

# SOLAR ABUNDANCES OF THE ELEMENTS

O.K. Manuel and Golden Hwaung

Department of Chemistry

University of Missouri

Rolla, MO 65401

*The isotopic compositions of noble gases in the solar wind show high enrichments of light isotopes. When corrected for mass fractionation all five noble gases there can be resolved in terms of the two primitive noble gas components that have been identified in planetary solids. Reasons are presented for assigning the fractionation to a solar process that selectively enriches lighter nuclei at the surface of the Sun. When abundances of the elements at the Sun's surface are corrected for this fractionation, it is shown that atomic abundances for major elements in the bulk Sun are (in decreasing order): Fe, Ni, O, Si, S and Mg. Solar elements at about the 1% atomic abundance level include He, C, Ne, Ca and Cr. These results suggest that fusion of hydrogen is probably not the Sun's primary energy source.*

## INTRODUCTION

Recently we reported (Manuel and Hwaung, 1983) that solar-wind-implanted noble gases, type-S noble gases, can be understood as a mixture of the primitive noble gas components — type X and type Y — identified earlier in planetary solids (Sabu and Manuel, 1980). To resolve type-S noble gases into these two primitive planetary components, it was first necessary to correct for a common, mass-dependent fractionation effect in the isotopic abundances of all five type-S noble gases. A general equation that could accommodate mass-dependent fractionation as a function of mass difference and/or the mass ratio was employed to calculate the value of the fractionation factor,  $f_j^i$ , relating values of the isotope ratio,  ${}^iG/{}^jG$ , in two mass-fractionation-related reservoirs,

$$f_j^i = ({}^iG/{}^jG)_2 / ({}^iG/{}^jG)_1 = f(j/i, j-i, \dots) \quad (1)$$

The main advantage of Eq. (1) is that it does not require specific information on the nature of the fractionation process, and multiple processes can be accommodated. The disadvantage is that its use requires the calculation of values for three constants, i.e., one must assume that fractionation alone has altered the values of three different isotope ratios in order to obtain values for the three constants. Since planetary type-Y noble gases contain no He or Ne (Sabu and Manuel, 1980), we assumed that fractionation alone produced differences in the values of  ${}^3\text{He}/{}^4\text{He}$ ,  ${}^{21}\text{Ne}/{}^{22}\text{Ne}$  and  ${}^{20}\text{Ne}/{}^{22}\text{Ne}$  ratios of type-X and type-S gases in order to use Eq. (1) to calculate the fractionation effect in Ar, Kr and Xe.

We recently realized that the fractionation relationship between planetary and solar type noble gases is essentially independent of the mass difference variable shown in Eq. (1). The fractionation shows a mass ratio dependence, as expected from a velocity-selection process such as diffusion. Eq. (1) can be simplified because fractionation that depends on mass difference, e.g., gravitational fractionation, is unimportant.

Isotopic fractionation is not the primary concern of this report, but a brief review of the mass-dependent fractionation relationship between the isotopic compositions of planetary and solar-wind-implemented gases is essential to our later discussion on the chemical composition of the bulk Sun.

ISOTOPIC FRACTIONATION

The fractionation factor,  $f_{20}^m$ , relating the ratio of any noble gases isotope,  $^mG$ , to that of  $^{20}\text{Ne}$  in planetary and solar-wind-implemented gases is simply

$$f_{20}^m = (^mG/^{20}\text{Ne})_s / (^mG/^{20}\text{Ne})_p = (20/m)^n \tag{2}$$

Table 1 shows the values that Eq. (2) yields for other isotope ratios if fractionation is assumed responsible for differences in the value of the  $^{22}\text{Ne}/^{20}\text{Ne}$  ratio in type-X gases (Reynolds *et al.*, 1978) and in the type-S gases of sample #bb18, lunar fines 12001 (Eberhardt *et al.*, 1972). The type-X Ar, Kr and Xe shown in Table 1 are from Allende mineral separate #58 (Frick, 1977). These and the noble gases in air are shown in Table 1, together with the values computed from Eq. (2) for fractionation-corrected noble gases in the solar wind. The errors shown on the fractionation-corrected ratios represent the sum of the uncertainty on the  $^{22}\text{Ne}/^{20}\text{Ne}$  ratio in type-X gas and that on each isotopic ratio in solar-wind-implemented gases.

Assuming only that fractionation is responsible for differences in values of the  $^{22}\text{Ne}/^{20}\text{Ne}$  ratio in type-X and in solar-wind-implemented gases and that Eq. (2) defines the corresponding change in the other isotopic ratios, we obtain values of the  $^3\text{He}/^4\text{He}$ ,

Table 1  
Isotopic data for planetary and solar-wind-implemented noble gases

Isotope	Type-X gases	Solar wind implanted gases in 12001	Fractionation-corrected gases in 12001 (Eq. 2)	Atmospheric gases
He-3	$(1.4 \pm 0.2) \times 10^{-4}$	$(4.17 \pm 0.12) \times 10^{-4}$	$(1.13 \pm 0.24) \times 10^{-4}$	$1.4 \times 10^{-6}$
He-4	$\equiv 1.000$	$\equiv 1.000$	$\equiv 1.000$	$\equiv 1.000$
Ne-20	$\equiv 100.0$	$\equiv 100.0$	$\equiv 100.0$	$\equiv 100.0$
Ne-21	$0.305 \pm 0.040$	$0.251 \pm 0.009$	$0.313 \pm 0.018$	0.296
Ne-22	$12.2 \pm 0.6$	$7.90 \pm 0.12$	12.2	10.20
Ar-36	$4.50 \pm 0.2$	$5.31 \pm 0.07$	$4.15 \pm 0.18$	5.32
Ar-38	$\equiv 1.000$	$\equiv 1.000$	$\equiv 1.000$	$\equiv 1.000$
Kr-78	$1.7 \pm 0.2$	$2.959 \pm 0.024$	$2.35 \pm 0.09$	3.0
Kr-80	$19.1 \pm 0.1$	$19.38 \pm 0.10$	$17.32 \pm 0.32$	19.6
Kr-82	$\equiv 100.0$	$\equiv 100.00$	$\equiv 100.00$	$\equiv 100.0$
Kr-83	$117.7 \pm 0.9$	$100.20 \pm 0.37$	$105.89 \pm 0.48$	99.7
Kr-84	$562.4 \pm 3.9$	$498.86 \pm 1.67$	$556.8 \pm 5.6$	494.6
Kr-86	$202.6 \pm 10.1$	$152.14 \pm 0.39$	$189.0 \pm 4.6$	151.1
Xe-124	$4.93 \pm 0.06$	$2.90 \pm 0.07$	$2.34 \pm 0.11$	$2.35 \pm 0.03$
Xe-126	$3.44 \pm 0.02$	$2.59 \pm 0.09$	$2.25 \pm 0.11$	$2.21 \pm 0.03$
Xe-128	$57.7 \pm 0.2$	$50.38 \pm 0.28$	$46.94 \pm 0.65$	$47.0 \pm 0.2$
Xe-129	$688 \pm 4$	$635.4 \pm 1.7$	$613.4 \pm 4.3$	$648.0 \pm 2.5$
Xe-130	$\equiv 100.0$	$\equiv 100.0$	$\equiv 100.0$	$\equiv 100.0$
Xe-131	$540 \pm 2$	$498.8 \pm 1.1$	$516.5 \pm 1.2$	$519.1 \pm 1.8$
Xe-132	$644 \pm 3$	$606.2 \pm 1.6$	$649.9 \pm 3.8$	$659.1 \pm 2.4$
Xe-134	$372 \pm 3$	$223.9 \pm 0.8$	$247.1 \pm 3.4$	$255.9 \pm 0.8$
Xe-136	$397 \pm 4$	$181.8 \pm 0.6$	$223.3 \pm 4.9$	$217.4 \pm 0.6$

$^{21}\text{Ne}/^{20}\text{Ne}$  and  $^{36}\text{Ar}/^{38}\text{Ar}$  ratios for solar-wind-implanted gases that match those in type-X gas, values for the  $^{78}\text{Kr}/^{82}\text{Kr}$ ,  $^{83}\text{Kr}/^{82}\text{Kr}$ ,  $^{84}\text{Kr}/^{82}\text{Kr}$  and  $^{86}\text{Kr}/^{82}\text{Kr}$  ratios that are intermediate to those in atmospheric and type-X gases, and values of the  $^{124}\text{Xe}/^{130}\text{Xe}$ ,  $^{126}\text{Xe}/^{130}\text{Xe}$ ,  $^{128}\text{Xe}/^{130}\text{Xe}$ ,  $^{131}\text{Xe}/^{130}\text{Xe}$ ,  $^{132}\text{Xe}/^{130}\text{Xe}$ ,  $^{134}\text{Xe}/^{130}\text{Xe}$  and  $^{136}\text{Xe}/^{130}\text{Xe}$  ratios in solar-wind-implanted gases that agree with those in air. The discrepancy at  $^{129}\text{Xe}$  indicates the presence of the decay product in extinct  $^{129}\text{I}$  in air (Boulos and Manuel, 1971), and that at  $^{80}\text{Kr}$  may indicate the presence of excess  $^{80}\text{Kr}$  in the isotopic spectrum of Kr-X in the Allende meteorite. Allende contains excess  $^{80}\text{Kr}$  and  $^{82}\text{Kr}$  from n-capture on bromine (Manuel *et al.*, 1972). Neutron capture on Br that generates a  $\approx 10\%$  excess of  $^{80}\text{Kr}$  would only produce a  $\approx 0.5\%$  excess of  $^{82}\text{Kr}$ , so a small component of these neutron-capture products may be responsible for the apparent excess of  $^{80}\text{Kr}$  in the type-X noble gases of Allende. The excellent agreement between calculated values of other isotopic ratios and those in major noble gas components of the planetary system reinforces the suggestion (Kuroda and Manuel, 1970) that correlated mass fractionation effects may account for major differences in the isotopic compositions of these five elements.

## THE FRACTIONATION SITE

The fractionation relationship between planetary and solar-wind-implanted noble gases might indicate (a) an enrichment of the heavy isotopes in planetary solids, or (b) an enrichment of the light isotopes in the solar wind. A third possibility, implantation fractionation, is relatively unimportant for the surface-correlated noble gas component of lunar soils. The isotopic fractionation pattern defined by Eq. (2) can therefore be used to evaluate the roles of solar and planetary fractionation.

Figure 1 shows the values of  $f_{20}^m$  that were used to calculate the isotopic composition of fractionated-corrected, solar-wind-implanted noble gases in lunar fines sample 12001 (column 4 of Table 1). The fractionation expected in the H/D ratio of solar-wind-implanted gases is included. The broken line in Figure 1 represents values of  $\log f_{20}^m$  expected from gravitational fractionation. This line was also calculated to fit differences in values of the  $^{22}\text{Ne}/^{20}\text{Ne}$  ratio of planetary and solar-wind-implanted neon. Obviously fractionation in a planetary or solar gravitational field cannot account for differences in the isotopic composition of planetary and solar-wind-implanted gases.

Since the fractionation relationship between the isotopic compositions of planetary and solar-wind-implanted noble gases depends on the mass ratio (see Eq. (2), Table 1 and Fig. 1), rather than on mass difference, gravitational fractionation will not be considered in the ensuing discussion of planetary vs. solar fractionation. The agreement between elemental abundances in the solar wind and those at the solar surface (Geiss, 1973; Ross and Aller, 1976) suggests that fractionation in solar wind acceleration is also unimportant. We will therefore focus our attention on the relative merits of a solar and planetary setting for the velocity-selection process that produced the relationship shown in Table 1 and Figure 1. Diffusive mixing and effusive gas loss are two familiar examples of processes that depend on the mass ratio. Velocity selection via pressure and temperature diffusion is less important under normal conditions, but these may play a major role in regions of steep pressure and temperature gradients.

Elemental abundances of noble gases in planetary solids show a strong depletion of these from more condensable elements. The depletion pattern of planetary noble gases somewhat resembles the inverse of the pattern shown in Figure 1 (Suess, 1949; Merrihue

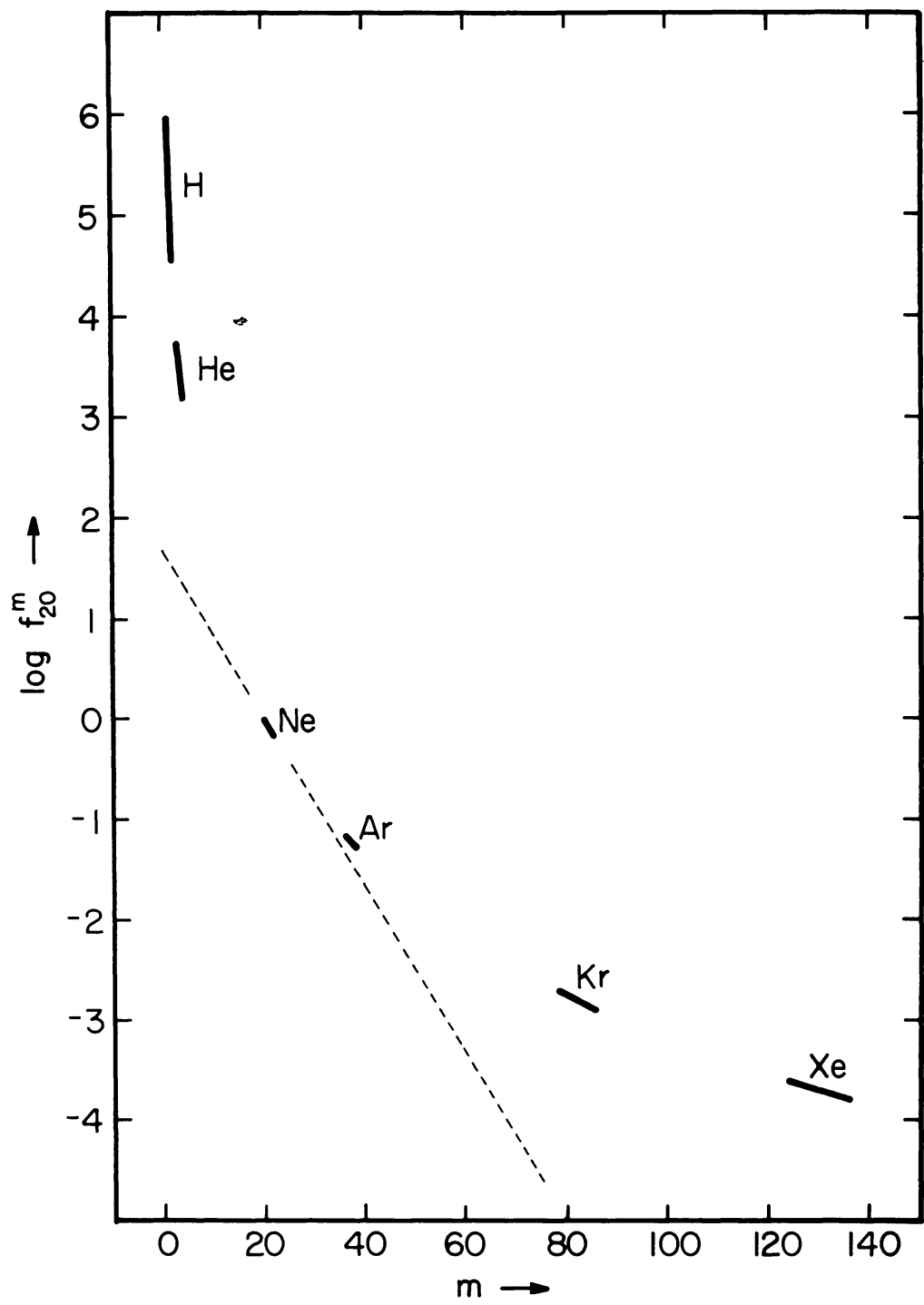


Fig. 1 Mass dependence of the fractionation factor,  $f_2^m$ , for hydrogen and the five noble gases. The heavy lines represent the fractionation factors that yield planetary values when applied to the isotopic ratios of solar-wind-implanted noble gases (see fractionation-corrected gases in 12001, Table 1). Differences in the isotopic compositions of planetary and solar-wind-implanted noble gases follow the mass ratio relationship shown in Eq. (2). Gravitational or other fractionation that depends on mass difference, represented here by the broken line, cannot explain differences in the isotopic compositions of solar and planetary noble gases. Note that both sets of fractionation factors are normalized to differences in the value of the  $^{22}\text{Ne}/^{20}\text{Ne}$  ratio.

*et al.*, 1962; Kuroda and Manuel, 1970; Manuel and Sabu, 1981). Since the abundance pattern of noble gases in planetary solids suggests preferential retention of the heavier gases, one might intuitively conclude that differences in the isotopic composition of planetary and solar-wind-implemented noble gases were produced by (a) fractionation that enriched the heavy isotopes in planetary solids, rather than (b) fractionation that enriched the light isotopes in the solar wind. It is precisely this type of reasoning that has plagued earlier attempts to decipher obvious evidence of a mass fractionation relationship in the isotopic abundances of planetary and solar noble gases. Our reasons for rejecting (a) planetary fractionation in favor of (b) solar fractionation are presented below.

1. Fractionation in a planetary site cannot account for the common, mass-dependent relationship in the isotopic compositions of the five noble gases shown in Table 1 and Figure 1 because the gases there represent a combination of components that were not mixed prior to trapping in planetary solids. All planetary He and Ne, for example, are contained in the primitive, type-X noble gas component that also contains very isotopically anomalous Xe, Xe-X (Manuel and Sabu, 1975, 1977; Manuel, 1977; Sabu and Manuel, 1980). Planetary fractionation might explain correlated fractionation effects in the isotopic compositions of He, Ne and Xe-X, but solar fractionation is required to explain the common, mass-fractionation effects across the isotopes of the five noble gases that constitute the solar mix of elements.
2. The abundance pattern of planetary noble gases does not show the separation of He from Ne that would accompany the isotopic fractionation pattern shown in Figure 1. The near equality of the He/Ne ratio of planetary and solar-wind-implemented gases is shown in Table 1 of Srinivasan and Manuel (1971) and in Figure 2 of Merrihue *et al.* (1962). The combined observations of nearly equal values of the He/Ne ratio and severely fractionated isotopic ratios of He and Ne cannot be explained by planetary fractionation of material initially having the composition of the solar surface. These two seemingly conflicting observations can be understood in terms of solar fractionation that enriches lighter nuclei at the Sun's surface. Regardless whether fractionation enriched the heavy isotopes of He and Ne in planetary solids or the light isotopes of He and Ne at the solar surface, the almost identical values of the He/Ne ratio in these two reservoirs and the isotopic mass fractionation relationship shown in Figure 1 and in Table 1 indicate that the He/Ne ratio of ambient type-X gases in the protoplanetary nebula was 3-4 orders of magnitude higher than that in the bulk Sun.
3. The abundance pattern of planetary noble gases fails to fit the fractionation pattern shown in Figure 1, but the 10-order-of-magnitude variation in values of  $f_{20}^m$  over the 1-150 amu range is remarkably similar to the abundance pattern of elements at the solar surface (Ross and Aller, 1976). In other words, the composition of material at the solar surface shows the high abundances of light elements that would be expected if solar fractionation enriches lighter particles at the Sun's surface.
4. Table 1 indicates the presence of type-Y Xe, type-X light noble gases, and a mixture of X and Y components for Kr in the solar wind. This distribution of X and Y components also suggests high abundances of heavy elements in the Sun. Specifically, values of the Xe/Kr and Kr/Ar ratios of the Y-type gases there must be higher than those of the X-type gases. Consequently, the values of these (heavy/light) elemental ratios for the bulk Sun must be higher than those of

planetary type-X gases. This and the conclusion of item 2 above indicate that noble gases of the bulk Sun are characterized by values of Ne/He, Kr/Ar and Xe/Kr ratios that are higher than those of planetary type-X noble gases. Fractionation that enriches lighter nuclei at the solar surface can accommodate these conclusions and the occurrence of high abundances of H, He and other low-Z elements in the Sun's atmosphere (Ross and Aller, 1976). Fractionation in a planetary site would not explain the solar distribution of X and Y type noble gases shown in Table 1.

5. The composition of the solar wind fluctuates in the manner expected if a solar fractionation process selectively enriches lighter particles in the solar wind. Several different measurements provide evidence of reduced fractionation in those elements that leave the Sun in high energy events. Values of the He/H ratio in the solar wind for example, correlate with sun spot number (Robbins *et al.*, 1970). High values of the He/H ratio are associated with solar flares, and values up to  $\approx 10$  times that of the normal solar wind have been observed (Geiss, 1973). Solar flares are also associated with reduced fractionation across the noble gas isotopes. Frick *et al.* (1975) note that the solar flare component is enriched in heavy noble gas isotopes when compared with the normal solar wind component.
6. If processes in the Sun are responsible for the fractionation relationship shown in Figure 1, then isotopic fractionation would be expected in other elements of the solar wind. The steepest fractionation is expected across the two stable isotopes of hydrogen, and Epstein and Taylor (1971) report very low values of the D/H ratio in the solar wind.

All six of the observations noted above can be understood if dynamic fractionation in the Sun enriches light mass nuclei at the solar surface. Several of these observations are unexplained if the fractionation relationship shown in Figure 1 was instead produced by the selective retention of heavy noble gas isotopes in planetary solids.

Before discussing the implications of solar fractionation for the abundances of the elements, it seems appropriate to acknowledge that several others have previously noted the possibility of a mass fractionation relationship between the isotopic compositions of solar and planetary noble gases (Signer and Suess, 1963; Manuel, 1967; Marti, 1969; Kuroda and Manuel, 1970; Srinivasan and Manuel, 1971). Failure to consider the possibility of fractionation in the Sun and the absence of information on the nature of two different types of planetary noble gases frustrated these early attempts to extract useful information from the fractionation relationship. For example, Kuroda and Manuel (1970) identified correlated mass fractionation effects in the isotopic compositions of planetary and solar Ne and Xe. However, they were unable to fit the fractionation relationship to the depletion pattern of terrestrial and meteoritic noble gases.

Srinivasan and Manuel (1971) had an advantage in trying to understand fractionation effects in He and Ne, noble gases that occur in only one planetary component, the type-X gases. They clearly recognized correlated fractionation in the isotopic compositions of planetary and solar-wind-implanted He and Ne, but they could not explain the almost identical values of the He/Ne ratio in these two gas reservoirs. The widespread belief that the bulk Sun has the same composition as the solar atmosphere undoubtedly contributed to their oversight of an obvious solution: Fractionation in the Sun might enrich light nuclei at the solar surface.

We conclude that the fractionation relationship between the isotopic compositions of planetary and solar-wind-implanted noble gases is caused by fractionation in the Sun



itself. Dynamic fractionation, probably from diffusive-like movement of nuclei to the solar surface, maintains a strong enrichment of lighter particles in the solar wind and at the solar surface. Less fractionated elemental and isotopic abundances are observed when the solar fractionation process is disrupted by high energy events, such as solar flares.

Finally, it seems appropriate to point out that solar fractionation is not unexpected. In discussing thermal diffusion, Chapman and Cowling (1952) noted that heavier ions will tend to diffuse towards the warmer region of an ionized gas. They concluded that, “This must happen in the sun and the stars, where thermal diffusion will assist pressure diffusion in concentrating the heavier nuclei towards the hot central regions” (Chapman and Cowling, Section 14.71, p. 255, 1952).

## ELEMENTAL FRACTIONATION

If the isotopic fractionation pattern shown in Figure 1 results from a solar process, the elemental abundances at the solar surface would be expected to show a similar fractionation effect. In other words, differences in the chemical properties that elements exhibit under normal conditions will be unimportant under the plasma conditions of a solar fractionation process, and the term  ${}^mG$  of Eq. (2) can be used to represent the isotope of mass,  $m$ , of any element,  $G$ .

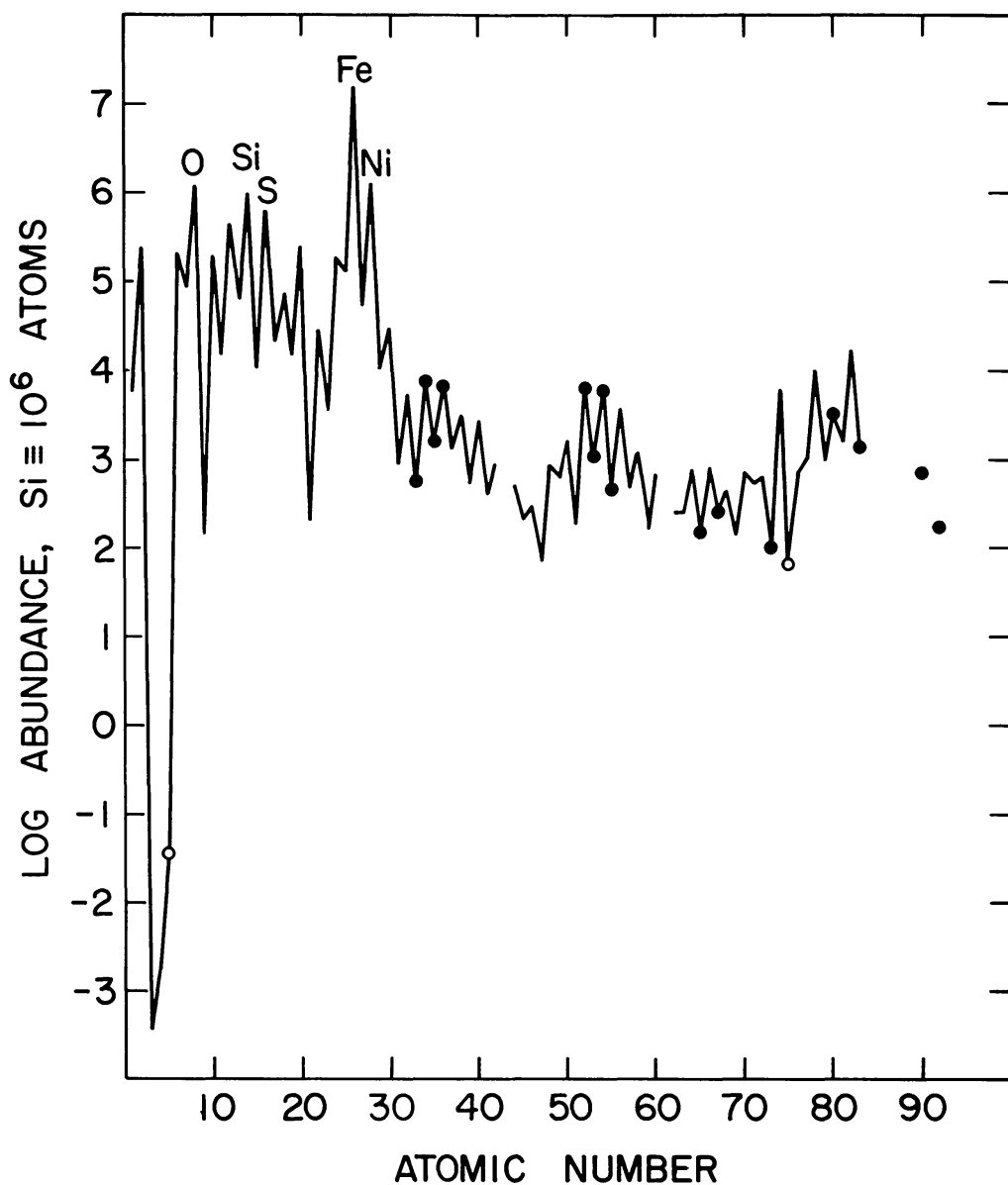
Figure 2 shows the solar elemental abundance pattern that is obtained when Eq. (2) is used to correct the solar surface abundance data (Ross and Aller, 1976) for fractionation. Chemical symbols are shown for the five most abundant elements. The open symbols at  $Z = 5$  and  $75$  (B and Re) represent upper limits from spectral data. The filled symbols represent other estimates (Cameron, 1973) of elements for which spectral data are missing.

The elemental abundance pattern shown in Figure 2 differs from the classical solar abundance pattern in the following ways.

1. A gradual slope from  $Z = 8$  to  $Z \sim 40$  replaces the steep exponential decrease in the classical abundance curve from  $Z = 1$  to  $Z \sim 40$ .
2. The abundance peak centered at  $Z = 26$  is more pronounced, and the most abundant element is Fe instead of H.
3. Above  $Z \sim 40$  the curve is essentially flat except for abundance peaks in the region of  $Z = 52-56$  and  $Z = 74-82$ .

The elemental abundance pattern shown in Figure 2 does not agree with the standard solar model, with classical estimates of the “cosmic” or “solar” abundance of chemical elements, nor with the analytical data of carbonaceous chondrites that is used to estimate “solar” abundances of many nonvolatile elements. Such an abrupt change of view may not seem justified for a solar model derived to explain only differences in the elemental and isotopic compositions of planetary and solar-wind-implanted noble gases. In order for the reader to appreciate other observations that favor the model presented here, it seems appropriate to digress for a brief review of recent developments pertaining to the origin of the Solar System.

Several years ago we suggested that the Solar System formed from the heterogeneous debris of a single supernova (Manuel and Sabu, 1975, 1977), with the Sun accumulating on the supernova core, iron meteorites and the cores of the terrestrial planets forming primarily from elements synthesized in the hot stellar interior, and the outer planets and carbonaceous phase of chondritic meteorites condensing from elements of the cooler



**Fig. 2** The abundance pattern of chemical elements in the bulk Sun. The pattern shown here was obtained by using Eq. (2) to correct solar surface abundance data (Ross and Aller, 1976). The open symbols represent upper limits for B and Re. Abundances of elements at the solar surface were used in all cases, except where other estimates (Cameron, 1973) had to be used for the elements represented by the darkened symbols.



outer zone — the only region which would contain low-Z elements. This conclusion was based primarily on the discovery that He and Ne trapped in meteorites always accompany isotopically anomalous Xe, Kr and Ar, and that no He and Ne is trapped in meteorite phases that contain isotopically normal Xe, Kr and Ar (Manuel and Sabu, 1975, 1977; Frick, 1977).

Isotopic anomalies from stellar nucleosynthesis reactions have been discovered in many other elements, and recent reviews by Podosek (1978), Lavrukhina (1980), Grossman (1980) and Clayton (1981) demonstrate widespread acceptance of the suggestion that the primitive solar nebula was chemically and isotopically heterogeneous. This is illustrated by the following quote from the conclusion of Grossman (1980): “In the coarse-grained inclusions alone, only 5% of the meteorite, we have uncovered remarkably well-preserved evidence for a supernova explosion that occurred just before condensation, for incompletely homogenized material from several nucleosynthetic sources and for solar nebular regions of different chemical and isotopic composition.”

If these recent conclusions of a heterogeneous solar nebula are correct, then chemical and isotopic gradients in the Solar System — rather than the abundance pattern of elements in a class of objects that formed in a particular region, e.g., the carbonaceous chondrites or the Jovian planets — should be the main criterion for evaluating the solar elemental abundance pattern. Below are a few observations that lend credence to the solar abundance pattern shown in Figure 2.

1. The abundance pattern shown in Figure 2 fits the general trend in the Solar System of increasing abundance of Fe toward the Sun. Fe-Ni accounts for < 1-2% of the mass of Jupiter, 30% of the mass of Mars, ~ 40% of the mass of Earth and Venus, and ~ 63% of the mass of Mercury (Miyake, 1965). The classical solar elemental abundance pattern does not fit this gradient in the abundance of Fe.
2. There are strong geochemical arguments in support of the view that the cores of the four inner planets formed in a central Fe-rich region of the protoplanetary nebula and then acted as accretion sites for troilite, silicates and other minerals of low-Z elements (Turekian and Clark, 1969; Vinogradov, 1975; Manuel and Sabu, 1975, 1977, 1981; Sabu and Manuel, 1980). Since the area between Mercury and the Sun is only  $\approx 0.6\%$  of that swept out by the four inner planets, for the classical solar system abundance pattern (Cameron, 1973; Ross and Aller, 1976) to be correct, a small void would be required in the middle of the central Fe-rich region suggested by the other studies. Although not impossible, uncertainties in our knowledge of events at the birth of the Solar System are rather broad compared to the abrupt elemental fine structure required to make the classical elemental abundance pattern of the Sun compatible with recent indications that Fe was highly enriched in the central part of the primitive nebula (Turekian and Clark, 1969; Vinogradov, 1975; Manuel and Sabu, 1975, 1977, 1981; Sabu and Manuel, 1980).
3. The abundance pattern of elements in carbonaceous chondrites is not a valid test of the solar abundance pattern. The presence of type-X noble gases (Manuel and Sabu, 1975, 1977; Sabu and Manuel, 1980) and isotopically anomalous Te (Ballad *et al.*, 1979; Oliver *et al.*, 1981) in the carbonaceous phase of chondrites led us to conclude several years ago that this phase consists mostly of elements from the outer layers of a supernova. Since high abundances of low-Z elements are expected in debris from the outer supernova layers, we suspect that abundances

of low-Z elements may be disproportionately high in carbonaceous chondrites. Isotopic anomalies of many other elements have been observed in carbonaceous chondrites, and these observations are frequently attributed to the presence of alien nucleogenetic material in this class of meteorites (Podosek, 1978; Srinivasan and Anders, 1978; Lavrukhina, 1980; Grossman, 1980; Clayton, 1981). Regardless whether carbonaceous chondrites contain material from outer layers of the single supernova from which the Solar System formed (Manuel and Sabu, 1975, 1977; Ballard *et al.*, 1979; Lavrukhina, 1980; Oliver *et al.*, 1981; Sabu and Manuel, 1980) or material from nucleosynthesis events totally alien to the rest of the Solar System (Podosek, 1978; Srinivasan and Anders, 1978; Lavrukhina, 1980; Grossman, 1980; Clayton, 1981), the discrepancy with the elemental abundance pattern of carbonaceous chondrites is not a valid objection to that shown in Figure 2.

4. We noted earlier that the fractionation relationship in the isotopes of He and Ne, and the near equality of the He/Ne ratio in planetary and solar-wind-implanted noble gases seem to require a much higher He/Ne ratio in ambient type-X gases than in the Sun. The abundance pattern in Figure 2 meets that requirement; the classical solar abundance pattern does not. This requirement is independent of the fractionation site.
5. We also noted earlier that the distribution of X and Y components in solar-wind-implanted Ar, Kr and Xe requires values of Xe/Kr and Kr/Ar ratios in the bulk Sun that are higher than those of type-X noble gases. The high abundances of heavy elements shown in Figure 2 probably meet that requirement; the Xe/Kr and Kr/Ar ratios there are approximately equal to those of the type-X gas that is trapped in meteoritic carbon. The classical solar elemental abundance pattern has much lower values for the Xe/Kr and Kr/Ar ratios.
6. Finally, it should be noted that the classical H-rich model of the Sun is fundamental to the theory of H-fusion as the source of the Sun's radiant energy. However, a large discrepancy has been found between H-fusion theory and the flux of solar neutrinos detected by their interaction with  $^{37}\text{Cl}$  (Bahcall and Davis, 1976). The solar abundance pattern shown in Figure 2, with the light nuclei enriched at the solar surface in the manner shown in Figure 1, would appear to exclude H-fusion as the primary energy source of the Sun. Thus, the elemental abundance pattern of Figure 2 is compatible with the results of the solar neutrino experiment (Bahcall and Davis, 1976); the classical elemental abundance pattern of the standard solar model is not.

It should also be noted that many of the arguments presented here mesh into a self-consistent network that is stronger than the individual arguments. One example is the agreement of the enhanced solar abundances of heavy elements shown in Figure 2 with the solar distribution of X and Y components shown in Table 1, column 4 for the bulk Sun. Another is the agreement between the low solar abundances of light elements shown in Figure 2, the low flux of solar neutrinos, and the mass-fractionation relationship that Eq. (2) predicts in the isotopic composition of planetary and solar-wind-implanted hydrogen and helium. Others have suggested that high values of the  $^3\text{He}/^4\text{He}$  and low values of the D/H ratio in the solar wind indicate the production of  $^3\text{He}$  from  $^2\text{H}$  during an early deuterium burning stage of the Sun (Geiss and Reeves, 1972; Boschler and Geiss, 1973; Smith *et al.*, 1978). However, our calculations show no evidence of residual

excess  $^3\text{He}$  (see Table 1) after the  $^3\text{He}/^4\text{He}$  ratio of the solar wind is corrected for the fractionation observed in the  $^{22}\text{Ne}/^{20}\text{Ne}$  ratio. It can be seen from Figure 1 that these same calculations predict a low value for the D/H ratio in the solar wind. Since deuterium fusion should occur at relatively low temperatures, the absence of excess  $^3\text{He}$  from this reaction in an early stage of the Sun's evolution is consistent with the absence of neutrinos from the fusion of hydrogen there now (Bahcall and Davis, 1976).

For the reasons cited above, we conclude that the elemental abundance pattern of Figure 2 better represents the bulk chemical composition of the Sun than does the classical abundance pattern of elements at the solar surface (Cameron, 1973; Ross and Aller, 1976).

## CONCLUSIONS AND PROPOSED TESTS

The isotopic compositions of solar-wind-implemented noble gases can be resolved in terms of the two major planetary noble gas components, once consideration is given to correlated fractionation in the isotopic abundances of all five noble gases. Dynamic fractionation, probably by diffusive movement of lighter particles to the Sun's surface (Chapman and Cowling, 1952), maintains a strong enrichment of lighter nuclei in the solar wind and at the solar surface. The classical "solar" abundance pattern of the chemical elements thus represents only the severely fractionated material at the solar surface. The fractionation-corrected abundance pattern of elements in the bulk Sun is also unlike the "cosmic" abundance pattern, but it does fit the Sun into the pattern of chemical and isotopic gradients that are observed in the rest of the Solar System.

Similarities between the "solar" and "cosmic" abundance patterns suggest that surface abundances of other stars may also be fractionated. Stellar fractionation might thereby explain the occurrence of large mass-dependent fractionation effects in the isotopes of O and Mg in meteorite inclusions that also contain nucleogenetic isotopic anomalies, e.g., the FUN inclusions of Allende (Grossman, 1980).

The most abundant element in the Sun is Fe, and other elements having atomic abundances of 2-6% are Ni, O, Si, S and Mg. Elements with atomic abundances of  $\approx 1\%$  include He, C, Ne, Ca and Cr. This composition of the bulk Sun and the strong enrichment of light elements at the cooler solar surface seem to exclude hydrogen fusion as the Sun's primary source of energy.

The elemental abundance pattern shown in Figure 2 is compatible with the results of the solar neutrino experiment (Bahcall and Davis, 1976), although the conclusions reached here offer no explanation for the Sun's radiant energy. Fission of actinides at the abundance level shown in Figure 2 could maintain the Sun's current rate of energy emission for only  $1.3 \times 10^7$  yr. The chemical composition of the Sun shown in Figure 2 and the isotopic components of solar noble gases shown in Table 1 are consistent with our earlier suggestion that the Solar System formed from the heterogeneous debris of a single supernova, with the Sun forming on the supernova core (Manuel and Sabu, 1975, 1977; Sabu and Manuel, 1980). Our conclusions are also compatible with the suggestion that the center of the Sun is a black hole (Clayton *et al.*, 1975), but we do not have the background to comment on their suggestion that solar radiation might result from the accretion of surrounding material into the central black hole.

The conclusions of this and our earlier papers on the origin of the Solar System (Manuel and Sabu, 1975, 1977; Sabu and Manuel, 1980) may seem extreme and controversial. It seems appropriate to end by listing a few viable tests for these conclusions.

1. The proposed solar site for fractionation could be tested by isotopic analysis of refractory elements, such as Mg or Sr, in the solar wind. The indigenous abundances of such elements in lunar soils are too high to permit isolation of the solar-wind-implanted component, but sufficient quantities for analysis could be gathered using collector foils at 1 AU from the Sun. Volatility would be unimportant for solar fractionation, and light isotopes of Mg and Sr would be enriched in the manner of Ne and Kr, respectively.
2. Target nuclei other than  $^{37}\text{Cl}$ , e.g.,  $^{71}\text{Ga}$  and  $^7\text{Li}$ , have been proposed for the detection of solar neutrinos from fusion reactions. The elemental abundance pattern in Figure 2 suggests that these targets would also detect far less neutrinos than expected if the standard solar model is correct.
3. Isotopic analysis of Xe in the He-rich atmosphere of Jupiter may be made in the upcoming Galileo mission. The finding of Xe-X there would provide experimental support for our suggestion that Jupiter consists mostly of elements from outer supernova layers and that the elemental abundance pattern there is not a valid criterion for that of the Sun.

## ACKNOWLEDGMENTS

We are grateful to E.C. Alexander, Jr., D.D. Clayton, C.M. Hohenberg, Gary R. Huss, Ichiro Kaneoka, Paul Pellas, Mitsunobu Tatsumoto and an anonymous reviewer for comments, and to NSF Grant NSF EAR8207588 for support of our work.

## REFERENCES

- Bahcall, J.N. and R. Davis, Jr.**, 1976. Solar-neutrinos: A scientific puzzle. *Science* **191**, 264-267.
- Ballad, R.V., L.L. Oliver, R.G. Downing and O.K. Manuel**, 1979. Isotopes of tellurium, xenon and krypton in Allende meteorite retain record of nucleosynthesis. *Nature* **277**, 615-620.
- Boulos, M.S. and O.K. Manuel**, 1971. The xenon record of extinct radioactivities in the earth. *Science* **174**, 1334-1336.
- Boschler, P. and J. Geiss**, 1973. Solar abundances of light nuclei and mixing of the sun. *Solar Physics* **32**, 3-17.
- Cameron, A.G.W.**, 1973. Abundances of the elements in the solar system. *Space Sci. Rev.* **15**, 121-146.
- Chapman, S. and T.G. Cowling**, 1952. *The Mathematical Theory of Non-Uniform Gases*, Cambridge University Press, 431 pp.
- Clayton, D.D.**, 1981. Some key issues in isotopic anomalies: Astrophysical history and aggregation. *Proc. Lunar Planet. Sci.* **12B**, 1781-1802.
- Clayton, D.D., M.J. Newman and R.J. Talbot, Jr.**, 1975. Solar models of low neutrino-counting rate: The central black hole. *Astrophys. J.* **201**, 489-493.
- Eberhardt, P., J. Geiss, H. Graf, N. Grögler, M.D. Mendia, M. Mörgeli, H. Schwaller, A. Stettler, U. Krähenbühl and H.R. von Gunten**, 1972. Trapped solar wind noble gases in Apollo 12 lunar fines 12001 and Apollo 11 breccia 10046. *Proc. 3rd Lunar Sci. Conf.*, 1821.
- Epstein, S. and H.P. Taylor, Jr.**, 1971.  $\text{O}^{18}/\text{O}^{16}$ ,  $\text{Si}^{30}/\text{Si}^{28}$ , D/H, and  $\text{C}^{13}/\text{C}^{12}$  ratios in lunar samples. *Proc. Lunar Sci. Conf. 2nd*, 1421-1441.

- Frick, U.**, 1977. Anomalous krypton in the Allende meteorite. *Proc. Lunar Sci. Conf. 8th*, 273-292.
- Frick, U., H. Baur, H. Ducati, H. Funk, D. Phinney and P. Signer**, 1975. On the origin of helium, neon, and argon isotopes in sieved mineral separates from an Apollo 15 soil. *Proc. Lunar Sci. Conf. 6th*, 2097-2129.
- Geiss, J. and H. Reeves**, 1972. Cosmic and solar system abundances of deuterium and helium-3. *Astron. Astrophys.* **18**, 126-132.
- Geiss, J.**, 1973. Solar wind composition and implications about the history of the solar system. *Proc. 13th Int. Cosmic Ray Conf.* **5**, 3375-3398.
- Grossman, L.**, 1980. Refractory inclusions in the Allende meteorite. *Ann. Rev. Earth Planet. Sci.* **8**, 559-608.
- Kuroda, P.K. and O.K. Manuel**, 1970. Mass fractionation and isotope anomalies in neon and xenon. *Nature* **227**, 1113-1116.
- Lavrukhina, A.K.**, 1980. On the nature of the isotopic anomalies in meteorites. *Nukleonika* **25**, 1495-1515.
- Manuel, O.K.**, 1967. Noble gases in the Fayetteville meteorite. *Geochim. Cosmochim. Acta* **31**, 2413-2431.
- Manuel, O.K.**, 1977. Reply to E.A. Anders 'A Superheavy Element in Meteorites'. *Proceedings of the Robert A. Welch Foundation Conferences on Chemical Research XXI. Cosmochemistry* (ed. Milligan, W.O.) 263-272 (The Robert A. Welch Foundation, Houston, TX, 1977).
- Manuel, O.K. and G. Hwaung**, 1983. Information of astrophysical interest in the isotopes of solar wind implanted noble gases. *Lunar Planet Sci. XIV*, 458-459.
- Manuel, O.K. and D.D. Sabu**, 1975. Elemental and isotopic inhomogeneities in noble gases: The case for local synthesis of the chemical elements. *Trans. Mo. Acad. of Sciences* **9**, 104-122.
- Manuel, O.K. and D.D. Sabu**, 1977. Strange xenon, extinct superheavy elements, and the solar neutrino puzzle. *Science* **195**, 208-209.
- Manuel, O.K. and D.D. Sabu**, 1981. The noble gas record of the terrestrial planets. *Geochem. J.* **15**, 245-267.
- Manuel, O.K., R.J. Wright, D.K. Miller and P.K. Kuroda**, 1972. Isotopic compositions of rare gases in the carbonaceous chondrites Mokoia and Allende. *Geochim. Cosmochim. Acta* **36**, 961-983.
- Marti, K.**, 1969. Solar-type xenon; a new isotopic composition of xenon in the Pesyanoe meteorite. *Science* **166**, 1263-1265.
- Merrihue, C.M., R.O. Pepin and J.H. Reynolds**, 1962. Rare gases in the chondrite Pantar. *J. Geophys. Res.* **67**, 2017-2021.
- Miyake, Y.**, 1965. *Elements of Geochemistry*, Maruzen Co., Ltd., Tokyo, 475 pp.
- Oliver, L.L., R.V. Ballad, J.F. Richardson and O.K. Manuel**, 1981. Isotopically anomalous tellurium in Allende: Another relic of local element synthesis. *J. Inorg. Nucl. Chem.* **43**, 2207-2216.
- Podosek, F.A.**, 1978. Isotopic structures in solar system materials. *Ann. Rev. Astron. Astrophys.* **16**, 293-334.
- Reynolds, J.H., U. Frick, J.M. Neil and D.L. Phinney**, 1978. Rare-gas-rich separates from carbonaceous chondrites. *Geochim. Cosmochim. Acta* **42**, 1775-1797.
- Robbins, D.E., A.J. Hundhausen and S.J. Bame**, 1970. Helium in the solar wind. *J. Geophys. Res.* **75**, 1178-1182.

- Ross, J.E. and L.H. Aller**, 1976. The chemical composition of the Sun. *Science* **191**, 1223-1229.
- Sabu, D.D. and O.K. Manuel**, 1980. Noble gas anomalies and synthesis of the chemical elements. *Meteoritics* **15**, 117-138.
- Signer, P. and H.E. Suess**, 1963. Rare gases in the Sun, in the atmosphere, and in meteorites. In *Earth Sciences and Meteorites*, J. Geiss and E.D. Goldberg, eds., North-Holland, 241-272.
- Smith, S.P., J.C. Huneke and G.J. Wasserburg**, 1978. Neon in gas-rich samples of the carbonaceous chondrites Mokoia, Murchison and Cold Bokkeveld. *Earth Planet. Sci. Lett.* **39**, 1-13.
- Srinivasan, B. and E.A. Anders**, 1978. Noble gases in the Murchison meteorite: Possible relics of s-process nucleosynthesis. *Science* **201**, 51-56.
- Srinivasan, B. and O.K. Manuel**, 1971. On the isotopic composition of trapped helium and neon in carbonaceous chondrites. *Earth Planet. Sci. Lett.* **12**, 282-286.
- Suess, H.E.**, 1949. Die Häufigkeit der Edelgase auf der Erde und in Kosmos. *J. Geol.* **57**, 600-607.
- Turekian, K.K. and S.P. Clark, Jr.**, 1969. Inhomogeneous accumulation of the earth from the primitive solar nebula. *Earth Planet. Sci. Lett.* **6**, 346-348.
- Vinogradov, A.P.**, 1975. Formation of the metal cores of the planets. *Geokhimiya* **10**, 1427-1431.

Manuscript received 6/15/83