Bees Have Magnetic Remanence

Abstract. *Honey bees orient to the earth's magnetic field. This ability may be associated with a region of transversely oriented magnetic material in the front of the abdomen. The magnetic moment apparently develops in the pupal state and persists in the adults.*

The orientation of a variety of animals is affected by magnetic fields. For example, pigeons usually fail to navigate well on cloudy days if small magnets are affixed to their heads (1). European robins kept in special cages during migration season orient themselves according to the magnetic field in the cages (2). Regrettably, magnetic-field orientation has proved extremely difficult to work with. In the case of the pigeons, one cannot rule out the possibility that the magnets are affecting the animals secondarily—making them sick, for example. The effect on robins is so weak that only by using one particular cage design and by averaging the results of many birds over many nights in a special way can the phenomenon be extracted from the noise.

Work on magnetic field orientation in honey bees, however, has uncovered more reliable bioassays. Bees show four variable but convincing effects of magnetic fields. (i) In their dances, bees convert the angle flown to the food with respect to the sun into an angle danced with respect to gravity. In this conversion, bees make small regular errors which depend largely on the orientation of the dance with respect to the earth's field. Canceling the field causes the errors to disappear (3). (ii) When the comb is turned on its side so that the bees must dance on a horizontal surface, depriving them of their usual gravity cue, some bees stop dancing, while others dance in a disoriented fashion. After several weeks, however, those dances that do occur become oriented to the four cardinal points of the magnetic compass. Canceling the earth's field eliminates this reorientation (4, 5). (iii) When a swarm of bees is placed into an empty cylindrical hive and otherwise deprived of orientation cues, they are reported to build their comb in the same magnetic direction as it was in the parent hive (4). (iv) In the absence of all other cues, bees seem to set their circadian rhythms by the regular daily variations in the earth's magnetic field. An abnormally strong field disrupts the rhythm (6).

At least three general theories have been invoked to explain how terrestrial animals could detect magnetic fields. The first supposes that animals have an electrically conducting loop in which a measurable current is induced when it moves quickly through the earth's field. Proponents of this hypothesis are en-

couraged by the inability of experimenters to condition restrained pigeons to magnetic stimuli in the laboratory (7). Of course, magnetic orientation, like many other behaviors, may simply be context-specific. The recent report of successful conditioning of a bird fluttering in a wind tunnel (8) could be interpreted in this way. Also, it is difficult to see how the static field of a bar magnet or electromagnet on a pigeon's head could affect an induced-current detector. A further problem for the induction hypothesis is the discovery that slow-moving cave salamanders orient to magnetic fields (9).

A second theory proposes that the detectors are paramagnetic; that is, when in a magnetic field, detector molecules respond by producing a field of their own, and this response is somehow measured by the nervous system. Advocates of this idea note that the errors in the bee dances do not completely disappear for 45 minutes after the earth's field has been canceled. True paramagnetic materials, however, respond almost instantaneously to changes in the applied field. Nevertheless, it is theoretically possible with precise control of size, shape, and chemistry to build paramagnetic-like ("superparamagnetic") detectors out of magnetic materials with virtually any magnetic decay time. Unfortunately, the 45-minute "adaptation time" in bee dances is not really explained by invoking paramagnetism of any sort. A long-delay system would provide the bee with a useless time average of all the field orientations it has experienced over several trips out to and back from a food source, as well as during the intervening dance bouts in the hive. Still, the paramagnetic properties of many organic molecules make this hypothesis attractive.

The third possibility is that animals might have magnetic detectors—permanent magnets that could twist in an attempt to align themselves with the earth's field, thereby producing a measurable torque. [As is discussed below, many organisms that regularly synthesize magnets are known (10, 11).] The magnet hypothesis may be directly tested, provided that the magnets are strong enough, since simply moving a magnet produces well-known electrical effects. The recent interest in continental drift and its record in the weak remanent mag-

netism of rocks has brought about the development of very sensitive magnetometers (12). These instruments, by means of superconducting quantum interference devices bathed in liquid helium, very accurately measure the current flow caused by the movement of a weakly magnetized sample into a superconducting loop.

Eighteen dead adult bees that had been dried in air for 2 months were tested first. Of the eight that were measured without any prior treatment with a strong magnetic field, none showed any significant magnetism (Table 1). When a strong field (about 700 gauss, as compared to the earth's field of about 0.5 gauss) was applied briefly to the bees before subsequent measurements, a substantial remanent (that is, permanent) field was induced in 15 of the 18 bees, with an average strength of 2.7×10^{-6} emu (electromagnetic units; this is equivalent to the field that would be produced by approximately 15 million 0.1-μm single domains of magnetite). The orientation of the induced remanent magnetization clearly tracked the most recently applied field (Table 2).

Two dead bees were then dissected with nonmagnetic tools to locate the source of the magnetism. The magnetic material was found almost exclusively in the front of the abdomen.

Twelve live or freshly killed bees were also tested. Each of these showed a substantial natural magnetism averaging 1.2×10^{-6} emu. After treatment with the same strong field used on the dead bees, the remanence averaged 1.7×10^{-6} emu (Table 1). Unlike the dead bees, however, the remanence had a strong preferred direction and showed little tendency to track the applied field (Table 2), suggesting a strong shape anisotropy or high coercivity (or both) of the magnetic domains. The magnetic fields of these live bees were oriented transversely and restricted to the horizontal plane of the bee (Table 2). Subdivision of two live bees revealed that the magnetic material was located in the front third of the abdomen, but relatively little was associated with the digestive tract.

Five older pupae were also tested and found to have similar natural field strengths (1.5×10^{-6} emu) with the same transverse-horizontal orientation (Tables 1 and 2). Just as with the adults, some had their north-seeking pole pointing to their left, while the others pointed to the right. One young pupa, two larvae, and an egg were also tested and found to have very little natural or inducible field (Table 1).

A second group of live bees and pupae were tested 2 months later and found to

have almost no natural remanence. Their induced remanence followed the same pattern as that of the first group: none in the pupae and young bees, but approximately 0.5×10^{-6} emu in older adults (13).

These results demonstrate that adult honey bees and older pupae can possess naturally magnetic material. They do not prove that bees orient to magnetic fields by using the magnets in their abdomens. The results do suggest, however, that the magnetic material is constructed in an orderly way which might well suit it for use as a detector (14). Despite the small sample size, we think it likely that bees often build oriented magnetic crystals. This suggestion is not unprecedented since some bacteria possess what appear to be single domains of magnetite (11), and all species of chitons are known to build teeth from orderly arrays of single-domain magnetite crystals (10). The chitons, for example, begin building a protein matrix (which includes ferrodoxin to store Fe^{3+}) upon which they deposit the Fe^{3+} to build magnetite (15). They then convert the Fe^{3+} through a number of species-specific intermediate phases to produce $FeO \cdot Fe_2O_3$ (magnetite). By controlling the size of the crystal so that it is large enough to become stably magnetic—a critical mass that produces a tiny unit magnet called a "single domain"—but not so large that a second, canceling domain is created, a crystal with a net magnetism could be built. Since the natural field that we can measure is the vector sum of all the fields of all the domains in the bee, our data represent the surplus of transversely aligned domains over some background of randomly aligned (and therefore self-canceling) domains. Since the induced remanence of the first group of bees was nearly the same as the natural remanence, there must have been relatively few domains which were not aligned in the transverse direction. This implies that a bee would have to build many single domains and space them apart, since otherwise they would interact and attempt to cancel each other's field. The size of the domains, if the mineral is magnetite, would be on the order of 0.1 μm (16).

The strong magnetic anisotropy—the transverse-horizontal orientation of the magnetic moments—could be the result of physical constraint, the crystals being forced to grow perpendicular to the bee's body axis as well as in the horizontal plane. All the bees used in these measurements came from hives whose combs were aligned north-south—by far the most common orientation in nature. Since the cells on the comb in which bees develop are perpendicular to the

comb, the earth's field was transverse to these bees during development. It could be that the growth direction of the crystals—and hence their fields—in the horizontal plane is established sometime during the several days of motionless development in the pupal stage. This would be consistent with our observation that some bees have their fields oriented left-right and others right-left. If this interpretation is correct, then bees must become magnetically "imprinted" during development. Perhaps this could explain the report that bees in new cavities build comb in the same direction as that in the hive in which they were born.

We suppose that the lack of a natural field in dead bees may be a consequence of desiccation during which the orientation of the crystals is randomized. As a result, an external field must be applied to realign the domains. The chemical environment after death, combined with the removal of biological controls, might even allow size, shape, and chemical changes in the crystals themselves. They could also become detached from the

matrix and clump, perhaps thereby producing more symmetrical units. The lack of natural remanence in the second group of bees suggests two possibilities. (i) Bees may normally build superparamagnetic detectors, and the observed natural remanence may thus represent domains which have become too large (17); or (ii) environmental conditions may determine whether or not bees make detectors (18).

We are now attempting to characterize the chemistry and the anatomical structures with which the magnets are associated. As the first step, the head, thorax, and abdomen of 100 dried bees were separated, crushed, sieved, and passed through a Frantz magnetic separator; only the crushed abdomens contained a magnetic fraction. Material isolated by the procedure used appeared proteinaceous and light-orange to red in color. Subsequent measurements in vacuum on a magnetic balance gave a Curie temperature of 580°C, thus identifying fine-grained magnetite as the primary magnetic phase. The magnetization of this

Table 1. Mean magnetic moments ($\times 10^{-6}$ emu = 10^{-3} A · m²) of samples before (natural remanence) and after (induced remanence) application of a strong magnetic field, and the standard error of the mean for each. N indicates the number of different measurements. In the case of induced moments, these include strong field applications in the horizontal plane of the bee (along and across the bee's axis) and in the vertical plane. The strongest induced moment was 5.1×10^{-6} emu, while the strongest natural remanence was 2.1×10^{-6} emu.

Sample	Natural remanence	N	Induced remanence	N
Empty sample box	0.2 ± 0.2	2	0.3 ± 0.1	6
Dead bees	0.2 ± 0.03	7	2.7 ± 0.2	41
Live bees	1.2 ± 0.2	12	1.7 ± 0.2	17
Older pupae	1.5 ± 0.4	4	1.5 ± 0.2	11
Young pupa, larvae, and egg	0.4 ± 0.1	2	0.5 ± 0.1	10

Table 2. Effects of applied magnetic fields on the direction of remanent magnetism in examples of three classes of bees. The natural moment of bees was measured first (left two columns). The declination (decl.) is the horizontal or compass direction of the bees' magnetic field (with the head defined as 0°). The inclination (incl.) is the vertical component or dip of the field with positive inclination defined as downward. The remaining measurements were made after an attempt to reorient the bee's magnetic field with a 700-gauss magnet. The first four applied fields were in the horizontal plane, while the last two were in the vertical. The magnetic material in dead bees tracks this intensity of applied field much better than live bees—that is, the dead bee remanence tends to be aligned with the applied field, while the live bee and pupae fields prefer to be aligned with the natural field, transverse to the axis of the bee. This suggests that the magnets are anisotropic (that is, asymmetrical) or that they have high coercivity (or both); and they are oriented in a regular way. Since it was almost impossible to align reproducibly the bees in the sample boxes and the magnet with the bees, the data may show more scatter than really exists. The two pupae for which data are presented were from opposite sides of a piece of comb.

Sample	Direction of natural remanence		Direction of applied field					
			Horizontal (decl.)				Vertical (incl.)	
	Decl.	Incl.	0°	90°	180°	270°	+90°	−90°
			Dead bee					
Eno 3	None		19°	80°	145°	275°	+86°	−77°
			−19°	84°	188°	283°	+72°	
			Live bee					
Barn 4	111°	+8°		92°	125°		+32°	
Barn 5	93°	+12°		90°	123°		+34°	
			Live pupa					
Field 3	279°	−4°		285°	273°		+10°	
Field 5	112°	0°		97°	92°		+3°	

same material increases linearly with the applied field until saturation is reached at about 1.8×10^3 Oersteds. The presence of magnetite in three live bees was tested by freezing them to $-196°C$ in liquid nitrogen, and then continually monitoring the remanence as they warmed up through the isotropic point of magnetite ($-143°C$). In each case, the remanence decreased slightly near this temperature, indicating the presence of magnetite (19). Regardless of what these attempts to characterize the magnets produce, only our behavioral experiments can establish whether or not bees actually use these magnetic crystals for orientation.

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13. We have traced the induced remanence to small (200 μm) dark specks, which are widely distributed in the digestive tract of older bees. Under the scanning electron microscope, one class of these objects has been identified as inorganic. The other class is still being investigated.
14. We are reminded of D. Griffin's remark in a similar context that "if they do not use it, perhaps they ought to try."
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17. This is consistent with our measurements of increased induced remanence at very low temperatures, indicating that superparamagnetic domains have become stable. This is also consistent with the transverse field orientation data, since, in that orientation, only superparamagnetic crystals can easily be arranged to construct a hypothetical detector which could explain the dance misdirection data.
18. For example, the concentration of iron in nectar [M. Shabanov and N. Ibrishimov, *Acta Microbiol. Virol. Immunol.* **2**, 105 (1975)] and pollen [M. H. Hadak and M. C. Tanguary, *Tech. Bull. Minn. Agr. Exp. Sta. No. 160* (1943), p. 23] depends on the species of plants in bloom. The iron content of honey, for example, varies from 0 to 45 ppm. Without enough iron in the diet, bees could not synthesize the crystals. Alternatively, like first-flight pigeons which cannot use magnetic field information when raised in sunny areas [W. T. Keeton, *Sci. Am.* **231** (No. 6), 96 (1974)], perhaps bees do not build detectors when they do not need them. This is consistent with the observation that bees in horizontal hives do not begin orienting their dances to magnetic fields for several weeks. Since the average life-span of a forager is 3 weeks, these could easily be, and probably are, a new generation of bees.
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20. A preliminary survey of 18 species of invertebrates revealed natural remanences larger than 0.5×10^{-6} emu (against a background of 0.02×10^{-6} emu) in a Vespid wasp, housefly (*Musca domestica*), roach (*Periplaneta americana*), and staghorn beetle (*Passalus cornutus*), as well as a marginal remanence in a *Tenebrio* beetle. We thank T. C. Onstott and N. Dorety for making preliminary measurements, as well as the director (D. P. Elston) and staff (S. L. Bressler and M. E. Puruckner) at the U.S. Geological Survey Paleomagnetics Laboratory in Flagstaff, Ariz., for help and interdisciplinary enthusiasm. Supported by NSF grant BNS 76-01653A02 to J.L.G.

4 April 1978; revised 26 June 1978

Primate Infant's Effects on Mother's Future Reproduction

Abstract. *Female savanna baboons* (Papio cynocephalus) *had a longer postpartum amenorrhea and thereafter cycled longer before conceiving if their previous infant survived than if that infant died. Among mothers of surviving infants, differences in maternal care produced differences in age of weaning and age of independence but did not result in differences in interbirth intervals.*

Parental care expended on current offspring can reduce a parent's future reproductive success if such activities delay subsequent reproduction. Such activities are "parental investment," in that they increase one offspring's chances of surviving at the expense of the parent's ability to produce other offspring (1). The recent speculative and theoretical literature on parental investment (2) highlights the paucity of relevant data from natural populations. In this report we present evidence that, in savanna baboons (*Papio cynocephalus*), infants reduce their mothers' future reproduction success by effecting a delay in her subsequent reproduction through effects on two phases of her reproductive cycle.

Primate interbirth intervals consist of three main phases: (i) a period of postpartum amenorrhea or sterility; (ii) a period of cycling, itself consisting of one or more estrus (menstrual) periods, each of which usually includes ovulation; and (iii) a period of gestation. We now have sufficient longitudinal data from yellow baboons inhabiting Amboseli National Park, Kenya, to examine effects of infants on phases of their mothers' reproductive cycles. Of the three phases, only gestation length is subject to virtually no variability in Amboseli baboons (the mean was 177 days from onset of last deturgescence of the sexual skin, the standard error of the mean was 1 day, the standard deviation was 4 days, and N was 25). Thus gestation length can be assumed to be essentially unaffected either by a female's current infant or by other potentially important factors, such as maternal age or habitat quality. In contrast, both amenorrhea and length of time spent cycling prior to conception showed great variability. We shall consider each of these in turn.

Female baboons in Amboseli resume cycles approximately 3 weeks after infant death, regardless of the infant's age at death, a value in striking contrast with that for females with surviving infants, for whom the range of postpartum amenorrhea is 6 to 17 months with a mean of 12 to 12.5 months (3). In contrast, laboratory and zoo reports suggest that the comparable value in such confinement but without separation of mother and infant is about 5 to 6 months (4). These results suggest that some of the reported differences in populations may be accounted for not only by infant presence, but also by nutritional effects and differences in energy demands [see Jain *et al.* (5) for similar differences that correlate with socioeconomic class in humans]. Baboons in Amboseli appear to experience shorter periods of postpartum amenorrhea in years of good rainfall, but the patterns are not clear-cut nor are the data yet adequate for statistical testing.

From laboratory work on primate reproductive physiology (6), it has long been recognized that the presence of an infant can delay resumption of menstrual cycles, thereby delaying a female's next conception. More recently, several researchers (7, 8) have reported that nonnursing females in two free-ranging, provisioned groups of rhesus monkeys (*Macaca mulatta*) produced infants approximately 1 month earlier in the birth season than did nursing females. In that population, earlier births are associated with higher infant survival and with greater probability of mothers giving birth in the following year (8). Kawai (9) and Tanaka *et al.* (10) reported that in