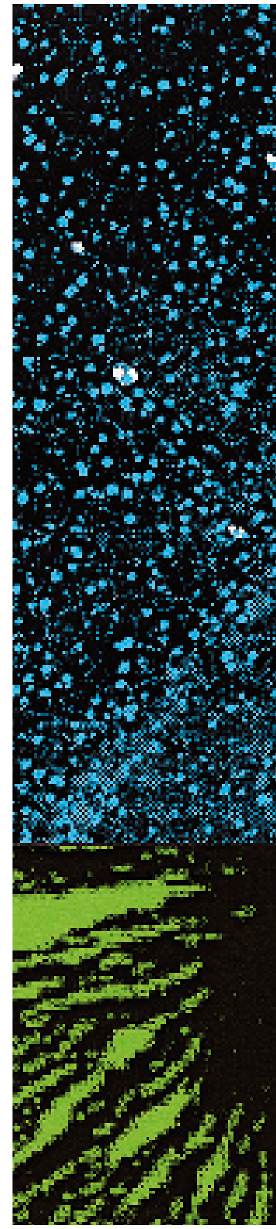
Magnetic fields that guide you on a trip through time? **Anil Ananthaswamy** sets his cosmic compass

North of the big bang



"MY EXERCISE every morning is to try and pour cold water on my fantasies." Don't worry, Massimo Giovannini is not thinking of anything salacious. He's a physicist at the CERN particle physics lab in Geneva, Switzerland, and Giovannini's flights of fancy concern the gigantic and mysterious magnetic fields that stretch through space.

Giovannini has good reason to fantasise: these cosmic magnetic fields, sometimes big enough to stretch across clusters of galaxies, are one of the last unexplored features of the universe, and could hone our theories about how the universe came to its present state. That's because there is a tantalising possibility that today's fields are the legacy of those created mere instants after the big bang. The information contained in these magnetic fields could tell us how the universe developed from the big bang into the vast cosmos around us. "Primordial magnetic fields could influence the whole history of the universe," says Giovannini.

Our best bet for studying the earliest moments of the cosmos is the cosmic microwave background (CMB), the fossil radiation of the big bang. At the moment, however, the information we can glean from it is somewhat limited. Cosmic magnetic fields – if we can get to grips with them – could offer a new, independent and extremely valuable source of cosmological data. It's an exciting prospect, says Ruth Durrer of the University of Geneva. "Cosmology is nothing but a search for fossils," she says, "and they are very rare."

No one knows how the first significant magnetic fields arose. Any charged particle racing across the universe will create its own tiny magnetic field, but it is not clear how we got from a random array of little fields to the huge fields we see stretching across galaxies today. In fact, it took a while for people to believe fields of such a size could even exist.

The Italian physicist Enrico Fermi was the first to suggest that the universe might be littered with magnetic fields on galactic scales. That was half a century ago, but although it was becoming clear that everything else astronomers could see – planets, stars and even the Milky Way's centre – supported huge magnetic fields, the idea of fields that spanned galaxies seemed absurd.

This attitude began to soften in the late 1970s when, using the 100-metre Effelsburg radio telescope near Bonn, Germany, Rainer Beck and his colleagues saw something mysterious. They were studying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"synchrotron" emissions from galaxies – radio waves emitted by charged particles spiralling around magnetic field lines. The emissions were polarised: that is, the plane of vibration of the electromagnetic waves was ordered – only not in the way that the astronomers expected.

The amount of polarisation of these emissions depends on the orientation and ordering of the magnetic field lines: if they are neatly ordered, there will be a high degree of polarisation. If the magnetic fields are small and randomly oriented, the polarisation will be small. Since no one believed galaxies contained ordered magnetic fields, the astronomers expected the latter. "But surprise, surprise, the degree of polarisation in galaxies was quite high," says Beck, who is at the Max Planck Institute for Radio Astronomy in Bonn.

The astronomers repeated their studies in the early 1980s with the Very Large Array radio telescope near Socorro, New Mexico. They again found a high degree of polarisation. Something in the galaxies was producing large, neatly patterned magnetic fields.

"Cosmic magnetic fields are one of the last unexplored features of the universe"

It wasn't until the Berlin Wall came down that Beck and his colleagues found the answer to this puzzle. Theoreticians in Potsdam, East Germany, had already done the maths and found that the rotational energy of galaxies, combined with turbulence generated by, say, supernovae, could amplify small "seed" magnetic fields. "When we had the first contact we realised that they had exactly predicted what we had observed: spiral magnetic fields in galaxies," Beck says (see Graphic, page 30).

Things have changed dramatically since then. Contrary to what everyone once thought, magnetic fields that stretch across galaxies have become a commonplace observation. Fields of about 10^{-10} tesla are routinely measured in galaxies like ours and Andromeda (Earth's magnetic field is roughly 10^{-5} tesla ▶

"Clues about the infant universe could be frozen into vast magnetic fields that span the cosmos"

GALACTIC MAGNETIC FIELDS

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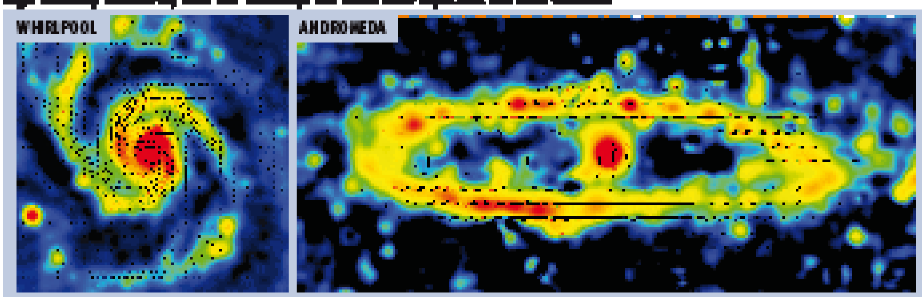

at sea level). They can also be seen on the scale of clusters of galaxies, and there are tantalising hints that they run in plasma filaments across even vaster tracts of space.

Supernovae and black holes produce minute fields of around 10^{-22} tesla. The rotational energy of galaxies can turn these small "seed" magnetic fields into large ones: as the galaxy turns, it moves charged particles across the existing magnetic field, which creates a further field. The combined field is stronger than the original, and it carries on building as the galaxy continues to spin. A similar dynamo effect caused by the rotation of the Earth probably explains the origin and continuing existence of the terrestrial magnetic field.

However, the dynamo effect doesn't seem to be able to explain all the observations. The main problem is that it should take several billion years to build up fields of the strength they seem to be, and yet some galaxies are much younger than that (see "The dynamo problem", right). That leaves another plausible and far more exciting explanation: that the seed fields were generated in the infant universe.

The excitement is not misplaced. Primordial magnetic fields – that is, those that formed during the first 300,000 years of the universe's existence – would have left clues about the nature of the infant universe frozen into the fields that span the cosmos today. What's more, they might have affected the fundamental shape of the universe (see "Shaping the cosmos", opposite). If we find any evidence of this, it will fundamentally affect our understanding of the evolution of the universe.

The first step towards understanding the magnetic universe is to pin down the mechanism that could have generated primordial magnetic fields. Among the best candidates are phase transitions, the times when the properties of a rapidly cooling universe changed dramatically from one instant to another. For instance, just 10^{-12} seconds after the big bang, in what is called the electroweak transition, the then unified electromagnetic force and the weak nuclear force split and became distinct from each other. About half a microsecond later, during a time known as the QCD transition, quarks and gluons combined to form subatomic particles such as protons. Could such events have created magnetic fields?

What we need to find out is just how violent these transitions were. That's because one thing that might have made magnetic fields possible is the creation of shock waves. These would turn the random movements of charged particles, such as electrons and protons, into flows of particles capable of creating significant magnetic fields. The more violent the transition, the more chance that the shock waves would have led to the charge separation that created long-lasting seed fields. We may have the answer within a couple of years: when the Large Hadron Collider starts up in 2007 at CERN, Switzerland, it will generate the energies needed to probe the electroweak transition in sufficient detail.

Another possibility is the idea that magnetic fields could be directly related to inflation – the period of time, long before the electroweak and QCD phase transitions, when the universe expanded by several orders of magnitude in a split second. The large galaxy structures we observe today were caused by fluctuations in the density of matter during this period. Could fluctuations in electromagnetic fields during inflation have given rise to primordial magnetic fields?

Larry Widrow of Queen's University in Kingston, Canada, first proposed this idea in the late 1980s while working as a graduate student with cosmologist Michael Turner of the University of Chicago. They found that to produce fluctuations in the electromagnetic field during inflation, they had to tinker with the famous equations formulated by James Clerk Maxwell that describe the behaviour of

The dynamo problem

How did weak "seed" fields – generated, for instance, by exploding stars or supernovae – get amplified by a factor of 100 billion into the gigantic spiral magnetic fields that are seen today in galaxies like ours and Andromeda?

One answer called the dynamo mechanism describes how the rotational energy of galaxies can cause magnetic fields to grow, but it can't explain everything. It's fine for spiral galaxies such as the Milky Way, but what about elliptical galaxies and clusters of galaxies, both of which rotate much more slowly than spiral galaxies, too slowly to build a magnetic field quickly. Also, even in spiral galaxies, dynamos should take billions of years to generate large-scale fields, yet some galaxies that are only about a billion years old have strong magnetic fields.

The problem could be solved if the original seed fields were stronger than previously thought. Active galactic nuclei (AGNs), that is, galaxies with a supermassive black hole in the middle, would be able to create such fields. AGNs spew out highly energetic jets of particles that carry magnetic fields with them over distances greater than 1 million light years. "AGNs would contaminate the rest of the cluster magnetically, and would act as much more efficient seed magnetic fields for galaxies," says Axel Brandenburg of the Nordic Institute for Theoretical Physics in Copenhagen, Denmark. Nevertheless, that still doesn't fully explain how elliptical galaxies and clusters get their magnetic fields.

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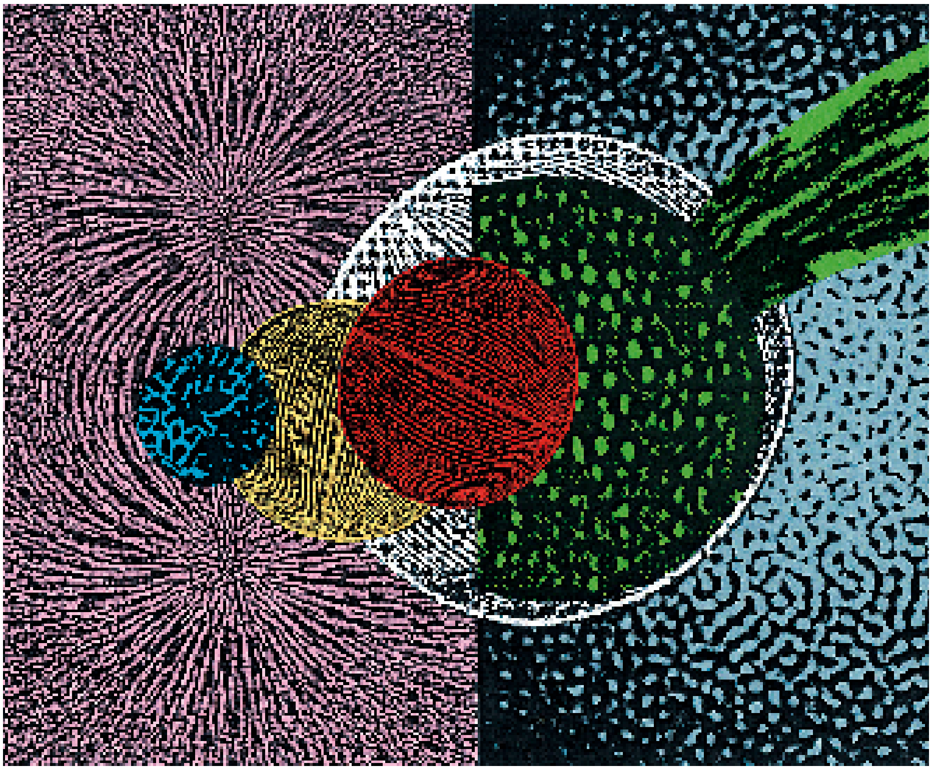

Shaping the cosmos

Primordial magnetic fields might have affected the universe's geometry. General relativity tells us that magnetic fields affect the fabric of space-time – but with different effects in different directions, depending on the polarisation of the field lines. This may have caused the infant universe to expand more in one direction than others.

Some evidence that this may have happened came last month from Luigi Campanelli of the University of Ferrara in Italy and his colleagues. They used data from NASA's WMAP satellite, which measures the cosmic microwave background (CMB), to show that primordial magnetic fields could have distorted the universe along one axis. The temperature of the CMB is mostly uniform, but there are tiny temperature fluctuations, or anisotropies, that reflect density variations in the early universe.

WMAP compares the anisotropy at different scales, and has found that the anisotropy at the largest possible scales is not as strong as predicted. Campanelli's team showed that a slight eccentricity in the shape of the universe would, however, produce exactly this effect (www.arxiv.org/astro-ph/0606266). If they are right, our universe is somewhat elliptical.

electric and magnetic fields. Their key idea was to endow the photon with mass during a time when immense energies dominated the universe. This would change the way electromagnetism coupled to gravity, in a way that cannot be seen today, and create the necessary fluctuations. The high conductivity of the universe would cause a short circuit that would leave behind a web of primordial magnetic fields.

Testing inflation

When the idea was first proposed, it didn't go down too well: physicists don't like messing with Maxwell's equations, the sacred cow of electromagnetic theory. The idea of magnetic fields generated during inflation has caught on more recently, though. For example, Giovannini and his colleagues, along with Gabriele Veneziano of the College of France in Paris, have shown that the fluctuating field scenario envisioned by Widrow and Turner arises naturally in string theory.

Inflation could create a magnetic universe in other ways, too. Kiyotomo Ichiki of the National Astronomical Observatory of Japan in Mitaka and his colleagues have shown that inflation's effects could have influenced the primordial magnetic fields long after the period of inflation was over.

When electrons and protons were combining to form the first hydrogen atoms 300,000 years after the big bang, the universe was filled with photons, which would have scattered off electrons and protons. Because protons are much heavier than electrons, the photons would have scattered differently off them, generating small differences in the velocities of protons and electrons. This would create electric currents, and hence magnetic fields. Ichiki's team points out that these fields would be related to fluctuations in the energy density that arose during inflation (*Science*, vol 311, p 827). These primordial fields, marked with the signature of inflation, would then have been amplified to become the fields seen today.

If primordial magnetic fields are caused by energy density fluctuations, then the magnetic fields we can detect today have a direct connection to the inflationary era. That has huge implications: "We could test some aspects of inflation with magnetic fields," Durrer says.

One way of doing that is to look for signatures of primordial magnetic fields in the CMB. Magnetic fields would have polarised the photons that make up the CMB, with the angle of their polarisation dependent on an effect called Faraday rotation. Finding Faraday rotation in the polarisation of the CMB could only mean that magnetic fields threaded the primordial universe.

To see that signature, we'll need a good map of the polarisation, and a newly proposed radio telescope might be the answer. The "Square Kilometre Array" will have antennas spread across 3000 kilometres and, as the name suggests, their combined surface area will be a square kilometre, giving the telescope an extraordinary resolution that should allow it to pick up synchrotron emissions from galaxies nearly 10 billion light years away.

Given that the universe is about 13.7 billion years old, and that galaxies took around 2 billion years to form, these galaxies would be just 1 or 2 billion years old. If polarised synchrotron emissions are coming from these galaxies, it means that ordered magnetic fields developed in just a billion years or so.

Another possibility is to look at the ripples in space-time known as gravitational waves. Magnetic fields can interact with space-time, so any primordial fields might modify gravitational waves in ways that could be seen by gravitational wave detectors. The only problem is that no one has detected a gravitational wave yet, so detecting the signature of magnetic fields imprinted on them remains a distant hope.

Despite such difficulties, it is clear that there is suddenly a lot at stake. Magnetic fields, one of the last unexplored features of the cosmos, may have played a crucial role from its beginning, and they may tell us much of what we want to know about the most inaccessible parts of the universe's history. "At the moment, the most crucial thing on the agenda is to understand if these fields are primordial or not," says Giovannini. If they are, his fantasising would not be in vain. ●