marsh muds a larger type or species of magnetotactic bacterium than that described. This organism measures 1.2 by 3.2 μm and differs from the aforementioned in a number of morphological details when viewed by phase contrast microscopy. Both types of magnetotactic bacteria contain chains of iron-rich particles. At least five morphologically distinct types of magnetotactic bacteria are recognizable in samples collected from marshes in the vicinity of Woods Hole. This raises the interesting possibility that several (perhaps previously unrecognized) species of bacteria may be among those organisms which can be separated from their environment by their magnetotactic responses.

Magnetotaxis could not result from a magnetic force tending to "pull" these bacteria northward since, in uniform magnetic fields such as those used to demonstrate cell responses to geomagnetism (*5*), a dipole would not translocate in any direction as a consequence of magnetism; it would merely rotate to a preferred orientation within the magnetic field. Cells suspended in seawater did not migrate when killed with vapors of osmium tetroxide. Those not stuck to glass surfaces rotated so as to remain aligned with an applied magnetic field when the direction of the field was changed. Thus, cell motility is required for magnetotaxis, and cell orientation is the primary response to magnetism. Freely suspended killed cells also frequently formed chains of up to ten cells. Each chain behaved as a single dipole in response to changes in the position of a nearby permanent magnet. Perhaps the iron-rich cell inclusions serve as magnetic dipoles which convey a magnetic moment upon the cell, thus orienting the cells in magnetic fields. Magnetotaxis would result if, within each cell, a fixed spatial relationship existed between the orienting mechanism and cell propulsion. Studies of the behavior of living and dead cells in uniform and nonuniform fields should contribute to an understanding of the magnetotactic mechanism. It may also be possible to detect a preferred orientation of cells or their flagella and their iron-rich inclusions in magnetic fields. Results of survival experiments indicate that these organisms are either microaerophiles or strict anaerobes. Because the vertical component of the earth's magnetic field has a greater magnitude than the horizontal in the locations where they have been found, magnetotaxis might serve to direct these organisms downward toward sediments and anaerobic areas favorable to their growth.

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References and Notes

1. W. T. Keeton, in *Animal Orientation and Navigation*, S. R. Galler, K. Schmidt-Koenig, G. J. Jacobs, R. E. Belleville, Eds. (Government Printing Office, Washington, D.C., 1972), p. 579; W. Wiltschko, in *ibid.*, p. 569.
2. A. J. Kalmijn, in *Handbook of Sensory Physiology*, A. Fessard, Ed. (Springer-Verlag, Berlin, 1974), vol. 3, section 3, p. 147.
3. R. P. Blakemore and E. Canale-Parola, *Arch. Mikrobiol.* **89**, 273 (1973).
4. In the absence of obvious artificial magnetic fields the organisms migrated downward and northward at about 100 μm/sec.
5. Dr. A. J. Kalmijn and I tested these organisms' orientation in the undisturbed earth's magnetic field and in fields where either the horizontal or the vertical component was reversed with Helmholtz coils. The applied field was uniform within 0.2 percent in a region 10 cm in diameter. The coils were adjusted and oriented appropriately for the geomagnetic component under consideration. Magnetotactic bacteria in sufficient numbers to be visible as a mass at the edge of a seawater drop (see Fig. 1) were sealed beneath a glass cover slip on a microscope slide. The bacteria migrated in the opposite direction when current was applied to the coils. The experiments were conducted in an isolated area free of detectable geomagnetic distortion.
6. C. C. Remsen *et al.*, *J. Bacteriol.* **95**, 2374 (1968).
7. I. E. Mishustina, *Ecol. Res. Comm. Bull.* **17**, 143 (1973).
8. Dr. J. Russ, W. MacMillan (of EDAX International Laboratories, Prairie View, Ill.), and I performed these analyses on unstained thin-sectioned cells and on unstained whole organisms. A Phillips EM 301G scanning-transmission electron microscope equipped with an EDAX x-ray detector and and multichannel pulse height analyzer coupled to an EDIT/NOVA solid state minicomputer was used. Conditions have been described [J. Russ, *J. Submicrosc. Cytol.* **6**, 55 (1974)].
9. Supported by PHS grant AI-08248 to Dr. E. Canale-Parola at the University of Massachusetts, Amherst, and by a grant from the Sarah Mellon Scaife Foundation to the Woods Hole Oceanographic Institution. I thank Drs. V. T. Bowen, E. Canale-Parola, H. W. Jannasch, and A. J. Kalmijn for stimulating conversations and helpful criticism of the manuscript. I thank L. Surprenant for her contribution to the work reported here and Dr. R. Turner for the use of her cinematographic equipment. Contribution 3581 of the Woods Hole Oceanographic Institution.

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Mass Measurement: A Study of Anomalies

Abstract. *It has always been assumed that the measurement of the difference in mass between two objects would be the same in all laboratories. Recent National Bureau of Standards measurements involving dissimilar objects (effective density ranging from 2.7 to 16.6 grams per cubic centimeter) at a wide variety of pressures (0.5 to 2 atmospheres) have been made with sufficient precision to test this assumption. The results show unsuspected discrepancies which may approach 1 milligram in a kilogram in the assignment of mass values when dissimilar materials are involved. These discrepancies have not been noted in the past because precision comparisons of both like and unlike materials have nearly always been made in a relatively restricted range of environmental conditions. The worldwide mass measurement system is therefore consistent, because similar materials have been used in the construction of weight sets, but possibly offset with respect to the mass unit as embodied in the platinum-iridium defining artifact.*

The unit of mass of the Système International d'Unités (SI) system of measurement units is defined by an artifact, the International Prototype Kilogram preserved at the Bureau International des Poids et Mesures near Paris. The transfer of a mass value from such a defining artifact to another cannot be done directly in a normal laboratory environment. The mass value assigned to another object must be inferred from the results of a comparison of the artifact and the "unknown" by means of a balance. The balance, in turn, is a force comparator, responding to both the gravitational force and the buoyant force of the atmosphere acting on the object or objects on the balance pan or pans. In a given location, the gravitational force acting on an object is a constant and proportional to the mass of the object. The buoyant force, however, is proportional to the displacement volume of the object and the density of the surrounding air. Although the buoyant force is not large with respect to the gravitational force, being only on the order of 0.015 percent for materials of normal density, it is large with respect to the precision of currently available balances. Commercial kilogram balances are available with standard deviations of a single weighing on the order of 0.03 mg, and research balances in national laboratories have standard deviations on the order of 0.005 mg. Careful attention must be given to the manner in which the buoyant force is accounted for if this precision is to be utilized in the transfer of the mass unit from one object to another.

In such a transfer the observed difference, as determined by the balance, is adjusted or corrected by the product of the computed air density, D, at the time of the measurement and the difference in the previously measured displacement volumes, V_1 and V_2, of the objects being compared. In essence, the observed difference, Y, is the difference between the resultant forces acting on the two objects (the gravitational force minus the buoyant force). To determine the gravitational force, one must add a correction of Y for the difference $D(V_1 - V_2)$ in buoyant force; that is, the value for the mass difference, $M_1 - M_2$, is given by

$$M_1 - M_2 = Y + D(V_1 - V_2)$$

One expects the mass difference for any given pair of objects to be constant regardless of location.

As a part of its continuing measurement assurance program, the Mass and Volume Section of the National Bureau of Standards has tested the adequacy of the total correction, $D(V_1 - V_2)$, in various laboratories located at altitudes ranging from near sea level to approximately 2000 m. Several test objects have been used, including kilograms made from a variety of materials ranging in density from 2.7 to 16.6 g/cm^3. An analysis of the data from the comparison of selected objects in this test indicated that $(M_1 - M_2)$ was not constant with location.

Through the courtesy of the Naval Medical Research Institute, Bethesda, Maryland, and the 1099th Physiological Training Flight, U.S. Air Force, Andrews Air Force Base, Maryland, the comparisons have been repeated at barometric pressures up to approximately 2 atm (in a decompression chamber) and down to approximately 0.5 atm (in an altitude chamber). These limited experiments tend to confirm the results of the earlier tests in the various laboratories. Over the pressure range from 0.5 to 2 atm, the magnitude of the effect appears to be 1 mg in 1 kg for objects having a volume difference of approximately 200 cm^3.

In the generally accepted method of computing D, it is assumed that moist air behaves as an ideal gas. Although this assumption may be "almost" true under standard environmental conditions, over the range of the conditions in these tests the lack of ideality could introduce an error in D on the order of 0.06 percent of D. For V_1 and V_2 determined by the best generally accepted methods, the error in the differential volume $(V_1 - V_2)$ is on the order of 0.035 percent of $(V_1 - V_2)$. The combined effect of these two possible errors would indicate an upper bound to the expected mass discrepancy of about 0.2 mg, only one-fifth of that observed.

The implications from the above experimental evidence are as follows:

1) There is an uncertainty in the realization of the mass unit in material other than that of the defining artifact which exceeds the instrumental limitations.

2) The inconsistency in the realization of the unit depends upon the volume difference between the objects being measured and the barometric pressure (the air density). Surface effects do not appear to be significant.

3) With regard to commonly encountered secondary standard weights, the resolution of the apparent problem may require a slight shift in value but will not affect the consistency of the unit so embodied. The magnitude of such an offset is below the level of significance in trade and commerce.

4) The magnitude of the inconsistency may be of consequence in certain areas of scientific study that lie outside of the realm of mass measurement, for example, physical constants, precise force measurements, and meteorology.

Most experiments are conducted at, or near, normal atmospheric pressure, that is, in environments in which there is a limited range of variability in air density. In these cases, the nature of the discrepancy discussed above is essentially that of a systematic error in the unit which is not detectable in terms of inconsistencies in the results of the experiments. Since there are no independent ways of assigning mass values to objects of interest, one must resort to a comparison of the results of measurements in a variety of environments in order to verify the consistency of the results from current measurement methods (*1*).

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References

1. Experiments are under way to determine the exact nature of the anomaly; these data, together with a detailed analysis of past experiments, will be presented elsewhere (P. E. Pontius, in preparation). It is anticipated that a workshop to discuss the problem will be organized later in 1975.

19 May 1975

Chemical Fractionation of the Lunar Regolith by Impact Melting

Abstract. *Impact-produced agglutinitic glass in both lunar highland and mare soils is enriched in mafic elements, in potassium, phosphorus, and sulfur, and in most lithophile elements, whereas it is depleted in plagioclase components including europium. It is proposed that the chemical fractionation is the result of a multistage partial-melting mechanism that accompanies micrometeoroid impacts into soils. The process would be expected to occur on solar system bodies that have an impact-produced regolith.*

Soils returned by Apollo and Luna missions are the products of both destructive and constructive processes. Rock fragments are broken down into smaller particles by micrometeoroid impacts, and glassy agglutinates are created through cementation of grains by impact melts. The decrease in particle size and the construction of agglutinates in lunar soils are indicators of the cumulative amount of exposure at the lunar surface (*1, 2*). It has been widely assumed that the chemical composition of the soils is an expression of the composition of the source rocks, and that impact-melting does not affect the distribution of the nonvolatile elements. We have now found evidence that the impact-melting of lunar soils is accompanied by significant chemical fractionation (*3*).

Agglutinitic glass is enriched in ferromagnesian elements and in most lithophile elements. We suggest that this fractionation is caused by a multistage partial-melting process due to micrometeoroid impacts. The change in the chemistry of the soil with increased exposure at the surface must be considered in attempting to relate soil composition to bedrock composition.

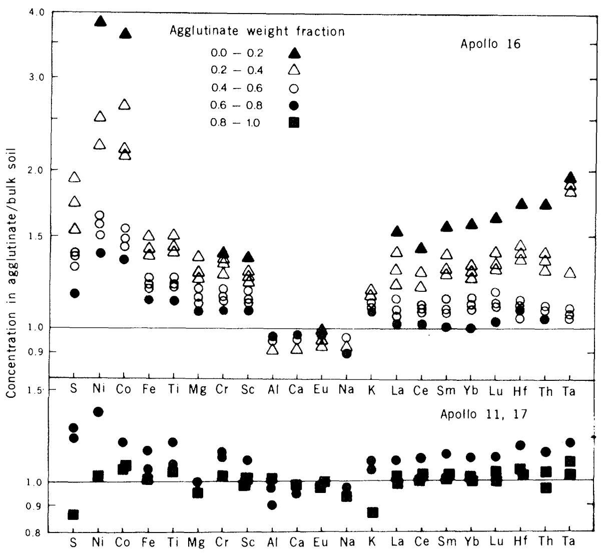

Fig. 1. Concentrations of elements in agglutinitic glass relative to the parent bulk soils. The Apollo 16 soils are from the lunar highlands, whereas the Apollo 11 and 17 soils are from mare regions. Different symbols represent different weight fractions of agglutinitic glass in the soils. The chemical differences between agglutinitic glass and the bulk soil are greatest for those soils containing small amounts of glass. When agglutinitic glass becomes dominant, its chemistry necessarily converges with that of the bulk soil. Agglutinitic glass is relatively enriched in mafic elements and in most lithophile elements but is depleted in the elements that are the components of plagioclase (Al, Ca, Na, and Eu).