Magnetic fields of spirals

Virginia Trimble

Our Galaxy had been known to have a large-scale magnetic field for about 20 years\(^1\) when Fritz Zwicky suggested as a hypothesis for its origin: \textit{Dixique Deus, fiat lux campaque magneticus}.\(^2\) Another 20 years later, new studies of the face-on spiral galaxy M83 (ref. 5) and of other galaxies discussed at a recent meeting\(^3\) show that we still do not understand galactic magnetic properties well enough to test competing theories of their origin much better than Zwicky could. The competitors are a pre-galactic field, amplified by differential rotation, and dynamos.\(^4\) More of their implications shortly, but it is worth noting immediately that each requires some primordial seed field, though a fairly weak one will do in the dynamo case.

What do real galactic magnetic fields look like? That depends on how you look. Polarization of scattered star light and of synchrotron emission reveal the orientation of the ordered field component, but only in the plane of the sky and to within \(\pm 180^\circ\). Faraday rotation of the polarization (with some assumptions about electron density distribution) indicates the strength of ordered fields and the absolute orientation, but again only in the plane of the sky. Thus we probe the field in the disk for spiral galaxies seen face-on and the field perpendicular to the disk for edge-on galaxies.

Most face-on spirals have ordered magnetic fields of a few microgauss (\(\mu G\)) lined up roughly along their spiral arms, according to Marita Krause (Max Planck Inst. for Radioastronomy), Yoshiaki Sofue (Univ. Tokyo) and others. The randomly oriented component is of similar strength. Rainer Beck (Max Planck Inst. for Radioastronomy) noted that, at least in NGC6946, the field direction is definitely that of the spiral arms, not that of the circular gas motion. For two galaxies, M31 (the Andromeda Nebula) and IC342, Faraday rotation data show that the field points the same direction along all the arms, a configuration called an axisymmetric spiral (ASS). In others (M81, M51 and possibly M33), the magnetic field lines change direction by about \(180^\circ\) between arms, forming a bisymmetric spiral (BSS).

In many face-on spirals, the intensity of the ordered field is largest between the arms, not in them. This sounds paradoxical, but seems to mean that the field in the arms has been tangled up by gas turbulence (caused by stellar winds and explosions) so that it is stronger than the inter-arm field, but less ordered. The study of M83 by Sukumar and Allen, reported on page 537 of this issue,\(^6\) reveals an extreme version of the apparent paradox. The entire inner 12-kiloparsec (kpc) region, with its active star formation and conspicuous spiral arms, shows a largely chaotic field (at 2-kpc resolution). The strongest linearly polarized emission is confined to two 30-kpc arcs, roughly opposite each other in the dark outer regions of the galaxy, and not associated with optical spiral structure.

In edge-on spirals also, we can see only a projection onto the plane of the sky. Field lines are largely perpendicular to the galactic planes, extending outward for several kiloparsecs. The enigmatic hedgehog, NGC4631 (see figure), is an extreme case, but most other edge-on galaxies studied show some similar structure. Surprisingly, this perpendicular field is not thought to be a separate (for example, a dipole) component, but rather represents disk field dragged up and out by expanding supernova remnants and other bubbles, columns and fountains of hot gas, according to Eugene N. Parker (Univ. Chicago) and Mitsuaki Fujimoto (Nagoya Univ.).

Our Milky Way is normal in having both an ordered field in the plane and spurs extending out of it, first seen via polarization of star light and radio synchrotron emission, respectively. But Faraday rotation of pulsar radiation tells us more, because the dispersion of the pulses measures the intervening electron density separately. Thus we can trace out the strength and orientation of both ordered and chaotic field.

Two analyses, by Richard J. Rand and Shrinivas R. Kulkarni (California Inst. Technology) and by Andrew G. Lyne and F. Graham Smith\(^7\) concur at least approximately. In our local spiral arm, a coherent magnetic field of 2--3 \(\mu G\) points at roughly \(90^\circ\) from the direction to the Galactic Centre. The chaotic component, on scales less than 100 pc, is, if anything, rather stronger. Alignment of the field with the arm is not firmly excluded, but a ring-like structure is a better fit. The observed Faraday rotation of extragalactic radio sources also favours field lines along gas-streaming directions rather than along the arms.\(^8\) Reversals of the field direction to about \(270^\circ\) occur within 1--2 kpc both inward and outward from our position, and at least one flip back to \(90^\circ\) is probably closer to the centre. Thus the Milky Way cannot readily be described as either an axisymmetric or a bisymmetrical spiral.

What do the models of galactic field origin predict? In the case of a pre-galactic ('primordial' or 'primeval') field, caught in conducting gas and so amplified and stretched out by differential rotation, we expect the field lines, whatever their initial orientation, to lie now largely in the plane, to point in the azimuthal direction, and to reverse their sense up to 100 times along a radius vector through the galactic disk (since spirals are about 100 rotations old). The first two expectations are met by real galaxies; the third distinctly is not. Reversals occur a few times, if at all, from disk centre to edge. But this need not be a fatal objection. When proper account is taken of the diffusion of field lines through the molecular component of the gas and between the galactic disk and halo, a typical spiral should display only one or two windings (Russell M. Kulsrud, Princeton Univ.). The resulting configuration will then resemble a bisymmetric spiral.

Dynamos are more complicated. The laboratory sort (the first of which was constructed by Werner von Siemens a bit more than 100 years and a bit less than 100 km away from the Symposium) consists of a conductor rotating through a magnetic field. This generates an electric current in the conductor, which can power an electromagnet to produce the requisite field, which then generates a current and so on. Once you get started. Energy is extracted from whatever keeps the conductor rotating. The simplest possible field configuration is a dipole, but you could twist the conductor into any shape you wanted.

In astrophysical contexts, the geometry is necessarily different, owing to the shortage of rigid conducting disks and thin wires. But it is true that there exist patterns of motion in conducting fluids that will regenerate magnetic fields\(^9\) (see also the forthcoming News and Views article by Moffatt\(^7\)). The flow pattern must include angular velocity that changes...
away from a rotation axis and cyclonic motions — loosely, turbulence with a net twist. And there has to be a bit of field (of almost any geometry) there to start with. The poloidal and toroidal components of the dominant field mode are both axisymmetric. Stars with convective envelopes (like the Sun) and terrestrial planets with metallic fluid cores (like the Earth) meet the required conditions, and their magnetic fields are generally attributed to dynamos.

The disk of a spiral galaxy has the requisite differential rotation, and turbulence is constantly fed in by stellar winds and supernova explosions. Two consequences suggest themselves if galactic fields are dynamo-produced. First, axisymmetric spiral morphology should be favoured, though the dominant mode can be suppressed in several ways, so that an $m = 1$ bisymmetric field is seen. Possible promoters of the BSS configuration include a nearby companion galaxy (Beck), a high ratio of turbulence to differential rotation (Friedrich Krause, Astrophysical Observatory, Potsdam), a relatively thick gas disk (Makoto Tosa and M. Chiba, Tohoku University) and other more subtle gas-dynamic effects (Alexander A. Ruzmaikin, IZMIRAN, Moscow; Yulia S. Krasheninnikova and Anvar M. Shukurov, Space Research Institute, Moscow).

Second, there ought to be some intimate connection between field morphology and the processes responsible for star formation, in and out of spiral density waves. Leon Mestel (Univ. Sussex), A. N. Nelson (Univ. Wales), Fujimoto, Tosa and Chiba all emphasized the synergic relationship between density waves and dynamos, especially BSS ones.

Galaxies where star formation is primarily driven by density waves are supposed to be the ones with grand designs dominated by two main arms, whereas localized star formation processes give rise to multi-armed and flocculent spirals.

Can we say that "all" BSS magnetic fields occur in grand design spirals? Yes, but "all" at the moment means two (M51, M81) or perhaps three (M33) examples. And both the ASS fields (M31 and IC342) occur in multi-armed spirals. But the Milky Way fits into neither category. It has several (perhaps four) major spiral arms and a number of subsidiary ones, but a magnetic field with several reversals. If the field lines follow the gas flow direction rather than the arms, then it is neither ASS nor BSS. Shukurov pointed out that a linear combination of several dynamo modes can produce such a ringlike (axisymmetric, but with reversals) field morphology. Kulskud’s primordially derived field configuration would seem to be an equally good fit. He also noted that, where the random field component $\langle B^2 \rangle$ is larger than the uniform component $\langle B^2 \rangle$, we find in the solar neighborhood, then the dynamo equations are not a good approximation anymore.

Perhaps we should not yet feel forced to accept Zwicky’s hypothesis, but it seems to have at least one serious problem and, at the moment, asking quite the right questions about the nature and origin of galactic magnetic fields.

Virginia Trimble is Professor of Physics at the University of California, Irvine, California 92717 and Visiting Professor of Astronomy at the University of Maryland, College Park, Maryland 20742, USA.


BEHAVIOURAL GENETICS

Nature — nurture and intelligence

Matt McGue

Philosophers, poets and scientists have long been intrigued by the relative influence of nature and nurture on human behavioural variability. Plato flirted with eugenics in designing his ideal society, Shakespeare emphasized heredity in character development, Locke and Mill espoused radical environmentalism and Galton devoted much of his illustrious career to a controversy that became synonymous with his name. For the past 50 years the nature–nurture debate has set the research agenda in human behavioural genetics. And, while a balanced review of behavourial genetic research on intelligence leads to the conclusion that both genes and the environment play an essential role in the development of individual differences in intelligence, as measured by IQ, for some the debate hinges on. The carefully designed French adoption study reported by Capron and Duyme on page 552 of this issue, by clearly showing that the IQ of children is influenced by both their biological background and the circumstances of their rearing, should help behavioural scientists move beyond these controversies and begin to address the real issues surrounding the mechanisms of genetic and environmental influence.

Genetics provide the behavioural scientist with a powerful set of tools for unravelling the sources of individual differences. The simple elegance of the Capron and Duyme design, lost perhaps on those accustomed to precise experimental control, is rarely seen in non-experimental behavioural research. They have no need for the obfuscating statistical models and attendant unanswerable assumptions that burden so much similar research. The effects Capron and Duyme report are strong and indisputable. Their study clearly illustrates the utility of behavioural genetic methods and highlights the issues that need to be addressed in future research. Four issues are relevant.

Environmental influence

Capron and Duyme report that the average IQ of French adoptees is some 12 points higher when they are reared by parents with high rather than low socioeconomic status (SES). This is a sizable difference between the mean IQ of students admitted to US colleges and that of the general population. At first this may seem a trivial observation because high-SES parents have children who perform well on IQ tests. But it is not. By demonstrating a relationship between characteristics of adoptive parents and the test performance of their non-genetically related offspring, Capron and Duyme necessarily implicate an environmental effect. There have been numerous studies relating parental SES to the IQ of their offspring in intact biologically related families. These studies, however, do not identify the mechanism of that influence. Parental education and SES are ambiguous indicators of the intellectual environment of the child. Working class parents can provide their children with intellectually stimulating experiences and professional parents can neglect the intellectual needs of their children. It remains unclear whether the SES effect is related to access to quality education, the variety and complexity of intellectual stimulation in the home, the parents’ press for scholastic achievement, or some other factor that differentiates between high- and low-SES homes. At least one adoption study has

Nature • VOL 340 • 17 AUGUST 1989

© 1989 Nature Publishing Group

507