Who needs a new magnetometer?

To every measurable effect there seems to be an instrument whose purpose sometimes seems to be simply to measure the measurable causes of those effects. The purpose of a neat new magnetometer is not yet clear.

THERE seems to be a general principle in the physical sciences that each newly discovered effect will eventually spawn an instrument of some kind. Sooner or later, somebody will make a microscope of each new particle of matter discovered, for example. More generally, the principle seems to be no more than the truism that if a cause has an effect that can be measured, the effect can be used to measure the cause. That is the spirit in which a French group has now built a magnetometer based on the interaction between a magnetic field (such as the Earth's) and the behaviour of a laser light.

As described (in *Phys.Rev.Lett.* **69**, 909–912; 3 August 1992), it has been thoroughly Cartesian. Those concerned are Fabien Bretenaker, Bruno Lépine, Jean-Charles Cotteverte and Albert Le Floch, all at the CNRS unit for quantum electronics at the University of Rennes.

The Cartesian point of the argument amounts to a taxonomy of magnetometers. There are classical magnetometers and quantum magnetometers, of which the latter are capable of inherent microsensitivity. But quantum magnetometers are themselves of two kinds. There are those based on the properties of individual atoms, as in the use of the precession frequency of, say, protons to measure the magnetic field to which they are externally exposed; the strength of the signal is bound to be an average of the values generated by many differently placed atoms, so that inhomogeneities of the field are untidily smeared out. And then there are microscopic quantum detectors best typified by the SQUID, in which the quantized collective motion of pairs of electrons in a superconducting element provides sensitivity almost free from noise. But lasers are also collective quantum systems; could they not do as well as SQUIDs? It would be interesting to know what set Bretenaker and his colleagues on the path to their magnetometer, or whether they simply had a hunch.

In practice, the laser they use is a curious animal, consisting of a 3 mm hole drilled along the axis of a cylindrical block of a proprietary material called Zerodur which is nonmagnetic, but is pleasantly stable to thermal change. The result is that the length of the 60 cm laser cavity remains essentially constant. A further curiosity is that the ends of the cavity are optically closed by what are called quasi-mirrors — pieces of glass that would have been mirrors had they been silvered, but which in reality reflect 3 per cent of the light incident on them. The cavity is filled with a mixture of helium-3 and neon-20 and is activated by an electrical discharge. The active principle is the neon-20, which has optical transition in the infrared at 3.9 μm.

The sense in which such a system is a macroscopic quantum system is crucial. "Laser", after all, means "light amplification by stimulated emission of radiation". During a single passage of a matching photon along the narrow cavity, the excited neon atoms are stimulated to emit no fewer than 700 further photons. Evidently, it is of little concern that 97 per cent of them are lost at each end of the 60 cm track. The quantum system that matters in this case is not the excited neon atoms, but the electromagnetic wave that propagates to and fro in the narrow tube, dimensions of which have been fixed to allow only the simplest possible wave with symmetry along the axis.

How can such a system be used as a magnetometer? An external magnetic field will bring about a splitting of the energy levels of the neon-20 atoms, but what will happen to the electromagnetic field or laser beam? The Faraday effect, of course.

This is indeed the standard means of measuring the strength of interstellar magnetic fields, by the degree to which it causes the rotation of the plane of polarization of a microwave signal from a distant quasar or other source.

With the Rennes laser, what happens is much the same. Given its symmetry, it is sensitive only to the components of magnetic fields along its axis. Since there is no reason why original laser should be polarized, it can be thought of as what it is — a mixture of oppositely polarized circular waves. But then the effect of the axial magnetic field, which would split the neon energy levels through the Zeeman effect, is to change the frequencies of the oppositely circularly polarized waves, if only slightly. And then it is possible to measure the differences between the two frequencies by beating the two waves against each other. The result is that a magnetic field comparable with that of the Earth shows up as a frequency difference measured in kilohertz. With the laser built at Rennes, 200 milligauss shows up as just under 250 kilohertz.

That, then, is the essence of the magnetometer. Its virtue is that it substitutes for the measurement of magnetic field the much more sensitive measurement of the frequency difference of two parallel beams of infrared radiation, whose mutual interference can be followed by passing them through a polarizing device and a detector. The response of the instrument appears exquisitely a linear function of the magnetic field, at least for field strengths of the order of 200 milligauss. The only snag is that the laser, in the absence of an external field, appears to lock into a preferred mode from which it must be dragged by the Faraday effect of a field of at least a few milligauss. The authors guess that the preferred locking position is determined by geometric irregularities in the quasi-mirrors.

So who will use the new magnetometer? The way things are, this would not be the first time that a spanking new instrument with exquisite sensitivity had found no uses. What Bretenaker and his colleagues find is that their device is quickly responsive to small changes in the magnetic field — 100 microseconds seems to be enough. And dynamic measurements, in which an artificially induced field of known frequency is added to the field to be measured allows for a sensitivity for a sensitivity of 10^{-5} gauss.

It should not take very long for interested people to think of plausible uses for this new instrument. The authors themselves suggest that investigations of the supposedly quickly changing magnetic fields in advance of earthquakes are a natural starting point. Presumably, they could study the natural variation of the Earth's magnetic field, with its ionospheric solar–terrestrial antecedents. In each case, the volumes of data generated would be huge — up to 1,000 measurements a second.

The era of multi-micro-magnetism seems at hand. And somebody is bound to have a laser magnetometer in a spacecraft very soon.

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