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# Thin films squeeze out domains

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# Thin films squeeze out domains

From **Jack Harris** and **David Awschalom** in the Department of Physics, University of California, Santa Barbara, US

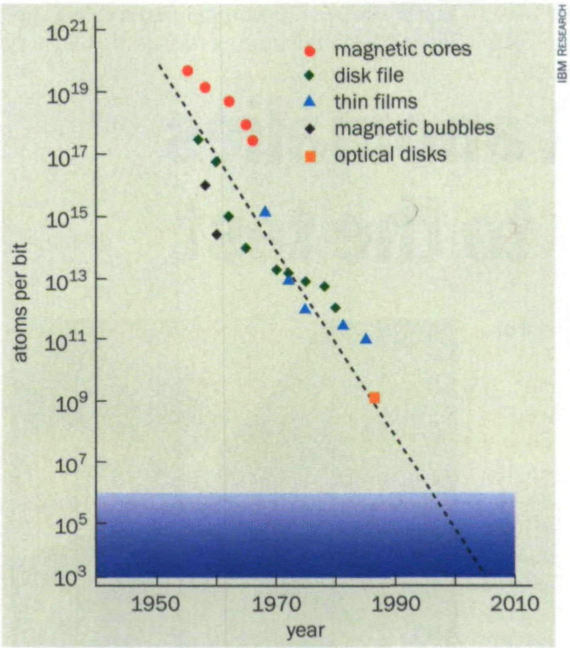
It might seem that the state of a magnet can be fully specified by labelling its poles as north and south. However, the true orientation of the magnetic moment is determined by the interplay of many different and competing energies. This generally ensures that the magnetization breaks up into a complicated pattern of regions, called domains, and that the magnetic moments in neighbouring domains point in different directions.

Although most of the domains can point in a single direction to yield a net magnetic moment, it is more common for competing domains to form, particularly at the edges of the magnet. However, researchers from ETH Zürich in Switzerland and the National Research Institute for Metals (NRIM) in Tsukuba, Japan, now argue that this may not be the case for two-dimensional magnets. They have shown that carefully prepared films of cobalt – just a few atomic layers thick but up to one millimetre wide – are entirely free of domains (C Stamm *et al.* 1998 *Science* **282** 449).

The key to this result is the careful tuning of the delicate balance between several competing energies. The first energy, and typically the most difficult to calculate, is due to the interaction of the magnet with its own field. It is this "demagnetization" energy that favours the formation of domains in the first place, particularly as regions at the edges of the magnet tend to become aligned with the non-uniform fields produced there. There are two energies that oppose the formation of domains. The anisotropy energy tends to align the magnetization along certain crystal axes, while the exchange energy acts to make the magnetic moment of each atom line up with the moments of its neighbouring atoms. It is this exchange energy that is the source of ferromagnetism.

For a normal bulk magnet, the demagnetization energy dominates above a critical size, causing the magnetization to break into domains. Below this size the exchange energy dominates and the magnetization is uniform. In practice, the critical dimension is usually much less than 100 nm.

The role of the interaction energy can be greatly reduced when one dimension is made much smaller than the others. This is because the non-uniform fields produced at the faces of the magnet create domains in which the magnetization is reversed compared with the rest of the magnet. The important point is that the faces that produce this demagnetizing field are the ones normal to the magnetization. If these faces are made smaller – for example by making the magnetization lie in the plane of a thin film – the demagnetizing field can be too weak to create domains. Just how thin the film needs to be, however, is hard to say.



IBM RESEARCH

The number of atoms used to store one bit of information with different forms of magnetic or optical storage has reduced over the years. The blue region indicates the superparamagnetic regime, below which thermal fluctuations at room temperature could alter the orientation of magnetic bits. The ultrathin magnets studied by Stamm and colleagues could help to improve the sensitivity of disk drive heads to smaller magnetic bits.

Christian Stamm and colleagues investigated this idea by growing thin films of cobalt on atomically flat copper crystals in ultrahigh-vacuum conditions. Cobalt grows quite uniformly on copper, and tends to produce films with in-plane magnetizations. The size and shape of the films (with lateral dimensions from 1 mm to 100 nm) were controlled by placing a diaphragm with small holes between the cobalt source and the substrate. Special optical and electron microscopes were also installed in the same vacuum chamber to determine the direction of the magnetization in the cobalt films. This experimental set-up made it possible to fabricate well controlled samples and measure their magnetic properties without exposing them to air.

For sufficiently thin films – in this case less than about 10 monolayers – the researchers found that the demagnetizing field had no effect on the magnetization of the sample. No domains were observed to form in films up to 1 mm long, and the preferred direction of the magnetization was completely determined by the crystal axes of the cobalt.

In most normal samples the demagnetizing fields tend to cause the magnetization to lie along the longest axis of the magnet. Competing with this tendency is the anisotropy energy, which results from interactions between the magnetization and the atomic lattice, and prefers that the magnetization lies along a certain "easy" crystal axis.

To test the relative importance of these energies, the researchers grew cobalt films 122 μm long and 1.9 μm wide that had their long axes orientated at different angles to the easy crystal axis. For such thin films they found that it is always the easy crystal axis that determines the orientation of the magnetization, rather than the long axis, confirming that the anisotropy energy has a much stronger effect than the demagnetizing fields. As a control experiment, the researchers also grew thin films of iron under similar conditions. In this case the magnetization tends to be normal to the film, which means that reducing the thickness of the sample should have no influence over the formation of domains. These iron films did indeed form domains, as did thicker cobalt films.

The researchers suggest that the work could have implications for magnetic data storage (see figure). In most common forms of data storage, bits are recorded by changing the orientation of the north and south poles in small domains in a magnetic film (much thicker than the films studied by Stamm and colleagues). A north pole pointing left might signify a "1", while a north pole pointing right would then signify a "0".

As the computer industry squeezes more memory into a disk, the domains must get smaller and closer together. But if the domains become too close together, the magnetic fields produced by neighbouring domains can interact and reduce the reliability of the storage medium. Even in today's disks, a correction for the tendency of like bits (a "1" next to another "1", for example) to attract each other must be made.

Stamm and colleagues point out that their quasi-two-dimensional magnets would interact with each other more weakly than thicker magnets of the same size and separation, simply because they contain less magnetic material and so produce smaller magnetic fields. However, the practical size of domains on a magnetic disk is limited by the ability to read the bits accurately, rather than by the magnetic properties of the disk. It is unclear whether smaller signals from much thinner bits would be compensated for by reduced interaction. However, the ability to produce thin magnetic layers without any demagnetizing effects might be useful for improving the sensitivity of the disk drive heads used to read the bits.

The industrial importance of thin magnetic films, particularly for data storage, is likely to continue for many years to come. From a physics point of view, thin magnetic films provide a fascinating arena for studying the gradual onset of magnetism – from the first few interacting atoms scattered on a surface to the familiar properties of the magnets on refrigerator doors. This new work makes contributions on both fronts. It shows that the properties of domains can be altered in very thin magnetic films and, more surprisingly, that they can be understood in terms of the same balance of energies that determines the properties of normal bulk magnets.

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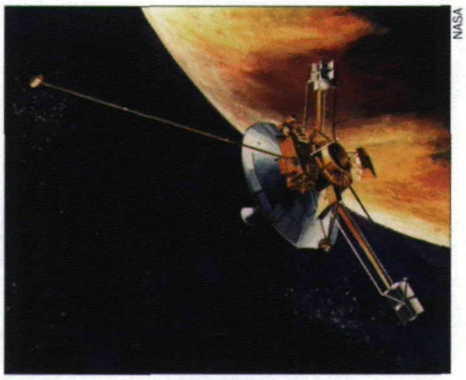
# Spacecraft anomalies put gravity to the test

From **Mordehai Milgrom** in the Department of Condensed Matter Physics, Weizmann Institute, Israel



NASA

Puzzling motion – a strange force may be at work

For centuries the solar system has been a source of inspiration for ideas relating to the physics of gravity and inertia. It has also provided an important test bed for new concepts and theories. Kepler's descriptive laws of planetary motion, for instance, led to Newton's discovery of the physical laws governing such massive objects, and the anomalous precession of Mercury's orbit was the first successful test of Einstein's theory of general relativity. As our astronomical horizons have expanded, however, we have looked beyond our solar system, and today it is the realm of galaxies and cosmology that provides the main testing ground for new ideas. And the first evidence for the existence of gravitational radiation was provided by studies of a binary pulsar.

However, measurements in the solar system can still provide us with important information. The high level of accuracy makes it possible to probe even minute effects and test new theories that challenge general relativity. And although general relativity endures as the dominant theory of gravity and inertia, with its predictions continuing to be confirmed with ever-increasing accuracy, researchers continue to test it by measuring the motions of bodies in the solar system. The tacit hope is that they will one day win the jackpot and detect some slight departure from the predictions of general relativity.

This is the underlying tenor of recent work by John Anderson of the California Institute of Technology and colleagues (*Phys. Rev. Lett.* **81** 2858). They report an intriguing anomaly in the recorded motion of three spacecraft: Pioneer 10, Pioneer 11 and Ulysses. Pioneer 10 and 11 are moving out of the solar system after completing their main missions – to explore the outer planets – while Ulysses is on an elongated orbit that roughly bridges the orbits of Jupiter and Earth.

The motion of these spacecraft is governed by the gravitational fields of the known bodies in the solar system, and can be calculated very accurately from general relativity. Anderson's analysis shows a small but systematic departure from the expected motion. Indeed, the spacecraft move as if they were subject to a new, unknown force pointing towards the Sun. This force imparts the same constant acceleration, $a_p$, of about $10^{-7}$ cm s$^{-2}$ to all three spacecraft, about ten orders of magnitude less than the free-fall acceleration on Earth. Such a finding, if it were not explained away by some mundane effect, would be a major break with accepted physics.

This may be one reason why many scientists are sceptical about a "new physics" interpretation of the measurements. Experience has taught us that findings of this nature that are interpreted as new physics often vanish after closer scrutiny or, as is more likely in the present case, can be explained by conventional physics. For example, a flurry of reports in the 1980s claiming a "fifth force" due to deviations from standard gravity at short ranges disappeared just as quickly as they arrived.

The problem is that the efforts that lead to such findings tend to stretch experimental finesse to extremes, and so tend to produce bogus results. Certainly, the results are only presented publicly after all the obvious explanations are very carefully eliminated, and Anderson and colleagues have indeed spent some time considering all of the possibilities. They have examined and eliminated the effects of radiation pressure due to solar radiation – which is quite important when spacecraft are near the Sun – gas leaks that could act as tiny jets, and several other effects. But there is always one cause that has not been thought about or has been impossible to eliminate completely, and Anderson and colleagues have suggested some possible explanations for the anomaly.

Researchers outside of the Anderson group have made still further suggestions. Jonathan Katz of the University of Washington, and Edward Murphy of Johns Hopkins University have independently attributed the effect to uneven radiation from the heat produced by the electricity generator or the electronic circuitry onboard the spacecraft. This would produce a net radiation pressure that would exert a push on the spacecraft that could account for the anomalous acceleration. Anderson and colleagues did in fact consider this effect, but they maintain that is not important enough to account for the observed effect.

Apart from the usual suspicion about new-physics results, in this case there is a more weighty reason for scepticism. The interpretation not only flies in the face of general relativity, but it also conflicts with other, much more reliable, measurements made in the solar system. The notion of an added, constant acceleration towards the Sun – acting on all bodies and of the reported magnitude – is ruled out by these measurements and by a large margin. Anderson and colleagues themselves point out that observations of Mars and Earth limit the value of a new, universal acceleration to less than a tenth of the value they detect from the spacecraft motion.

In 1983 I considered the possibility of a constant anomalous acceleration of the order of $a_p$ in the solar system, because this arose naturally in a version of my "modified dynamics" theory. I showed then that this acceleration would destroy the close agreement of the measured orbital precession of Mercury with the theory of general relativity, and so ruled it out by a considerable margin. Improved measurements since 1983 have only confirmed this view. And more recently Bob Sanders of the University of Groningen in the Netherlands showed that a universal acceleration would grossly conflict with the measured orbital precession of the asteroid Icarus, as well as with the accuracy of Kepler's third law in its relativistic form.

All these other solar-system measurements concern the motions of planet-size bodies (an asteroid in one case), while the effects observed by Anderson and colleagues result from the motion of spacecraft – much less massive bodies. We can contrast