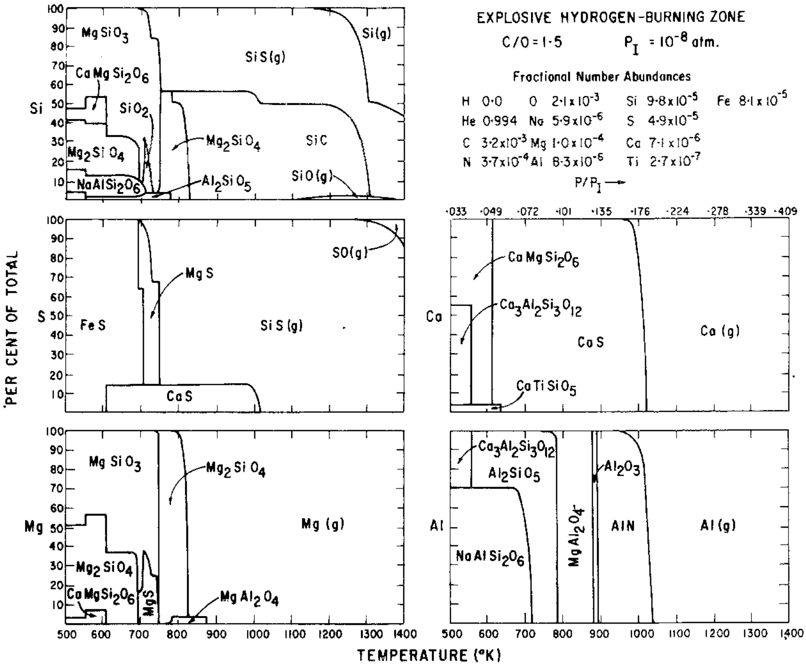

Fig. 4. Same as Figure 3 except that that C/O = 1.5.

TABLE III

(C) zone ($P_I = 10^{-8}$ atm)

a. C/O = 0.5			b. C/O = 2.0		
Mineral	Condensation temperature	Disappearance temperature	Mineral	Condensation temperature	Disappearance temperature
Al_2O_3	1830	1617	C	2150	
$MgAl_2O_4$	1617		TiC	1530	792
melilite	1595	1495	SiC	1470	920
Mg_2SiO_4	1522		Al_2O_3	1120	990
$Ca_3MgSi_2O_8$	1495	690	Fe_3C	1095	1055
MgO	1460		CaS	1065	
$CaTiO_3$	1451		Fe	1055	
FeO	1208		$MgAl_2O_4$	990	
Na_2SiO_3	780		Mg_2SiO_4	935	
FeS	740		MgS	918	703
Ca_2SiO_4	690		MgO	905	
			Mg_2TiO_4	793	670
			Na_2S	703	
			$CaTiO_3$	670	
			Na_2SiO_3	652	
			FeS	550	

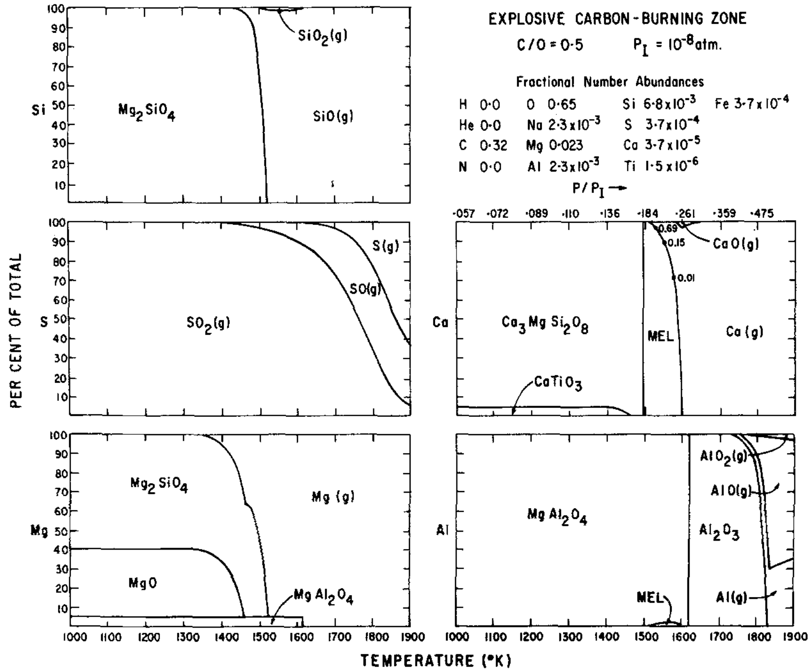

Fig. 5. Same as Figure 3 except that abundances for the (C) zone, with C/O = 0.5, are utilized.

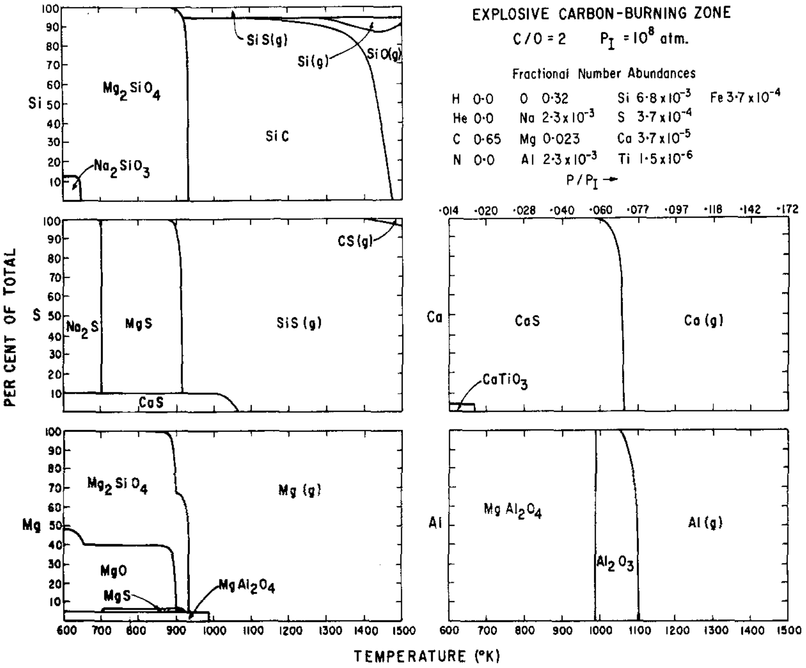

Fig. 6. Same as Figure 5 except that C/O = 2.

TABLE IV

(O) zone ($P_I = 10^{-8}$ atm)

a. O-rich			b. S, Si-rich		
Mineral	Condensation temperature	Disappearance temperature	Mineral	Condensation temperature	Disappearance temperature
melilite	1655	1340	Si	1390	
Ca_2SiO_4	1610	1370	TiO	1169	
$CaTiO_3$	1480	1320	CaS	1130	
$CaSiO_3$	1394	865	Fe	1110	
$CaAl_2Si_2O_8$	1340	820	Al_2O_3	1077	1060
$CaTiSiO_5$	1320	1040	melilite	1060	1020
SiO_2	1287		$Ca_3Al_2Si_3O_{12}$	1020	940
$CaMgSi_2O_6$	1140	807	$CaSiO_3$	1015	880
Fe	1110		$CaAl_2Si_2O_8$	940	830
Ti_2O_3	1040	965	$CaMgSi_2O_6$	913	810
TiO	965		SiO_2	880	
Si	915		Al_2SiO_5	830	
CaS	880		$MgSiO_3$	810	760
Al_2SiO_5	820		MgS	760	
$MgSiO_3$	807	750	$NaAlSi_2O_6$	690	
MgS	750		SiS_2	610	
$NaAlSi_2O_6$	690				
SiS_2	600				

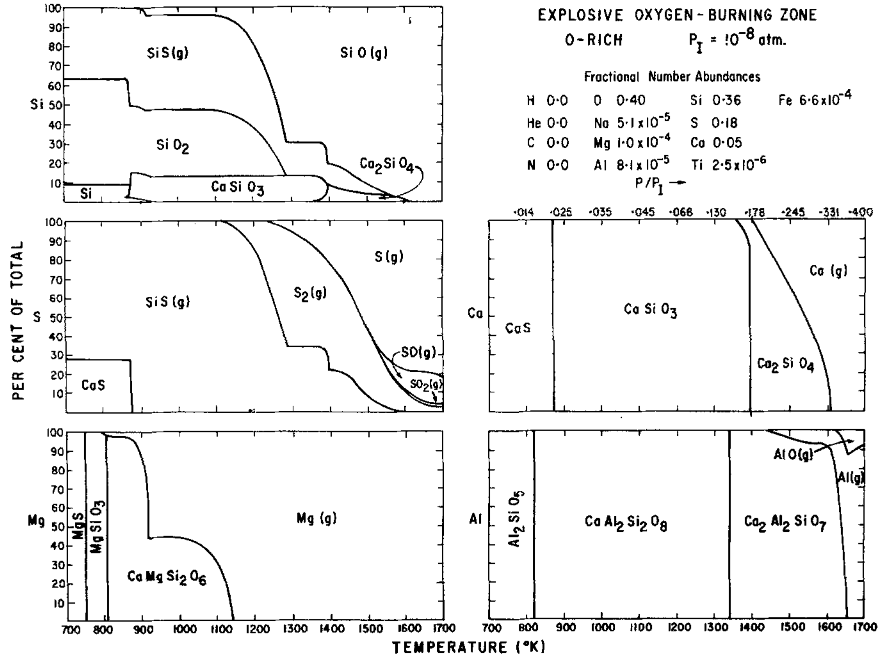

Fig. 7. Same as Figure 3 except that abundances for the O-rich (O) zone are utilized.

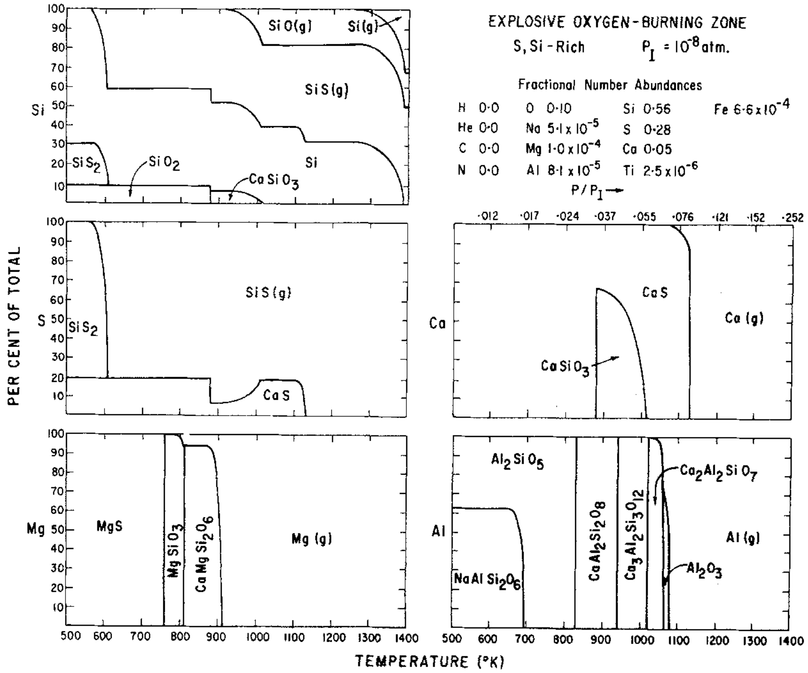

Fig. 8. Same as Figure 7 except that abundances for the S, Si-rich (O) zone are utilized.

of Ca-rich phases among the initial condensates and the concomitant absence of Al_2O_3 and $MgAl_2O_4$. The Si/Mg ratio is so high that the mass fraction of Mg-silicates is negligible. In fact the Si/O ratio is large enough, relative to solar, for Si to condense as a metal after SiO_2 totally consumes the O. Including the effects of a Si-Fe alloy would lead to the appearance of Si 200 K higher in temperature. Figure 7 shows that Al, Ca and Mg are totally condensed by 1450 K, 1400 K and 800 K, respectively. Ti, O, Fe, Na, and Si are completely solidified by 1300 K, 875 K, 800 K, 650 K, 550 K and 550 K, respectively.

The S, Si-rich case (Table IVb and Figure 8) is analogous to the $C/O > 1$ cases encountered earlier. Both are extremely reducing. Because carbides and nitrides cannot appear owing to the lack of C or N, metallic Si and Fe, the sulfide CaS, and TiO are the initial condensates. As in the other reducing gases investigated herein, oxides and silicates appear at much lower temperatures than the earliest condensates and at much lower temperatures than in cases with larger O abundances. The order of complete solidification in this zone are: Ca and Ti (1100 K), Al (1050 K), Fe (1000 K), O (900 K), Mg (800 K), Na (675 K), and S and Si (575 K).

The final zone considered was the (Si) zone, whose abundances and condensation sequences at 10^{-4} and 10^{-12} atm are shown in Table V. There is little choice but for metals to condense first, followed by sulfides of Ca, Fe and Si at much lower temperatures, if they form at all. D. Clayton and Ramadurai (1977) suggest the possibility that sulfides of Ti condense in this zone. Since no thermodynamic data as yet exist for these phases, this idea must be considered purely speculative. Titanium sulfides simply may not

TABLE V

(Si) zone

Fractional number abundances	
Ca	0.03
Fe	0.75
S	0.10
Si	0.11
Ti	5×10^{-4}

Mineral	Condensation temperature	Mineral	Condensation temperature
Fe	1820	Fe	1089
Si	1670	Si	1083
Ti	1620	Ti	1075
CaS	1490	CaS	950

have stability fields in a gas of this composition because they may be unstable relative to their constituent elements or sulfides of the much more abundant elements Fe and Ca.

4. Discussion

The scenario that forms the background for our discussion has been described in LSG and is reviewed elsewhere (Schramm, 1978). Basically, it presumes that the presolar nebula, originally containing well-mixed gas and dust, was contaminated by the debris from one or more nearby supernovae within a million or so years of the epoch of meteorite formation. This contamination is pictured as the cause of some or all of the isotopic anomalies discovered in Allende so far. The timescale follows from the halflife of ^{26}Al (700 000 yr), which decayed in-situ in Allende inclusions, producing the ^{26}Mg anomaly (Lee *et al.*, 1976).

Three questions remain regarding the supernova debris. First, is nucleation and grain growth possible in SN ejecta at all? Second, can SN grains survive post-explosion energetic particle irradiation before being incorporated in the presolar nebula? Finally, how much SN gas and dust can actually be injected into the nebula? The first question was discussed by Hoyle and Wickramasinghe (1970). More recently, Falk *et al.* (1978) and Lattimer and Falk (1978) have examined the first two questions in more detail. Their calculations suggest that the possibility for the production and survival of small (10^{-3}–$10^{-1}\,\mu$) grains in current models of SN ejecta is good. With regard to the third question, hydrodynamic calculations by Woodward (1976) showed that the collapse of the nebula may be triggered by the collision of the SN ejecta with the cloud. In his model, the ejecta never penetrate the cloud, flowing around it instead. Margolis (1978) used a two-component fluid model for the gas and dust to study this problem. He found that the dust, but not the gas, was able to penetrate to some extent. The dust tended to concentrate in the outer regions of the nebula, thereby producing a concentration gradient in the nebula.

This scenario thus implies that dust grains from a supernova could have introduced isotopic anomalies into the solar nebula. The exotic compositions become less diluted than if they were originally in the gas phase, which would tend to homogenize rapidly with the nebular gas due to mixing. This holds even if heating of these grains, as the collapse proceeds, caused them to melt or even vaporize. Rapid enough re-condensation could preserve exotic compositions in regions of the nebula where the SN grains were originally concentrated.

An important point is that, in equilibrium, the only condensed phases that are stable against evaporation or other reactions in the presolar nebula are those that appear in a solar equilibrium condensation sequence. Our justification for using equilibrium sequences is that the composition of many refractory inclusions in Allende and other C chrondrites appear remarkably similar to the predicted condensates in Table Ia (for $T > 1435$ K). Although we do not require that SN grains remain intact throughout the meterorite fomation process, the probability of preserving isotopic anaomalies is much greater if some of the major SN condensates do not have to undergo substantial chemical processing in the solar nebula. A striking result of the calculations reported here is that many minerals produced in SN ejecta are the same as those predicted to be stable in the solar nebula. However, it must be kept in mind that SN zones with non-solar elemental compositions produce mineral abundances that differ greatly from those observed in high-temperature inclusions, even if the same assemblage of minerals is present. This information is readily obtainable from Figures 1–8. For example, even though the minerals Al_2O_3, melilite, $MgAl_2O_4$ and $CaTiO_3$ appear in the condensation sequence for the O-rich (C) zone, spinel should be 60 times more abundant than melilite. These phases have nearly the same abundances in Allende inclusions. Similarly, although melilite appears in the condensation sequence for the O-rich (O) zone, its abundance is 600 times less than that of Ca_2SiO_4 which is not found in Allende inclusions. On the basis of these arguments and other comparisons that can be made from Figures 1, 2 and 5–8, it is clear that no Allende inclusions so far described can have condensed directly from unmixed (C) or (O) zones, the only zones in which ^{16}O and/or ^{26}Al are produced in abundance (Truran and Cameron, 1978).

A discussion of the isotopic composition of each zone is given in LSG. The range of condensation temperatures in the high-temperature inclusions is 1743 to 1435 K at 10^{-3} atm total pressure. Assuming that only those minerals that are stable in solar environments above 1435 K can carry anomalies into the inclusions, LSG tabulate the anomalies to be expected of SN condensates from each zone. This is conservative since stability in the solar nebula may not be a necessary condition for them to be carriers of isotopic anomalies.

Recent experimental studies of O (R. Clayton and Mayeda, 1977) and Mg (Wasserburg *et al.*, 1977) show that large isotopic mass fractionations occurred when some of these inclusions condensed. Such effects are the rule, rather than the exception, in the case of Si (R. Clayton *et al.*, 1978; Yeh and Epstein, 1978). R. Clayton *et al.* (1978) found δ^{30} Si and δ^{29} Si values from 1.7 to 2.9 and 0.8 to 1.3, respectively, in coarse-grained Allende inclusions. The δ-value is defined as the deviation, in parts per thousand, of the ratio of the isotope to ^{28}Si relative to the terrestrial rose quartz standard. They also found values of -0.6 and -0.3, respectively, in a fine-grained inclusion and suggested that this type of inclusion could have formed from a gas which had been depleted in ^{30}Si and ^{29}Si by the prior condensation and removal of large amounts of Si. They pointed out, however, that on the order of 50%–60% of the Si had to be removed in the form of higher temperature condensates than the fine-grained inclusions and noted that insufficient Si can be removed by the coarse-grained inclusions in the case of a gas of solar composition (Figure 1). We note that if forsterite is removed in addition to coarse-grained inclusions before the condensation of fine-grained inclusions, as suggested by Grossman and Ganapathy (1976), a fractionation of the required magnitude can be produced. Reference to Figures 3–8 shows that such a requirement holds even in SN ejecta we consider since in no SN zone is it possible to remove large amounts of Si in combination with Ca-Al rich phases similar to those found in coarse-grained inclusions. This could only occur in a gas in which Ca and Al are both comparable in abundance to Si. Such conditions are obviously not representative of SN zones which give rise to solar-like abundance distributions; hence, the required matter is unlikely to be a dominant component of supernova debris. One can also anticipate that the isotopic abundance patterns would be enormously distorted in such matter (Truran, 1978).

Finally, we examine chemical fractionation in SN ejecta and its consequences for elemental abundances in the interstellar medium. It is apparent from Figures 1–8 that, in most zones, the elements can be grouped as follows, according to the order in which they become totally condensed in cooling ejecta: Al, Ca and Ti before Mg and Si before Na and S before C, N and O. In addition, in relatively oxidizing conditions ($C/O < 1$ or O-rich (O) zone) Fe falls into the Mg and Si group, while in relatively reducing conditions ($C/O > 1$ or S, Si-rich (O) zone), it condenses with Al, Ca and Ti.

Routly and Spitzer (1952) and later others (e.g., Field, 1974) have noted that many major elements have gas phase abundances. The most likely interpretation seems to be that a large fraction of the most refractory elements are bound up as dust. Specifically, the observations collected by Field (1974) show that the H-normalized abundance of Ca is 2×10^{-4} and of Al and Ti is $\lesssim 5 \times 10^{-3}$, relative to solar. For Fe, Mg, Si and Na, the relative depletions are $\lesssim 10^{-1}$, 10^{-1}, $\sim 1/3$ and $\sim 1/5$, respectively. Field (1975) proposed that grain formation in circumstellar (protosolar) nebulae of solar composition could account for the gross features of the abundance data, at least for the more refractory elements. He specifically eliminated supernovae as sources of dust, believing that they could only contribute gas to the interstellar medium. Recent theoretical studies, (e.g., Hoyle and Wickramasinghe, 1970; LSG, Falk *et al.*, 1978), suggest that grains can not only form in SN ejecta, but can also survive the post-explosion evolution of SN remnants. In fact, the groupings discussed above show that taking a weighted average of the gas phase elemental abundances over all SN shells and over all SN masses is capable of reproducing the observed elemental abundance pattern. A requirement of any model that uses condensation processes to explain the composition of the interstellar gas is that the probability of cessation of condensation must increase with decreasing temperature

(Grossman, 1975). This is a natural consequence in cooling SN ejecta (LSG) where P and T are both decreasing with time, but why this must be so in circumstellar nebulae is unclear.

In summary, equilibrium condensation calculations for supernova ejecta suggest that many of the supernova condensates are the same as high-temperature solar nebula condensates, especially for the major elements Al, Ca, Mg, Si and Ti. These SN condensates could be stable in the presolar nebula and are thus potential sources of the observed isotopic anomalies in Allende. In particular, ^{26}Al, synthesized in the (C) SN zone, and ^{16}O, made in the (C) and (O) zones could have given rise to the anomalies in Mg and O. The mineral abundances in these zones differ greatly from those predicted from solar condensation calculations and observed in high-temperature Ca-, Al-rich Allende inclusions, even though similar assemblages of minerals are present. Thus these inclusions could not have condensed directly from unmixed (C) or (O) zones and attempts, based on this hypothesis, to explain the large mass dependent isotopic fractionations observed for Si in these inclusions must fail. The order in which the major elements become totally condensed has been found to be nearly independent of the SN zone considered, being the same as that for a solar gas. A consequence of this is that the observed depletion of heavy elements in the interstellar gas could be due to dust formation in SN ejecta.

Acknowledgements

It is a pleasure to thank R. Clayton, Sydney Falk, Dave Schramm and Jim Truran for interesting and helpful conversations regarding this work. This research was supported in part by NSF grant AST 76-22673 (J.M.L.), NASA grant NGR 14-001-249 (L.G.) and the Alfred P. Sloan Foundation (L.G.).

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