

Josephson Junction Detectors

Josephson devices are sensitive detectors of magnetic fields, voltages, and far-infrared radiation.

John Clarke

How can I measure a voltage of 10^{-15} volt? Can I detect the magnetic field generated by the human brain? What is the most sensitive detector of far-infrared signals reaching us from distant galaxies? The answers to these seemingly unconnected questions, and to others requiring very sensitive instrumentation, are being provided to an increasing extent by devices based on the Josephson effect (1). These devices offer unprecedented sensitivity in certain applications and enable us to measure incredibly small signals that are totally inaccessible to other instruments. The Josephson effect is a superconducting phenomenon and occurs only at temperatures below a few degrees Kelvin. Consequently, until recently, the operation of Josephson devices was restricted to the low-temperature physics laboratory. However, with the advent of robust and portable cryostats, these instruments are now being used in the field in a variety of applications.

It is my purpose in this article to explain the principles of the Josephson effect, to describe how practical devices have been made, and to discuss some of the applications. I have divided the applications into two broad classes. The first involves the measurement of voltages, magnetic fields, magnetic field gradients, and magnetic susceptibilities at or below audio frequencies (2). In these areas the Josephson devices have no competitors for sensitivity. The second class is concerned with the detection of high-

frequency (microwave and far-infrared) electromagnetic radiation (2). In this application the Josephson devices appear to be comparable in performance with other detectors, but improvements are likely to be made in the reasonably near future.

In this short review, I have not been able to even mention a great deal of elegant and important work in these two areas. I should also point out that there are several other very important applications of the Josephson effect. As I shall describe later, when a superconducting junction exhibiting Josephson tunneling is irradiated with microwaves of frequency f , a series of constant-voltage steps appears in the current-voltage characteristic of the junction at voltages $|V_n| = nhf/2e$ (where n is an integer, h is Planck's constant, and e is the electronic charge). Parker and his colleagues (3) used this effect to make a very precise measurement of the fundamental constant ratio e/h . Their value differed significantly from the previously accepted value. Taylor *et al.* (4) subsequently used their value of e/h in a new least-squares adjustment of the fundamental constants. The National Bureau of Standards and a number of other national laboratories now use the Josephson voltage-frequency relation to *maintain* (but not to define) the standard of electromotive force (5). The final major application is in computers. The extremely fast switching time and very low dissipation of Josephson junctions make them promising as logic and

storage elements for computers (6).

Josephson tunneling is a phenomenon of great fundamental physical interest and has found an amazingly wide variety of applications. Brian Josephson shared the 1973 Nobel Prize in Physics for his prediction of the Josephson effects (7).

Superconductivity

In a normal metal, some of the electrons are not bound to the atoms but wander more or less freely through the lattice. It is these free electrons that carry an electric current. The free electrons are scattered by impurities, lattice defects, and lattice vibrations (phonons), and a normal metal therefore has resistance. At a sufficiently low temperature, typically a few degrees Kelvin, certain metals become superconducting: examples are lead, tin, and niobium. An electric current flows freely through a superconductor without experiencing any resistance. This phenomenon was explained by Bardeen, Cooper, and Schrieffer (8) in a theory for which they were awarded the 1972 Nobel Prize. The basis for their theory is the pairing together of some of the free electrons to form Cooper pairs. These pairs are responsible for carrying the resistanceless current or supercurrent without developing any voltage across the superconductor.

Each pair may be described by a quantum mechanical wave function

$$\psi(\mathbf{r}, t) = |\psi(\mathbf{r}, t)| \exp[i\phi(\mathbf{r}, t)]$$

where $|\psi(\mathbf{r}, t)|^2$ represents the probability of finding a pair at a point $\mathbf{r}$ at a time t and $\phi(\mathbf{r}, t)$ is the phase of the wave function. The pair density at any point is found by adding together the contributions from all pairs. In the absence of a current, each pair consists of two electrons of equal and opposite momenta. Each pair therefore has zero momentum. A very important prop-

The author is professor of physics at the University of California, Berkeley 94720, and principal investigator at the Inorganic Materials Research Division of the Lawrence Berkeley Laboratory.

erty of a superconductor is that all the pairs are in this same zero momentum state and have the same value of the phase, ϕ . The absolute phase is not defined, but the relative phase is constant throughout the superconductor which is said to exhibit phase coherence. The whole collection of pairs may be described by a single macroscopic wave function or order parameter

$$\Psi(\mathbf{r}, t) = |\Psi(\mathbf{r}, t)| \exp[i\phi(\mathbf{r}, t)]$$

For this reason, superconductivity is a macroscopic quantum phenomenon: quantum effects are observable on a macroscopic scale.

The concept of phase coherence is central to our understanding of superconductivity, and it has intriguing and unique consequences. One of them is zero resistance. Another is flux quantization. Consider a closed superconducting ring that encloses a magnetic flux (the product of magnetic field and the area of the ring). The phase ϕ of the wave function then increases uniformly with distance around the ring. The gradient of the phase is proportional to the enclosed flux. In order for $|\Psi| \exp(i\phi)$ to be single-valued at any point, ϕ must change by $2\pi n$,

where n is an integer, in going exactly once around the ring. It is this requirement that imposes flux quantization. The total flux must be equal to $n\phi_0$, where $\phi_0 = h/2e \approx 2 \times 10^{-7}$ gauss-centimeter squared is the flux quantum.

Suppose we have a superconducting ring in zero magnetic field: the ring is in the $n=0$ quantum state. If we apply a magnetic field along the axis of the ring, the ring must remain in the $n=0$ state. Consequently, a supercurrent flows around the ring and generates a flux which exactly opposes the applied flux. This supercurrent persists as long as the field is applied, and maintains the $n=0$ state. On the other hand, if we cool the ring through its superconducting transition temperature in the presence of a field, the ring will be locked into a quantum state with $n \neq 0$ (in general, a small circulating supercurrent will be required to make the enclosed flux exactly $n\phi_0$). If the field is removed from the superconducting ring, the ring will remain in the n th quantum state indefinitely with the creation of a circulating supercurrent that maintains the flux at its initial value. The idea of flux quantization is of great importance in the operation of some of the Josephson devices.

The d-c Josephson Effect

A third consequence of phase coherence was first pointed out by Josephson (1) in 1962. He considered the behavior of the pair wave function at a junction consisting of two superconductors separated by a thin (10 to 20 angstroms) insulating barrier, as shown in Fig. 1a. Above the transition temperature of the superconductors, when the metals are normal, the barrier resistance might be several ohms. However, when the metals are superconducting, Josephson predicted that the barrier resistance would vanish. It would then be possible to pass a small supercurrent through the junction without developing any voltage across the barrier. This process is known as the d-c Josephson effect.

The effect involves quantum mechanical tunneling. Cooper pairs are able to "tunnel" from one superconductor to the other through the barrier, retaining their phase coherence in the process. In the absence of any applied fields or currents, the phase is constant throughout the junction. However, if an external current is passed through the junction, there is a phase change $\delta\phi$ across the barrier. The phase change is governed by the external current through the relation (1, 9)

$$I = I_c \sin(\delta\phi) \quad (1)$$

The maximum value of current that can flow as a supercurrent is I_c , known as the critical current. The value of I_c depends upon junction parameters and temperature. If the external current exceeds I_c , a voltage appears across the junction.

The a-c Josephson Effect

When there is a voltage across a Josephson junction, the supercurrent still exists but oscillates with time. This phenomenon is the a-c Josephson effect. The frequency ν of the oscillation is related in a simple way to the voltage V across the junction by the Josephson voltage-frequency relation (1)

$$\nu = \frac{2eV}{h} = \frac{V}{\phi_0} \quad (2)$$

As far as is known at present, this relation is exact. The factor relating frequency and voltage is roughly 484 megahertz per microvolt. The oscillating supercurrents persist for voltages of up to at least several millivolts and frequencies in excess of 10^{12} hertz.

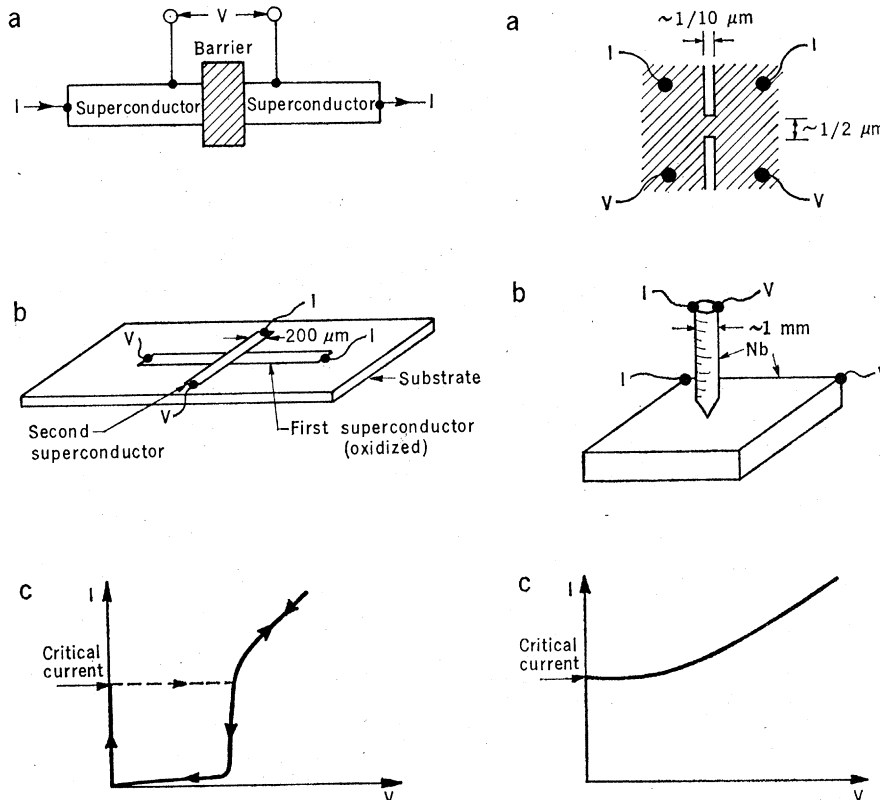


Fig. 1 (left). (a) Idealized Josephson junction; (b) an SIS tunnel junction; and (c) current-voltage (I - V) characteristic of tunnel junction. Fig. 2 (right). (a) Anderson-Dayem bridge evaporated on substrate; (b) point contact; and (c) idealized I - V characteristic of an SNS junction, a Dayem bridge, a Notarys-Mercereau bridge, a point contact, or a SLUG.

Practical Josephson Junctions

The Josephson effect was first observed experimentally by Anderson and Rowell (10) in a junction similar to that shown in Fig. 1b. A strip of tin (for example) is evaporated in a vacuum chamber through a mask onto a glass microscope slide. The strip is oxidized, and a second strip of tin is evaporated across it. The junction therefore consists of two tin strips separated by an insulating barrier (SIS junction). Leads are connected to the tin strips, and the sample is immersed in liquid helium. At temperatures well below the transition temperature of the tin (3.7°K), the current-voltage (I - V) characteristic of the junction is similar to that shown in Fig. 1c. As the current is increased from zero, no voltage appears until the current exceeds the critical current I_c . The voltage then jumps to a nonzero value (dashed line). As the current is increased further and then reduced to zero again, the solid curve is traced out. The critical current may vary from a fraction of a microampere to tens of milliamperes.

Other Josephson junctions have been developed and studied. In one variation (11), the oxide barrier of Fig. 1 is replaced by a nonsuperconducting metal, such as copper (SNS junction). The copper may be 1 micrometer or more in thickness. The Cooper pairs now tunnel through a metal barrier rather than an insulating barrier. This type of junction is particularly durable. Figure 2a shows the Anderson-Dayem bridge (12). The two superconductors are connected by a superconducting bridge of very small cross section. Because the bridge is so tiny, the maximum supercurrent it can sustain is relatively small. Another related type of structure has been developed and very successfully used by Notarys and Mercereau (13). In this structure the bridge is "weakened" by the fact that a normal metal is deposited on the substrate before the superconductor is evaporated. The point contact junction of Zimmerman and Silver (14) (Fig. 2b) has been very popular. The junction consists of a sharpened niobium wire pressed against a flat niobium block. Still another type of junction is the SLUG (superconducting low-inductance undulatory galvanometer) (15). This device consists of a bead of tin-lead solder (a superconductor) frozen onto a length of niobium wire. The solder

forms a tight contact around the natural oxide layer of the niobium. However, instead of a continuous junction, two or three discrete junctions are formed. In the cases of the Anderson-Dayem and Notarys-Mercereau bridges, the point contact, and the SLUG, there is no true tunneling process. However, the essential features of Josephson behavior—a limited and phase-dependent supercurrent—are exhibited. All these devices are collectively known as weak links. Figure 2c shows the idealized I - V characteristic of all the junction types except the tunnel junction. The resistance at currents above the critical current varies from 10^{-6} ohm for junctions with copper barriers to 100 ohms for point contacts. Sometimes the characteristics are nonreversible; however, for the device applications I shall mention, it is essential to avoid such hysteresis.

Cryogenics

In the first sections of this article, I have tried to give some feeling for the basic ideas of Josephson tunneling. Before I describe their application to devices, I shall first briefly mention the necessary cryogenic systems. The devices are usually operated at 4.2°K, the boiling point of liquid helium under atmospheric pressure. The junctions are often immersed in the liquid. However, the boiling of the liquid helium sometimes generates excess noise, and for the most sensitive measurements it may be necessary to mount the device inside a can containing helium gas which is surrounded by the liquid. The traditional low-temperature cryostat consists of a double-walled glass Dewar containing liquid helium surrounded by a second Dewar containing liquid nitrogen. This cryostat is somewhat cumbersome and fragile for use in the field, and more compact and robust versions have been developed. These cryostats are made of metal or fiber glass. The fiber glass Dewar is nonmagnetic, an important consideration in the measurement of external magnetic fields. The liquid helium is contained in an inner vessel suspended inside a larger evacuated container. A cooled thermal radiation shield between the two vessels reduces the heat load caused by thermal radiation. A typical cryostat can hold one charge of liquid helium for several days, consuming as little as one liter per day.

SQUID's

The basic detector for low-frequency measurements is the SQUID (superconducting quantum interference device). The SQUID combines flux quantization and Josephson tunneling. There are two types of SQUID: the d-c SQUID and the radio frequency (rf) SQUID.

In the d-c SQUID, two Josephson junctions are mounted on a superconducting ring (Fig. 3a). The I - V characteristic (which must be non-hysteretic) is similar to that of a single junction. However, if a magnetic field is applied along the axis of the ring, the combined critical current oscillates as the field is increased. The period of the oscillations with respect to the magnetic flux threading the ring is the flux quantum ϕ_0 (Fig. 3b). This periodic behavior reflects the macroscopic quantum nature of the SQUID and was first observed by Jaklevic *et al.* (16). Suppose the critical current is measured by applying an alternating current whose amplitude exceeds I_c . The SQUID is alternately driven into a state in which voltage appears across the weak links and then into one in which the voltage is allowed to fall back into a zero-voltage state. As the external flux is steadily increased from zero, the SQUID does not always fall back into its original state. Instead, it makes transitions to higher states: for example, from the n th state to the $(n+1)$ th state when the applied flux is $(n + \frac{1}{2})\phi_0$. As a result, the circulating current in the SQUID in the zero voltage state is periodic in the applied flux, the period again being ϕ_0 (in the case of a fully superconducting ring, the circulating current would increase linearly with the applied flux and the quantum state would not change). The circulating current is zero whenever the applied flux is $n\phi_0$ and a maximum whenever the applied flux is $(n + \frac{1}{2})\phi_0$. The presence of the circulating current reduces the combined critical current of both weak links. The critical current is therefore a maximum when the applied flux is $n\phi_0$ and it is a minimum whenever the applied flux is $(n + \frac{1}{2})\phi_0$.

In a practical application, the junctions are biased at a nonzero voltage, typically 10 microvolts, by a constant current I_0 , which always exceeds the maximum value of critical current (Fig. 3c). If the applied field is changed, the voltage across the SQUID oscillates about its mean value with

an amplitude of a few microvolts. These voltage changes are amplified by conventional room-temperature electronics.

The SLUG is also a d-c SQUID. The critical current of the SLUG oscillates as a function of the current in the niobium wire on which the solder bead is formed. This behavior indicates that only two (or perhaps three or four) junctions are formed between the wire and the solder. The magnetic flux generated by the current in the niobium wire modulates the critical current.

The rf SQUID was developed by Zimmerman and his co-workers (17), Mercereau (18), and Nisenoff (19). It consists of a single Josephson junction mounted on a superconducting ring (Fig. 4). Here again, a steadily increasing magnetic field induces quantum transitions in the SQUID. If the junction is repetitively driven into a voltage-supporting state, there will be an average circulating supercurrent that is periodic in the applied flux, with a period ϕ_0 . This current is detected by coupling the SQUID to the inductance of a resonant inductance-capacitance (LC) circuit (Fig. 4). An alternating current at the resonant frequency (typically 30 megahertz) gen-

erates an alternating voltage across the resonant circuit. The amplitude of this rf voltage depends on the value of the circulating supercurrent in the SQUID and is therefore periodic in the flux applied to the SQUID. The rf voltage is amplified and rectified by conventional electronics.

Both the d-c and rf SQUID's produce a voltage that is periodic in the flux applied to them, with a period ϕ_0 . In fact, SQUID's are digital magnetometers: one has only to count the oscillations in voltage to measure any change in the applied field. However, in practice they are almost never used in a digital mode. Instead they are incorporated in a feedback circuit, the whole system producing a voltage output that is linearly proportional to changes in the applied flux. The principle is illustrated in Fig. 5 for a d-c SQUID.

The SQUID is biased with a current I_0 as described earlier. The voltage appearing across the SQUID is amplified by conventional electronics. The output from the amplifier is fed via a resistance R_F into a coil L_F which is coupled to the SQUID. Suppose a small field δH is applied to the SQUID. The change in the SQUID voltage is

amplified and fed back as a current I_F into the coil L_F . The flux produced by this current opposes and exactly cancels δH . The total flux threading the SQUID is therefore zero, and the output voltage $V_0 = I_F R_F$ is linearly proportional to δH . The SQUID is thus the null detector in a feedback system.

Exactly the same principle is used in the operation of the rf SQUID. (In both cases, the electronic readout from the SQUID is a little more complicated in practice.) The performances of the d-c and rf SQUID's are comparable. Either type of SQUID may be used in the applications that follow. In the linearized mode, the resolution of a SQUID is a fraction of a flux quantum. A good system will resolve $10^{-4} \phi_0$ in a bandwidth of 1 hertz ($10^{-4} \phi_0$ hertz $^{-1/2}$). The frequency response is from zero up to typically a few kilohertz. It is intriguing to realize that this sensitivity represents the detection of a very small amount of energy. The change in magnetic field energy δE arising from a flux $\delta \phi$ is $(\delta \phi)^2/2L$, where L is the inductance of the SQUID. If $\delta \phi = 10^{-4} \phi_0 \approx 2 \times 10^{-11}$ gauss-centimeter squared $\approx 2 \times 10^{-19}$ weber, and $L \approx 10^{-9}$ henry, we find that $\delta E \approx 2 \times 10^{-29}$ joule.

The area of a SQUID is typically 10^{-2} square centimeter. The resolution in magnetic field is therefore roughly 10^{-9} gauss hertz $^{-1/2}$. In order to take advantage of this high sensitivity, it is essential to shield the SQUID against fluctuations in the earth's magnetic field, typically 10^{-7} gauss over a period of 1 second. In an urban environment the noise may be as much as two orders of magnitude higher. This shielding is achieved by enclosing the SQUID in a superconducting can. The can does not reduce the external field to zero but "freezes in" a constant field.

Two typical SQUID's and a SLUG are shown in Fig. 6. The rf SQUID shown (Fig. 6b) contains a double loop with a point contact across the narrow region. This device was originally developed by Zimmerman *et al.* (17) and is now available commercially from Superconductivity Helium Electronics Corporation. The d-c SQUID (Fig. 6c) and the SLUG (Fig. 6a) are from my own laboratory. A further type of rf SQUID (not shown) has been developed by Mercereau (18) and Nisenoff (19). A thin ring of superconducting film is evaporated onto a quartz rod, and a constriction is

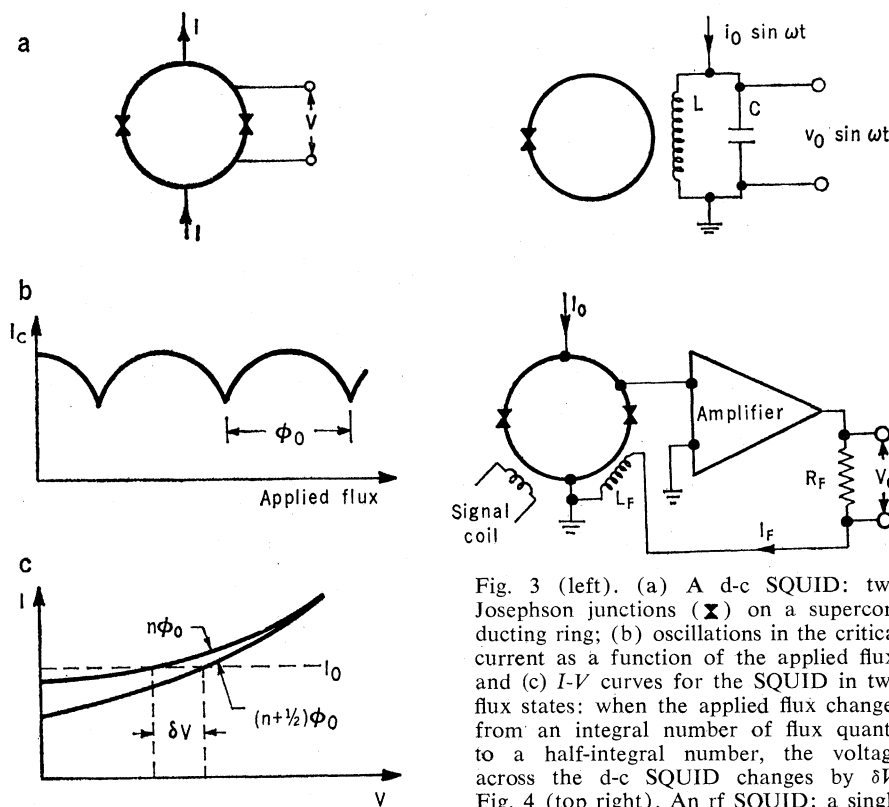


Fig. 3 (left). (a) A d-c SQUID: two Josephson junctions (X) on a superconducting ring; (b) oscillations in the critical current as a function of the applied flux; and (c) I - V curves for the SQUID in two flux states: when the applied flux changes from an integral number of flux quanta to a half-integral number, the voltage across the d-c SQUID changes by δV . Fig. 4 (top right). An rf SQUID: a single junction (X) on a superconducting ring.

The ring is coupled to an LC resonant circuit to which an rf current $i_0 \sin \omega t$ is applied. The amplitude of the voltage across the resonant circuit v_0 is an oscillatory function of the flux applied to the SQUID. Fig. 5 (lower right). Feedback circuit for a d-c SQUID.

etched or cut into the ring. This type of SQUID is also commercially available. Although point-contact devices have been very widely used, it is probable that they will ultimately be replaced by thin film devices, which are more stable. The d-c SQUID preceded the rf SQUID, and was and is used successfully. However, present trends favor the rf SQUID, which involves only a single junction and which is available commercially.

Flux Transformer

The superconducting flux transformer, shown schematically in Fig. 7a, is used in almost all measurements of magnetic field. The transformer is entirely superconducting and consists of a pick-up loop (primary coil) and a secondary coil tightly coupled to a SQUID. The SQUID and secondary are enclosed in a superconducting can. A magnetic field applied to the pick-up loop generates a persistent current, which in turn induces a flux in the SQUID. The sensitivity of the SQUID can be appreciably enhanced by proper transformer design, and resolutions of better than 10^{-10} gauss hertz $^{-1/2}$ have been achieved.

However, this high sensitivity is of limited use in an unshielded environment because of the noise in the earth's field. Of far greater practical importance is the magnetic field gradiometer, illustrated in Fig. 7b. In this configuration, the transformer has two pick-up coils of equal area. They are arranged so that a uniform magnetic field does not induce a supercurrent. If the field has a gradient (for example, $\partial H_z / \partial x$), the fields applied to the two coils will differ and the induced supercurrent will be proportional to the difference. The SQUID system thus measures a gradient. The gradiometer can be made in many configurations: gradiometers measuring $\partial H_z / \partial z$ are commonly used, and higher derivatives could, in principle, also be measured. The first published account of a gradiometer appears to be that of Zimmerman and Frederick (20), who reported a resolution of 10^{-10} gauss per centimeter per hertz $^{1/2}$. These investigators subsequently achieved a sensitivity of 3×10^{-12} gauss per centimeter per hertz $^{1/2}$, using a multihole SQUID and a resonant circuit frequency of 300 megahertz (21).

The great advantage of a gradiometer is that it discriminates against sig-

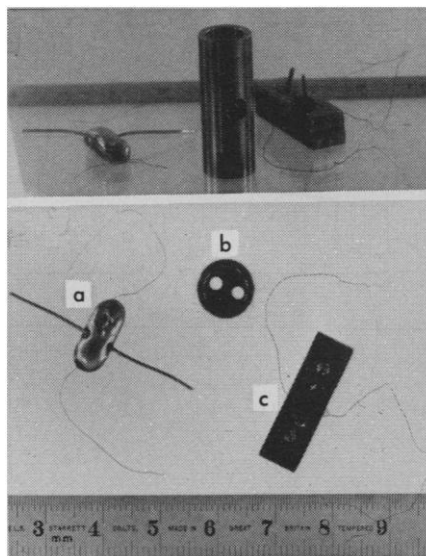


Fig. 6. Three devices; the mirror at the top shows a side view; the lower part of the photograph shows a view looking down. (a) A SLUG; (b) an rf SQUID; and (c) a d-c SQUID.

nals generated a large distance away in favor of signals generated locally. Apart from man-made interference, the main sources of magnetic noise are disturbances in the upper atmosphere and fluctuations in the earth's field. Both sources are relatively distant, so that, although their fields at the detector may be large, their field gradients are small. Suppose that we are concerned with measuring a small magnetic signal from a nearby source. Although its field amplitude may be below the ambient field noise, its gradient amplitude may be considerably above the ambient gradient noise. In the same way, the gradient produced by a source a few centimeters away

may exceed the gradient noise generated by a passing automobile or a power line tens of meters away. For these reasons, most of the practical devices for use in an open environment are likely to be gradiometers.

Apart from measurements in the physics laboratory, there appear to be several other important applications of magnetometers and gradiometers. Cohen *et al.* (22, 23) have pioneered the use of superconducting devices in magnetocardiography, using a magnetometer in a magnetically screened room. In one study, Cohen and McCaughan (23) obtained magnetocardiograms at various points on the torso of a patient. Their results are shown in Fig. 8. The outline of the heart is shown dotted. The signals obtained at different points clearly differ substantially. The peak-to-peak signal amplitude is about 5×10^{-7} gauss, much greater than the background noise. At present, it is not known how to interpret the differences in these signals. However, it is to be hoped that intensive clinical studies will eventually enable one to obtain a more precise diagnosis than is possible from electrocardiograms. In clinical practice, one would take magnetocardiograms with a gradiometer, so that a shielded room would be unnecessary (20).

Cohen has also detected alpha- and delta-waves from the brain magnetically (24). The alpha-wave amplitude is smaller than that developed by the heart, perhaps 10^{-9} gauss. It seems likely that magnetoencephalography would require that both patient and detector be in a magnetically shielded room to reduce the background noise to an acceptable level. Here again, this

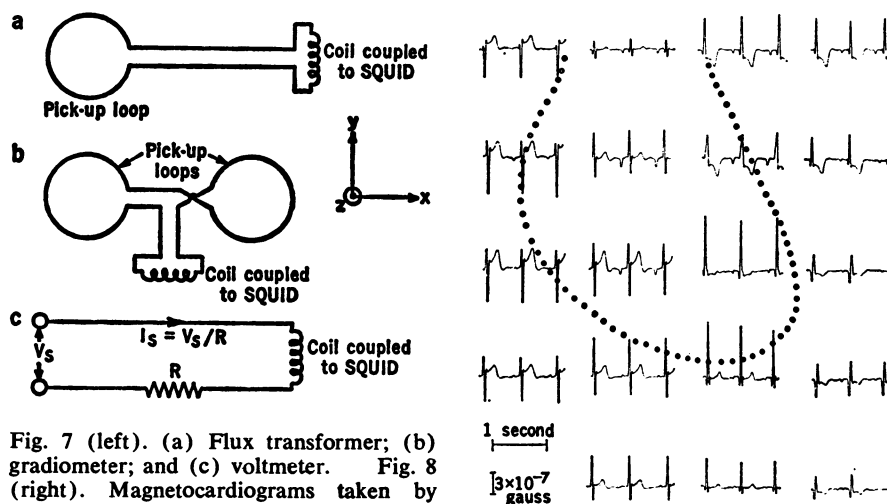


Fig. 7 (left). (a) Flux transformer; (b) gradiometer; and (c) voltmeter. Fig. 8 (right). Magnetocardiograms taken by Cohen and McCaughan (23) at various points outside the torso of a male patient. The dotted outline represents the position of the heart. [Courtesy *American Journal of Cardiology*, New York]

application has exciting possibilities, but extensive clinical studies are obviously needed.

Magnetometers and gradiometers have considerable potential in geophysics. For example, it might be possible to search for mineral deposits by means of gradient surveys. Morrison at the University of California, Berkeley (25), is investigating an alternative surveying technique. He applies an electric current pulse between two probes in the ground a few hundred meters apart. The induced polarization is characteristic of the rocks through which the current flows and is detected by a SQUID magnetometer. Another intriguing possibility is in the prediction of earthquakes or volcanic eruptions. There is evidence to suggest that, over periods of a few days prior to an earthquake, there are magnetic disturbances along the fault line. Such disturbances were observed by Moore just before the 1964 Alaskan earthquake (26). Similar effects were observed by Johnston and Stacey before the eruption of Mount Ruapehu, New Zealand, in 1968 (27). The physical origin of these disturbances is not firmly established. However, a likely cause is piezomagnetism, that is, the magnetization of a body under stress. All of the data so far have been collected with magnetometers: the reading on a magnetometer near the disturbance is compared with that on one placed some distance away (typically 10 kilometers). This procedure minimizes noise due to distant fluctuations, for example, in the ionosphere. It would obviously be of some interest to observe changes in the magnetic field gradient near a fault or a volcano. As mentioned above, the gradiometer would discriminate against distant noise in favor of more local signals. To my knowledge, no such observations have yet been made.

I should also like to mention the use of SQUID's to measure magnetic susceptibility, that is, the ratio of the magnetization to the applied magnetic field. The sample is inserted into one loop of a gradiometer (Fig. 7b), and a uniform magnetic field is applied to both loops. If the sample has a non-zero susceptibility, it will change the magnetic flux threading the loop in which it is placed. The SQUID output will be proportional to the susceptibility. Careful shielding against external field fluctuations is essential. In this way, Mercereau and his co-workers have measured the susceptibility of

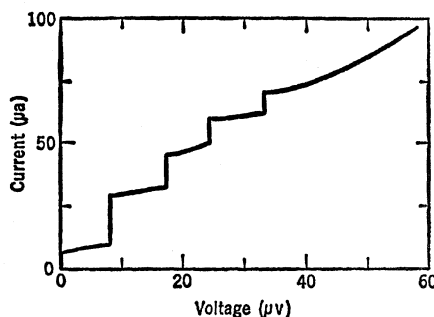


Fig. 9. The I - V characteristic of a point contact irradiated with microwaves at 4 gigahertz.

biochemical samples over a temperature range from 4° to 300°K (28). A related application is the measurement of susceptibility in rock samples. Day has measured nuclear magnetic resonance curves in a similar manner (29). In all of these measurements, the high sensitivity of the SQUID enables one to use minute samples, an important consideration, especially in biological work.

Voltmeter

A SQUID or SLUG can be used readily as a voltmeter. In Fig. 7c, a resistance R is in series with the superconducting coil coupled to a SQUID. Alternatively, the resistance may be connected to the niobium wire on which a SLUG has been made (Fig. 6a). In either case, a signal voltage V_s applied to the terminals generates a current $I_s = V_s/R$ that is detected by the superconducting device. These voltmeters have been widely used in solid-state physics to measure tiny voltages. The sensitivity is very great, and voltages as low as 10^{-15} volt hertz $^{-1/2}$ can be detected routinely. The resolution is often limited by the Johnson noise generated in the series resistance or the source resistance: the Johnson noise in 10^{-8} ohm at 1°K is about 10^{-15} volt hertz $^{-1/2}$. This fact has been utilized by Giffard, Webb, and Wheatley (30) in their noise thermometer. The terminals marked V_s in Fig. 7c are shorted together, so that the circuit consists of a superconducting loop containing a resistance R . The mean square Johnson noise current is proportional to the absolute temperature and is measured by the SQUID in the usual way. Giffard *et al.* have been able to measure temperatures down to a few thousandths of a degree Kelvin with this techniques.

Effect of Microwaves on Josephson Junctions

I will briefly discuss the effect of high-frequency (microwave and far-infrared) radiation on Josephson junctions (31). If microwaves of a single frequency f are coupled to a Josephson junction, for example, a point contact, the I - V characteristic is modified as shown in Fig. 9. A series of steps is induced, the voltage along each step being constant. The steps appear at voltages

$$|V_n| = nhf/2e \quad (3)$$

where n is an integer. The range of current over which the voltage remains constant (that is, the step height) oscillates as the microwave power is increased. The detailed theory of the behavior of a junction in a microwave field is complicated. The essential point is that the microwaves at frequency f are mixed in the nonlinear junction with the a-c Josephson currents whose frequency ν depends upon the voltage across the junction. Whenever $(\nu \pm nf) = 0$ (Eq. 2), there is a zero-frequency beat, which is manifested as a current step. A simple quantum description of the effect has been given by Josephson (1). When the junction is biased at a voltage V , the energy difference between Cooper pairs on opposite sides of the barrier is just $2eV$. Whenever this energy difference is exactly nhf , pairs can cross the barrier coherently with the emission or absorption of n microwave photons.

Josephson junctions can be used as detectors of electromagnetic radiation in a number of different ways. I have decided to discuss just two of these methods which seem to me the most promising. The devices concerned are the square law broadband detector and the heterodyne linear detector. I should emphasize that there is considerable work in progress in this field and that it is not yet entirely clear which devices will ultimately demonstrate the best performance. In any case, different applications may be better suited to different modes of operation.

Square Law Broadband Detector

The use of a Josephson junction as a broadband detector was first investigated by Grimes, Richards, and Shapiro (32). When microwaves generate constant current steps, at the same time they reduce the magnitude of the critical

current. In fact, the critical current is also an oscillatory function of the microwave field. The critical current corresponds to the $n = 0$ induced step. Suppose one applies broadband radiation (that is, radiation containing a wide range of frequencies) to a junction. The steps on the I - V characteristic will be blurred out, and no discrete steps will be visible. However, the critical current responds to each frequency component of the radiation and will be correspondingly modified. (Equation 3 is satisfied for $n = 0$ by all values of frequency f .) The critical current does not respond uniformly to all frequencies, the response becoming less sensitive as the frequency increases. For small signal levels

$$\Delta I_c \propto V_s^2 / \omega_s^2 \quad (4)$$

where V_s is the voltage induced across the junction by radiation at a frequency ω_s and ΔI_c is the resulting depression in the critical current. The fact that ΔI_c is proportional to V_s^2 implies that the junction is a square law detector and that it responds to the power rather than to the amplitude of the radiation.

In all successful detectors point-contact junctions have been used. It appears that the point contact couples more efficiently to the radiation than other types of junction, although the coupling properties of Anderson-Dayem bridges (12) are now being extensively studied. The point contact is mounted transversely across a wave guide or light pipe (oversized wave guide) so that the electric field of the incoming radiation generates currents through the junction. The wave guide is usually terminated by a movable plunger which is adjusted to maximize the coupling efficiency. Changes in the critical current in response to radiation are detected by a method identical to that used for the d-c SQUID (Fig. 3c). A constant current I_0 biases the junction at a nonzero voltage. When the critical current changes, the I - V characteristic and hence the voltage across the junction are modified. Since the detector responds to a wide range of frequencies, the bandwidth is often restricted externally to a narrow range about some central frequency (for example, by an interferometer). One sweeps the central frequency to obtain the spectrum of the radiation. It is usual to chop the incoming radiation at a few tens of hertz and to detect the resulting a-c signal that appears across the junction.

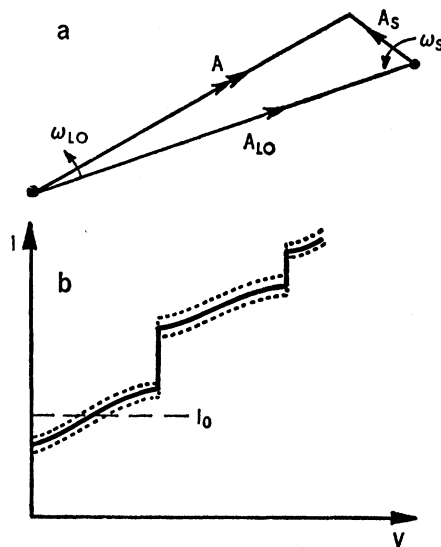


Fig. 10. Heterodyne detector: (a) phasor diagram, showing the addition of A_{LO} , which has a frequency ω_{LO} , and A_s , which has a frequency ω_s . If $\omega_{LO} \approx \omega_s$, the resultant vector A is amplitude modulated at a frequency $\omega_I = |\omega_{LO} - \omega_s|$. (b) The solid line shows the effect of the local oscillator on the I - V characteristic. An applied signal modulates the characteristic between the limits set by the dotted lines; I_0 (dashed line) is a constant current bias.

The most important frequency range for the Josephson detector is in the far-infrared, around 300 gigahertz (1-millimeter wavelength). Presently available detectors at these frequencies are relatively less sensitive than those available in the microwave or infrared regions. Apart from laboratory experiments, the most significant application of these detectors appears to be in far-infrared astronomy. Ulrich has used a point-contact detector for astronomical observations at the McDonald Observatory of the University of Texas (33). He has observed the sun, the moon, Venus, Jupiter, 3C273, and the galactic center. At 1 millimeter the sensitivity of his detector is comparable with the sensitivity of the best semi-conducting broadband bolometers (34).

Heterodyne Detector

In the heterodyne detector, the signal to be detected is combined (mixed) with the output from a local oscillator in the nonlinear Josephson junction. In the simplest case, the signal frequency, f_s , is close to the local oscillator frequency, f_{LO} . The amplitude of the local oscillator output is much greater than the signal amplitude. Under these conditions, the signal and local oscillator output add in a relatively simple way,

as indicated in the phasor diagram of Fig. 10a. The local oscillator output is represented by a vector of length A_{LO} rotating at an angular frequency $\omega_{LO} = 2\pi f_{LO}$. To this vector is added the signal vector, of length A_s , rotating at a frequency ω_s . Relative to the local oscillator vector, the signal vector rotates at a frequency $\omega_I = |\omega_{LO} - \omega_s|$ (the intermediate frequency), which is much less than either ω_{LO} or ω_s . The resultant vector A therefore rotates with a frequency ω_{LO} , but its amplitude is modulated at a frequency ω_I between the limits $(A_{LO} + A_s)$ and $(A_{LO} - A_s)$.

The mixing process that occurs in the Josephson junction can be readily understood. In the absence of a signal, the large local oscillator output induces a series of steps in the I - V characteristic, as shown in Fig. 9. When the signal is applied, the effect of the local oscillator on the junction is modulated at a frequency $f_I = |f_{LO} - f_s|$. Consequently, the whole I - V characteristic is modulated at f_I , as shown in Fig. 10b. A constant current I_0 biases the junction at a voltage roughly one half that of the $n = 1$ step. In the presence of a signal, the voltage across the junction oscillates at a frequency f_I , and with an amplitude that is proportional to the signal amplitude. This voltage is amplified by an intermediate frequency amplifier and subsequently measured.

The best characterized Josephson heterodyne detector at present appears to be that of Taur, Claassen, and Richards (35). They used a point-contact device, mounted in the way described for the broadband detector. The local oscillator frequency was 36 gigahertz. Taur *et al.* chose this relatively low frequency to enable them to make a thorough study of the properties of the detector. Eventually, it should be possible to operate the detector at 300 gigahertz. It is a little difficult to assess just how well the device will perform at this frequency. If the performance extrapolates in the expected way, the Josephson heterodyne detector is likely to be the most sensitive available for some applications. However, the performances of the Josephson detectors and of competing detectors (31) are steadily improving, and it is not clear which of them will eventually have the highest resolution. I can probably best sum up the heterodyne detectors by saying that the Josephson devices are at least holding their own in a rapidly changing field, but that much work remains to be done.

Josephson Junction Broadband Bolometer

Clarke, Hoffer, and Richards (36) have developed a bolometer that employs a Josephson junction in a quite different way from the devices already described. A bolometer consists of a small piece of material of heat capacity C_h suspended inside a vacuum can by a thermal link of conductance K . When electromagnetic radiation of power ΔP is absorbed by the bolometer, its temperature is increased by $\Delta T = \Delta P / K$. If we measure the change in some temperature-sensitive parameter of the bolometer, we can estimate ΔT and thus ΔP . The response time of the bolometer is C_h / K . It is necessary to make K small to achieve high sensitivity. Therefore C_h should be small to keep the response time down to a reasonable level.

Figure 11 is a photograph of this bolometer. It consists of a sapphire substrate (of low heat capacity) suspended by two pairs of nylon threads. A lead-copper-lead (SNS) Josephson junction is evaporated onto the sapphire. The critical current of this junction increases exponentially as the temperature is lowered. Hence, a small change in the temperature of the substrate produces a substantial change in the critical current. Electrical connection is made to the SNS junction by evaporating lead onto the edges of the substrate and onto the two pairs of nylon threads on the left side of the photograph. A heater is mounted next to the SNS junction for calibration purposes and is connected to the two pairs of right-hand, lead-coated threads. The rear of the substrate is coated with a thin film of bismuth to couple the bolometer to the incoming electromagnetic radiation. The whole device is mounted in a vacuum can which is immersed in liquid helium. A SQUID detects changes in the critical current of the SNS junction.

The bolometer was tested by determining the smallest power in the heater that could be detected. The best sensitivity that has been achieved to date is 4×10^{-15} watt hertz $^{-1/2}$. Clarke *et al.* (36) believe that the ultimate sensitivity of the bolometer is about 10^{-15} watt hertz $^{-1/2}$. Preliminary measurements of the absorptivity of the bismuth-coated sapphire substrate have indicated that it absorbs strongly over a range of wavelengths from 0.1 to a

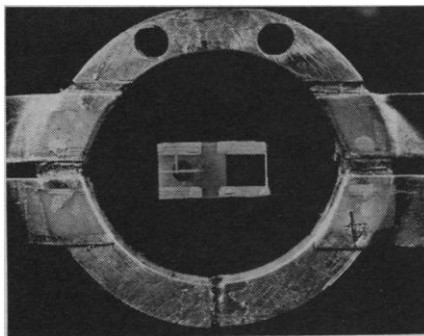


Fig. 11. An SNS bolometer. An SNS junction is evaporated onto the left side of the sapphire substrate. The two pairs of lead-coated threads on the left side provide electrical connection to the junction. A copper film heater is on the right side of the substrate; electrical connection is provided by the two pairs of threads on the right.

few millimeters. This result suggests that the bolometer should have a sensitivity to far-infrared radiation approaching 10^{-15} watt hertz $^{-1/2}$, a resolution which would make it the most sensitive broadband detector available.

Summary

Josephson tunneling is a phenomenon of very great fundamental physical interest and also of diverse and far-reaching application. We have already seen a very precise measurement of e/h which has had considerable impact on the values of many of the fundamental constants (5). The National Bureau of Standards now maintains the standard volt in terms of a Josephson frequency. The use of Josephson junctions in computers offers the possibilities of increased speed and reduced size. The use of SQUID's gives us unprecedented resolution in the measurement of low-frequency voltages, magnetic fields, field gradients, and susceptibilities. This particular area is presently one of rapid growth, largely because of the availability of SQUID's commercially (37). Thus scientists formerly unconnected with low temperature physics are now able to take advantage of the great sensitivity of SQUID's. It seems very likely that these devices will be used in other fields to an increasing extent. Finally, the Josephson junction has considerable promise as a broadband detector and as a heterodyne detector in the far-infrared.

References and Notes

1. B. D. Josephson, *Phys. Lett.* **1**, 251 (1962); *Adv. Phys.* **14**, 419 (1965).
2. A detailed review of the low-frequency applications has been given by J. Clarke [*Proc. Inst. Elec. Electron. Eng.* **61**, 8 (1973)]; a detailed review of the high-frequency detectors has been given by P. L. Richards, F. Auracher, and T. Van Duzer (*ibid.*, p. 36).
3. W. H. Parker, D. N. Langenberg, A. Denenstein, B. N. Taylor, *Phys. Rev.* **177**, 639 (1969).
4. B. N. Taylor, W. H. Parker, D. N. Langenberg, *Rev. Mod. Phys.* **41**, 375 (1969).
5. —, A. Denenstein, *Metrologia* **3**, 89 (1967).
6. J. Matisoo, *Proc. Inst. Elec. Electron. Eng.* **55**, 172 (1967); T. A. Fulton, R. C. Dynes, P. W. Anderson, *ibid.* **61**, 28 (1973).
7. B. D. Josephson, *Science* **184**, 527 (1974).
8. J. Bardeen, L. N. Cooper, J. R. Schrieffer, *Phys. Rev.* **168**, 1175 (1957).
9. P. W. Anderson, in *Lectures on the Many-Body Problem* (Ravello, Italy, 1963), E. R. Caianiello, Ed. (Academic Press, New York, 1964), vol. 2, pp. 113–135.
10. — and J. M. Rowell, *Phys. Rev. Lett.* **10**, 230 (1963).
11. J. Clarke, *Proc. Roy. Soc. (Lond.) Ser. A* **308**, 447 (1969).
12. P. W. Anderson and A. H. Dayem, *Phys. Rev. Lett.* **13**, 195 (1964).
13. H. A. Notarys and J. E. Mercereau, in *Proceedings of the International Conference on the Science of Superconductivity* (Stanford, California, 1969), F. Chilton, Ed. (North-Holland, Amsterdam, 1971), p. 424; *J. Appl. Phys.* **44**, 1821 (1973).
14. J. E. Zimmerman and A. H. Silver, *Phys. Rev.* **141**, 367 (1966).
15. J. Clarke, *Phil. Mag.* **13**, 115 (1966).
16. R. C. Jaklevic, J. Lambe, A. H. Silver, J. E. Mercereau, *Phys. Rev. Lett.* **12**, 159 (1964).
17. J. E. Zimmerman, P. Thiene, J. T. Harding, *J. Appl. Phys.* **41**, 1572 (1970).
18. J. E. Mercereau, *Rev. Phys. Appl.* **5**, 13 (1970).
19. M. Nisenoff, *ibid.*, p. 21.
20. J. E. Zimmerman and N. V. Frederick, *Appl. Phys. Lett.* **19**, 16 (1971).
21. —, "Ultrasensitive superconducting magnetic gradiometer" [unpublished National Bureau of Standards report No. 10 736 (1972)].
22. D. Cohen, E. A. Edelsack, J. E. Zimmerman, *Appl. Phys. Lett.* **16**, 278 (1970).
23. D. Cohen and D. McCaughan, *Am. J. Cardiol.* **29**, 678 (1972).
24. D. Cohen, *Science* **175**, 664 (1972).
25. H. F. Morrison, unpublished data.
26. G. W. Moore, *Nature (Lond.)* **203**, 508 (1964).
27. M. J. S. Johnston and F. D. Stacey, *ibid.* **224**, 1289 (1969).
28. H. E. Hoenig, R. H. Wang, G. R. Rossman, J. E. Mercereau, in *Proceedings of the 1972 Applied Superconductivity Conference* (Annapolis, Maryland) (Institute of Electrical and Electronics Engineers, New York, 1972), p. 570.
29. P. E. Day, *Phys. Rev. Lett.* **29**, 540 (1972).
30. R. P. Giffard, R. A. Webb, J. C. Wheatley, *J. Low Temp. Phys.* **6**, 533 (1972).
31. S. Shapiro, *Phys. Rev. Lett.* **11**, 80 (1963).
32. C. C. Grimes, P. L. Richards, S. Shapiro, *ibid.* **17**, 431 (1966); *J. Appl. Phys.* **39**, 3905 (1968).
33. B. T. Ulrich, in *Proceedings of the International Conference on Detection and Emission of Electromagnetic Radiation with Josephson Junctions*, Perros-Guirec, France, 1973 [*Rev. Phys. Appl.* **9**, 111 (1974)].
34. For a recent review of the sensitivity of various detectors, see A. Penzias, *ibid.*, p. 7.
35. Y. Taur, J. H. Claassen, P. L. Richards, *ibid.*, p. 263.
36. J. Clarke, G. I. Hoffer, P. L. Richards, *ibid.*, p. 69.
37. I am aware of the following manufacturers: Develco, Inc., Superconductivity Helium Electronics Corporation, and Superconducting Technology, Inc.
38. I thank Prof. P. L. Richards, Dr. J. H. Claassen, and Y. Taur for discussion of far-infrared detectors, Prof. Bhattacharyya, Dr. M. J. S. Johnston, and Prof. H. F. Morrison for discussion of geophysical measurements, and Dr. D. Cohen for discussion of magnetocardiography and for supplying Fig. 8 [which was originally published in *Am. J. Cardiol.* **29**, 678 (1972)]. This work was supported in part by the U.S. Atomic Energy Commission.