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Magnetic activity in stars, discs and quasars

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1. Introduction

Although magnetic fields in interstellar matter were postulated almost 50 years ago, magnetohydrodynamic theory was then much hampered by our inability to see what the magnetic field configurations were like and, after a decade of innovative development, cynics, not without some justification, began to claim that *anything* can happen when magnetism and an imaginative theorist get together. Thus cosmic lightning in particular received a bad press. More recently, great advances in observational techniques that we shall hear of from Title, Beck, Moran and Mirabel have enabled us not only to see the Sun's magnetic field with unprecedented clarity but also the fields in galaxies, quasars and microquasars which are now measured and not merely figments of fertile imaginations. Let me return to the beginnings of the subject.

2. History

Passing by the earthly endeavours of Gilbert, Michell, Gauss and others in earlier centuries, our subject sprang to life with Hale's (1914) discoveries of kilogauss magnetic fields in sunspots and his laws governing their polarities in successive sunspot cycles. His invention of the spectroheliograph also gave the first pictures of the magnetically dominated chromospheric structures. After a long struggle Babcock & Babcock (1955) finally developed a magnetograph sensitive enough to measure the 'general' field of the Sun. It was commonly believed to be there because the polar plumes seen in eclipse photographs at sunspot minimum look remarkably similar to iron filings around a bar magnet. However, in 1961 H. W. Babcock went on to show that the Sun's general field reversed every 11 years—far, far shorter than the many magennia required for the diffusion of a magnetic field through a solid conductor. Babcock's paper, which should be read by all those interested in solar magnetism, went on to explain how reconnections in the solar atmosphere can lead to flux expulsion and he modelled the topology of the field throughout the 22-year cycle.

3. The heating of the corona

Spectroscopy of the corona during total eclipses has a long history too. My wife owes her life to it since her grandparents first met when expeditions from Harvard and Cambridge, UK, set up their 1905 eclipse apparatus in the same Spanish field! In 1931 Grotrian derived a million degree temperature for the corona. However, it took until World War II before the high temperatures of the chromosphere and the corona were agreed. By then the pioneering work of Grote Reber (1944), who built his own radio telescope, had also shown million degree temperatures. How can it be that the outer atmosphere of the Sun is so much hotter than the photosphere although the heat comes from inside? Fred Hoyle (1949) suggested it was the splash of the interstellar gas falling onto the Sun, but soon afterward the solar wind was found to blow in the opposite direction. Lighthill (1952) had developed the theory of sound generated by turbulence and it was thought that nonlinear sound waves generated in the convection zone would build up into shocks and so might heat the corona by mechanical dissipation. However, this proved inadequate by a factor of 30 or more, so it was soon abandoned in favour of a more sophisticated theory of magnetohydrodynamic waves. Here the magnetic field acts like a duct bringing the wave energy to greater heights and dissipation occurs primarily at resonances. Although such heating may still be inadequate, such wave motions have certainly been seen and this mechanism has had quite a wide following in the solar physics community.

However, Babcock's reversal of the whole flux of solar poloidal field clearly required much dissipation as flux is reconnected at neutral points or rather the critical lines that join them. Thus in 1974 R. H. Levine wrote his paper 'A new theory of coronal heating'. In this theory flares are only the largest and most rapid reconnections of magnetic field and the generation of mildly suprathermal particles by reconnections goes on at all scales. Thus this year is in fact the 25th anniversary of the microflaring idea. The paper formed part of a Harvard thesis supervised by David Layzer, who undoubtedly played a part in instigating the investigation. There may be something of an NIH (not invented here) complex in the slowness of the solar community to adopt Levine's explanation but it was only with the Yohkoh satellite's observations, reviewed here by Harra, that the dominant role of magnetism in the heating of the corona became clear, and even then reconnection was not obvious as the magnetohydrodynamic waves also needed magnetism to duct their energy up into the corona. It is up to the very high resolution of the TRACE Satellite (see Title, this issue, and Parnell's analysis) to show us whether there is sufficient microflaring to heat the corona.

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4. Jets and accretion discs

Many of the other papers involve accretion discs. These are formed in the following systems:

1. Around the giant black holes postulated in galactic nuclei as a theory of quasars (Lynden-Bell 1969; Bardeen 1970; Rees 1984). They were first definitively found there by a team involving Moran (Miyoshi *et al*. 1995). Indeed, the concept of such giant black holes and the way they would eventually be found first arose in the remarkable work of the Reverend John Michell, a Fellow of The Royal Society, in 1784.

2. In X-ray binary stars that transfer mass onto the compact partner (Prendergast & Burbidge 1968; Pringle & Rees 1972; Shakura & Sunyaev 1973).

3. Around proto-stars (Lüst 1952; Pringle 1981).

4. In the exotic SS 443-like objects in some supernova remnants (Margon 1984).
5. In the microquasars that give superluminal apparent motions within the galaxy. (Mirabel & Rodriguez 1998, 1999). We shall hear of these from Mirabel, who discovered the motions.
6. As neutron stars tear each other apart during their coalescence to form a stellar mass black hole. Such events are thought to be the origins of the famous γ-ray bursts of which we shall hear more from Martin Rees.

Jets were first discovered in the giant elliptical galaxy M 87 (Curtis 1918) then in the first quasar 3C 273; then following Rees's 1971 suggestion that radio lobes must be continuously fed in radio galaxies, Cygnus A (Hargrave & Ryle 1974) and NGC 6251 (Baldwin *et al*. 1977) and in many other radio galaxies and quasars such as 3C 345, a quasar notable for its violent variability in the optical and 3C 279, notable for the high energy of its sporadic γ-ray emission thought to be associated with the jet pointing in our direction.

Although the enigmatic Herbig–Haro objects were seen in emission before 3C 273 was discovered their association with jets from star-forming accretion discs was only established later as infrared and millimetre wavelength observations enabled astronomers to penetrate the swathes of dust in which stars are formed. The jets of HH 212 seen at 2.12 μm and of HH 30 'filmed' by the Hubble Space Telescope are good examples.

5. Why do flat accretion discs form very narrow highly collimated jets perpendicular to their planes?

Rees's first suggestion (1971) was that strong electromagnetic waves generated by pulsars would push plasma aside and channel out of a surrounding medium. When the circular polarization expected from such an explanation was not seen, Blandford & Rees (1974) gave their twin exhaust model of squirting relativistic plasma. Not convinced that this would collimate stably enough, in 1978 I tried collimation by relativistic vortices in a thick accretion disc but had difficulty in getting the beams narrow enough; meanwhile Lovelace (1976) had concentrated on magnetic models in which the collimation arises from the direction of the magnetic field that permeates the system. A new and exciting role for magnetism was found by Blandford & Znajek (1977), who showed how flux through a black hole could withdraw spin energy from it and give electric currents of electrons and positrons travelling into the hole from opposite sides. Later Blandford & Payne (1982) showed that, if the meridional magnetic field lines splayed by more than 30° to the spin axis, then an accretion disc would drive a centrifugal wind which could be collimated later by the field. Blandford reviews quasar jets and their magnetic fields in this issue. There are many magnetohydrodynamic jet simulations starting with different initial conditions. Shibata & Uchida (1985, 1986), like Lovelace, start with a large-scale pervading magnetic field. While this must surely be there in their star-formation applications, it is less clear how such an external weak field can make the precessing jets of SS 433 or the microquasars. I therefore favour mechanisms that can produce the collimation from the disc itself. In groping towards such a theory I have found magnetic towers that grow taller with every turn of the accretion disc (Lynden-Bell 1996), but others, including

Pudritz, have beautiful simulations that produce truly dynamical jets (Ouyed *et al.* 1997). However, let me not leave you with the idea that everything is understood. Many will tell you that toroidal loops of field pinch, whereas I showed in the above paper that their magnetic energy *does not change* when the whole magnetic field is expanded in the direction perpendicular to the jet axis. In a delightful swashbuckling samurai manner Okamoto (1999) has criticized everyone in sight over their proposed collimation mechanisms. 'How are jets collimated?' is still a live question.

6. γ-ray bursts

No introduction should be without provocative questions, so let me end with another.

When a body with binding energy $\frac{1}{2}GM^2/R$ forms in its own dynamical time-scale $(GM/R^3)^{-1/2}$, the rate of emission of the energy will be the ratio $\frac{1}{2}G^{3/2}M^{5/2}/R^{5/2}$, which may be rewritten in terms of its final velocity dispersion v, where $\frac{1}{2}Mv^2 = \frac{1}{2}GM^2/R$ by the Virial theorem. Hence the rate of emission $\dot{E} = \frac{1}{2}v^5/G$. For $v = c$ this gives an emission rate of 1.8×10^{59} erg s^{-1} or 1.8×10^{52} W. This is far greater than the emission rate of even the most powerful γ-ray bursts; thus either 'we ain't seen nothing yet', or, more likely, γ-ray bursts are only radiating a tiny fraction of the total energy involved the rest being swallowed into a black hole or emitted in neutrinos and gravitational waves. Certainly, the problems concerned with absorption by baryons are avoided if γ-ray bursts come from the ends of long jets along which the energy flows as electromagnetic Poynting flux, thus converting only the magnetic field energy.

Do γ-ray bursts come from the heads of magnetically driven relativistic jets formed by the accretion discs of binary neutron stars coalescing to form a black hole?

Sir Martin Rees introduces us to these exotic events and gives his latest ideas about them in this issue.

References

Babcock, H. D. & Babcock, H. W. 1955 *Astronom. Jl* **121**, 340.
Babcock, H. W. 1961 *Astronom. Jl* **133**, 572.
Baldwin, J. E., Waggett, P. C. & Warner, P. J. 1977 *Mon. Not. R. Astron. Soc.* **181**, 465.
Bardeen, J. 1970 *Nature* **227**, 64.
Blandford, R. D. & Payne, D. G. 1982 *Mon. Not. R. Astron. Soc.* **199**, 883.
Blandford, R. D. & Rees, M. J. 1974 *Mon. Not. R. Astron. Soc.* **169**, 395.
Blandford, R. D. & Znajek, R. L. 1977 *Mon. Not. R. Astron. Soc.* **179**, 433.
Curtis, H. D. 1918 *Publ. Lick. Observatory* **13**, 31.
Grotrian, W. 1931 *Z. Astrophys.* **3**, 220.
Hale, G. E. 1914 *A. Rep. Mt Wilson Observatory.*
Hargrave, P. J. & Ryle, M. 1974 *Mon. Not. R. Astron. Soc.* **166**, 305.
Hoyle, F. 1949 *Some researches in solar physics.* Cambridge University Press.
Levine, R. H. 1974 A new theory of coronal heating. *Astronom. Jl* **190**, 457.
Lighthill, J. 1952 *Proc. R. Soc. Lond.* A **211**, 564.
Lovelace, R. V. E. 1976 *Nature* 262, 649.
Lüst, R. 1952 *Z. Naturf.* **7a**, 87.
Lynden-Bell, D. 1969 *Nature* **223**, 690.
Lynden-Bell, D. 1996 *Mon. Not. R. Astron. Soc.* **279**, 389.

Margon, B. 1984 *A. Rev. Astron. Astrophys.* **22**, 507.
Michell, J. 1784 *Phil. Trans. R. Soc. Lond.* **74**, 50.
Mirabel, I. F. & Rodriguez, F. I. 1998 *Nature* 392, 673.
Mirabel, I. F. & Rodriguez, F. I. 1999 *A. Rev. Astron. Astrophys.* **37**
Miyoshi, M., Moran, J., Hernstein, J., Greenhill, L., Nakai, N., Diamond, P. & Inoue, M. 1995 *Nature* **373**, 127.
Okamoto, I. 1999 *Mon. Not. R. Astron. Soc.* **307**, 253.
Ouyed, R., Pudritz, R. E. & Stone, J. E. 1997 *Nature* **385**, 409.
Prendergast, K. H. & Burbidge, G. R. 1968 *Astronom. Jl* **151**, L83.
Pringle, J. E. 1981 *A. Rev. Astron. Astrophys.* **19**, 137.
Pringle, J. E. & Rees, M. J. 1972 *Astron. Astrophys.* **24**, 1.
Reber, G. 1944 *Astronom. Jl* **100**, 279.
Rees, M. J. 1971 *Nature* **229**, 312.
Rees, M. J. 1984 *A. Rev. Astron. Astrophys.* **22**, 47.
Shakura, N. I. & Sunyaev, R. A. 1973 *Astron. Astrophys.* **24**, 182.
Shibata, K. & Uchida, Y. 1985 *Publ. Astron. Soc. Jap.* **37**, 31.
Shibata, K. & Uchida, Y. 1986 *Publ. Astron. Soc. Jap.* **38**, 631.