The Magnetic Universe

BY BRYAN GAENSLER

Magnets are everywhere, but we don't know how they got here.

Magnets have been part of our lives since antiquity. The ancient Greeks wrote of the mineral lodestone (which they called the "stone of Magnesia") and its ability to attract iron. For centuries until the advent of GPS, navigation relied on the fact that a compass will always point north. And remarkably, some bird species seem to be able to actually see magnetic fields, allowing them to unerringly migrate over thousands of kilometres.

Such spectacular feats of navigation rely on the fact that the entire Earth is a weak magnet. Modern understanding is that the rotation of the Earth induces currents in electrically conducting material in the planet's core. This drives a process called a "dynamo", which generates an overall planetary magnetic field.

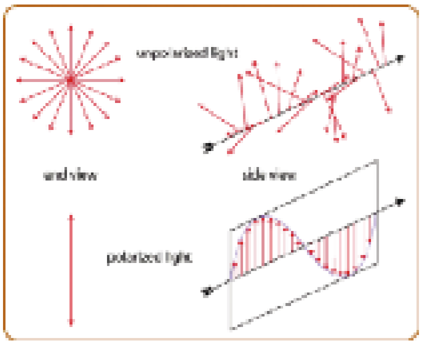

Figure 1. Light can be thought of as a wave that oscillates back and forth at right angles to the direction of motion. If each component of light has a random orientation, the light is unpolarised, as shown in the top half of the figure. But if the oscillations occur at a specific angle, the light is polarised. In the example shown in the lower half of the figure, the light is vertically polarised.

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At the moment, the magnet inside the Earth lines up almost exactly with the Earth's spin axis. So just as a paper clip will be attracted to the end of a toy magnet, a compass needle will be attracted to the Earth's pole.

Magnetic Planets and Magnetic Stars

The Earth's magnetic field is not just a curiosity or a handy navigation aid, but is vital for the existence of life. The Sun continually generates a stream of high-energy charged particles that flow out in all directions as part of the solar wind. Exposure to this particle stream can cause serious damage to living tissue; any humans who one day travel to Mars will need heavy shielding around their spacecraft to protect them from this onslaught. However, we experience no such ill-effects on Earth, because these particles are deflected and diverted by the Earth's magnetic field. The only place these particles approach anywhere near the Earth's surface is near the north and south poles, where they fluoresce in the atmosphere and generate the aurorae.

Several other planets in the solar system (most notably Jupiter and Saturn) are also magnetic, as is the Sun itself. The Sun's magnetism is responsible for a whole range of phenomena, such as sunspots, solar flares and coronal mass ejections. On average the Sun's magnetism has about the same strength as the Earth's, but in sunspots the magnetic field is about 1000 times higher.

Ingenious techniques have allowed astronomers to also study magnetism in other, much more distant stars. In some cases the presence of strong magnetic fields is inferred indirectly by observing "star spots", "stellar flares" and other energetic activity analogous to what we see up close for our own Sun. For other stars we can detect and study magnetic fields directly because the light travelling to us from the star is slightly distorted as it passes through the magnetism on the star's surface.

Just in the past 10 years a new class of stars, "magnetars", has been discovered. These bizarre beasts are only about 25 km across, and appear to be the most magnetic objects in the Universe, with magnetic fields up to a quadrillion (1,000,000,000,000,000) times stronger

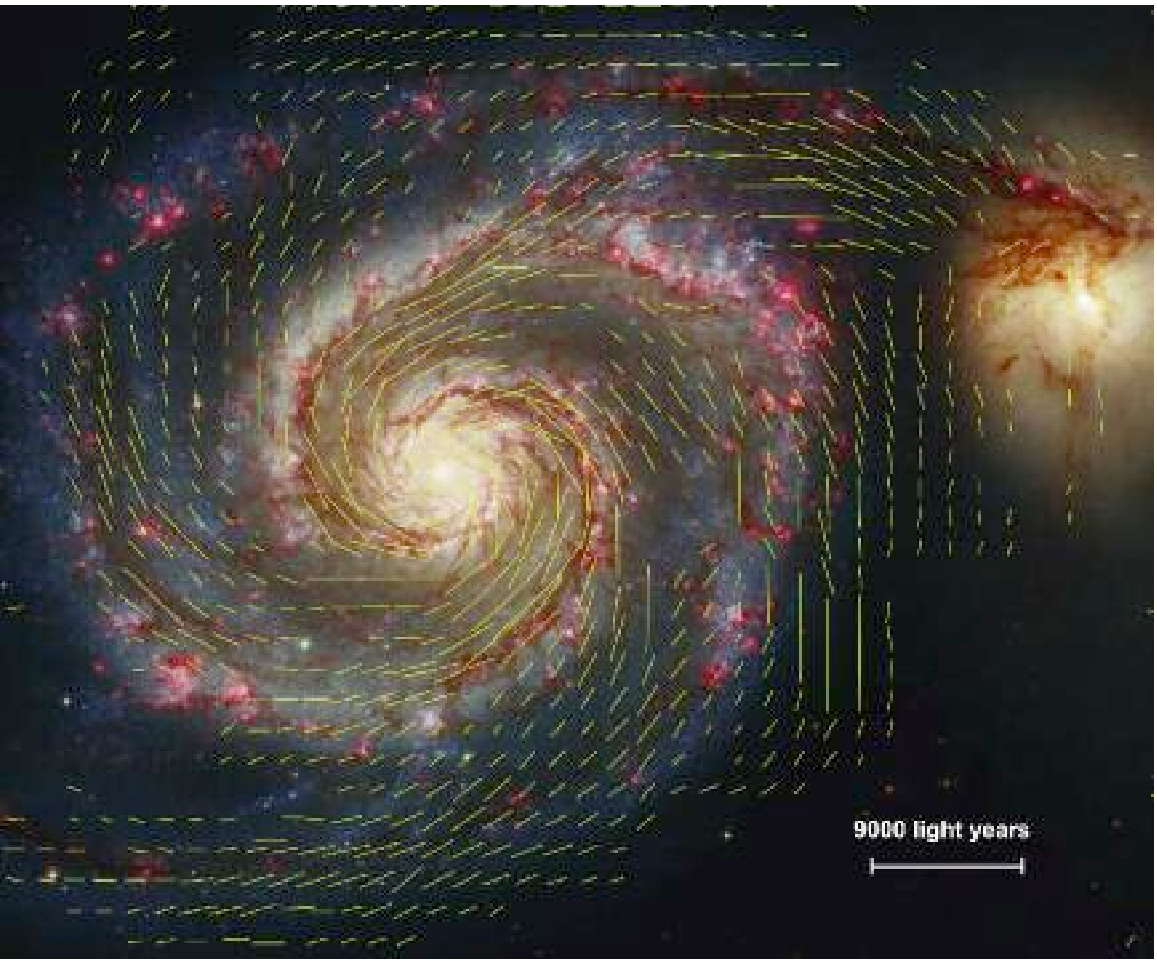

Figure 2. A Hubble Space Telescope image of the spiral galaxy Messier 51, with the direction of the magnetic field superimposed. Viewed from above, the magnetic field of the Milky Way probably has a similar appearance.

Image: Hubble Heritage/NASA/STSci, Rainer Beck/MPIfR. Graphics by Sterne und Weltraum.

than the Earth's! In comparison, the most powerful magnet ever constructed in the laboratory produces a field that is a mere million times stronger than the Earth's.

Magnets in Space

The sky seems full of magnets. Where does this magnetism come from?

Although the rotation of a star can amplify an existing magnetic field in the object's interior, this can only work if one starts with some weak initial magnetism. This presumably was present when the star first formed. Since we know that stars form out of collapsing gas clouds, this means that the gas in interstellar space must be magnetic also.

This was spectacularly verified in 1949, when two American astronomers, John Hall and Albert Hiltner, independently discovered that the light from some stars was polarised. Polarisation refers to the orientation of the oscillation of light waves as viewed directly head-on; that is, light can be polarised vertically, horizontally, or at some intermediate angle (Fig. 1).

Starlight, like most naturally occurring light sources, should be unpolarised, meaning that each parcel of light has a random orientation. However, Hiltner and Hall clearly showed that this was not the case. If starlight is supposed to be unpolarised, then something must be polarising the light on its journey from the star to our telescope.

It was quickly realised that this must be the result of interstellar magnetism. Space turns out to be quite dusty, and most dust particles in space are not tiny spheres but are elongated, like tiny grains of rice. In the presence of magnetism, these dust grains act like tiny compasses, and line up with the direction of the magnetic field. When starlight then passes through a region filled with these aligned dust particles, most polarisation angles are absorbed, and the light that emerges is polarised at the angle that the dust lets through.

Detecting polarised starlight therefore tells us that there must be invisible magnetic fields between the star and us. And what's more, the angle of polarisation tells us the orientation of the aligned dust grains, and hence the direction of the field. Although this explanation seems a little convoluted, it has been confirmed by the fact that the more dust is in front of a star, the larger fraction of that star's light is seen to be polarised.

Hiltner and Hall's pioneering measurements have now been repeated for more than 10,000 stars all over the sky. In the same way that sprinkling iron filings over a magnet on a bench top reveals the pattern of its magnetic field, starlight polarisation has allowed us to build up a picture of the magnetic field in our Milky Way. If we could somehow step outside our Galaxy and look down on it from above, the Galactic magnetic field might look something like what is shown in Figure 2. Each spiral arm can be thought of as a curved bar magnet, with one pole near the centre of the galaxy and the other pole at the outer tip. This beautifully ordered pattern seems to be the form that magnetism takes in many other spiral galaxies too.

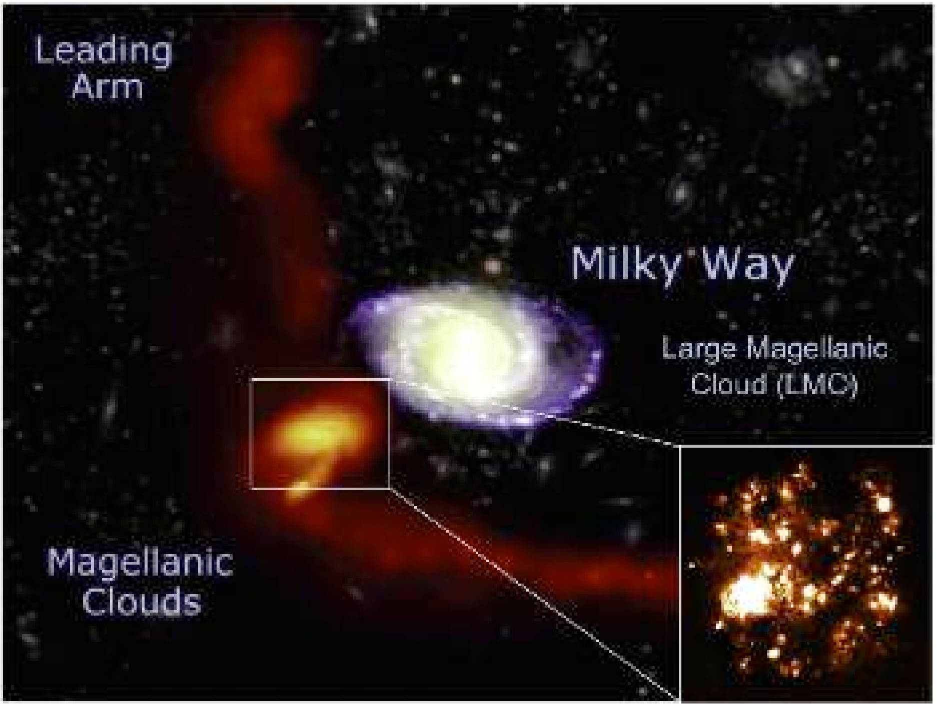

Figure 3. A simulation of the Large and Small Magellanic Clouds in orbit around the Milky Way. The Milky Way's gravity has stripped long streams of gas from the two smaller galaxies. The inset shows a detailed map of hot gas in the Large Magellanic Cloud. Main image: Daisuke Kawata, Chris Fluke, Sarah Maddison and Brad Gibson, Swinburne University of Technology. Inset: The Southern H-Alpha Sky Survey Atlas , supported by the National Science Foundation

These magnetic fields are very weak – about one millionth the strength of the Earth's. But because of the vast volume they encompass, a massive amount of energy is required to create and sustain them. Standard theories suggest that, just like in the Earth, this magnetism is the result of a rotating dynamo, and that it has taken billions of years for these magnetic fields to gradually take shape.

A Magnetic Mystery

It is remarkable that magnetism is so pervasive in the Universe. If you drop a fridge magnet on the floor a few times, it quickly loses its magnetism. Similarly, all the dramatic explosions and collisions that galaxies experience as they evolve should serve to quickly tangle and destroy their magnetism before it can accumulate appreciably. And yet galaxies like the Milky Way are clearly magnetic. What is going on?

The first thing to examine is whether violent episodes indeed destroy a galaxy's magnetism. We set out to test this by looking for magnetism in the Large Magellanic Cloud (LMC), a small galaxy in orbit around our Milky Way, at a distance from Earth of about 170,000 light years.

The LMC and its companion, the Small Magellanic Cloud, are slowly being torn apart by the gravity of the Milky Way (Fig. 3). The violent battering that the LMC is experiencing should ensure that even if it had a magnetic field at some point in the past, it probably doesn't have one now.

To study the magnetism of the LMC, we used an obscure effect discovered by English physicist Michael Faraday more than 150 years ago. Faraday discovered that, under certain conditions, polarised light will have its angle of polarisation rotated as it passes through a region in which magnetism is present. And the stronger the magnetic field, the more rotation is produced.

If we study the polarised radio signals produced by distant galaxies, we can see this "Faraday rotation" effect produced as the signals pass through clouds of foreground magnetised gas (Fig. 4).

To study the magnetism of the LMC, we took this phenomenon to its extreme: we found about 300 very distant galaxies behind the LMC and measured the polarisation and Faraday rotation of each. This allowed us to map out what magnetism might be present in this nearby galaxy.

To our surprise, we found that the LMC has quite a strong magnetic field, and that this field is beautifully ordered into a spiral pattern, just like in our own galaxy. This simply should not be the case – any magnetism that the LMC might have been able to build up over billions of years should have been destroyed as our galaxy gradually tears its companion apart.

The implication is that magnetism in galaxies must be generated very rapidly. At the same time as the Milky Way disrupts the magnetism of the LMC, the LMC must be regenerating new magnetism to replace it. Since most galaxies throughout the Universe are undergoing some sort of violent interaction (and indeed our own Milky Way has had many such encounters in the past), the conclusion is that magnetism is something that galaxies can create very quickly (relatively speaking!) – in 100 million years or less.

This supposition has recently been confirmed by a different set of experiments in which Swiss and American teams have measured the magnetism in galaxies that are billions of light years away. Since the speed of light is finite, looking out into space is also looking back into time. These distant galaxies are thus much younger than our Milky Way, and we can use them to see how magnetism in galaxies has changed over time.

Measurements of background polarisation for these younger galaxies has shown that they, too, are magnetic, and that this magnetism is just as strong, billions of years ago, as we see in our

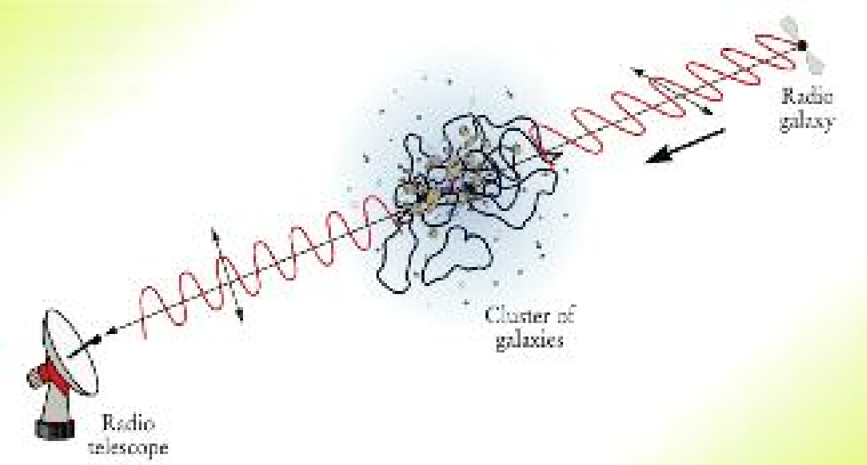

Figure 4. When the polarised radio emission from a background galaxy passes through a foreground cloud of magnetic gas, the emission undergoes Faraday rotation. This effect can be detected with a radio telescope, and can be used to measure the strength of cosmic magnetic fields. Image reprinted with permission from "Intergalactic Magnetic Fields" by Philipp P. Kronberg, *Physics Today*, December 2002, p.40. © 2002, American Institute of Physics

neighbourhood. Once again, this contradicts the simple idea that the magnetism we see in galaxies today has grown slowly to its present strength over billions of years. Some as-yet unidentified process allows magnetism in galaxies to grow very quickly.

Cosmic Magnetism with the Square Kilometre Array

There is clearly something fundamental that we are not understanding about where magnetism comes from and how it evolves as galaxies evolve. The problem in making further progress is that measuring these weak magnetic fields is difficult and time-consuming – the 300 measurements of Faraday rotation that we carried out through the LMC took about 1000 hours of observations with one of the world's most powerful radio telescopes.

Motivated by this puzzle of cosmic magnetism, along with several other fundamental unsolved problems, a new generation of radio telescopes is now taking shape, culminating in the largest telescope ever conceived, the Square Kilometre Array (see p.38). The SKA will have such exquisite sensitivity that every inch of the sky will be filled with distant polarised radio sources.

Thus, for any galaxy at all, in any direction and at any distance, we will always be able to measure the effects of Faraday rotation as this background polarised light passes through it. This will give us a spectacular census of magnetism in galaxies of all types and of all ages, with which we hope we can finally determine how magnetic fields emerge, evolve and perhaps are also destroyed.

While we eagerly await the results of the SKA, it is important to realise that the great leaps forward in the study of magnetism will not come simply from collecting magnetic galaxies like stamps in an album. We know from studying the magnetic field of the Earth and the Sun that when viewed in detail, magnetism can be unbelievably complicated and dynamic.

To quote the astronomer Lo Woltjer: "The larger one's ignorance, the stronger the magnetic field". We are only now beginning to appreciate the major role that magnetism plays in many of the most complicated and perplexing processes in astrophysics and cosmology.

So when we begin to open the window to the "Magnetic Universe" with the SKA, it is virtually certain that we will find many remarkable and unexpected phenomena. These new discoveries will undoubtedly provide the answers to many long-standing problems, but at the same time they will raise a new set of magnetic mysteries for the next generation of astronomers to puzzle over.

Does Magnetism Matter?

The discovery that interstellar space is magnetic was unexpected and remarkable. But is this just a piece of cosmic trivia, or is magnetism an important part of the big picture?

It turns out that many previously unsolved problems in astronomy suddenly make sense once one includes the effects of interstellar magnetism. As far as life on Earth is concerned, probably the most crucial role that magnets play in space is in the formation of new stars.

The Sun and our solar system formed five billion years ago in a dark cloud of interstellar gas, which gradually became hotter and denser as it collapsed under its own gravity. But under the influence of gravity alone, such clouds would collapse too rapidly to form stars like the Sun. However, we now realise that the strong magnetic fields present in these clouds resist the force of gravity, and slow down the collapse enough so that stars can form in the way we expect. If it were not for cosmic magnetism, our Sun and its planets would never have come into existence.

A similar problem applies to the entire Milky Way. Viewed from the side, the stars and gas in our galaxy form a circular disk that is about 100,000 light years across, and a few thousand light years thick. If we calculate the gravity of all the material in this disk, we find that the disk should collapse down on itself until it is paper-thin. However, this doesn't happen – something is holding up the gas and keeping it floating thousands of light years above the centre.

We now believe that this is the result of magnetic pressure, which provides the buoyancy needed to keep the galaxy "inflated".

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