obtained from the two instruments, although somewhat different, basically agree and that the difference between the two teams is in the interpretation.

Krimigis and co-workers use three main facts to make their case. First, the average anisotropy of cosmic-ray protons with energies of about 1 MeV is small and directed radially outward. If this is interpreted as being entirely the result of convection with the ambient solar wind, then the speed is low and consistent with what is expected in the post-shock region. It should also be noted that they observe large fluctuating anisotropies along the magnetic field, which come from the solar direction and which are difficult to interpret.

Second, the energy spectra at energies well below 1 MeV per nucleon show behaviour that is expected at or behind the shock. Finally, the composition of the enhanced intensity of energetic particles is not consistent with solar particles, but it is consistent with anomalous cosmic rays.

On the other hand, McDonald and co-workers insist that the event was a precursor to crossing the shock, and that the shock was not actually crossed. They make two main points. First, the spectrum of anomalous cosmic rays at energies near 25 MeV per nucleon shows a peak, which is a signature of the spacecraft being a significant distance upstream of the shock (i.e. on the solar side). They also point out that the large – and unexpected – anisotropies that are observed by both teams are very highly variable and generally in the azimuthal direction. Finally, and correctly, they point out that the average anisotropy is actually the result of the combined effect of diffusion (which is neglected by Krimigis and co-workers) and convection, and so cannot be used unambiguously to determine the underlying plasma velocity.

Bottom lines

These measurements of energetic particles are both noteworthy because they strongly suggest that Voyager I is, at the very least, quite near the shock. To this author, the most convincing data are the energy spectra. However, the simultaneous observation of a smooth power law from MeV energies to less than 0.1 MeV, and also a peak at about 25 MeV per nucleon, are difficult to fit into one picture. The former suggests that Voyager was at or downstream of the shock, while the latter suggests equally strongly that it is still a significant distance upstream. The different interpretations show that the shock is probably considerably different from what we had expected.

Voyager I also sent back magnetic-field and radio-wave data during this period. Both sets of data should show characteristic signatures of crossing the shock , but nothing was found. A significant increase in magnetic-field strength would have been detected for the entire duration of the event if Voyager were indeed in the post-shock flow. This was not seen (L F Burlaga *et al.* 2003 *Geophys. Res. Lett.* **30** 2072). This is a very important finding that supports the argument that the shock was not crossed. It is not at all clear how to slow down the solar wind, with or without a shock, without an associated increase in the magnetic field. The radio-wave data show no evidence of crossing the shock either (D A Gurnett *et al.* 2003 *Geophys. Res. Lett.* at press).

At the time of writing, I learned of another event similar to the 2002 event, but with only about 40% of its amplitude. It began in August 2003 and is still in progress.

Irrespective of how the current controversy is resolved, Voyager I is moving away from the Sun at a speed of about 4 AU per year and the termination shock or its equivalent will eventually be crossed. Voyager I will then enter a totally new region of space called the heliosheath and, if it lasts long enough, go on to become the first spacecraft to leave the solar system and observe the plasma between the stars.

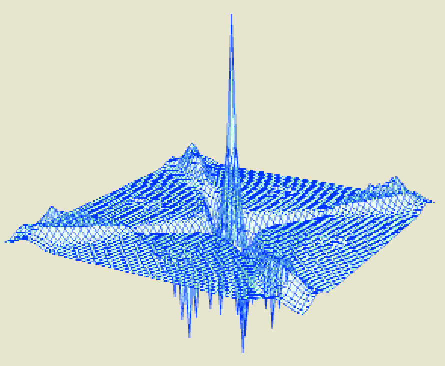
New twist for magnetic monopoles

Have isolated magnetic charges – also known as magnetic or Dirac monopoles – been seen in momentum space?

From **Allan MacDonald** and **Qian Niu** in the Department of Physics, University of Texas, Austin, US

There is a surprising lack of symmetry in Maxwell's equations of electromagnetism. Electric fields are created by electric charges, while magnetic fields are produced by the movement of electric charges. Magnetic charges are completely absent from the theory, not because Maxwell forgot to put them in, but because isolated magnetic charges do not seem to exist in the real world.

In 1931 Paul Dirac showed that if magnetic charge exists, it has to be quantized in units of h/e, where h is Planck's constant and e is the charge on the electron. Now an experiment in Japan has found evidence for an effective magnetic charge – also known as a magnetic or Dirac monopole – in the abstract momentum space that is routinely used by condensed-matter physicists to analyse the properties of crystals. The results, which rely on theoretical work by Zhong Fang of the National Institute of Advanced Industrial Science and Technology in Tsukuba, suggest that monopoles can have direct physical consequences in systems as common as a ferromagnet (Z Fang *et al.* 2003 *Science* **302** 92–95).



Crystal clear – the presence of an effective magnetic monopole in momentum space shows up as a peak in this calculation of its flux distribution in strontium ruthenate.

We should stress that these are "effective" monopoles. Although they exist naturally in the ground state of the crystal, they have no meaning outside it. The coupling of electrons to these momentum-space monopoles is mathematically similar to their coupling to the real-space magnetic monopoles that have long been sought by particle physicists.

Phases and fluxes

To fully appreciate the significance of the latest work we need to recall some subtle effects related to the role of phase in the quantum theory of matter. Quantum particles such as electrons are described by wavefunctions that depend on both space and time. The wavefunction is the solution of the time-dependent Schrödinger equation for the particle. Since the wavefunction is complex, it can be written in the form $\psi = A\exp(i\varphi)$, where A is the amplitude and φ is the phase.

In 1959 Yakir Aharonov and David Bohm predicted that the phase of a charged particle moving round a loop would acquire an additional phase that is equal to 2π times the number of magnetic flux quanta passing through any surface bounded by the loop. The Aharonov–Bohm effect has been confirmed in many experiments, but there is still no experimental evidence for isolated or quantized magnetic charges. (There is not space here to go into the reasons why the Aharonov–Bohm effect is important, apart from to say that it shows that the magnetic vector potential has physical significance and is not simply a mathematical convenience.)

To see how quantum phases constrain the possibilities for magnetic monopoles consider a loop like the equator of the Earth. The Aharonov–Bohm phase associated with this loop is 2π times the magnetic flux leaving the surface of either the northern or southern hemisphere. To be physically consistent these two values of the Aharonov–Bohm phase must be the same, or must differ by an integer multiple of 2π.

We can then show with simple algebra that the total flux leaving the sphere must be an integer multiple of h/e. Finally, we use Gauss's law, which states that the total flux through a closed surface is proportional to the total charge enclosed. If the magnetic flux through the surface is quantized, then the magnetic charge enclosed inside must also be quantized.

In 1984 Michael Berry of Bristol University in the UK discovered a more general form of the Aharonov–Bohm effect by working in a general "parameter space" rather than real space. However, many of the arguments about charges, quantum phases, closed loops and fluxes through surfaces are similar to the ones used above.

Berry predicted that the wavefunction of a particle can acquire a geometric phase when a parameter, such as the potential energy, is slowly varied before eventually returning to its original value. The geometric phase acquired by the particle is equal to the flux of a new field called the Berry curvature through the surface defined by this loop. Again, the requirement that the wavefunction can only have one value means that the total flux is quantized.

The Berry curvature is a field that is essentially a combination of second derivatives of the wavefunction with respect to the parameters used to define the parameter space, and the charge associated with it is given by the divergence of the field. Just as the Aharonov–Bohm phase allows for monopoles in real space, the geometric phase allows for monopoles in more general parameter spaces. However, the charge associated with the Berry curvature is only non-zero at points where the curvature field becomes singular or infinite.

Adventures in momentum space

The parameter space discussed by Fang and co-workers is the momentum space of a crystal. Solutions of the Schrödinger equation in a crystal have a definite crystal momentum and, in the very simplest terms, working in momentum space involves exploring how the properties of the electrons depend on their crystal momentum.

In the presence of an external electric field, it turns out that the group velocity of the wavepacket that is used to describe an electron has an extra term that is proportional to its Berry curvature. This is closely analogous to the way in which a magnetic field in real space contributes to the rate of momentum change through the Lorentz force. It therefore makes sense to look for monopoles in momentum space because the associated field – the Berry curvature – can exert a real effect on the dynamics of particles in crystals.

One such dynamic effect is the anomalous Hall effect. In the conventional Hall effect a sample is placed in a magnetic field that points in the z direction, and the resistivity (or conductivity) is measured in the y direction as an electric current flows in the x direction. In the anomalous version of the effect, a Hall current flows in the transverse (y) direction in the absence of a magnetic field. It turns out that the Hall conductivity can be accurately approximated in many systems by simply summing the Berry curvatures of all occupied states: each state has an extra velocity and, added together, these extra velocities lead to an extra current.

The present authors and co-workers have calculated the anomalous Hall effect caused by the Berry curvature for a number of magnetic semiconductors and transition-metal ferromagnets, and the results are in good agreement with experiment.

Fang and colleagues have now shown that the Berry curvature is also responsible for the anomalous Hall effect in ferromagnetic compounds as complicated as strontium ruthenate ($SrRuO_3$). Moreover, they have gone on to predict that the Berry curvature will become singular at some points in momentum space in $SrRuO_3$, and that these monopoles will lead to characteristic patterns in the behaviour of both the Hall conductivity and transverse optical conductivity of the material. Finally, they claim to have found evidence of such behaviour in their experiments (see figure).

Different dimensions

Seeing the Berry curvature, however, is not the same as seeing monopoles. Magnetic fields can be produced without monopoles, and so can the Berry curvature field. In 1982 David Thouless and co-workers showed that the Hall conductivity in a 2D system in which the electron energy bands are full could be related to a "Chern number", which is the integral of the Berry curvature. However, the curvature field only becomes singular when two energy bands cross, and since this is does not usually happen in two dimensions, there was little chance of finding a monopole in this system.

The situation should be different in 3D crystals, like the $SrRuO_3$ samples studied by Fang and colleagues. Energy bands usually cross at isolated points in momentum space in three dimensions, so monopoles should be commonplace. However, these materials have very complex electronic structures, and conclusive proof of monopoles in momentum space will probably have to wait for experiments in simpler materials.

HIGHLIGHTS FROM PHYSICSWEB

Another superconductor shows up

Physicists at the University of Tokyo have discovered a new superconductor made of potassium, osmium and oxygen. KOs_2O_6 has a superconducting transition temperature of 9.6 K, remains a superconductor in high magnetic fields, and is the second superconductor with a so-called pyrochlore structure to be discovered by the group. However, the transition temperature of the other material, $Cd_2Re_2O_7$, is only 1 K. The nature of the superconductivity in the new material is not yet clear.

Switching light on and off

Researchers have demonstrated a new method for "storing" light in a gas of atoms. In recent years several groups have "stopped" light by storing it as a stationary pattern of excited atomic spins, and then releasing it again. Now a US–Russia team has shown that actual photons can also be stored as a stationary electromagnetic excitation in the gas. The team claims that the new approach offers greater control.

The sharpest focus ever

Physicists in Germany have focused a specially polarized beam from a helium–neon laser to a spot with an area of just $0.06\ \mu m^2$ – almost half the previous record for the smallest ever focal spot. The team used half-wave plates to convert a standard laser beam with linear polarization into a "hollow" beam with radial polarization. An annular aperture was then used to focus this beam so that the hole in the middle shrunk and the electric field at the edges largely cancelled itself out. The electric field in the resulting focal spot pointed along the beam direction.

Plasmas move into medicine

Researchers in the Netherlands have developed a "plasma needle" that could offer an alternative to conventional surgery in the future. The temperatures in most plasmas are too high for medical applications, but the Eindhoven team has found a way to overcome this problem by applying a high-frequency voltage to a sharp tungsten needle. In addition to keeping the temperature low, the use of small regions of plasma means that the technique is more accurate and selective.

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