Reports

Planetary Systems Associated with Main-Sequence Stars

Abstract. *The luminosity function is used to estimate the number of invisible planet-like objects in the neighborhood of the sun, taking into account the likely chemical composition of planets in relation to the composition of main-sequence stars. There may be about 60 objects more massive than Mars for every visible star. An attempt is made to estimate the distribution of these planet-like cold bodies in relation to stars. It is suggested that stars, together with cold objects, were formed in clusters of bodies of random size distribution. Clusters averaging about 50 bodies each account for the observed distribution of frequencies of double and triple star systems relative to single stars. On this basis, virtually every star should have a planetary system associated with it. As a corollary, systems of cold bodies in which there are no luminous stars should be abundant. The possible distribution of planets around such stars has been studied, making use of the observed orbital characteristics of double star systems. It is concluded that favorable conditions for life processes may be far more abundant than has generally been thought possible.*

How many planetary systems are there? In recent years this question has received increased attention, but for the most part the opinions expressed have been speculative. Recently, however, Kumar (*1, 2*) has studied the properties of stars of very low mass and has concluded that bodies smaller than about 0.07 of the mass of the sun ($M_\odot$) cannot support thermonuclear reactions and will accordingly contract to become cold bodies or "black dwarfs." Although the apparent existence of M-dwarf stars as small as 0.04 $M_\odot$ would indicate that this estimate is only approximate, Kumar's work suggests that, when celestial bodies are viewed solely in terms of frequency as a function of mass, there is no basic discontinuity in their abundance in the low-mass region. We are aware of an abundance of heavy bodies because their rates of energy production permit us to see them. Although bodies of mass smaller than 0.07 $M_\odot$ may be extremely abundant, we are generally unaware of their existence because they are invisible.

Kumar (*3*) has also speculated that invisible bodies may represent a significant addition to the matter which is observed near the sun. Noting that it takes a body of mass 0.01 $M_\odot$ (which he assumes to be the average mass of a "planetary object") only 20×10^6 years after birth to become invisible, he suggests the presence of some 60,000 such objects within 20 parsecs of the solar system. This would correspond to about two such bodies per pc^3, or about 20 invisible bodies for each visible star.

An attempt is made in the present report to estimate the number of invisible planet-like objects in the solar neighborhood, making use of the luminosity function and taking into account the chemical composition of planets in relation to their size and the composition of the main-sequence stars. On the basis of available statistics of multiple star systems, the spatial distribution of planet-like bodies in relation to visible stars is estimated.

Types of planets. Planets of the solar system fall into three rather well-defined classes (*4*). The inner planets are small and dense, with highly oxidized atmospheres. They are apparently composed largely of metals and metal oxides which altogether comprise less than 0.3 percent of the mass of the sun. The outer planets are massive, possess low specific gravity, and highly reduced atmospheres. They are composed of much lighter substances than the inner planets. Elements which make up these lighter substances are very abundant in the sun.

The low specific gravities of Jupiter and Saturn cannot be explained unless we assume that they are composed primarily of hydrogen and helium. Uranus and Neptune appear to be composed largely of light substances such as water, methane, and ammonia, with but little hydrogen and helium present. DeMarcus (*5*) has studied theoretically the mass-radius relationship of cold bodies composed of pure hydrogen and has shown that Jupiter lies quite close to the theoretical curve. Öpik (*6*) has also concluded that Jupiter is composed virtually entirely of hydrogen and helium.

I have suggested (*4*) that the existence of these three types of planets is related to the fact that a gas composed of cold solar matter would contain three major types of chemical compounds. Table 1 shows the composition by weight of such a mixture, based upon the solar abundance values given by Aller (*7*). Such a mixture contains a small proportion of easily condensable substances (metals and oxides), a larger proportion of substances of intermediate condensability (H_2O, NH_3, CH_4), and a very large proportion of substances of class I were incorporated (H_2 and He).

It was suggested that the conditions of planet formation were such that the substances of class I were incorporated into all planets. Between the asteroid belt and the sun the conditions were such that the more volatile substances were not incorporated into planets to an appreciable extent. Beyond the asteroid belt, substances of class II could condense and lead to the growth of considerably larger planets. Watson, Murray, and Brown (*8*) have shown that the asteroid belt represents the transition of stability for solid water being evaporated by solar heating.

In the neighborhood of Jupiter and Saturn substantial quantities of hydrogen and helium were incorporated into the planets, possibly as the result of the more rapid rate of growth of the protoplanets, the greater gravitational fields associated with the resultant bodies, and the higher gas density in the region at the time.

It is tempting to conclude that cold bodies throughout the galaxy, produced from clouds of gas and dust which possess the chemical composition of main-sequence stars, will end up as class I, class II, or class III planets, depending on the conditions of temperature and pressure in the region of formation. Presumably, bodies of class I can only be formed in regions of high-energy flux, such as those close to a star. A body formed in a colder region will end up as either a class II or class III planet, depending on the conditions of temperature and pressure in the region of formation. The small bodies will be-

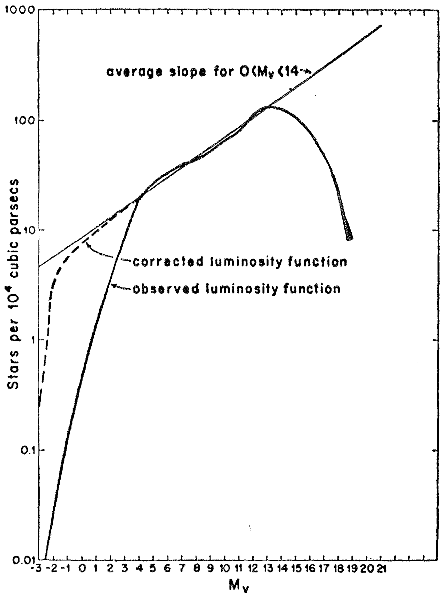

Fig. 1. Observed and corrected luminosity function for main sequence stars.

long to class II, composed of metals and oxides, ice, methane, and ammonia. Larger bodies capable of retaining hydrogen and helium may belong either to class II or to class III, depending on the conditions of formation.

Thus, a quantity of solar matter containing metals and oxides totaling one earth mass could end up as an earth-like planet in a high energy flux, as a Uranus-like planet weighing 8.2 earth masses in a colder region, or as a Jupiter-like planet weighing 395 earth masses if all molecules were retained in proportion to their solar abundances. Also, there could be gradations between these extremes.

Luminosity function. In a volume of 10^4 cubic parsecs in the vicinity of the sun there are about 1000 visible main-sequence stars. The distribution of these stars with absolute visual magnitude (the luminosity function) as given by Schmidt (*9*) is indicated by the dark solid curve in Fig. 1. The mass-luminosity relationship permits the magnitude to be converted to mass.

Stars of large mass have shorter lifetimes than those of small mass. For this reason we must correct the observed luminosity function in order to obtain the "original" distribution of the bodies with respect to either magnitude or mass. This has been done by Salpeter (*10*), and his corrections give rise to the dotted curve in Fig. 1, which joins the uncorrected curve at about $M_v = 4$, M_v being the visible magnitude. Between $M_v = 1$ and $M_v = 13$, the relation between the logarithm of the frequency and the absolute magnitude is well represented by a straight line.

$$\log f = 0.0911\, M_v + 0.936 \qquad (1)$$

This range embraces masses extending from about 3 down to 0.15 solar masses.

Above $M_v = 13$, the frequency falls off rapidly. It is reasonable for us to assume that this decrease in observed frequency with increasing magnitude does not represent any drop in the actual frequency of bodies with respect to decreasing mass. It seems likely that the frequency curve falls rapidly because, first, as stars become fainter they become increasingly difficult to see. Second, and probably even more important, such small stars approach Kumar's (*1*) upper limit of 0.07 solar masses below which thermonuclear reactions will not take place. This could correspond to a star of about the 15th absolute magnitude.

At high magnitudes ($M_v > 10$) the relationship between magnitude M_v and mass M is well represented by

$$M_v = -6.65 \log M + 7.87. \qquad (2)$$

Thus for bodies smaller than about 0.5 $M_\odot$ we have the relationship

$$\log f = -0.61 \log M + 1.65 \qquad (3)$$

where M denotes the mass of the object relative to that of the sun, and f denotes the number of bodies per 10^4 pc^3 which possess masses in an interval of $\Delta \log M = 0.15$.

This relation has been used to estimate the number of invisible bodies down to masses comparable to those of the planets of the solar system. The results are shown in Table 2, where the term "earth equivalent" denotes a cold body which contains metals and metal oxides equivalent to one earth mass. As already discussed, the actual total mass of such a planet will depend on its location and on the mode of its formation. An "earth equivalent" planet can range in size from a class I earth-like planet of unitary weight to a class II planet of 8.2 earth masses, to a class III planet of 395 earth masses.

If we assume that most bodies larger than Saturn will be of class III composition, and that most of those smaller than Saturn will belong to class II, we can estimate the total mass of invisible bodies. From Table 3 it can be seen that the estimated total mass contribution of cold bodies might be of the order of 0.011 $M_\odot/pc^3$. This is about one-fifth the total mass contribution of known stars as estimated by Gliese

Table 1. Chemical composition by relative weight of a cold gas composed of solar matter.

Substance	Relative weight		Class
H_2	290	387	III
He	97		
H_2O	4.3	7.2	II
CH_4	2.4		
NH_3	0.5		
Metals and oxides	1.0		I

(*11*) Thus the use of Eq. 1 over a wide range of mass does not give us an unreasonably large contribution to the average density of matter in the galaxy.

Extrapolation of the luminosity function leads us to the conclusion that there may be about 60 unseen bodies of "substantial size" for every visible star. By "substantial size" we mean class I planets greater in mass than Mars, class II planets larger than about 0.8 earth mass, and class III planets larger than about 40 earth masses. Clearly, were we to extend the extrapolation to smaller masses, the estimated numbers of bodies would be even larger.

The luminosity function used here is strictly applicable only to stars in our own region of the galaxy. There is evidence, for example, that within certain galactic clusters the frequency falls off more rapidly with decreasing mass than it does in the solar neighborhood.

Multiple-body systems. When we examine the 100 stars nearest the sun we find that 48 are apparently single stars, 40 are grouped in 20 double star systems, and 12 are grouped in 4 triple star systems. The catalog of Gliese (*12*) lists 915 stars within a distance of 20 parsecs. Of these, 159 are classified as being at least double; 10, as being at least triple. It is reasonable to assume that the lower ratios of double and triple to single stars in the larger assemblage results from observational selection. Systems which are more complicated than triple ones appear to be fairly abundant, and one apparent six-star system (Castor) has been observed.

Let us assume that the ratio of single

Table 2. Estimated number of invisible bodies per 10^4 pc^3 in the vicinity of the sun (number of visible stars = 1000).

Mass range	No.
0.16 $M_\odot$–0.021 $M_\odot$	1,430
0.021 $M_\odot$–1 "Earth equivalent"	11,300
1 "Earth equivalent"–1 "Mars equivalent"	47,600
Total unseen bodies down to size of "Mars equivalent"	60,330 or 6.0 per pc^3

to double star systems observed in the assemblage of the 100 stars nearest the sun is correct, and let us use this figure to correct the underestimates of multiple star systems in Gliese's (*12*) list which result from observational selection. The corrected numbers of single, double, triple, and quadruple systems are shown in Table 4. The corrections throughout are made on the assumption that a certain fraction of the observed individual stars (0.205) are probably unresolved pairs of stars.

Kuiper (*13, 14*) has made a careful study of the statistics of double star systems and concludes that, within a radius of 10 parsecs, about 50 percent of the objects of spectral classes A through K are either binaries or more complicated multiple systems. This is a higher proportion than the 35 percent indicated in Table 4.

Thus far, over 50,000 visual binaries and about 1500 spectroscopic pairs have been identified. It is clear that the great abundance of multiple star systems must be regarded as a fundamental aspect of our galaxy that requires explanation. It is generally assumed that binary stars of all types originated through condensation and accretion of interstellar gas and dust, as single stars and clusters apparently do. But why should the apparent abundance of single to double to triple star systems be in the particular ratios which are observed?

Statistics of multiple star systems are of course based on visible stars. As already indicated, these may be few in number when compared with the abundant cold bodies of substantial size. What proportion of these cold bodies are coupled gravitationally with visible stars? What proportion are coupled with each other?

Invisible planetary companions of stars are extremely difficult to detect. Nevertheless, in a few visible binaries the presence of a very faint companion may be inferred from the wavy form of the apparent orbit. Thus, studies of the two stars of the binary system 61 Cygni reveal the presence of a companion to one of the stars, having a mass 0.008 $M_\odot$ and a period of 4.8 years. Particularly noteworthy is the recent discovery by Van de Kamp (*15*) of a small invisible companion to Barnard's Star, of mass about 0.0015 $M_\odot$. This mass is but 50 percent greater than that of Jupiter.

Thus far, there is reasonably good evidence for the existence of seven invisible planetary companions having

Table 3. Estimated mass contribution of small unseen bodies in the solar neighborhood.

Type of object	Total mass per 10^4 pc^3 (solar units)
0.16 $M_\odot$–0.021 $M_\odot$	55
0.021 $M_\odot$–1 "Earth equivalent"	47
1 "Earth equivalent"—Saturn	10
Saturn—1 "Mars equivalent"	0.10
Smaller material class II down to mass 7.1×10^{-11} $M_\odot$	0.2
Total mass of unseen smaller bodies	112 or 0.011 $M_\odot$/pc^3

masses in the range 0.0015 $M_\odot$ to about 0.02 $M_\odot$ (see Table 5). The stars are close to the sun, all of them being among the 100 nearest stars. When we add the Jupiter-Sun system to the list it would appear that at least 8 percent of the visible stars have invisible companions of mass greater than Jupiter. When we consider the observational selection effects, the fraction of stars which possess invisible companions must be very much greater than this.

Extrapolation of the luminosity function suggests that there are in the solar neighborhood 1270 bodies the size of Jupiter, or larger, for every 100 visible stars. The number of such bodies observed to be attached to the 100 nearest stars corresponds to 0.6 percent of those estimated. The luminosity function also indicates the presence in the solar neighborhood of some 60 cold bodies per visible star, with masses ranging downward to about that of Mars. If 0.6 percent of these bodies were also gravitationally bound to stars, there would be an average of 60 $\times$ 0.006 = 0.36 planetary bodies attached to each star. Further, as indicated above, this would represent a lower limit. This high figure would make it appear that a very large proportion of visible stars may have planetary systems.

Planetary-stellar clusters. It is usually assumed that stars and planets were formed through gravitational contraction and condensation of interstellar gas and dust. Let us suppose that these processes take place in discrete regions of space separated from each other by interstellar distances, and that within each region a cluster is formed containing an average of n bodies, the masses of which range upward from the size of Mars-equivalent objects to stellar masses. Let us assume further that the mass distribution of all bodies in all clusters is given by a function similar to the extrapolated luminosity function, but that the distribution within a given cluster is purely random. Zero, or more, of the objects in a given cluster will become sufficiently large to generate thermonuclear energy. Most of the objects will remain cold. Let us denote the ratio of cold to visible bodies by the ratio r. The numbers of single and multiple visual star systems can now be calculated in terms of n from the binomial distribution:

$$f(x) = \frac{n!}{x!\,(n-x)!\,(r+1)^x}\left(\frac{r}{r+1}\right)^{n-x} \quad (4)$$

where x represents the number of visible stars in the system.

Let us assume a value of r = 60 for bodies larger than a Mars-equivalent, as indicated by the luminosity function, and assume a ratio of visible single to double stars of 2.40, corresponding with observations in the group of 100 nearest stars. The average cluster size then becomes n = 50. With this figure, the frequencies of all possible multiple star systems can be calculated. The calculated frequencies are shown in Table 6, where they are compared with the corrected observations. The agreement is well within the observational error.

As long as n is much greater than x, the expected frequencies of multiple star systems depend only on n/r. Thus, if r should turn out to be smaller than 60, the expected frequencies can be duplicated by lowering n proportionally. Thus if r were reduced from 60 to 30, n would be reduced from 50 to 25.

The fact that the frequencies of multiple relative to single star systems can be estimated in this rather simple way adds further weight to the concept that

Table 4. Frequencies of stellar systems.

System	100 nearest stars: Observed number of systems	100 nearest stars: Observed individual stars	Stars within 20 parsecs: Observed number of systems	Stars within 20 parsecs: Observed individual stars	Stars within 20 parsecs: Corrected number of systems (if f = 0.205)
Single	48	48	746	746	593
Double	20	40	159	318	247
Triple	4	12	10	30	69
Quadruple	0	0	0	0	6

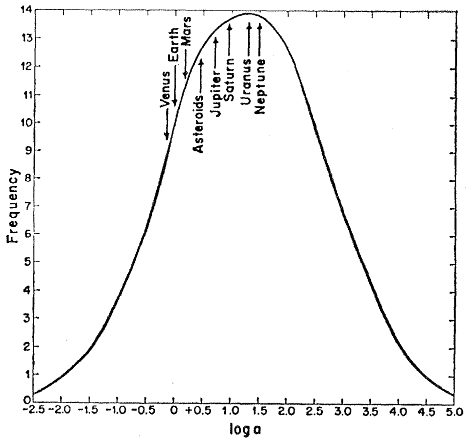

Fig. 2. Frequency distribution of semi-major axes (in astronomical units) of binary stars.

each stellar system is really a complicated system containing numerous cold bodies. A corollary of this concept is that invisible clusters of bodies should exist in which none of the bodies has become a star. Table 6 indicates that such invisible systems should be nearly as numerous as visible stellar systems.

Distribution of planetary bodies around stars. Figure 2 shows the frequency distribution curve for the semi-major axes of double stars as constructed by Kuiper (*13, 14*). For reference, the locations of the planets of our own system are indicated. Assuming that the distribution of the semi-major axes of invisible stellar components is given approximately by the same curve, we can combine this distribution with the luminosity function and thus obtain a distribution curve for the frequency of cold bodies as a function of the heat flux received. This combined frequency curve is shown in Fig. 3.

It can be seen that the vast majority of the bodies (about 92 precent) would receive less heat than do the asteroids and would probably therefore be, depending on size, class II or class III planets. About 85 percent of the bodies would receive less heat than does Neptune. About 8 percent of the planetary

Table 5. Invisible stellar companions.

Star	Mass (solar units)	Ref.
Barnard's Star	$\sim$ 0.0015	*15*
Lalande 21185	$\sim$ 0.01	*20*
61 Cygni	$\geqslant$ 0.008	*21*
Krueger 60A	$\sim$ 0.009–0.025	*22*
Bd + 20° 2465	$\geqslant$ 0.02	*21*
Ci 2354	$\geqslant$ 0.02	*21*
η Cas*	$\sim$ 0.01	*22*

* Existence not completely established.

bodies, however, would receive more heat than do the asteroids and might therefore have evolved as planets of class I. Assuming an average of 50 planet-like bodies associated with each star would give an average for each star of about four class I planets of mass greater than that of Mars.

About 4.3 percent of the planets under these assumptions would receive a heat flux lying between that received by Venus and that received by the asteroids. It is widely believed that life processes might take place in this zone of heat flux, but not outside. If this view is correct, it would mean that on the average some two planets per visible star might provide suitable environments for the emergence of life processes which are based upon chemical systems similar to those on earth.

Conclusions. If we are correct in assuming that the function describing the frequency of celestial bodies with respect to mass is valid for masses lower than about 0.5 $M_\odot$, and if we are also correct in assuming that stars, together with cold objects, were formed in clusters of bodies of random size distribution, then we must conclude that planetary systems are far more abundant than we have so far suspected. Virtually every main-sequence star should have a planetary system associated with it. Class I planets, similar in composition to the earth or Mars, should be abundant, and we might expect on the average as many as four such planets per star. Such bodies should exist in greater abundance near stars of high luminosity than near stars of low luminosity.

The conclusion that each star should have on the average two planets in the "life zone" of heat flux gives considerable grounds for further speculation. Clearly, this favorable situation may mean that life is far more abundant in our universe than we have previously thought possible.

Discussion in this report has been arbitrarily confined to bodies the size of Mars and greater. If the discussion should include substantially smaller bodies, the number of objects estimated from Eq. 1 would be greatly increased. As most of these bodies would belong to class II, it may well be that these smaller bodies, formed at the time of cluster formation, provide the primary source of comets.

The most useful approach, aimed at estimating the degree of validity of these assumptions, conclusions, and speculations, would be to intensify ef-

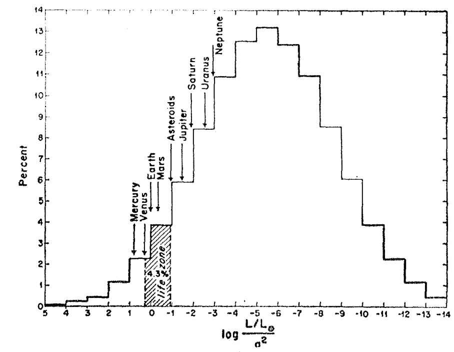

Fig. 3. Frequency distribution of heat flux received by hypothetical planets; distribution of orbits possessed by binary stars and the luminosity function being assumed. $L/L_\odot$ is the luminosity of the star relative to that of the sun; a is the semi-major axis of planetary orbit in astronomical units.

forts designed to find extra-solar planetary bodies (*16*). The detection of such objects is extremely difficult, but as Spitzer (*17*) has emphasized, there are potential solutions, particularly if we are able to place large telescopes in orbit outside the earth's atmosphere. A great deal could also be accomplished by intensifying ground-based searches for gravitational perturbations on stars. F. D. Drake has pointed out to me (*18*) that the effectiveness of such an approach could be greatly improved by increased observations of stellar motions, the use of long integration times, possibly the use of photoelectric techniques, and the use of Fourier analysis on the perturbation data to extract perturbations from noise.

If it develops that planetary systems are indeed as abundant as this discussion indicates, the search for intelligent extraterrestrial life is placed in a somewhat new perspective. With 10^{11} planetary systems available in our galaxy, life forms may well be both abundant and diverse. Although Simpson (*19*) may be correct in his conclusion that man, in effect, is a sta-

Table 6. Expected frequency of multiple star systems; $n = 50$, $r = 60$.

Number of stars in system	Estimated frequency	Estimated frequency with respect to visible systems	Corrected observations within 20 parsecs
0	0.437		
1	.362	0.643	0.650
2	.149	.265	.270
3	.0398	.0707	.075
4	.0066	.0117	.0066
5	.0012	.0021	
6	.00015	.00027	

tistical miracle, we simply do not know enough about the physical, chemical, and biological evolution of planets to assess with any degree of accuracy the sets of circumstances under which intelligent life forms may or may not emerge. If planetary systems are indeed extremely abundant one might conclude with equal conviction that man is not alone—that his equivalents may occupy hundreds or even thousands of bodies within our galaxy. Listening for evidence of the existence of such forms may indeed prove to be in the long run a profitable and exciting pursuit.

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Isotopic Composition of Lead and Strontium from Ascension and Gough Islands

Abstract. *Isotopic composition of lead and strontium has been determined in a series of rock samples from two islands on the Mid-Atlantic Ridge. Both inter- and intra-island variations exist in the abundance of radiogenic isotopes of both elements. Lead from basalt of Ascension Island has a Pb^{206}-Pb^{204} ratio of 19.5, while the corresponding ratio at Gough Island is only 18.4. The Pb^{208}-Pb^{204} ratios from the two islands do not differ. Conversely, strontium from basalt of Ascension Island is less radiogenic than that from Gough Island basalts. The trachytes of both islands have lead and strontium that is more radiogenic than that found in the basalts. The inter-island differences indicate the existence of regional variations in the uranium-lead and rubidium-strontium ratios of the upper mantle source of these rocks and show that isotope compositions are a means for investigating chemical heterogeneities in the mantle.*

The isotopic composition of strontium in rocks derived from the mantle, for example, oceanic volcanic rocks, is determined by the relative abundances of rubidium and strontium during geologic time in the parent materials that produce the rock magmas. Gast (*1*) used this principle to place certain restrictions on the composition of the upper mantle of the earth. He showed that basaltic rocks contain strontium with much lower Sr^{87}-Sr^{86} ratios than would be expected if the outer mantle had the same chemical composition as chondritic meteorites, an assumption that has been widely used in various calculations. Another use of isotopic data for strontium in basic rocks is based on knowledge of the amount of variation in isotopic composition from one rock to another; this information can be used to infer the amount and extent of regional variations in the ratio of rubidium to strontium in the upper mantle. Data obtained thus far indicate that the Sr^{87}-Sr^{86} ratio of strontium from basic rocks is quite uniform (*1–3*). The isotopic composition of strontium in surface rocks is highly variable, depending on the age and rubidium-strontium ratio of the rock and on the isotopic composition of strontium initially inherited by the rock. If basic rocks contain strontium of narrowly defined isotopic composition, a potentially useful tracer is provided that can delineate rocks of deep-seated origin from those containing large admixtures of crustal materials. Several authors have discussed the use of strontium in this manner to study the origin of granitic rocks (*1, 3, 4*).

Arguments similar to those used for strontium can also be applied to the uranium-lead and thorium-lead systems. The former system is particularly valuable since two different isotopes of uranium, U^{235} and U^{238}, with greatly different half-lives decay to form two isotopes of lead, Pb^{207} and Pb^{206}. There are relatively few data in the literature on the isotopic composition of lead in rocks. We have begun to investigate the isotopic composition of lead and strontium in a series of rocks from two typical islands on the Mid-Atlantic Ridge, Ascension Island and Gough Island, to establish the magnitude of both inter- and intra-island variations in the isotopic composition of these elements. An oceanic rather than a continental environment was chosen for these experiments to avoid possible contamination by radiogenic lead and strontium from the granitic rocks associated with the crust in continental areas. Rather detailed petrologic studies of both islands have been made by previous investigators (*5, 6*).

Isotopic compositions of lead and strontium, together with brief descriptions of individual samples used in this study, are given in Table 1. Analyses labeled U.S. Geological Survey were made on the mass spectrometer, having a 12-inch (30-cm) radius of curvature, that was used by Hedge and Walthall (*3*). Those labeled University of Minnesota were made on a mass spectrometer having a 6-inch (15-cm) radius of curvature, as described by Gast (*7*). Analyses labeled Department of Terrestrial Magnetism were made on a mass spectrometer [9-inch (22.5-cm) radius of curvature] with an electron multiplier ion detector. The lead analyses were interspersed with analyses of the reference sample from California Institute of Technology described by Chow and McKinney (*8*). Corrections for electron multiplier discrimination were determined from results on the reference sample. The reliability of the ratio determinations can be estimated from the duplicate measurements in Table 1. The duplicate data in this table represent chemical processing of two separate rock samples. The lead concentrations varied from 2 to 8 parts per million, except that G-19D contained about 20 parts per million. Five-gram samples were generally used; the reagent blanks were about 0.1 μg for this amount of sample. Hedge and Walthall (*3*) give additional data bearing