lying water column indicated a biogenic source whereas measurements of dissolved gases in the underlying sediments indicated a petrogenic source.

The most probable mechanism for addition of the methane to the overlying water column is bubbling seepage—as has been extensively observed in the Gulf of Mexico (*9, 10*). The total methane contributed to the overlying waters by this seepage could amount to 1×10^8 to 10×10^8 liters per day considering that the total transport of water across the Jamaica Ridge is approximately 31×10^6 m³/sec (*6*) and that the integrated excess methane in the upper 1200 m is in the 500 to 5000 nl/liter range.

Other gases measured in the northwest Caribbean showed no anomalous depth trends. The concentration of nitrous oxide (N_2O) was fairly uniform (160 to 190 nl/liter) in the upper 200 m and increased to a maximum of ~ 550 nl/liter at 800 m, which coincides with the core of the antarctic intermediate water. Similar profiles have been presented by Yoshinari (*11*) for the North Atlantic and the Caribbean, showing that the maximum concentration of N_2O corresponds to the minimum concentration of oxygen. The large methane maxima in Fig. 2 coincide somewhat with small increases in TSM. Suspended matter may also be added to the water column as the current moves across from the Jamaica Ridge.

The deep methane maxima in the northwest Caribbean are of interest not only because of the unusual geological processes that create them but because they may provide tracers for Caribbean Current waters. This system of currents is important since it flows through the Yucatan Strait to form the Loop Current in the Gulf of Mexico and exits through the Florida Straits to contribute to the Gulf Stream. No methane profiles have been obtained for the core of the Loop Current or the Gulf Stream waters. If the seepage along the Jamaica Ridge is a relatively constant addition to the waters flowing over that sill, then the deep methane maxima may be useful tracers of these current systems if methane is fairly conservative in its action as a tracer. It was shown in (*2*) that in polar regions deep waters formed with a concentration of ~ 70 nl per liter of methane are depleted to ~ 10 nl/liter by the time they reach the deep basins of the ocean. Methane depletion is evident in the water deeper than 1000 m in the Cayman and Mexico basins (Fig. 1).

The mechanism and rate of methane utilization in the ocean is unknown. Most deep profiles, however, indicate that the greatest utilization occurs at depths above 500 m, with the half-life for methane below this depth being hundreds of years. Such large additions of methane in the 80- to 1000-m depth interval may provide an ideal condition for studying methane consumption in the water column.

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Electrical Origin of the Outbursts on Io

Abstract. *The outbursts seen on Jupiter's satellite Io have been described as volcanic eruptions. They may instead be the result of large electric currents flowing through hot spots on Io and causing evaporation of surface materials. A strictly periodic behavior would then be expected.*

In the course of the Voyager 1 mission photography of Jupiter's satellite Io, at least seven violent eruptions were identified, apparently throwing material to heights up to 270 km and emanating from caldera-like markings. The eruptions were regarded as volcanic in origin by the various scientific teams that had the primary responsibility for the analysis of the data (*1, 2*). Thus one of the teams writes, "Probably the most spectacular discovery of the Voyager mission has been the existence of active volcanoes on Io, erupting material to heights of several hundred kilometers above the surface" (*1*, p. 961).

A volcanic interpretation of the eruptions seemed favored by several associated circumstances. Fluid flow patterns that may represent lava flows are seen in association with some of the calderas. Infrared observations show increased temperatures in these locations (*3*). A paper on the tidal energy dissipation in Io, published shortly before the observations (*4*), suggested that much internal melting in Io can be expected and that volcanic features on the surface should be anticipated.

Nevertheless, the volcanic interpretation presents great difficulties. For material to be thrown to the heights observed, it must have been propelled to velocities up to 1 km/sec. Volcanic events can expel materials with high velocities only with the aid of volatile substances. On the earth, water and carbon dioxide are the chief volatiles involved. If the activity on Io was as incessant as it appears now to be, then in a small fraction of geologic time all the volatiles would have been driven off and would no longer be available as propellants. Indeed, the spectroscopic evidence indicates an absence of water in the atmosphere of Io.

Sulfur or sulfur compounds have been mentioned (*1*) as a possible propellant. Although there are good indications that sulfur is abundant on Io, neither elemental sulfur nor any of its compounds are likely to be suitable for causing such eruptions. The volatile compounds of sulfur would be expected to have been lost, together with the other volatiles. In any case, whatever the compound, the atomic weight of sulfur, 32, virtually rules it out as the propellant to achieve such velocities. Only in very special circumstances is it possible for solid particles to gain speeds in excess of the speed of sound in the propelling gas. In most actual circumstances applicable to a volcano, expulsion speeds would be less than the speed of sound in the propelling gas (*5*). For a gas of the molecular weight of diatomic sulfur or sulfur dioxide to have a speed of sound of 1 km/sec, it would have to be heated to 6000 K. Even for the molecular weight of hydrogen sulfide, the figure would be 3300 K. The temperatures that can be expected in volcanic regions are limited to the melting temperatures of the rocks concerned, and those are below 1500 K for nearly all rock-forming minerals.

Io is subjected to a tidal deformation as a result of the forced eccentricity of its orbit. This must result in dissipation of energy in the material. The discussion by Peale *et al.* (*4*) shows this effect to be favorable for internal melting, but not too remarkable for the heat flow out of the surface. A comparison with the earth is of interest. The heat flow out of the surface of the earth is estimated as 10^{28} erg/year (*6*), which translates into 65 erg/cm^2-sec. The value given by Peale *et al.* for Io (for their suggested value of 100 for the dissipation function Q) would amount to 46 erg/cm^2-sec. Even values a few times that, which could occur with the runaway melting process suggested by Peale *et al.*, would not be too different from those in terrestrial regions with enhanced heat flow. Nevertheless, volcanic activity on the earth is much more limited than the activity now attributed to Io.

The electrical surroundings of Io provide another energy source, which has been estimated to be comparable with that of the tides (*7*). A current of 5×10^6 A is known to be shunted across flux tubes of the Jovian field by the presence of Io (*7*-*9*). While it has sometimes been assumed that this current is carried above the surface of Io from one side to the other in Io's ionosphere, it is also possible, and we would argue even very probable, that such a current is instead largely conducted through the body of Io.

The mean density of Io is appropriate to rocks, and one therefore has to be concerned with the problems of electrical conductivity in such materials. The conductivity of such semiconductors usually rises extremely steeply with increasing temperature, and this must lead to an unstable pattern of current when the currents are large enough to cause ohmic heating [an effect that was referred to by Ness *et al.* (*7*)]. In these circumstances currents will contract down to narrow paths which can be kept hot, and along which the conductivity is therefore high. Tidal heating will certainly have ensured that the interior of Io has a very low electrical resistance, causing a negligible extra amount of heat to be deposited by this current. It is only the outermost layers, kept cool by radiation into space, that will present a large resistance and in which a concentration of the current into hot spots must be expected.

Whether these hot spots are volcanic regions on Io, where hot or even liquid rocks have penetrated to the surface, or whether they are hot spots caused and maintained by the large current cannot be decided with the present information. If volcanoes existed, but without causing the incessant and violent outbursts, they would still become the pathways through which the large current would be shunted to the conducting interior. If, on the other hand, Io possessed a cool crust, it could still be kept hot along particular narrow pathways by ohmic dissipation of the pinched-down currents. The figure quoted for the available power to be dissipated in Io by these currents is 10^{12} W (*7*), approximately the same as the total figure estimated for the tidal heating. It may well be that this figure is too high and that a larger proportion of the impedance around the entire circuit lies in the ionosphere of Jupiter. Nevertheless, even a small fraction would be more favorable for causing local hot spots, since this energy would necessarily be delivered in sharply concentrated spots and in the place of the highest resistance, which must be near the surface where the rocks are the coolest (*10*).

It is not only the rock resistivity but also the contact resistance (*11*) that will contribute to generate high temperatures on the surface. In such conditions of electric arcs, temperatures up to ionization levels—that is, several thousand kelvins—can be produced. By contrast, the tidal heating would be distributed without any sharp concentration into spots, and the bulk of it would be radiated away, causing no observable activity (just as the fraction of the heat flow of the earth that appears in volcanic outbursts is very small).

We therefore propose that the outbursts that are seen are the result of the large current known to be flowing in and out of the domain of Io, that this current is in part conducted in the ionosphere, but that the low resistance of hot spots and of Io's hot interior causes preferential pathways through which current is shunted. Most current spots are likely to be volcanic calderas, either provided by tectonic events within Io or generated by the current heating itself. On the surfaces of these spots, as in any electric arc, very high temperatures are generated, and the locally evaporated materials, whatever they are, would be turned into gas hot enough to expand at a speed of 1 km/sec. If this expansion commences in any caldera or volcanic vent, an approximately upward collimation and a nearly common velocity of the expanding gas can be produced. As this gas cools and condenses at higher levels, the resulting particles (whose light scattering is what is seen) will all have a common speed, which is a requirement for producing the umbrella-shaped plume with a definite upper edge that was clearly seen on two of the photographs (*1*).

The fine powder that is generated is then thought to fall ballistically and produce the fuzzy outline ring patterns that surround most or all of these spots as striking features. The ballistic velocities required to throw particles to the distances of the radii of these rings are again of the order of 1 km/sec. Differently shaped ring patterns, such as the single very large heart-shaped one, may then result just from the shapes of the caldera rims defining the patterns of the expanding gas flow. The ring patterns, like the umbrella-shaped plumes, also require that a very nearly constant speed was imparted to all the material so deposited. In any sporadic eruptions of an explosive nature, a wide range of velocities of the propelled material would be expected in any one eruption, and successive eruptions would not be alike. A patch rather than a ring would then be caused by the fallback. On the other hand, the electric arc can be expected to be an accurately repeating process, and the temperature can be high enough for the ejected material to be all in the form of a vapor initially, so that it all reaches the common gas velocity before condensing.

The electric arc interpretation of the outbursts leads to a number of predictions, some of which may be verifiable in subsequent missions.

1) The outbursts should repeat in a systematic way, controlled by the repetition cycle of the external field configuration. The skewness of the Jovian field provides the main variation, and the repetition cycle should thus be the time for Io to return to the same Jovian magnetic longitude (*9*) (a little longer than the rotation period of Jupiter). Individual arcs may strike or go out in a particular phase of the cycle.

2) The hot spots should be very hot in the small areas struck by the arc, and thus luminous spots in the caldera may be visible at night. The infrared spectrum should be appropriate to small (presumably unresolved) spots of high temperature rather than large areas of slightly raised temperature.

3) Spectra of some ionized components of gas may be visible in the outbursts.

4) Radio emission may be correlated with the periodic changes, as arcs strike or extinguish.

5) Gaseous components from Io, requiring higher-than-volcanic temperatures for evaporation from the body, may be fed into a gas torus at the orbit of Io.

6) X-ray emission from the current spots may be expected (*12*).

Note added in proof: Voyager 2 has since confirmed that at least six of the eight spots were still producing plumes 4 months later. The active spots show a strong concentration to the equator (seven being within 30° of it), an effect expected for the present interpretation but not for volcanoes powered by the tides (*13*).

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5. In terrestrial volcanic eruptions, dust is often carried to great heights by the buoyancy of hot gases in the atmosphere, an effect that would be absent on Io. High-speed ejection of steam has been observed in terrestrial outbursts, with speeds of ~ 500 m/sec, and rock projectiles thrown from volcanoes ("volcanic bombs") are found at distances that imply ejection speeds of 100 m/sec. The speed of sound in water vapor at a temperature of 1500 K is 930 m/sec [A. Rittman and E. A. Vincent, *Volcanoes and Their Activity* (Wiley, New York, 1962), pp. 38 and 44; S. Self, L. Wilson, I. A. Nairn, *Nature (London)* **277**, 440 (1979)].
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10. A detailed estimate of the conductivity of Io as a function of depth cannot be made at this stage. The electrical properties of rocks cover a very wide range, and the composition of Io is not known. All that is necessary for the present discussion is to see that the electrical pathway discussed here would be favored. The interior of Io, if it is liquid rock, would be expected to have a conductivity of at least 10^{-2} ohm^{-1} cm^{-1} (the terrestrial value at a depth of 600 km). A current of 5×10^6 A would then provide a potential drop across the body of the order of 1 V only, a negligible amount compared with the voltage in the circuit of 2×10^5 V (*7*). A cold crust might have a conductivity of 10^{-10} ohm^{-1} cm^{-1} (representative of dry cold rocks) and at a thickness of 50 km would then have a total resistance of 0.3 ohm. A hot pathway through an area of 10 km^2 of the crust, with a conductivity of 10^{-2} ohm^{-1} cm^{-1}, has a resistance of 0.005 ohm and would thus take 60 times the current that would flow diffusely through the crust. These values show that the range of conductances through crust and core that can be expected would favor a current flow through hot spots in the crust and through the core, over an ionospheric path or over a diffuse flow through the crust.
11. Contact resistance arises from the various dissipative effects at such an interface. The kinetic energy of the plasma charge carriers is dissipated there, and the emission of charge from the solid consumes energy, some of which is left in the surface layers.
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14. I am grateful for discussions with S. Soter and S. F. Dermott.

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Melting of Helium at Room Temperature and High Pressure

Abstract. *Helium has been solidified at room temperature. The melting pressure at 24°C is 115 kilobars, in complete agreement with the Simon equation. An original apparatus was developed for this experiment, which allows loading of the cell at room temperature. Applications to various areas of research are suggested.*

Within the last 10 years, significant progress has been achieved in very high pressure technology (*1*). This progress has been largely due to improvements in the design of pressure generators (*2*) and in measurement procedures (*3*), based on the use of diamond anvil cells which now can be used into the megabar range. Recently (*4*), diamond anvil cells were used in the study of gases; liquid hydrogen was introduced into a diamond anvil cell with a cryogenic setup, and solidification of fluid hydrogen was observed at 57 kbar and room temperature. In this report, we describe a different method in which the cell is loaded at room temperature under a gas pressure of 2000 bars. We could thus measure the melting point of helium (^{4}He) at 24°C and compare it with the melting temperature predicted by existing melting laws. We also found that solid helium may be used as an inert and plastic pressure-transmitting medium for very high pressure research in the diamond cell.

Figure 1 is a sketch of the apparatus that was designed for the experiment.

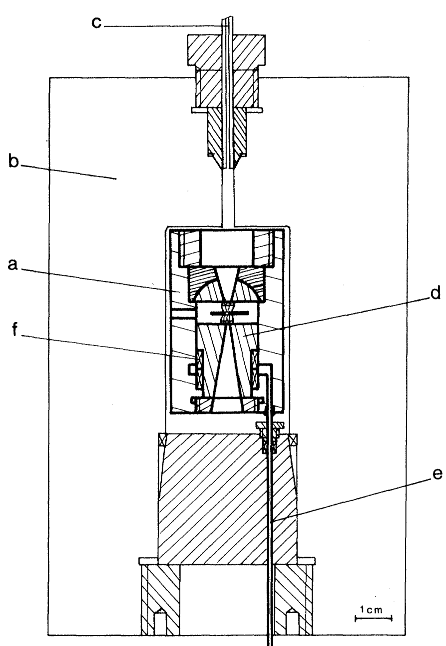

Fig. 1. Sketch of the diamond cell (dark lines) inside the low-pressure vessel (light lines): a, diamond cell (maraging steel); b, low-pressure bomb (5 kbar) (maraging steel, 52RC); c, stainless steel gas-loading capillary; d, moving piston; e, stainless steel capillary feeding the pressure control fluid (helium in this experiment); and f, piston seal.

The diamond anvil cell (a, heavy lines) is contained inside a low-pressure (5-kbar) vessel (b, light lines). At this stage, the diamonds are not pressed against the Inconel gasket. The gas to be studied, helium under a pressure of 2 kbar, is then introduced into bomb b through tubing c. It fills the volume inside the low-pressure bomb, including the sample space between the diamonds and the gasket.

To close the cell, a small overpressure (300 bars) is exerted on piston d, which supports the moving anvil. The necessary pressure, 2300 bars, is fed through capillary e. The resulting force is about 300 kg on ram d, which has a surface area of 1 cm^2. The pressure is sufficient to press the diamonds into the gasket and bring the pressure on the ^{4}He sample up to about 100 kbar. Both pressures controlled through tubings c and e are then decreased from 2000 and 2300 bars, respectively, to 0 and 300 bars, maintaining a difference of 300 bars throughout the whole process. Bomb b can then be opened and the cell extracted with the gas sample still contained between the diamonds.

One can use the cell for optical experiments under variable pressure by changing the pressure on piston d through the capillary e, which is still attached to the cell. The internal pressure is measured on the Ruby fluorescence scale.

The gas used here is U-grade ^{4}He with a nominal impurity content of less than 30 parts per million. Its melting upon slow decompression was directly observed and photographed at the crystal-fluid equilibrium point.

This particular experiment was designed so that we could observe the melting point of helium at around 100 kbar. Thus the dimensions of the anvils, holes, and seats (Fig. 1) that we used would not be suitable for pressures above 200 kbar. At higher pressures, we use a sturdier geometry for the anvils, although the dimensions of the cell remain the same (31 mm in outside diameter and 57 mm long).

Figure 2, a to d, shows the melting process of helium at room temperature (24°C). The two dark objects, near the center and at 4 o'clock, are ruby chips. The diameter of the hole is 130 μm.

Figure 2a shows the solid phase. Grain boundaries between individual microcrystals appear as an irregular network. In Fig. 2b, two crystals are present in the

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