Magnetic Navigation an Attractive Possibility

Investigators find magnetic particles in organisms ranging from bacteria to man; their role in orientation is still problematic

"Personal magnetism" may no longer be just a catch phrase describing individuals with a charming personality. New evidence indicates that humans are among the many different species that may have magnetic centers which could assist them in orientation in the earth's magnetic field. This discovery joins the recent announcements that magnetic material has also been discovered in algae, tuna, dolphins, sea turtles, rodents, and even certain types of tumors. It is beginning to appear that the presence of magnetic material in living creatures is a much more universal phenomenon than had previously been suspected.

Scientists have known for more than a decade that homing pigeons, migrating birds, honey bees, and other species may somehow be able to sense the earth's magnetic field to orient themselves on their travels. Adrianus J. Kalmijn of the Woods Hole Oceanographic Institution had shown that elasmobranchs, such as sharks and eels, could sense the earth's magnetic field through its inductive effect on the electric field that they generate, but the mechanism by which other organisms might sense the field was still a mystery.

It was not until 1975 that Richard P. Blakemore, now at the University of New Hampshire, first reported navigation along magnetic field lines or magnetotaxis in bacteria commonly found in the mud of brackish marshes. Perhaps triggered by Blakemore's results, other investigators began looking for such magnetic organs with surprising success. In 1978, James L. Gould, Joseph L. Kirschvink, and Kenneth S. Deffeyes of Princeton University reported the presence of magnetic material in honey bees. The following year, Kirschvink, Gould, and Charles Walcott of the State University of New York at Stony Brook made a similar observation in pigeons. These first discoveries, says Richard B. Frankel of the Massachusetts Institute of Technology, were "the beginning of a new chapter in the story of the interaction of the biosphere with the geomagnetic field."

The function of the magnetic material is understood fairly well only in bacteria. Blakemore discovered the first magnetotactic bacteria in sediments collected at Woods Hole, Massachusetts. He observed that these bacteria always swam toward the North Pole and that their swimming direction could be changed by reversing the external magnetic field. Using electron microscopy, he also found that they contained a generally linear string of as many as 20 cuboidal particles, each about 50 nanometers on an edge, that were rich in iron. With Kalmijn, he showed that the bacteria contained a permanent magnetic dipole. And finally, using Mössbauer spectroscopy, Frankel and Blakemore showed that the iron grains are composed of magnetite (Fe_3O_4, often called lodestone). These grains are each surrounded by a membrane or envelope; Blakemore and his colleagues christened them magnetosomes. They account for as much as 2 percent of the dry weight of the bacteria—and contain about 10 to 100 times as much iron as is present in nonmagnetotactic bacteria.

The magnetosome chain is large enough, and has a sufficient magnetic moment, to physically orient the bacteria in a magnetic field. Dead bacteria, for example, continue to orient along magnetic field lines. When live bacteria swim, this orientation causes them to migrate along the field lines. In the Northern Hemisphere, the field lines are inclined downward in such a fashion that swimming toward the North Pole is equivalent to swimming downward. Magnetotaxis, Blakemore reasoned, might serve to direct the bacteria downward toward the oxygen-depleted sediments where they thrive best.

In order to test this hypothesis, Blakemore, Frankel, Kalmijn, and Nancy Blakemore of the University of New Hampshire collected bacteria from sediments in New Zealand and Tasmania in 1980. This region has the same magnetic inclination as New England, but with the opposite sign. The group found that bacteria there were predominantly south-seeking, which again allows them to navigate toward the bottom. Independently, Kirschvink found south-seeking bacteria in Australia.

Frankel and Blakemore subsequently collected bacteria at the magnetic equator near Fortaleza, Brazil, where magnetic lines of force are parallel to the earth's surface. There, they found approximately equal numbers of north- and south-seeking bacteria. Magnetotaxis would not help these bacteria find the bottom, they say; but for bacteria in the sediments, swimming along the field lines would help prevent them from inadvertently swimming toward the higher oxygen concentrations at the surface. It might also be a more efficient feeding strategy.

To date, the Blakemores and others have identified about a dozen morphologically different bacteria that possess magnetosomes. Some of these—such as *Aquaspirillum magnetotacticum*, the only one that has been grown in pure culture—have flagella at both ends, so that they can swim in either direction along the field lines. Blakemore and Ralph S. Wolfe of the University of Illinois have shown that these are also sensitive to oxygen, so that they swim along the field lines "while at the same time seeking just the right oxygen concentration." The investigators are now studying the physiology of the bacteria to learn, among other things, how the magnetosomes are synthesized and whether the iron may play a role in electron transport.

In January of this year at the American Association for the Advancement of Science meeting in Washington, Frankel and Henry G. P. Lins de Barros of the Centro Brasileiro de Pesquisas Fisicas in Rio de Janeiro, Brazil, and their colleagues reported the discovery of magnetotaxis in a green alga. The algae, of the genus *Chlamydomonas*, were isolated from a polluted coastal lagoon in Rio de Janeiro. They are south-seeking, and the response is similar to that observed in bacteria—passive orientation of the cell by its magnetic moment (which is, interestingly, about ten times as large as that of the bacteria)—but they have not yet been able to grow enough of the algae in culture to identify magnetite within the cells. More recently, Frankel has isolated a similar north-seeking alga in Florida waters. These discoveries, he says, are "the first unequivocal observations of magnetotaxis in eukaryotic organisms." (Bacteria are prokaryotic, which means that they do not have a cell nucleus and certain other intracellular organelles, while algae and higher organisms are eukaryotic and do have them.)

The function of the magnetotactic re-

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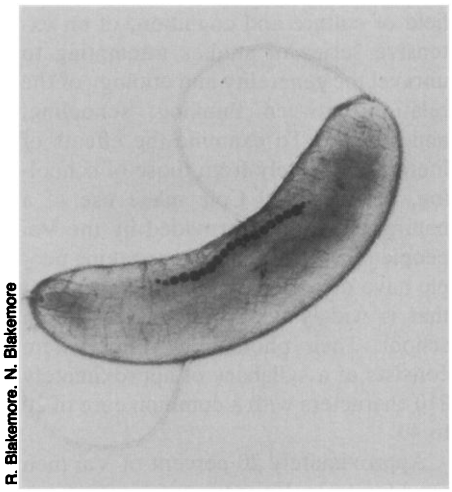
sponse in the algae is not clear-cut. It is known, says Frankel, that *Chlamydomonas* can live either heterotrophically or autotrophically; that is, it can either absorb all the nutrients it needs from surrounding waters or manufacture many of them by photosynthesis. He speculates that the magnetotactic alga may obtain a selective advantage by occupying a heterotrophic niche in its environment. Negative phototaxis (migration away from light) has previously been observed in *Chlamydomonas*.

Several investigators have observed magnetite in other eukaryotes. In August, Michael D. Fuller and J. Robert Dunn of the University of California at Santa Barbara and John Zoeger of Los Angeles Harbor College reported (*Science*, 21 August 1981, p. 892) observing magnetite in the heads of four common Pacific dolphins. The magnetite was found between the dura mater and the skull, the same location where Walcott and his colleagues observed magnetite in pigeon skulls. Working with Michael Walker of the University of Hawaii, Fuller and Zoeger have more recently identified magnetite at the same location in the head of a Cuvier's beaked whale. (All of the experiments were performed on stranded, dead animals provided by the Los Angeles County Museum of Natural History.)

Several related reports were presented at the December meeting of the American Geophysical Union in San Francisco. Kirschvink, who is now at the California Institute of Technology, Walker, and Andrew Dizon of the U.S. National Marine Fisheries Service in La Jolla observed magnetic particles in yellowfin, skipjack, and kawakawa tuna, blue marlins, and green turtles. The magnetic particles in the turtles "were scattered through all the tissues," says Kirschvink, but in the tuna and marlin they were concentrated in the ethmoid cavity, where the bones of the walls and septum of the nasal cavity join. This, he adds, is "more or less the same area" where magnetite was found in dolphins and pigeons. Robin R. Baker and Jan Mather of the University of Manchester reported finding magnetite in the ethmoid cavities of both rodents and humans; Kirschvink had previously reported it at the same site in monkeys. In all cases, the investigators found that the magnetic particles appeared to be surrounded by nervous tissue, suggesting the possibility of interaction between the particles and the brain.

In the most surprising study, Kirschvink and Frank L. Tabrah and Stanley Batkin of the University of Hawaii School of Medicine observed remanent magnetism in two types of mouse tumor, YC-8 lymphoma and Lewis lung tumor. "I wanted a magnetite-containing tissue that could be grown in the laboratory," says Kirschvink, "and these just happened to be the first tumors they gave me to test." Tissues from human gastric, colon, and renal carcinomas that they subsequently tested did not contain significant residual magnetism, nor did healthy mouse tissue.

The investigators observed that the mouse tumor cells contained the equivalent of about five magnetite particles per cell (as determined by their magnetic moment), compared to less than one particle per thousand cells in human tumors and other tissues. Tabrah and Batkin also exposed the cultured tumors to varying magnetic fields to determine the effect on growth. The Lewis lung tumor cells showed no response, but the YC-8 cells did. Exposure to a 10-millitesla magnetic field oscillating at 2000 hertz significantly accelerated cell growth, while exposure to a similar field rotating at 60 hertz significantly retarded growth. The group is now trying to identify precisely where in the cell the particles are located and what possible function they might have, such as storage of iron.



R. Blakemore. N. Blakemore

A moment in space

The magnetic moment of Aquaspirillum magnetotacticum *is provided by the string of magnetite particles that appear as black circles in this micrograph (× 20,000).*

The function of the magnetic particles in other organisms is still problematic. Walcott, Wolfgang Wiltschko and his colleagues at the Universität Zoologie in Frankfurt, West Germany, and the late William T. Keeton and his colleagues at Cornell University have all shown that there is a magnetic component to the navigation of pigeons and other birds. Such a demonstration is particularly difficult, however, because of the more important contribution to navigation by orientation with respect to the sun. Similarly, Herman Martin and Martin Lindauer of the University of Würzberg have shown that there is a magnetic component to the orientation of honey bees, but that demonstration is also complicated by the insects' response to light and other external clues.

Baker has reported that humans can use a magnetic sense to orient themselves, but those studies have been highly controversial because other scientists have had difficulty reproducing them. Walker has reported magnetic orientation in yellowfin tuna, and he and Dizon are attempting to test the theory of magnetic navigation in both tuna and dolphins. And finally, Ronald Merrill, Ernest Brannon, and Thomas Quinn of the University of Washington have demonstrated that sockeye salmon use the earth's magnetic field to navigate through lakes, although no one has yet demonstrated the presence of magnetic particles in salmon.

Nonetheless, most investigators agree that many of the findings must be interpreted with caution. For one thing, says Blakemore, the amount of residual magnetism involved is very small, and it is easy to introduce adventitious magnetism during sample preparation; investigators must use only nonmagnetic tools (scalpels, microtomes, and so forth) and Kirschvink, in fact, is constructing a special magnetically shielded clean laboratory.

Finally, the magnetosomes may have some function completely unrelated to navigation. Magnetite, notes Frankel, is the densest and the hardest material that can be synthesized biologically. It has a density greater than 5 (water is 1), compared to a density of 2 to 3 for bones and similar structures. In fact, the first demonstration of magnetite in animals had nothing to do with orientation.

In the early 1960's, Heinz Lowenstam of the California Institute of Technology discovered magnetite in chitons, marine invertebrates (mollusks) that scrape and eat algae from the surface of the rocks. The teeth of the chitons are composed of magnetite, and it seems clear that the mineral is used for its hardness rather than for any magnetic properties. It is equally clear that tumor cells have no need for magnetic navigation. It thus remains possible that magnetite in other organisms may also have some function unrelated to orientation. Most of the investigators, however, hope to prove that it is indeed there for navigation.

—Thomas H. Maugh II