

# NOBLE GAS ANOMALIES AND SYNTHESIS OF THE CHEMICAL ELEMENTS

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*There are two types of planetary noble gases: One, containing isotopically "anomalous" argon, krypton and xenon but isotopically "normal" helium and neon, was derived from outer stellar regions. The other, consisting almost entirely of isotopically "normal" argon, krypton and xenon, with little or no helium or neon, was derived from inner stellar regions.*

*Mixing of nucleosynthesis products from different regions of a supernova is responsible for the observed correlations between elemental and isotopic ratios of planetary noble gases in different classes of meteorites. The solar system condensed directly from the chemically and isotopically heterogeneous debris of a single supernova.*

*There is no convincing evidence, however, of separate nucleogenetic components in neon. Fractionation and spallation can account for all previously identified components of trapped meteoritic neon, Ne-A, Ne-B, Ne-C, Ne-D, Ne-E, Ne-Al, Ne-A2, Ne-E(L), Ne-E(H) and Ne-O, and this same mechanism also explains differences between the isotopic compositions of meteoritic, atmospheric, and solar wind neon.*

*Variations in the abundance pattern of planetary noble gases are primarily the result of stellar fusion reactions and physical adsorption, rather than gas solubility.*

## INTRODUCTION

Measurements of the abundance and isotopic composition of noble gases have provided a wealth of information on the origin of the chemical elements and the history of the solar system, as shown in the reviews by Bogard (1971), Reynolds (1977) and Podosek (1978). Generally it had been assumed that solids condensed from a homogeneous mixture of chemical elements of solar proportions (Larimer and Anders, 1967; Grossman and Larimer, 1974). Thus differences in the abundance patterns of noble gases were attributed to physical processes, such as adsorption, solubility, metamorphism or exposure to the solar wind, and differences in the isotopic compositions of noble gases were assigned to *in situ* nuclear processes which

occurred since condensation of matter to form planetary solids. There has been some overlap in these two noble gas records, *e.g.*, physical fractionation was found to be responsible for some variations in the isotopic composition of the solar-wind implanted noble gases in meteoritic (Manuel, 1967) and lunar (Srinivasan, 1973) samples, but even in these cases the largest fractional changes in isotopic compositions were assigned to *in situ* nuclear reactions.

However, in 1972 it was noted that carbonaceous chondrites contain two isotopically distinct components of trapped Xe which could not be explained on the basis of nuclear or fractionation processes within the meteorites, *i.e.*, these two isotopically distinct components of Xe had existed *prior* to incorporation into the meteoritic minerals (Manuel *et al.*, 1972). The isotopically anomalous Xe, labeled X, was shown to be enriched in both the proton-rich and the neutron-rich isotopes, and it was noted that the isotopic anomaly pattern seen in Xe-X might have been produced in a nearby supernova *via* the *p*- and *r*-processes of nucleosynthesis described by Burbidge *et al.* (1957). Subsequent studies have revealed the presence of isotopically anomalous tellurium and uranium (Arden, 1977; Tatsumoto and Shimamura, 1980; Ballad *et al.*, 1979) in the host phase of Xe-X (Lewis *et al.*, 1975).

A hint of the light isotope enrichment of Xe-X had been seen earlier in Renazzo by Reynolds and Turner (1964). Sabu and Manuel (1974) suggested that Xe-X constitutes an appreciable fraction of bulk, meteoritic and solar-type Xe, and later proposed Xe-Y for the component which remains after subtraction of Xe-X from bulk AVCC Xe (Sabu and Manuel, 1976a). Thus, Xe-X is enriched in *r*- and *p*-products of nucleosynthesis and Xe-Y is enriched in *s*-products of nucleosynthesis. Alternately, the same nucleogenetic properties of these two xenon components could be indicated by stating that Xe-X is deficient in *s*-products and Xe-Y is deficient in *r*- and *p*-products of nucleosynthesis.

For many years it was thought that there were only two types of noble gases in meteorites, one consisting of unfractionated gases, called “solar”, and another comprised of fractionated gases, called “planetary” (see review by Pepin and Signer, 1965). However, it has been shown that the two isotopically distinct forms of xenon, Xe-X and Xe-Y, are indicative of two types of planetary noble gases (Manuel and Sabu, 1975, 1977; Sabu and Manuel, 1976a, 1976b; Frick, 1977; Reynolds *et al.*, 1978; Frick and Pepin, 1980). Type-X noble gases contain isotopically “strange” components of Xe, Kr and Ar which are hereafter referred to as Xe-X, Kr-X and Ar-X. Type-X compositions are those which Pepin and Signer (1965) call “planetary”. Type-Y noble gases contain only Ar, Kr and Xe, and these are isotopically normal or “planetary”. Thus, the original term “planetary” actually referred to a mixture of He and Ne from type-X gases and Ar, Kr and Xe from type-Y gases.

The division of primordial noble gases into two basic groups, type-X gases from the outer stellar layers and type-Y gases from the stellar interior,

may be further subdivided as additional analyses indicate characteristic elemental and isotopic compositions for other subdivisions, such as those which are associated with the *s*-products of meteoritic Xe and Kr (Srinivasan and Anders, 1978; Ballad *et al.*, 1979; Alaerts *et al.*, 1980). In fact, Pepin and Phinney (1979) have attempted to subdivide the isotopes of meteoritic Xe alone by multidimensional correlation analysis, apparently unaware of the constraints imposed by correlations between the isotopic ratios of Xe with those of Ar and Kr and with elemental ratios of the noble gases (Manuel and Sabu, 1975, 1977; Sabu and Manuel, 1976b; Frick, 1977). Some of these subdivisions are, in our opinion, arbitrary because the authors ignore the elemental and isotopic correlations of Xe with other noble gases.

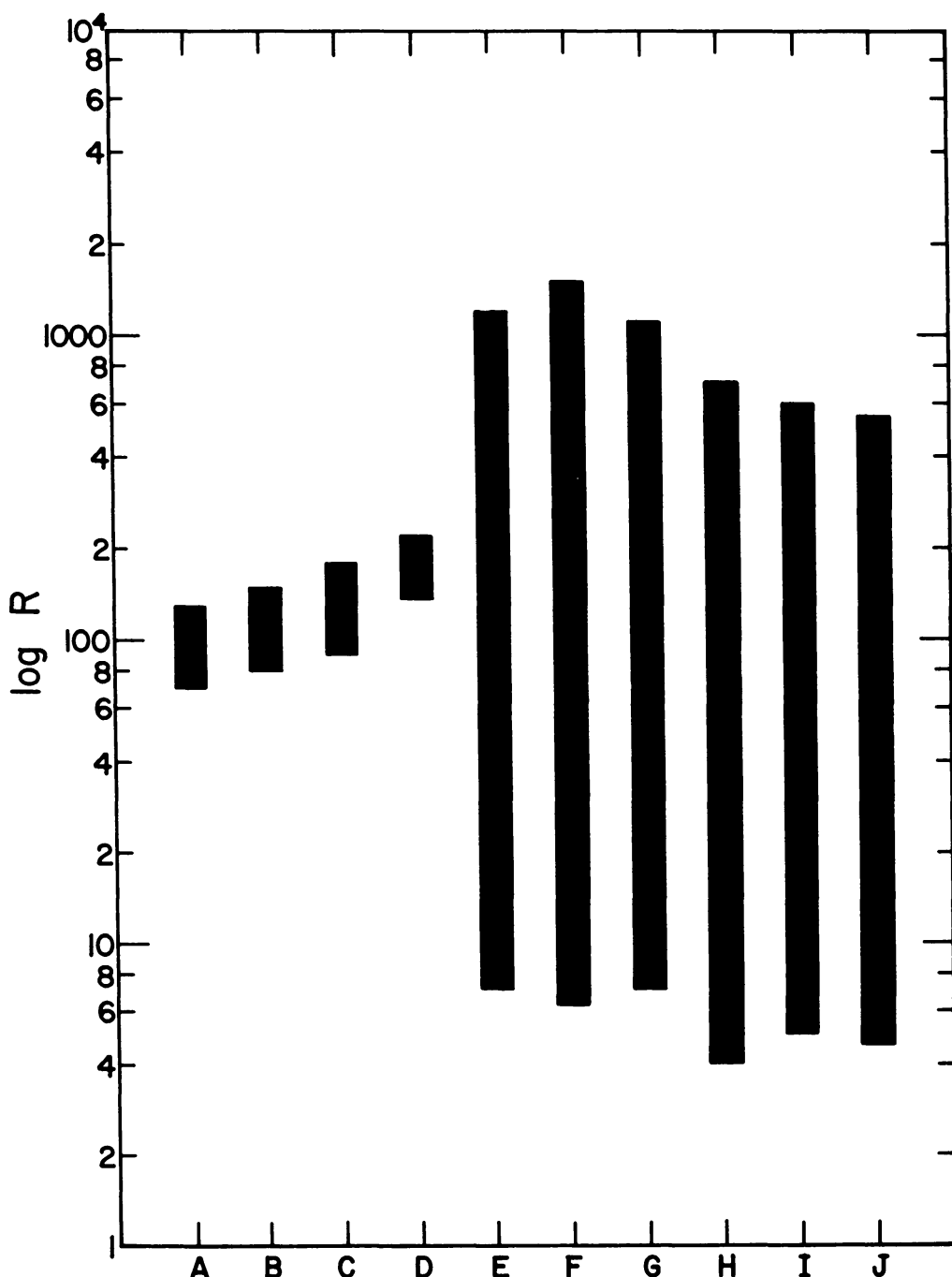
An earlier version of this paper was submitted for publication, widely circulated and cited as a preprint (Frick and Moniot, 1976, 1977; Lattimer *et al.*, 1978). In the present version, we have retained the same divisions of planetary noble gases, X and Y, and the designation of solar-wind-implanted gas (Suess *et al.*, 1964) as type-S. The present report differs from the earlier one mainly in the consideration of additional noble gas data which have become available since 1976.

## ISOTOPIC AND ELEMENTAL ABUNDANCE PATTERNS

Anders and coworkers have shown that the major noble gas carrying phases of chondrites are in HC1, HF-resistant residues (Lewis *et al.*, 1975, 1977a; Srinivasan *et al.*, 1977). The acid-etched residues contain the host phase of both planetary noble gases, type-X and type-Y, but the host phases of most type-S gases are HC1, HF soluble. According to the Chicago group the host phase of type-Y gases is the hypothetical mineral "Q" and the host phases of type-X gases are carbon and chromite. However, studies at Berkeley indicate that carbon is the major host phase of both planetary noble gases (Frick, 1977; Frick and Reynolds, 1977; Frick and Chang, 1978; Reynolds *et al.*, 1978), and a recent study at Minnesota strongly supports this (Frick and Pepin, 1980). This latest study does not, however, conflict with reports of an extreme form of type-Y noble gases, highly enriched in *s*-products, in phases such as spinels (Srinivasan and Anders, 1978; Ballad *et al.*, 1979).

To demonstrate differences in the elemental abundance patterns for type-X and type-Y noble gases in residues of chondrites, the range of values for each elemental ratio, *R*, is shown in Figure 1. Included there are noble gas ratios in the residues of Allende (Lewis *et al.*, 1975; 1977a), Ornans, Kansaz, Lancé (Alaerts *et al.*, 1979a), Krymka, Bishunpur, Chainpur, Parnallee, Hamlet, Olivenza, St. Severin, Manbhoom and Dhurmsala chondrites (Alaerts *et al.*, 1979b). The three elemental ratios on the left,  $R_A = (^{84}\text{Kr}/^{132}\text{Xe}) \times 10^2$ ,  $R_B = ^{36}\text{Ar}/^{132}\text{Xe}$  and  $R_C = ^{36}\text{Ar}/^{84}\text{Kr}$ , consist only of the three heavy noble gases, Ar, Kr and Xe. The relative abundances of these are very similar

in both types of planetary noble gases; hence, the ratios exhibit very limited ranges. The next elemental ratios,  $R_D = {}^4\text{He}/{}^{20}\text{Ne}$ , consists of the light gases which occur only in type-X planetary noble gases, and the ratio is remarkably constant. However, the last six ratios,  $R_E = {}^4\text{He}/{}^{36}\text{Ar}$ ,  $R_F = ({}^4\text{He}/{}^{84}\text{Kr}) \times 10^{-2}$ ,



**Fig. 1** Variations in the range of elemental noble gas ratios,  $R$ , in gas-rich residues of chondrites. The very limited ranges of  $R_A$ ,  $R_B$ ,  $R_C$  and  $R_D$ , representing  $({}^{84}\text{Kr}/{}^{132}\text{Xe}) \times 10^2$ ,  $({}^{36}\text{Ar}/{}^{132}\text{Xe})$ ,  $({}^{36}\text{Ar}/{}^{84}\text{Kr})$  and  $({}^4\text{He}/{}^{20}\text{Ne})$ , respectively, are in sharp contrast to the extended ranges displayed by  $R_E$ - $R_J$ , representing  $({}^4\text{He}/{}^{36}\text{Ar})$ ,  $({}^4\text{He}/{}^{84}\text{Kr}) \times 10^{-2}$ ,  $({}^4\text{He}/{}^{132}\text{Xe}) \times 10^{-2}$ ,  $({}^{20}\text{Ne}/{}^{84}\text{Kr})$ ,  $({}^{20}\text{Ne}/{}^{132}\text{Xe})$  and  $({}^{20}\text{Ne}/{}^{36}\text{Ar}) \times 10^2$ , respectively.

$R_G = (^4\text{He}/^{132}\text{Xe}) \times 10^{-2}$ ,  $R_H = ^{20}\text{Ne}/^{84}\text{Kr}$ ,  $R_I = ^{20}\text{Ne}/^{132}\text{Xe}$  and  $R_J = (^{20}\text{Ne}/^{36}\text{Ar}) \times 10^2$ , show large variations because the gas in the numerator of each ratio occurs only in type-X, but the gas in the denominator occurs in both type-X and type-Y, planetary noble gases. Low values of these last six elemental ratios are associated with Ar, Kr and Xe having isotopic compositions characteristic of type-Y planetary gases; high values of these last six elemental ratios are associated with Ar, Kr and Xe having isotopic compositions characteristic of type-X planetary gases.

The limited extent of the first three ratios demonstrates correlated abundances of Ar, Kr and Xe. Similarly, the limited range of the fourth ratio indicates correlated abundances of He and Ne. The wide range of values for the last six elemental ratios demonstrates the lack of correlation between abundances of light and heavy noble gases, and the limited range of ratio  $R_D$  shows that mass fractionation is not responsible for the variations observed in ratios  $R_{E-J}$ .

The correlation of He and Ne is a common property of meteoritic noble gases. Figure 2 shows the concentrations of these two noble gases in all of the residues shown in Figure 1, and in bulk carbonaceous chondrites (C1, C2 and C3) except those with solar-wind implanted gases. Data for the gases in bulk chondrites are from the compilation by Mazar *et al.* (1970). The residues shown by darkened symbols are highly enriched in He and Ne, compared to bulk samples shown by the open symbols. Data points on the upper right end of the correlation in Figure 2 exhibit isotopic compositions characteristic of Ar-X, Kr-X and Xe-X for those residues which have been etched in oxidizing acids. Type-Y noble gases, containing Ar, Kr and Xe but no He or Ne, are in a  $\text{HNO}_3$ -soluble phase (Manuel and Sabu, 1975, 1977; Sabu and Manuel, 1976b; Manuel, 1979, 1980). The abundances of the two light gases in bulk carbonaceous chondrites follow the same trend as that in their residues, as expected if He and Ne occur only in the type-X planetary noble gases. Thus, it appears that all of the He and Ne in bulk carbonaceous chondrites, which have not been exposed to the solar-wind, reside in a small, carbon-rich fraction ( $< 0.5\%$  by weight) of the bulk chondrite.

Differences in the abundance patterns of the two types of planetary noble gases and solar-wind implanted noble gases can be illustrated in terms of the depletion factor,  $D$  (Suess, 1949).

$$D = (\text{Observed Abundance})/(\text{Solar Abundance}) \quad (1)$$

The abundance patterns of type-X, -Y and -S noble gases are shown as values of  $\log D$  in Figure 3, normalized to the abundances of solar-wind implanted noble gases in the Pesyanoe achondrite (Marti, 1969). Thus, the abundance pattern of noble gases in Pesyanoe are indicated by the open symbols at  $\log D \equiv 0$ .

The abundance pattern of type-X noble gases, shown in the upper left section of Figure 3, varies as a smooth function of mass. The gases shown

there are in residues of Allende which have been etched with oxidizing acids, 4C57 (Lewis *et al.*, 1977a) and 3CS4 (Lewis *et al.*, 1975).

The abundance pattern of type-Y noble gases, shown in the lower left section of Figure 3, is similar to that of type-X for the three heavy noble gases, but there are negligible amounts of He and Ne in type-Y gases. The gases shown there are in mineral "Q" (Lewis *et al.*, 1975) and in a bulk sample of the Kenna ureilite (Wilkening and Marti, 1976). Although the Chicago group reports that "Q" contains He and Ne, the experimental data consistently define correlations which suggest that there is little or no He or Ne in the noble gas component which contains "fission-free" or type-Y xenon (Manuel and Sabu, 1975, 1977; Sabu and Manuel, 1976b; Manuel, 1979, 1980). The confusion may result from the fact that carbon is slightly soluble in oxidizing acids, and the Chicago group defines "Q" as that which dissolves under various experimental conditions, *e.g.*, by their "definition" only "Q" dissolves in conc.  $\text{HNO}_3$  at  $80^\circ\text{C}$  for 3.5 hrs (Lewis *et al.*, 1975), or in red fuming  $\text{HNO}_3$  at  $70^\circ\text{C}$  for 16 hrs (Lewis *et al.*, 1977a), or in aqua regia (Anders, 1978), etc. Frick and Pepin (1980) have recently shown that

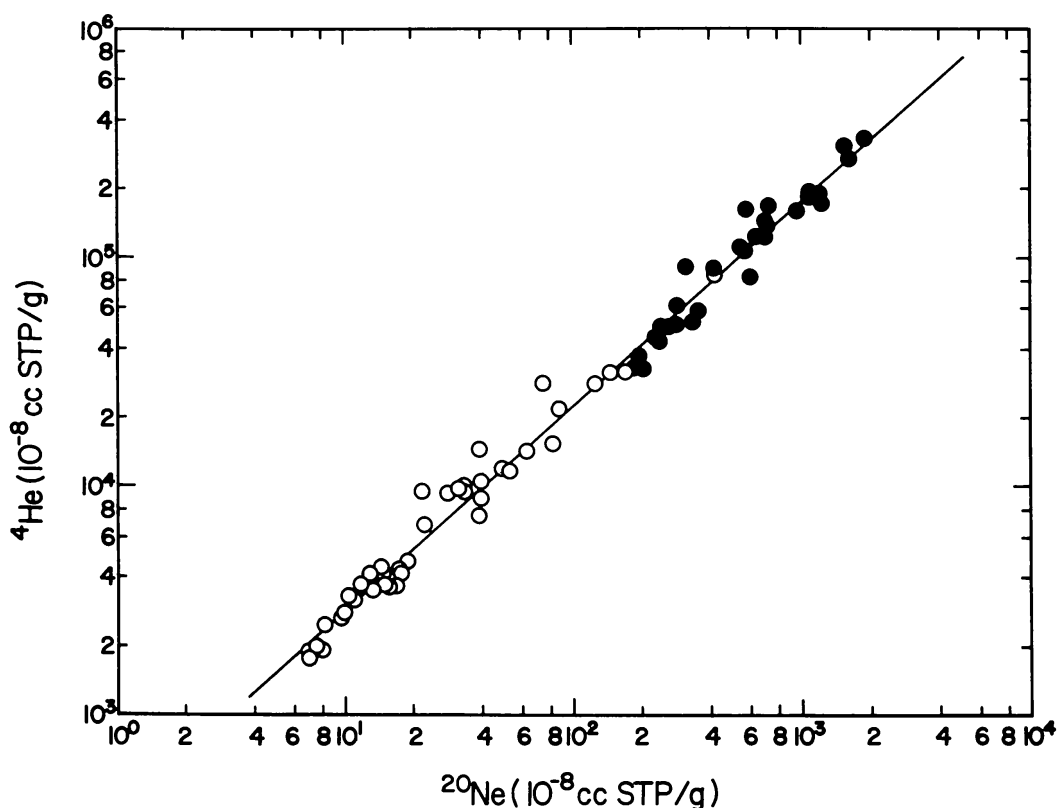


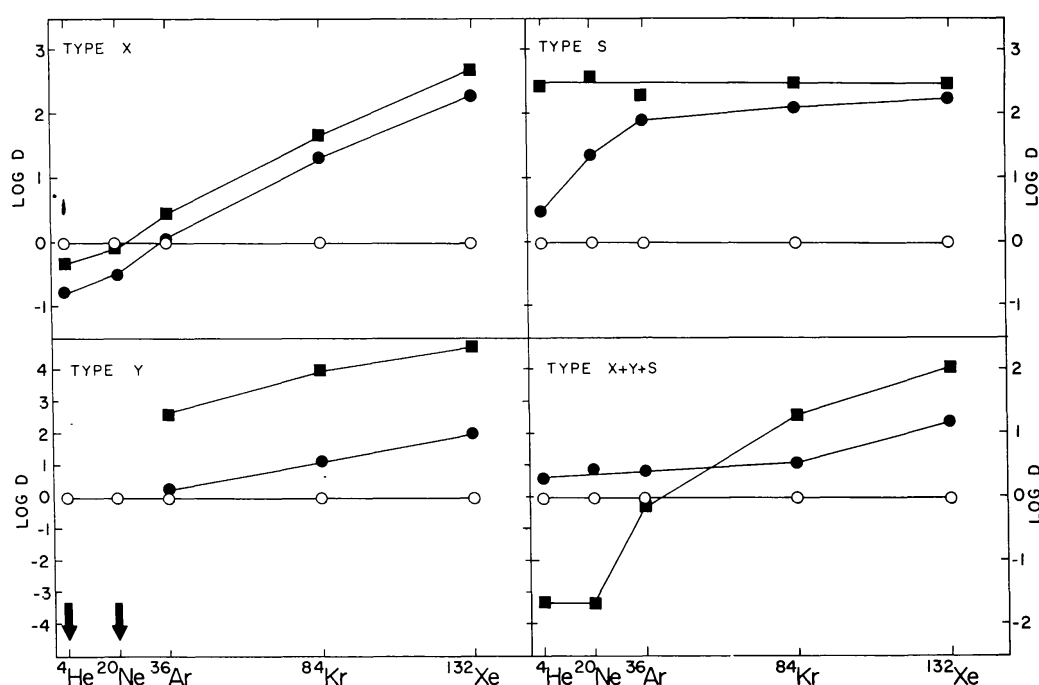
Fig. 2 The correlation of elemental abundances of He and Ne in gas-rich residues (●) and bulk carbonaceous chondrites (○). The common correlation of these gases in carbon-rich residues and in bulk samples suggests that carbon is the carrier of all He and Ne in carbonaceous chondrites.



combustible carbonaceous material is the carrier of both type-X and type-Y gases in Allende residues, and we will show below that neither He nor Ne are associated with noble gases having characteristic type-Y isotopic compositions.

The abundance pattern of type-S noble gases, those implanted by the solar-wind, are shown in the upper right section of Figure 3. The ilmenite fraction of lunar soils, # bb-57 (Eberhardt *et al.*, 1972), contains noble gases in approximately the same proportions as Pesyanoe (Marti, 1969), but the bulk grain fraction of those soils, # bb-12, shows evidence of fractionation, as noted earlier by Eberhardt *et al.* (1972).

Most meteorite samples seem to contain mixtures of these three types of noble gases in varying proportions, as illustrated by the two meteorites in the lower right section of Figure 3. The abundances of the light noble gases in Fayetteville are predominantly solar, but the xenon is predominantly type-Y (Müller and Zähringer, 1966; Manuel, 1967). The noble gases in the Tonk, C-1 carbonaceous chondrite (Mazor *et al.*, 1970) are predominantly a mixture of the two planetary noble gases. Although not shown in Figure 3, the heavy



**Fig. 3** The different abundance patterns of noble gases identified as type-X (upper left), type-Y (lower left), type-S (upper right) and mixtures of these (lower right). Examples of type-X gases are those in the acid-etched residues of Allende, 4C57 (■) and 3CS4 (●). Examples of type-Y gases are those in Allende's mineral "Q" (■) and in the Kenna ureilite (●). Examples of type-S gases are those in the ilmenite fraction of lunar soil, # bb57 (■), and in the bulk lunar soil, # bb12 (●). Mixtures of these are indicated by the noble gases in bulk samples of the Tonk carbonaceous chondrite (■) and the Fayetteville meteorite (●). References are in text.

noble gases, Ar, Kr and Xe, in urelites (Wilkening and Marti, 1976; Göbel *et al.*, 1978) and in the Earth (Manuel and Sabu, 1980) are planetary type-Y, but their He and Ne are of solar wind origin.

The association of He and Ne with type-X noble gases, characterized by anomalously low values of the  $^{134}\text{Xe}/^{136}\text{Xe}$  ratio, is illustrated in Figure 4. All of the data shown there are from analyses of acid-etched residues of the carbonaceous chondrites, Allende (Lewis *et al.*, 1975, 1977a), Murray (Reynolds *et al.*, 1978), Ornans (Srinivasan *et al.*, 1977; Alaerts *et al.*, 1979a), Orgueil (Frick and Moniot, 1977), Cold Bokkeveld (Reynolds *et al.*, 1978), Kainsaz and Lancé (Alaerts *et al.*, 1979a), the enstatite chondrite Abee (Srinivasan *et al.*, 1977) and the ordinary chondrites, Krymka, Bishunpur, Chainpur, Parnallee and Hamlet (Alaerts *et al.*, 1979b). Residues of Allende have been most extensively studied, and the results of these analyses are represented by darkened symbols.

The two lines in each section of Figure 4 represent a typical  $1\sigma$  spread of  $\pm 10\%$  in the elemental abundance measurements. Linear correlations are only expected for a two component system on such diagrams if a common dominator is used. The two diagrams on the left show that most of the data

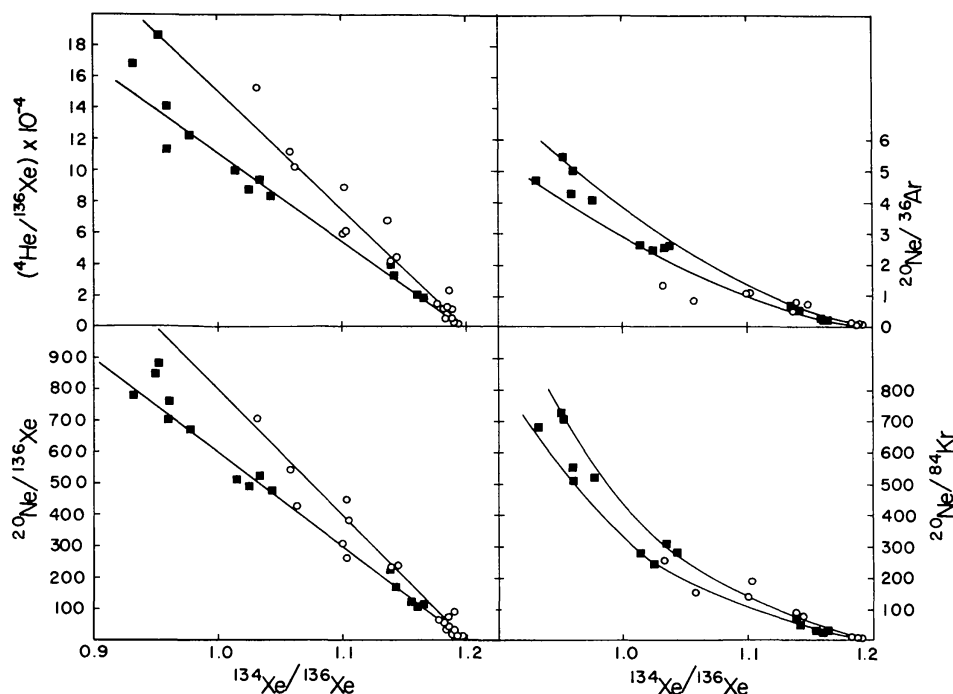


Fig. 4 Correlations between elemental and isotopic ratios of noble gases in acid-etched meteorite residues. The correlations and their intercepts at  $\text{He} = \text{Ne} = 0$  are the result of mixing type-X and type-Y planetary noble gases. The dark squares represent the noble gases in residues of Allende and the open circles represent noble gases in residues of other meteorites.



indeed form a linear array within the  $1\sigma$  limits, and the elemental abundances of He and Ne extrapolate to zero at  $^{134}\text{Xe}/^{136}\text{Xe} = 1.2$ . In both Allende's mineral "Q" (Lewis *et al.*, 1975) and in the Kenna ureilite (Wilkening and Marti, 1976), the two examples of type-Y noble gases shown in Figure 3, trapped Xe is characterized by  $^{134}\text{Xe}/^{136}\text{Xe} = 1.21$ .

Thus, the linear correlations shown on the left, between elemental and isotopic ratios, are the result of mixing type-X gases, which contain He, Ne and isotopically "anomalous" Xe, with type-Y gases which contain "normal" Xe but little or no He or Ne. Correlations between other isotopic ratios of Ar, Kr and Xe with elemental abundances of He and Ne have been shown earlier for individual meteorites (Manuel and Sabu, 1975, 1977; Sabu and Manuel, 1976b; Ballad *et al.*, 1979; Manuel, 1980). In all cases, the gases in individual meteorites also yield He = Ne = 0 at  $^{134}\text{Xe}/^{136}\text{Xe} = 1.2$ .

The correlations in the right sections of Figure 4, though not linear, also indicate finite amounts of Ar and Kr, but little or no He or Ne in the gas component with  $^{134}\text{Xe}/^{136}\text{Xe} = 1.2$ . It should be stressed that all nonradiogenic isotopic ratios of Ar, Kr and Xe in these residues correlate with the  $^{134}\text{Xe}/^{136}\text{Xe}$  ratio which we have shown in Figure 4 (Manuel and Sabu, 1975, 1977; Sabu and Manuel, 1976a, 1976b; Frick, 1977), and there are six elemental ratios, He/Xe, Ne/Xe, He/Kr, Ne/Kr, He/Ar and Ne/Ar, which correlate with each isotopic ratio. This is illustrated in Figure 5 of Ballad *et al.* (1979).

The negligible abundances of He and Ne in type-Y gases, and the close association of these two light gases with the anomalous Ar, Kr and Xe of type-X gases, are consistent with our earlier suggestion that type-Y gases were derived from a stellar interior where fusion reactions had consumed the low-Z elements and the type-X gases were derived from outer regions of a local supernova (Manuel and Sabu, 1975, 1977; Sabu and Manuel, 1976b; Ballad *et al.*, 1979). Isotopic ratios are not, however, frozen at the values which exist in the supernova, and we endorse Kuroda's suggestion (Kuroda, 1979) that the intense irradiation which occurs in the region of a supernova may produce short-lived radioactivities, such as  $^{26}\text{Al}$ , and detectable alterations in isotopic ratios. In fact, the solar system's supply of deuterium, lithium, beryllium and boron may have been produced during this period of intense irradiation (Sabu and Manuel, 1980).

## THE TRAPPED COMPONENTS OF NEON

Recognition of nucleogenetic anomalies in the isotopes of other elements has revived interest in the possibility of separate nucleogenetic components in Ne. Early studies had suggested a large number of isotopically-distinct, trapped components of meteoritic neon, Ne-A, Ne-B, Ne-C, Ne-D, Ne-E (Pepin, 1967, 1968; Black and Pepin, 1969; Black, 1972a, 1972b, 1972c) and more recent studies have identified subdivisions of Ne-A and

Ne-E, viz. Ne-A1, Ne-A2, Ne-E(L) and Ne-E(H) (Alaerts *et al.*, 1980; Eberhardt *et al.*, 1979), and an eighth Ne component, Ne-O (Eberhardt, 1978). None of these trapped Ne components matches the isotopic composition of this element in the solar wind (Geiss *et al.*, 1972) or in the Earth's atmosphere (Nier, 1950), and spallation reactions produce yet another component of neon in meteorites. We have serious reservations about the identification of so many isotopically distinct components in an element with only three isotopes.

Numerous explanations have been proposed to explain variations in the isotopic composition of Ne. Suggested origins for these components include implantation from the primitive solar wind, from the modern solar wind and from solar flares (Black, 1972a), trapping of planetary (Signer and Suess, 1963) and extra-solar system Ne (Black, 1972b), *in situ* ternary fission of a superheavy element (Black, 1972b), irradiations of the primitive solar nebula by negative muons (Jeffery and Hagan, 1969), or by neutrons, protons, etc. (Anders *et al.*, 1970; Heymann and Dziczkaniec, 1976), *in situ* decay of extinct  $^{22}\text{Na}$  ( $t_{1/2} = 2.6$  yr) (Black and Pepin, 1969; Clayton, 1975a) and mass fractionation (Zähringer, 1962; Manuel, 1967; Kuroda and Manuel, 1970; Arrhenius and Alfvén, 1971).

Arrhenius and Alfvén (1971) list seven fractionation mechanisms which might alter the isotopic compositions of elements in the primitive nebula. Of particular interest for noble gases is the multiple desorption process in which gases impinge, diffuse and desorb from the solid surfaces of growing condensate. Detailed studies on solar-wind implanted Ne (Ne-S) in lunar soils, in fact, suggested that mass fractionation is responsible for isotopic variations over the range of  $8.5 \lesssim {}^{20}\text{Ne}/{}^{22}\text{Ne} \lesssim 14$  (Hohenberg *et al.*, 1970; Megrue and Steinbrunn, 1972; Srinivasan, 1973).

Variations in the isotopic compositions of neon from mass dependent fractionation can be quantitatively represented by the equation (Srinivasan, 1973).

$$\partial \ln({}^{21}\text{Ne}/{}^{22}\text{Ne})/\partial \ln({}^{20}\text{Ne}/{}^{22}\text{Ne}) = 0.5 \quad (2)$$

This equation is valid for each stage of any mass dependent fractionation mechanism, since it only requires that the fractional change in the  ${}^{20}\text{Ne}/{}^{22}\text{Ne}$  ratio be twice that in the  ${}^{21}\text{Ne}/{}^{22}\text{Ne}$  ratio. Equation (2) can be used to distinguish isotopic compositions of Ne which might be produced by mass fractionation, or by mass fractionation plus the addition of spallation-produced Ne, from those which might indicate the presence of separate nucleogenetic components of Ne. This is illustrated in Figure 5.

On such a diagram, Equation (2) predicts a linear relationship between the isotopic compositions of Ne in various compartments of a reservoir which have been partitioned by a mass-dependent process. Thus, Ne released from the 2C10m residue of Murchison at 1600 °C (Alaerts *et al.*, 1980) may have

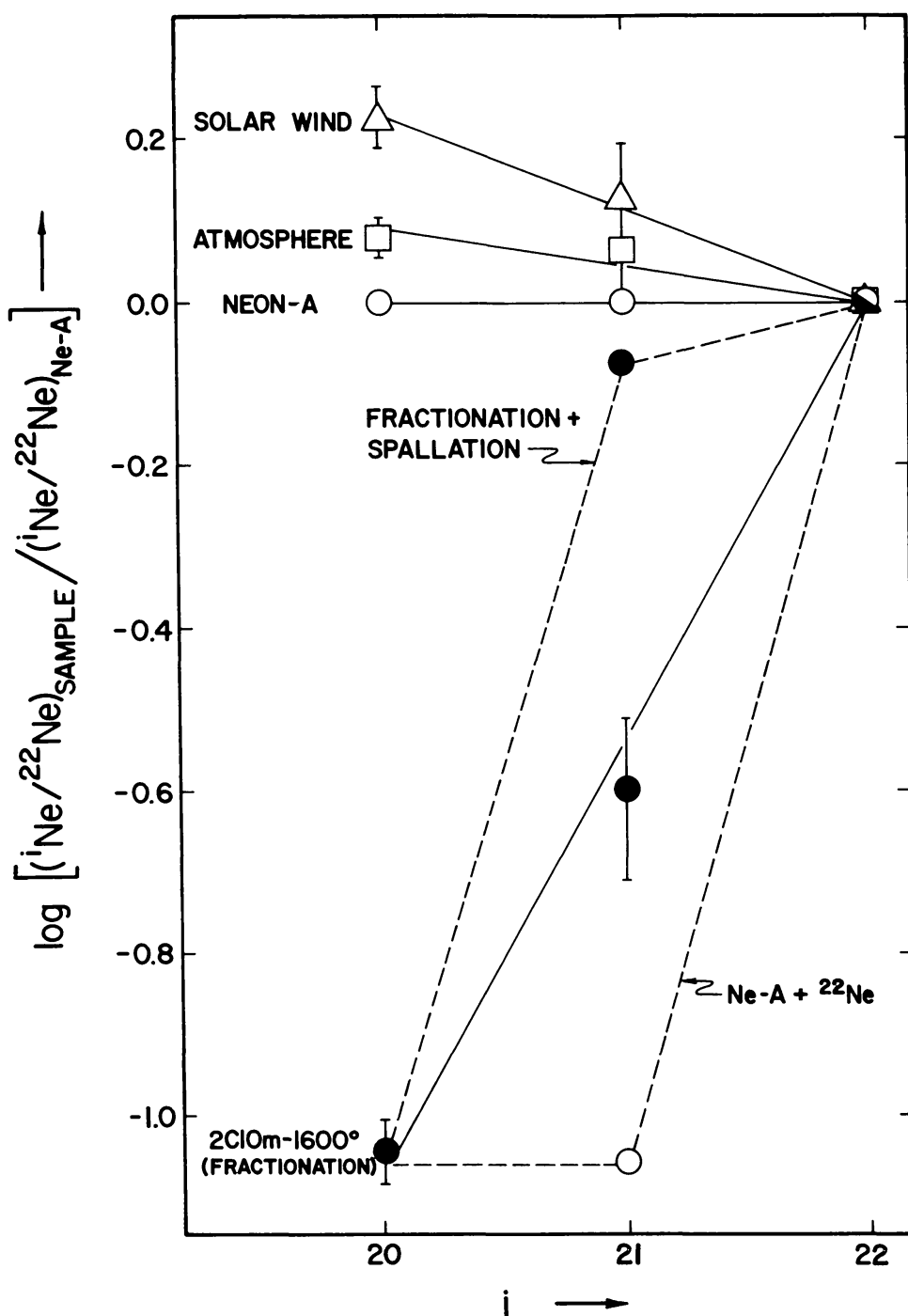


Fig. 5 The isotopic compositions of neon in the solar wind, air, Ne-A and in the 1600 °C fraction of the 2Cl0m residue of Murchison vary in the manner which Equation (2) predicts for neon which has been partitioned by a mass dependent process. The upper dashed line shows the anomaly pattern expected for a mixture of spallation and fractionated neon. The lower dashed line shows the anomaly pattern which would be produced by the addition of monoisotopic  $^{22}\text{Ne}$  to planetary-type Ne-A. None of the presently available data on meteoritic neon show the anomaly pattern illustrated by the lower dashed line.

been derived from planetary type Ne-A (Pepin, 1967) by such a process. Differences between the isotopic compositions of Ne-A, atmospheric Ne (Nier, 1950) and Ne in the solar wind (Geiss *et al.*, 1972) are also as expected from mass dependent fractionation.

Cosmic-ray induced spallation reactions generate the three stable Ne isotopes in almost equal proportions, and the presence of these products in neon would cause a sharp peak at  $^{21}\text{Ne}$  because of the low, natural abundance ( $< 0.3\%$ ) of this isotope. The anomaly pattern which would be produced by the addition of spallogenic Ne to that in the 1600 °C fraction of 2C10m residue of Murchison is illustrated by the upper dashed line in Figure 5. However, the addition of monoisotopic  $^{22}\text{Ne}$ , the recently suggested composition of Ne-E (Jungck and Eberhardt, 1979), would produce an opposite anomaly pattern. The anomaly pattern expected by the addition of  $^{22}\text{Ne}$  to Ne-A is indicated by the lower dashed line in Figure 5. Thus, Equation (2) permits us to eliminate interference from fractionation and spallation reactions in seeking evidence for nucleogenetic anomalies of Ne.

A detailed discussion of all available data on meteoritic neon is beyond the scope of this review. However, we have recently considered this problem in detail (Sabu and Manuel, 1980) and shown that none of the published data display the anomaly pattern indicated by the lower dashed line in Figure 5. In all cases, mass fractionation or mass fractionation plus spallation can explain the observed neon, including that released in each temperature fraction of each meteorite or its mineral separates, that in air and in the solar wind, and that in all previously identified components of meteoritic neon: Ne-A, -B, -C, -D, -E, -A1, -A2, -E(L), -E(H) and -O.

The main objections to fractionation as a viable mechanism for variations in the isotopic composition of neon have been (i) the severity of gas loss required if fractionation were limited to single stage diffusion (Black and Pepin, 1969) and (ii) the absence of correlated fractionation effects in the isotopes of argon (Zähringer, 1968; Black and Pepin, 1969; Anders *et al.*, 1970). Both objections are dealt with elsewhere (Sabu and Manuel, 1980). Suffice it to note here that (i) there is no reason to assume that diffusive gas loss was limited to a single fractionation stage, (ii) there are many possible fractionation mechanisms other than diffusive gas loss (Arrhenius and Alfvén, 1971; Frick *et al.*, 1979), and (iii) planetary neon is associated with type-X Ar, Kr and Xe (see Fig. 4) and these constitute such a small fraction of the bulk Ar, Kr and Xe in meteorites that absence of correlated fractionation effects in Ar does not rule out fractionation effects in Ne. We have also noted (Manuel and Sabu, 1977) that the severe depletion of He and Ne in type-Y noble gases are nucleogenetic and cannot be explained by fractionation, since values of the Ar/Xe ratio do not covary with values of the He/Xe and Ne/Xe ratios in the manner expected for fractionation.

## CONDENSATION AND NOBLE GAS SOLUBILITY

Prior to the discovery of correlated elemental and isotopic heterogeneities in the noble gases (Manuel and Sabu, 1975, 1977; Sabu and Manuel, 1976b), it was widely assumed that the distribution of elements in primitive meteoritic solids might be explained by equilibrium condensation from a monotonically cooling, chemically homogeneous nebula of average solar system composition (Larimer and Anders, 1967; Grossman and Larimer, 1974). Based on this view of condensation, it has been suggested that the abundance pattern of meteoritic noble gases might have been established by equilibrium solubility in the various host phases, *e.g.*, chromite, mineral "Q", magnetite, etc. (Jeffery and Anders, 1970; Lancet and Anders, 1973; Lewis *et al.*, 1975; Alaerts *et al.*, 1977; Alaerts *et al.*, 1979a, 1979b).

It has also been suggested that the  $^{20}\text{Ne}/^{36}\text{Ar}$  ratios in mineral "Q" can be used as a cosmo thermometer, once the heats of solution of noble gases in "Q" are measured (Alaerts *et al.*, 1977). Unfortunately this novel suggestion for the utilization of noble gas data has not yet been realized, due to the failure to isolate and characterize mineral "Q" (Gros and Anders, 1977; Frick and Chang, 1978; Frick and Pepin, 1980). However, even if the heats of solution of Ne and Ar in the hypothetical mineral "Q" were known, it would be difficult to accept the validity of the proposed Ne/Ar cosmo thermometer (Alaerts *et al.*, 1977). Values of the  $^{20}\text{Ne}/^{36}\text{Ar}$  ratio in the meteorite residues reflect the fractional abundance of type-X gases. Thus, values of the  $^{20}\text{Ne}/^{36}\text{Ar}$  ratio correlate linearly with isotopic ratios of the heavy noble gases, *e.g.*,  $^{124}\text{Xe}/^{132}\text{Xe}$ ,  $^{136}\text{Xe}/^{132}\text{Xe}$ ,  $^{86}\text{Kr}/^{82}\text{Kr}$  and  $^{38}\text{Ar}/^{36}\text{Ar}$ . These correlations are unexplained by equilibrium solubility and provide sufficient evidence alone for rejecting the gas solubility cosmo thermometer.

The abundance pattern of heavy noble gases in meteorite minerals is in general agreement with that expected from adsorption (Fanale and Cannon, 1972) but opposite to that expected by equilibrium solubility (Grimes *et al.*, 1958; Blander *et al.*, 1959; Kirsten, 1968; Lancet and Anders, 1973). The former mechanism preferentially enriches the heavier, and the latter preferentially enriches the lighter noble gases, both in theory and in the minerals studied to date. Figure 6 compares values of the depletion factor, *D*, defined by Equation (1), in mineral "Q" (Lewis *et al.*, 1975), Allende residue 4C57 (Lewis *et al.*, 1977a), and Pesyanoe (Marti, 1969) with the values expected by adsorption (Fanale and Cannon, 1972) and by solution into growing magnetite crystals (Lancet and Anders, 1973) from a gas having cosmic abundances (Cameron, 1973). The abundances of He and Ne are not considered here because these exist in only one type of the planetary noble gases. However, it is evident from the abundance patterns shown in Figure 6 that equilibrium solubility played a minor role, if any at all, in determining

the abundances of meteoritic noble gases.

Blander (1975), Arrhenius and Alfvén (1971), Wasson (1977), and many others have suggested mechanisms and scenarios that might be considered applicable to the early solar system and that differ markedly from the equilibrium condensation model (Larimer and Anders, 1967; Grossman and Larimer, 1974) and its various elemental cosmothermometers (Keays *et al.*, 1971; Larimer, 1973; Alaerts *et al.*, 1977). A full discussion of these issues is beyond the scope of this report, but it should be noted that a basic premise of equilibrium condensation — a homogeneous primitive nebula of average solar composition — is inconsistent with our suggestion that the solar

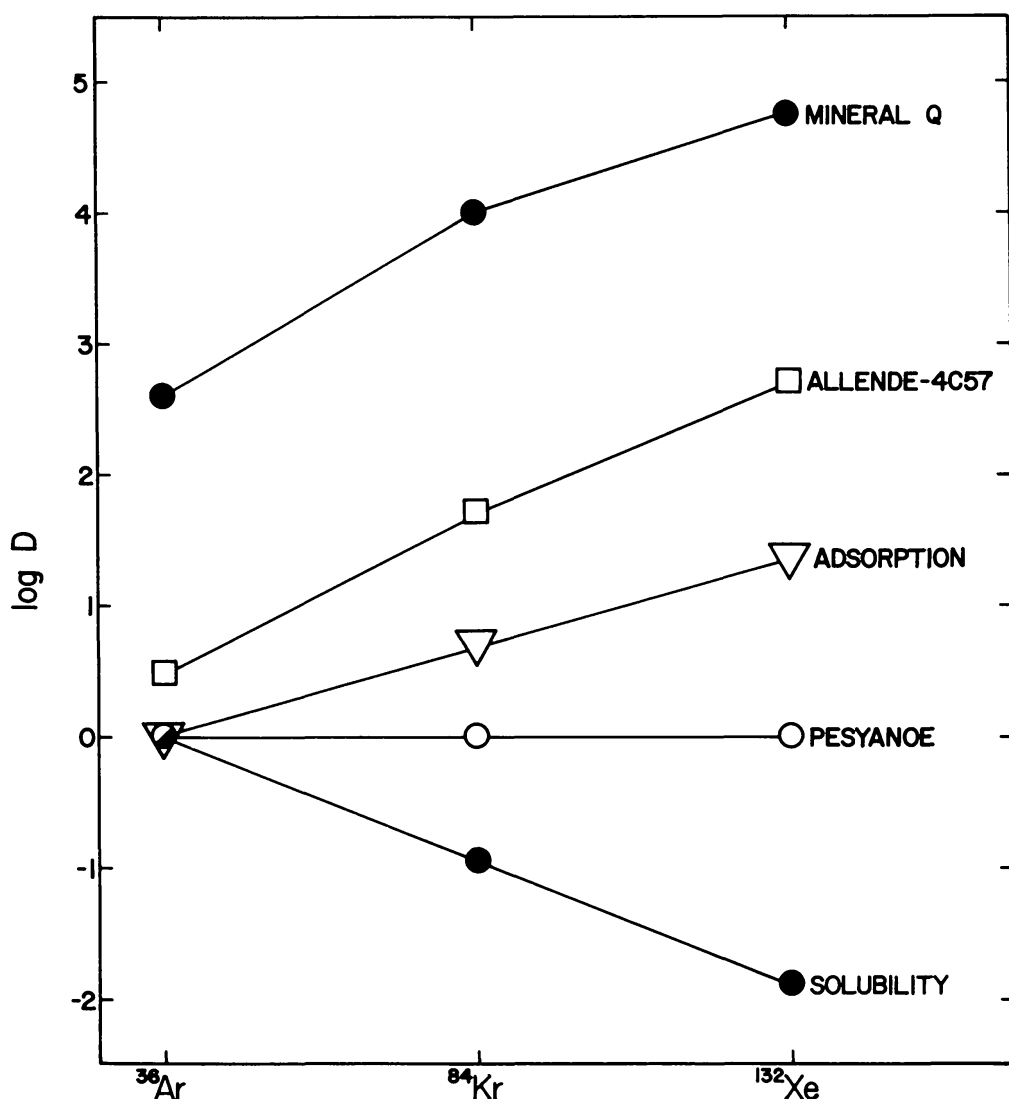


Fig. 6 A comparison of the elemental abundance patterns of Ar, Kr and Xe in Allende residues with the patterns expected by adsorption and solubility. The pattern predicted by gas solubility does not agree with the observed pattern, suggesting that this model and its Ne/Ar cosmothermometer are invalid.



system condensed from the chemically and isotopically heterogeneous debris of a single supernova (Manuel and Sabu, 1975, 1977; Sabu and Manuel, 1976b).

An outline of events which might produce the heterogeneous nebula which we suggested to explain the noble gas data — a chemically and isotopically zoned protoplanetary nebula surrounding a central supernova core remnant on which the sun formed (Manuel and Sabu, 1975, 1977; Sabu and Manuel, 1976b) — is presented below. This brief description is presented to avoid possible confusion of our view with alternate models of (i) an injection of isotopically anomalous elements from a nearby supernova (Cameron and Truran, 1977; Schramm and Clayton, 1978; McCulloch and Wasserburg, 1978), and (ii) refractory interstellar dust grains carrying isotopically anomalous elements into the early solar system (Clayton *et al.*, 1973; Black, 1973; Clayton, 1975b).

We assume that essentially all of the chemical elements in the solar system were derived from a single, massive precursor star which synthesized elements as the star proceeded through the basic stages of stellar evolution (Burbidge *et al.*, 1957; Trimble, 1975). Stellar evolution is always more advanced at the elevated temperatures of the deep interior, and the star reaches an unstable stage when the central region has consumed those elements which release energy by fusion, *i.e.*, when gravitational collapse of the core will no longer be inhibited by radiation pressure from fusion reactions.

At this stage the star is chemically zoned, with an outer layer of essentially unprocessed light elements such as H and He, followed by layers of elements of successively higher atomic numbers (except for the easily fused nuclei of Li, Be and B) up to a central Fe-rich region. Collapse of the core causes light elements from the outer stellar layers to fall inward, and their sudden heating causes a profusion of reactions which trigger the explosion (Burbidge *et al.*, 1957).

If the star is rotating, then conservation of angular momentum will cause the collapse to occur preferentially at the poles, and the explosion in the outer region will generate equal and opposite forces toward the center. In this case, the explosion may have an axial direction, leaving a remnant supernova core surrounded by a protoplanetary disk of material in the equatorial plane with angular momentum and with a spatial distribution of the chemical and isotopic heterogeneities of the parent star. Remnant radiation from the explosion might appear to be isotropic to terrestrial observers (Penzias and Wilson, 1965).

According to this view, the type-Y noble gases were derived from the stellar interior where fusion reactions had destroyed the He and Ne. The isotopic compositions of Ar-Y, Kr-Y and Xe-Y appear “normal” to the inhabitants of an inner planet because the bulk of the heavy elements in that part of the solar system were derived from the stellar interior.

Type-X noble gases were derived from the outer stellar regions, and they therefore contain He and Ne. The isotopic compositions of Ar-X, Kr-X and Xe-X differ from those in type-Y noble gases because of the different nuclear reactions which occurred at different stellar depths. The isotopic compositions of He and Ne in type-X gases appear “normal” and these gases are trapped in a matrix of isotopically “normal” carbon because essentially all of these low-Z elements in the solar system were derived from the outer stellar regions.

The giant Jovian planets condensed primarily from elements of the outer stellar region, and the noble gases in these are expected to be predominantly type-X.

## CONCLUSIONS

Meteorites trapped two types of planetary noble gases, type-X and type-Y, and differences in their elemental and isotopic compositions suggest that they were derived from the outer and inner regions, respectively, of a local supernova. The absence of He and Ne in type-Y noble gases and the common occurrence of Ar-Y, Kr-Y and Xe-Y in bulk meteorites and in the inner planets indicate that the supernova was concentric with the present sun. We have shown earlier that condensation from the heterogeneous debris of this supernova can also account for differences in the bulk chemical compositions of the planets, the internal structures of the terrestrial planets, the occurrence of both type-Y and type-X gases in the solar wind, and the current low flux of solar neutrinos. This may also explain 3 °K background radiation.

Differences in the abundance patterns of planetary noble gases are primarily the result of stellar fusion reactions and adsorption, rather than gas solubility. The carrier phase of type-X noble gases sampled one chemically and isotopically distinct region, and the carrier phase of type-Y gases sampled another. The overall abundance of other trace elements in bulk meteorites also depends on the relative amounts of carrier phases from different regions of this heterogeneous supernova debris.

Many of the components which have been identified in meteoritic neon, Ne-A, Ne-B, Ne-C, Ne-D, Ne-E, Ne-A1, Ne-A2, Ne-E(L), Ne-E(H), and E-O can be explained by mixtures of spallogenic and mass fractionated neon. There is little or no evidence of nucleogenetic anomalies in neon.

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