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Cosmic Magnetic Fields*

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COSMIC MAGNETIC FIELDS[1]

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ABSTRACT. After a summary of the observations of cosmic magnetic fields in the Introduction I briefly discuss the status of dynamos in Section 2, the use of electric circuits in Section 3, the physics of magnetic explosions in Section 4, the role of magnetic tension in Section 5 and our strongest magnet known, the radio pulsar, in Section 6. In the Conclusion I mention a few problem areas which may show a breakthrough in the near future.

1 Introduction

Magnetic fields play an important role in the cosmos in a variety of places, from galaxies and the interstellar medium to planets and stars (spanning a range of field strengths from below 10^{-13} to 10^{9} T, see Table 1), for a number of different reasons: from the transport of angular momentum and energy to the containment of hot plasmas and the acceleration of particles (Alfvén & Fälthammar 1963; Parker 1979; Melrose 1980; Ginzburg 1989; for a physicist's introduction to the universe see Bowers & Deeming 1984 or Harwit 1991).

The presence of magnetic fields in various objects becomes immediately clear from the *filamentary* or *loop-like* appearance of images taken at suitable wavelengths (which, depending on the object, range from the radio domain to X-rays). What causes a spatially smooth magnetic structure such as the hot and dilute outer solar atmosphere to show an inhomogeneous distribution of threads and fibrils of gas (Priest 1982) is, however, unknown.

Apart from in situ detections by satellite, *measurements* of magnetic fields in the universe are indirect, mostly by their effect on the emission and propagation of radiation (Zeeman splitting and polarization, Hanle effect, cyclotron lines and polarized continuum

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emission, linear synchrotron polarization, plasma masers and wave coupling, Faraday rotation, polarization in the infrared by aligned dust particles) and sometimes on energetic arguments (the observed agreement of rotational losses in radio pulsars with theoretical estimates of magnetic dipole losses).

Since this review necessarily contains a selection of highlights of the magnetic cosmos, I will just list here some of the important magnetic problems which are not even mentioned later on: the origin of primeval magnetic fields in the interstellar medium; the origin of bundles of magnetic fields or discrete flux tubes at the solar surface (and in many stars); stellar magnetic cycles and their temporary interruption; mass loss driven by cyclotron line radiation pressure in strongly magnetized white dwarfs (electron degenerate stars with a typical radius of 10^4 km and a mass below 1.4 $M_\odot$; 1 $M_\odot = 2\cdot10^{30}$ kg is one solar mass) and neutron stars (neutron degenerate stars below 1.4 $M_\odot$ and with a typical radius of 10 km); mass loss driven by the ponderomotive force of Alfvén waves; magnetic shaping of jets in active galactic nuclei and protostars; magnetic extraction of rotational energy from massive black holes in galactic nuclei; the origin of magnetic field filaments in the center of our galaxy; coherent emission processes in radio pulsars, planetary magnetospheres, sun and stars; particle acceleration in shocks, particle propagation and magnetic trapping; magnetic monopoles.

Below I have selected the problems of dynamos (Section 2), the use of electric circuits (Section 3), magnetic explosions (Section 4), the role of magnetic tension (Section 5), and finally (Section 6) radio pulsars, which have the largest magnetic field strengths known to man.

Plasma astrophysics (Sturrock 1994) and cosmic magnetohydrodynamics (MHD) (Biskamp 1993) benefit greatly from *terrestrial magnetospheric research* and from *laboratory plasma physics* (Galeev & Sudan 1983; Freidberg 1987) although the interest of fusion plasma physicists usually is to keep the plasma quiet while the very existence of instabilities make plasma astrophysics interesting. Another difference is that laboratory plasmas are produced for nuclear fusion while astrophysical plasmas result from fusion and ultimately from gravity. Finally, the ratio between macroscopic and kinetic length scales in astrophysics is far larger than in laboratory plasmas which make the latter much more complicated in their description. Many of the unsolved problems in present-day plasma astrophysics and in MHD are connected with the collisonless nature of the plasma: the *magnetic Reynolds number*, defined as $R_m = \mu_0 Lv/\eta$, and the *Lundqvist number*, defined as $S = \mu_0 L v_A/\eta$, reach extremely high values up to 10^{13}. Here L is the characteristic gradient scale, η the electrical resistivity, v the characteristic (differential) speed, $v_A \equiv B(\mu_0\rho)^{-0.5}$ is the *Alfvén speed* or propagation speed of magnetic perturbations along the magnetic field (named after the founder of magnetohydrodynamics and Nobel prize winner, Hannes Alfvén (born 1908)), B is the magnetic induction, H is the magnetic field (in astrophysical plasmas usually $B = \mu_0 H$), and ρ is the gas density. The present

Table 1: Magnetic Fields in the Universe

Object	**Field strength** (T)	**Linear dimension** (m)
intergalactic	$\leq 1_E - 13$	3_E24
quasar	$1 - 100$	1_E16
galaxy	$2_E - 10$	1_E20
extragalactic jets	$1_E - 9$	1_E21
galactic centre	$1_E - 7$	3_E17
molecular cloud	$1_E - 7$	3_E16
sunspot	0.2	1_E7
solar wind	$3_E - 9$	1_E11
comet	$6_E - 8$	1_E7
planet	$\leq 1_E - 4$	7_E7
magnetic star	1	1_E9
white dwarf	$1_E2 - 1_E4$	1_E7
neutron star	$1_E5 - 1_E9$	1_E4

capacity of computers, which can handle Lundqvist numbers up to 10^5, sets limits to the modelling of MHD turbulence and chaotic phenomena. Understanding the *interplay between macroscopic MHD and plasma kinetic effects* is one of the important goals of research (van den Oord 1994).

2 Dynamos

As magnetic fields have a positive *pressure*, $B^2(2\mu_0)^{-1}$, they must be anchored in gravitationally bound, electrically conducting objects. The amplification and maintanance or periodic regeneration of magnetic fields by the action of conducting moving fluids is called a *dynamo* or *generator*. The field evolution is obtained from Maxwell's induction equation ($\partial\vec{B}/\partial t = -\vec{\nabla}\wedge\vec{E}$) supplemented with a suitable *Ohm's law* for the conducting fluid ($\vec{E} = \eta\vec{j} - \vec{v}\wedge\vec{B} - (n_e e)^{-1}\vec{\nabla}p_e + ...$) and after elimination of the current density $\vec{j}$ with Ampère's law ($\vec{j} = \mu_0^{-1}\vec{\nabla}\wedge\vec{B} + ...$, neglecting the displacement current for low-frequency phenomena):

$$\frac{\partial\vec{B}}{\partial t} = \vec{\nabla}\wedge(\vec{v}\wedge\vec{B}) + \eta\Delta\vec{B}/\mu_0 + \vec{\nabla}\wedge[(n_e e)^{-1}\vec{\nabla}p_e] + ... \tag{1}$$

The first term on the right-hand side, the "convection" term, expresses the *advection* of magnetic field with the fluid flow. If only the convection term plays a role magnetic flux ($\int\vec{B}\cdot d\vec{S}$) is conserved for any comoving cross-section $\vec{S}$. The magnetic field is then said to be *frozen-in*. A seed field can now be amplified as is clear from Fig. 1. For example at the solar surface differential rotation amplifies an initially purely meridional *(poloidal)* field into a wound-up azimuthal *(toroidal)* field (Fig. 3 left). Another interesting example is the theoretical *rope dynamo* construction (Fig. 2).

The second term is a *diffusion* term and represents *Ohmic losses* due to the resistivity η. Under astrophysical conditions field diffusion is very slow: the Ohmic diffusion time of a sunspot of 1000 km is 300 yr and this time increases quadratically with the linear dimensions.

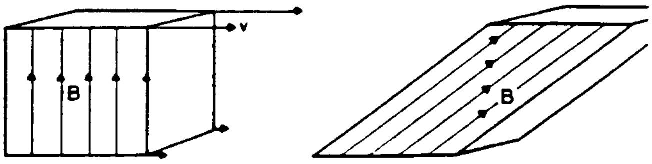

Figure 1: Amplification of a seed field embedded inside a plasma by shearing motion.

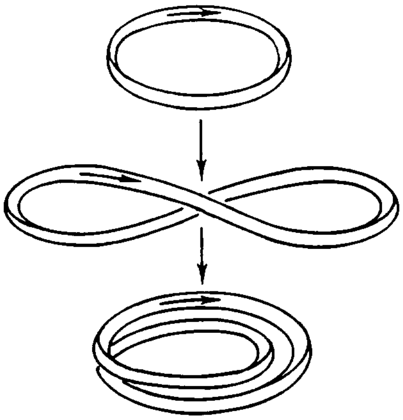

Figure 2: Rope dynamo (Zeldovich et al. 1983)

Finally the third term in Eq. (1) represents a *battery term.* The battery term or thermoelectric field requires a non-alignment of the gradients of electron density (or temperature) and of electron pressure, which can happen under nonuniform rotation or for a nonspherically symmetric chemical distribution in a star. Of the three terms discussed it is the only one which can *create* a magnetic field.

For an asymptotic or periodic dynamo in general both the convection and the diffusion terms are important. The reason is that, whereas the convection term leads to amplification of the field in a direction perpendicular to the original field direction, this original field component has to be restored at some stage, which can be done by diffusion of field amplified in the correct direction elsewhere. It can be shown that a dynamo can not be axially symmetric and a breakthrough occurred when it was realized that the solar convection cells below the surface are cyclonic: solar rotation (the Coriolis force) causes the turbulence on the northern and southern solar hemispheres to have non-zero and opposite *helicities.* As a result the turbulence can recreate a poloidal component out of the toroidal component (Fig. 3). It should be added that this so-called "$\alpha\Omega$"-dynamo is obtained from Eq. (1) by substitution and averaging of a velocity field which has a small-scale fluctuating part superposed on a large-scale mean flow pattern (and similarly for the magnetic field). As a result an *effective diffusion* appears which is far larger than the astrophysically unimportant

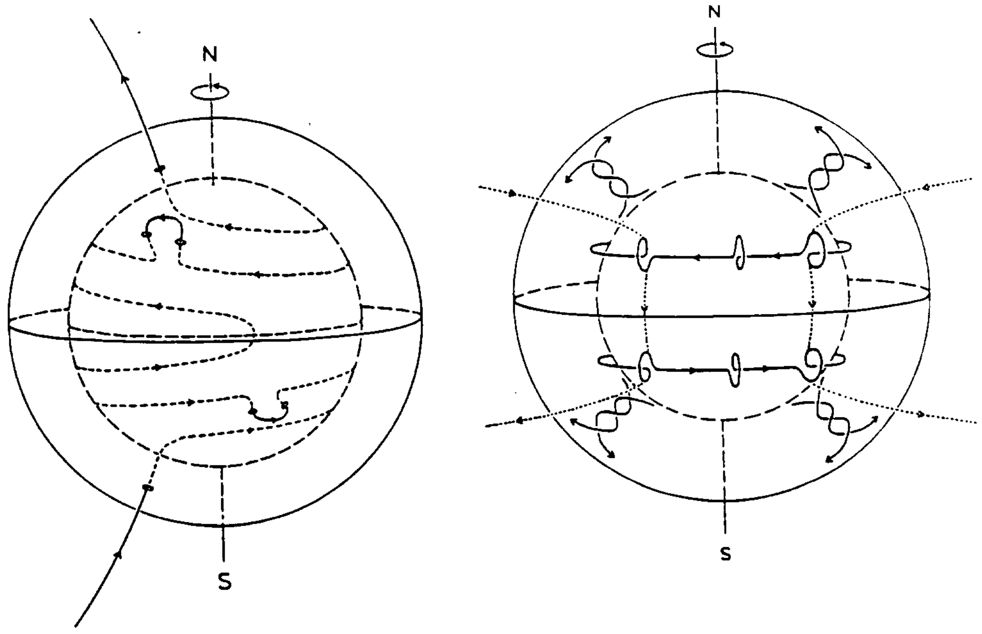

Figure 3: Illustration of a solar dynamo: a toroidal field component is created out of the initial poloidal component by shearing motions; out of the toroidal component a poloidal component can again be formed by helical turbulence (van Geffen 1993).

atomic diffusion.

Much effort has been spent on these *mean-field dynamos*. Unfortunately they cannot reproduce the observed discrete flux tubes. Further in the case of the sun, to reproduce the solar cycle these dynamos require an internal radial differential rotation in conflict with the rigid rotation as determined from solar surface oscillations, which act as probes of the solar interior. Presently for the sun a primordial toroidal field is assumed to reside at the bottom of the convection zone which "feeds" the dynamo.

Moreover this description is not a dynamic but a kinetic one, as no account is taken of feedback by the Lorentz force on the driving flow pattern. Interestingly, if one allows for such a feedback a model system can be set up which shows chaotic properties and nonlinear suppression of the periodic dynamo during certain periods (Torkelsson & Brandenburg 1994).

In fully convective stars and in the galaxy no place exists to store a stably stratified primordial field as in the sun and therefore a different dynamo is required. Recently it has been found that in such cases a so-called fast dynamo could operate. A *fast* dynamo is a dynamo which persists in the limit of infinite magnetic Reynolds number (which is not a bad approximation for astrophysical conditions). Such dynamos can exist if the flow pattern is sufficiently complex or *chaotic* (Galloway & Proctor 1992).

3 Electric circuits

The magnetic field amplification in a dynamo as described by Eq. (1) corresponds to the generation of an electric current system (Alfvén 1981). It is often helpful to consider the corresponding electric circuit by integration of Eq. (1) along a suitable, closed contour:

$$\frac{\partial \Phi}{\partial t} = - \oint \vec{E} \cdot d\vec{\ell} = \oint (\vec{v} \wedge \vec{B} - \eta \vec{j}) \cdot d\vec{\ell}, \qquad (2)$$

or, when the current is confined to a thin tube:

$$\frac{d}{dt}(LI) = \mathcal{V} - IR, \tag{3}$$

where Φ is the total magnetic flux contained by the closed curve and we have defined the total inductance of the circuit by $\Phi = LI$, $I = j\Delta S$ is the total current, the first term on the right-hand side plays the role of an "electromotive force" (EMF) $\mathcal{V} \equiv \oint(\vec{v} \wedge \vec{B}) \cdot d\vec{\ell}$, R is the total resistance defined by $R = \oint \eta\vec{j} \cdot d\vec{\ell}/I$, and ΔS is the current cross-section.

As is the case for the common vacuum circuit equation, Eq. (3) implicitly assumes that at arbitrary times the circuit carries the same current everywhere. It can therefore only describe changes taking place on time scales longer than the *circuit crossing time* for (low-frequency) electromagnetic signals. Since the circuit is embedded inside a plasma with inertia the signal propagation speed is not now the speed of light but only the Alfvén speed (see below).

Eq. (2) has a direct bearing on the *acceleration of particles* in magnetic atmospheres. In astrophysics often differential motions set up a voltage source along a suitable, closed curve. An example is given by the recent impact of fragments of the comet Shoemaker-Levy 9 onto Jupiter: ultraviolet observations with the Hubble Space Telescope show an increased auroral activity on the opposite Jovian hemisphere, possibly due to a new current circuit driven by motion of the (conducting) fire ball across the field. In general the circuit curve passes through a very inhomogeneous (because of gravitational stratification) gas distribution consisting of well-conducting parts but at some places including near-vacuum gaps. In such a case a current cannot at first be set up. However, the total voltage drop then quickly condenses to such narrow vacuum gaps and can lead to the creation and acceleration of charge carriers, so that eventually a current will flow. Probably, such a process occurs in the atmosphere of a fast rotating magnetized neutron star or radio pulsar, and is responsible for the observed intense radio and gamma ray emission. It may even play a role near black holes (Thorne et al. 1988; van Oss 1994). Conversely it is a quite general observation that magnetic fields in the universe often are associated with copious particle acceleration (IAU coll. 142, 1994).

4 Magnetic explosions

Upon their amplification by a dynamo inside the stellar interior or inside a gaseous disk, magnetic fields are *buoyant* and have a tendency to rise. The reason is that a magnetic field with the same pressure as plasma at a given particle density n and temperature T ($B^2(2\mu_0)^{-1} = nKT$) has a much lower equivalent matter density than the plasma. As a result the scale height of the magnetic field at the surface of a star or disk is much larger than the scale height of the gas density (Fig. 4). An atmosphere with magnetic fields is therefore dominated by magnetic effects. In particular the equation of motion for such *coronal* gas (named after the hot, dilute, magnetized envelope of the sun which becomes visible as a radiant ring during a solar eclipse) reduces to

$$\rho d\vec{v}/dt = -\rho\vec{g} - \vec{\nabla}p + \vec{j} \wedge \vec{B} \approx \vec{j} \wedge \vec{B}, \tag{4}$$

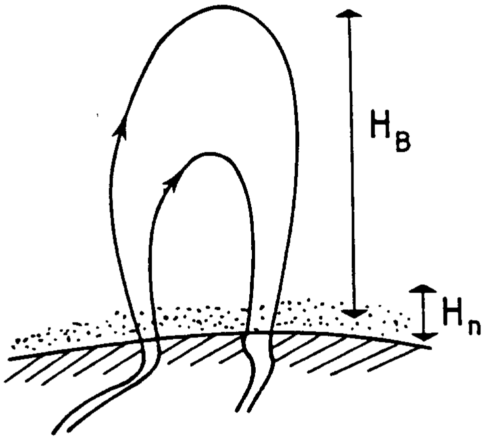

Figure 4: Magnetic fields are buoyant and often have a much larger scale height than the gas density above the stellar surface.

which shows that static equilibria in a corona satisfy

$$\vec{j} = \alpha \vec{B}, \tag{5}$$

where α is constant along a field line (since $\vec{\nabla} \cdot \vec{j} = 0$ for low-frequency phenomena). Such fields are called *force free* and a whole industry exists to find force free field solutions for specified boundary conditions. It should be stressed that a magnetic atmosphere can only be partially force free and must be anchored in the stellar or disk gas where by necessity it is not force free.

As the subsurface dynamo continues to operate and the motion of dense stellar or disk plasma reshuffles the footpoints of coronal magnetic fields, the electric currents running into and out of the corona increase. Now, since coronal fields are nearly force free (the Alfvén crossing time is much less than the variation time in boundary conditions) they must expand to redistribute the extra magnetic stresses so as to remain force free. In the presence of neighbouring magnetic structures (Fig. 5) arbitrarily *thin sheets* can develop over which the magnetic field direction changes abruptly. In such a thin sheet resistivity cannot be neglected any longer and the field line topology changes by field line *reconnection*, whereby magnetic energy is explosively released on a few Alfvén crossing time scales. In the lower solar atmosphere such a reconnection event leads to spectacular optical, UV, X-ray, gamma and radio emissions and is known as a *solar flare.* Similar explosions are now known to occur in magnetic atmospheres of many stars including white dwarfs, neutron stars and in plasma disks around black holes (Kuijpers 1992; Volwerk et al. 1993) in galactic binaries and in nuclei of active galaxies.

Note that, despite the high Lundqvist number the localized effect of resistivity in only a thin sheet suffices for a global release of magnetic energy stored in a force free structure. The reconnection process breaks the force free state and allows a number of processes to develop simultaneously: the action of strong Lorentz forces leading to bulk motion and supersonic expulsion of plasmoids, the onset of localized strong electric fields and of shocks leading to particle acceleration (Achterberg 1992), the excitation of magnetic fluctuations and plasma waves, and the onset of turbulent resistivity leading to sudden heating. At present it is an unsolved but important question what determines the energy partitioning between these various forms of energy release. It is this interplay between large scale magnetohydrodynamics and kinetic plasma theory where much of the present research is focussed on.

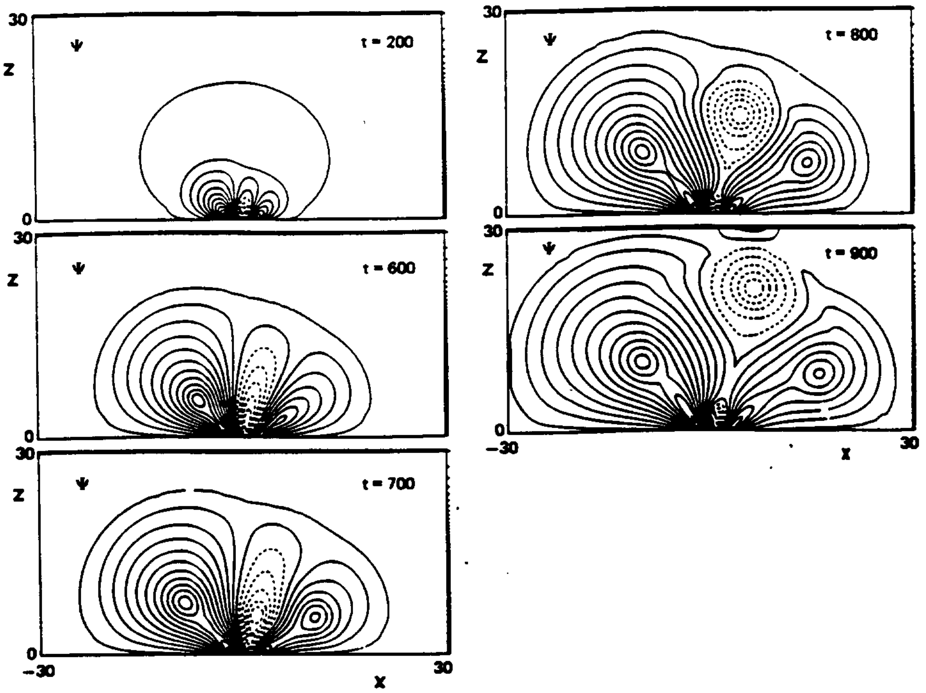

Figure 5: Shown is the evolution of field line projections of a triple magnetic arcade onto the vertical plane under the action of shearing motion at the footpoints perpendicular to this plane (Biskamp & Welter 1989; see also Mikić & Linker 1994).

5 Magnetic Tension

In the previous section we have considered the energetic aspects of magnetic fields based on the associated energy density $B^2(2\mu_0)^{-1}$. We will now consider direct *dynamic* effects of magnetic fields in astrophysics. Apart from an isotropic pressure $B^2(2\mu_0)^{-1}$ a magnetic field also exerts a local *tension* B^2/μ_0 along its direction.

This property allows the transport of *angular momentum* along field lines. An important example is *star formation.* Stars with magnetic fields on their surface are observed to rotate relatively slowly. For instance in the solar system the total angular momentum is 3.1×10^{51} kg m^{-2} s^{-1} of which the sun contains only half a per cent. It is thought that magnetic fields play a dominant role during the contraction of a protostellar cloud as it condenses to a thin Keplerian disk, by braking the relatively fast rotating inner parts while speeding up a small amount of material in the outer regions (Fig. 6a).

Finally as the protostar forms, a *stellar wind* develops which consists of supersonically, outward moving plasma. The stellar magnetic field acts as a *lever arm* which enforces corotation of the stellar wind up to the *Alfvén radius* r_A, defined as the distance where the *dynamic wind pressure* ρv^2 surpasses the poloidal field pressure $B^2_{pol}(2\mu_0)^{-1}$ (Fig. 6b). The loss rate of angular momentum by the star $\vec{J}$ is given by

$$d\vec{J}/dt = r_A v_A dM/dt, \tag{6}$$

and is even for a loss rate as small as -10^{-9} M$_\odot$ yr^{-1} sufficient to slow down the star during its formation to the observed rotation speeds at the surface of order 50 km/s.

Magnetic transport of angular momentum plays also an important role in the rotational or *spin history of white dwarfs and neutron stars.* As is true for 50 % of the stars, many of

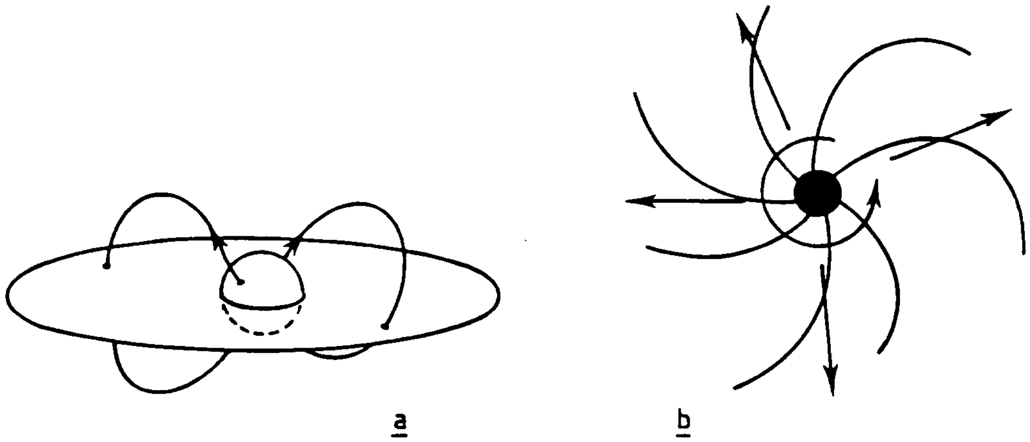

Figure 6: Figure **a** shows magnetic connections transporting angular momentum outward in a differentially moving, Keplerian, protostellar disk; Figure **b** illustrates braking of a protostar by a stellar wind (arrows) in the rotating archimedean magnetic spiral pattern.

these compact stars occur in double stars or binaries. At some stage during the evolution of such a binary the nuclear fusion inside the ordinary star causes it to expand and shed its outer gas layers onto the compact companion which can be spun up, depending on its magnetic field strength (Frank et al. 1992). The infalling gas assembles in a Keplerian *accretion* disk in which magnetic fields can transport angular momentum outward and enhance the inward mass accretion rate (Schramkowski 1994). During the infall of gas down the deep potential well of the compact object the gas is heated up considerably and gravitational energy is radiated away, mainly in X-rays with a total power L_X

$$L_X = GMR^{-1}dM/dt. \tag{7}$$

where M is the mass of the compact object, R its surface radius and $dM/dt > 0$ the mass *accretion rate*. The double star shows up as an X-ray binary. If the neutron star has a high magnetic field strength ($10^6 - 10^9$ T at the surface) plasma is canalized along the field onto the magnetic poles and the X-rays are beamed as in a lighthouse. Such objects are *X-ray pulsars* (Fig. 7). Weaker field stars are spun up to considerably faster rotation rates by the incoming plasma than strong field stars because the star strives to corotation with the Keplerian gas at the Alfvén radius. In this way it is now thought that the progenitors of *millisecond pulsars*, neutron stars rotating close to their break-up speed, are produced in X-ray binaries. When eventually the binary breaks up due to a supernova explosion of the ordinary component, the fast-spinning neutron star leaves its dense environment and starts to radiate as a *radio pulsar* (Bhattacharya & van den Heuvel 1992).

Magnetic *suspension* of gas above a stellar surface is another spectacular effect of magnetic tension. On the sun huge amounts of plasma (about one Mont-Blanc mass) can be seen to stand against the solar disk in absorption in the form of beautiful cathedral-like structures (up to 10^5 km) or towering above the limb in emission. These so-called *filaments* or *prominences* are held-up by magnetic fields (Fig. 8) (Kuperus & Raadu 1974).

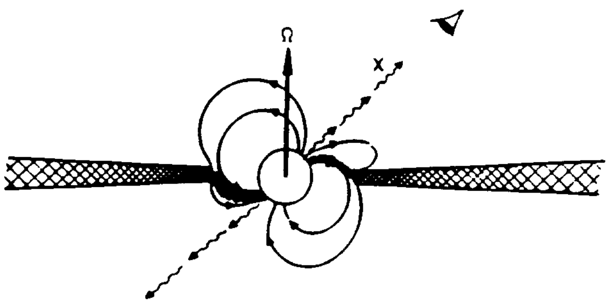

Figure 7: The strong magnetic field of a rotating X-ray pulsar canalizes infalling matter (hatched) from an accretion disk onto the magnetic poles. The gravitational energy is released in the form of beams of X-ray emission illuminating a fortunate observer at the rotation frequency.

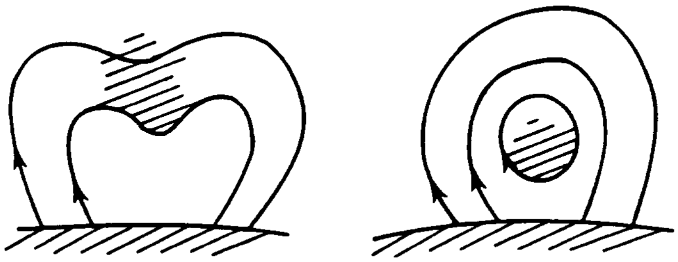

Figure 8: Sketch of two ways to suspend plasma magnetically in a stellar atmosphere. The electric currents in both cases are oppositely directed.

Finally the elastic property of a magnetic field sustains *Alfvén waves*, transverse oscillations in a plasma of density ρ with a propagation speed equal to the so-called Alfvén speed

$$v_A \equiv (c^{-2} + \mu_0\rho/B^2)^{-0.5} \approx B(\mu_0\rho)^{-0.5}, \tag{8}$$

where the last equality applies to non-relativistic speeds. The latter expression can be easily understood if one realizes that a magnetic field has a tension B^2/μ_0 while the plasma has an inertial density ρ. Alfvén waves are thought to *heat* stellar coronae to temperatures of $10^6 - 10^7$ K (cf. temperatures at the stellar surface of only $10^3 - 10^4$ K). The waves are excited in the convective mantles of stars when the footpoints of magnetic fields are being reshuffled. The wave energy is dumped by *resonant absorption* in coronal loops for which the wave frequency $\omega(2\pi)^{-1}$ coincides with the inverse of the Alfvén transit time of the particular loop of length L: $\omega = 2\pi v_A/L$ (Halberstadt & Goedbloed 1993).

6 Radio Pulsars

Radio pulsars are strongly magnetized ($10^4 - 10^9$ T), fast-rotating ($0.002 - 4$ s) neutron stars (mass 1.4 $M_\odot$, radius R =10 km) of which the magnetic dipole axis is not aligned with respect to the rotation axis (Blandford et al. 1993; Michel 1990). Let us first assume that the star is placed *in vacuum* and can be approximated by an obliquely rotating magnetic dipole of strength $\vec{m} = \vec{B}_p R^3 2\pi/\mu_0$ and rotation frequency Ω. Then the star emits magnetic dipole radiation at a rate

$$P = \frac{1}{6\pi\epsilon_0 c^5}\left|\frac{d^2\vec{m}}{dt^2}\right|^2, \tag{9}$$

where we can put $d^2\vec{m}/dt^2 = \vec{\Omega} \wedge (\vec{\Omega} \wedge \vec{m})$. Note that this radiation is emitted at the, very small, rotation frequency ($500 - 0.25$ Hz) and cannot be observed near the earth due to intervening plasma which has an electron plasma frequency of at least 20 kHz. The received radio pulses (in the band 100 MHz - 30 GHZ) are due to a different but badly known process, operating at the magnetic poles in the form of search lights.

These magnetic dipole losses cause the neutron star to slow down at a rate

$$I\Omega d\Omega/dt = -2\pi\epsilon_0 B_p^2 R^6 \Omega^4 sin^2\chi(3c)^{-1}, \tag{10}$$

where the inertia I of the neutron star can be estimated both from theory and from observations (the mass from e.g. the Hulse-Taylor binary pulsar and the radius from X-ray black-body power in nuclear fusion bursts at the stellar surface), Ω and $d\Omega/dt < 0$ can be directly determined from the observations. The observed energy loss rate can be as high as $8 \cdot 10^{31}$ Watt, more than 10^5 solar luminosities! With Eq. (10) the field strength then follows if the obliquity χ is known. The fields turn out to be in the range 10^4 - 10^9 T in agreement with field determinations in other neutron stars from X-ray cyclotron lines.

Similar computations have been done for a realistic magnetized ordinary star in vacuo in 1955 by A.J. Deutsch, long before the discovery of radio pulsars in 1967. Not surprisingly, in view of the non-inertial frame, he found that strong electric fields exist in the vacuum magnetosphere of a rotating star with components along the magnetic field of order $E \approx$

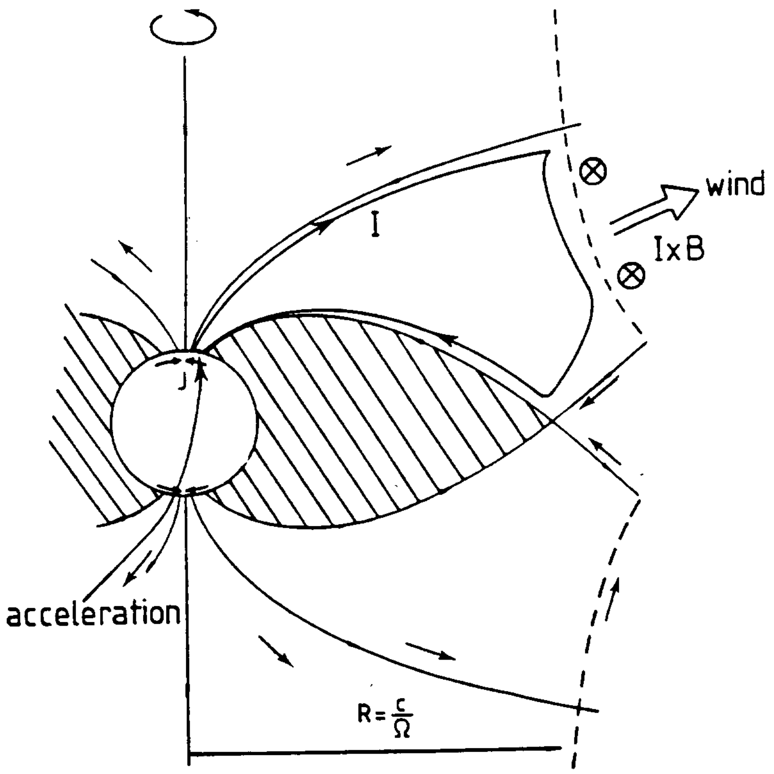

Figure 9: Current system in the magnetosphere of a rotating neutron star. Shown are the meridional projections of field lines and currents. Their toroidal components show a relative increase with increasing distance from the star.

$\Omega R B_p$. For a neutron star electric fields of order $10^{12} - 10^{14}$ V/m are found, sufficiently strong to pull charges out of the star so that the vacuum assumption above is violated. Instead it is more realistic to consider the magnetosphere as a good *electric conductor.* The accelerated primary electrons follow the curved magnetic field lines and emit curvature radiation in the form of gamma rays at a frequency $\omega \approx \gamma^3 c/R_c$. In the strong magnetic field these photons can create electron positron pairs by a single photon process when $\hbar\omega sin(\theta) \geq 2m_e c^2$ and momentum need not be conserved in the presence of the magnetic field. Thereafter these processes repeat and an avalanche of pairs results if the field is strong enough with respect to the *critical field strength* $B_c = (m_e c)^2 (e\hbar)^{-1} = 4.4 \cdot 10^9$ T and leads to a well-conducting plasma. Here γ is the Lorentz factor of the primary electrons, R_c the radius of curvature of the field lines, and θ is the angle between the photon and the magnetic field direction.

As a result an electric current system (cf. Eq. (2)) is set up between the star and plasma near the light cylinder (at a distance c/Ω where corotation must break down). At those places where the current closes across the field, plasma is accelerated outward to form a *relativistic wind* (Fig. 9). Altogether a realistic pulsar looses its rotational energy partly in the form of a Poynting flux and partly in the form of a relativistic particle wind. As the wind flows out Poynting flux is gradually converted into wind energy by magnetic annihilation in current sheets (Fig. 10). The Crab nebula is thought to be powered by such a relativistic wind.

The *internal* state of a neutron star of 1.4 $M_\odot$ is formed by a liquid core of 10 km radius probably consisting mainly of neutrons, surrounded by a crystalline crust of 2 km thickness consisting mainly of nuclei with $Z = 40$ and 50 and a pervading neutron liquid (Baym and Epstein 1992). The internal density estimate is around 3 – 4 ρ_s where $\rho_s \equiv 0.16$ fm^{-3} is the saturation density of nuclear matter. At these densities the Fermi energy for the neutrons is

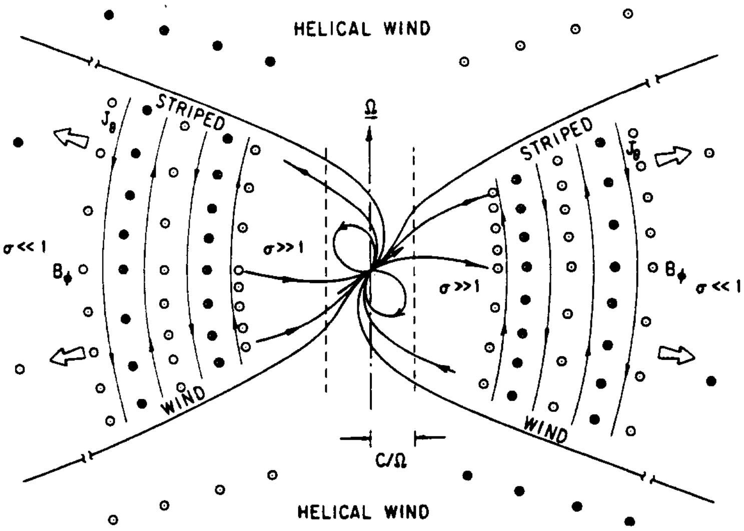

Figure 10: A pulsar wind streams out along open field lines starting from the magnetic poles: at high rotational latitudes a helical wind goes out; in the equatorial regions a striped wind flows consisting of plasma and magnetic fields of alternating polarity, separated by current sheets. In the Crab Nebula the typical number of current sheets between light cylinder and interstellar shock is $3 \cdot 10^8$. σ is the local ratio of Poynting to kinetic energy flux (Coroniti 1991).

100 MeV and since the stellar temperature is of order 10^6 K, far below 10^{12} K, the neutrons in the core are completely degenerate. The neutrons attract each other and form a BCS type *superfluid* with a superfluid transition temperature of 10^{10} K. At the high internal densities the pairing is in the $^3P_2$ state; at the lower densities near the stellar surface the $^1S_0$ attraction dominates. The protons (and electrons) are in beta equilibrium with the neutrons and have a density of a few up to ten percent of the neutrons, and are therefore also degenerate. The protons are *superconducting* (see Gould (1994) for the present status of exotic superconductors). At these densities the electrons are extremely relativistically degenerate.

In a neutral superfluid the velocity field $\vec{v}$ satisfies $\vec{\nabla} \wedge \vec{v} = 0$ and the circulation is *quantized* in a paraxial array of *vortex* lines each of magnitude $\oint \vec{v} \cdot d\vec{\ell} = \pm \pi\hbar / m_n$, where m_n is the neutron mass. Averaged over many vortex lines one has $< \vec{\nabla} \wedge \vec{v} >= 2\Omega$ and $\vec{v} = \Omega \wedge \vec{r}$. It follows that the vortex lines have an area number density $n_V = 2 m_n \Omega (\pi\hbar)^{-1} = 10^7/P$ m^{-2} for a rotation period $P = 2\pi/\Omega$ in seconds.

Similar to the the quantization of momentum $m_n \vec{v}$ in the neutron superfluid also the electromagnetic momentum $e\vec{A}$ of the superconductor is quantized. The magnetic flux through the type II superconducting proton interior is made up of elementary *quantized flux tubes* $\Phi_0 = \oint \vec{A} \cdot d\vec{\ell} = \pi\hbar/e = 2 \cdot 10^{-15}$ weber. A typical pulsar magnetic flux of 10^{16} weber then consists of over 10^{30} elementary flux tubes compared to 10^{15} vortex lines. As the vortex lines carry a strong magnetic field of their own (10^{11} T over the short distance of a proton skin depth $c/\omega_{pp} \approx 10^{-13}$ m, due to entrainment of superconducting proton neighbours by superfluid rotating neutrons around each vortex line) the stellar magnetic flux is locked in between the vortex lines. The magnetic flux distribution and the field decay at the surface are then determined by the spin history of the star. Coupling with the crystal lattice of the crust, *vortex pinning*, is thought to lead to huge stresses and *plate tectonics* (Chen and Ruderman 1993).

Both magnetic solid state physics of the interior of a neutron star and electrodynamics of its fast revolving magnetosphere belong to the most fascinating fields of research in present-day high-energy astrophysics.

7 Future work

In the past decade research of cosmic magnetic fields has grown into an interdisciplinary field of study, in particular because the fundamental questions are of interest to the theoretical physicist and at the same time because of detailed observations which make laboratory experiments with high magnetic fields extremely useful: e.g. radiation pressure by cyclotron resonance in fields of 10^2 T as occur in some white dwarfs; coherent plasma radiation from localized intense electric fields in strongly magnetized plasmas in relation to radio pulsars; experimental study of hydrogen and helium spectra in strong fields.

Our knowledge of the superconducting interior of neutron stars is very poor, in particular because of the uncertainty in the equation of state at these high densities (perhaps a pion condensate or a quark plasma exists in the center). Much work is needed to understand the physics of the interactions between elementary magnetic fluxoids and quantized vortices of the superfluid neutrons. A second major theme of research in years to come will be the development of dynamos with discrete flux tubes. Finally research in particle acceleration in magnetospheres, both of planets and of compact objects is expected to receive a boost, the former from in situ satellite observations, the latter from the discovery of TeV and PeV gamma rays.

References

Achterberg, A.: 1992, in Galactic High-Energy Astrophysics, High-Accuracy Timing and Positional Astronomy, eds. J. van Paradijs and H.M. Maitzen, Springer-Verlag, Berlin.

Alfvén, H.: 1981, Cosmic Plasma, Reidel Publ. Cy, Dordrecht, Holland.

Alfvén, H. and Fälthammar, C.-G.: 1963, Cosmical Electrodynamics, Oxford, Clarendon Press.

Baym, G. and Epstein, R.: 1992, Astrophys. J. 387, 276.

Bhattacharya, D. and van den Heuvel, E.P.J.: 1991, Phys. Rep. 203, 1.

Biskamp, D.: 1993, Nonlinear Magnetohydrodynamics, Cambridge Univ. Press.

Biskamp, D. and Welter, H.: 1989, Solar Phys. 120, 49.

Blandford, R.D., Hewish, A., Lyne, A.G., Mestel, L., eds.: 1993, Pulsars as Physics Laboratories, The Royal Society, Oxford Univ. Press.

Bowers, R.L. and Deeming, T.: 1984, Astrophysics, Jones and Bartlett Publ. Inc., Boston.

Chen, K. and Ruderman, M.: 1993, Astrophys. J. 408, 179.

Coroniti, F.V.: 1991, Astrophys. J. 349, 538.

Deutsch, A.J.: 1955, Annales d'Astrophysique 18, 1.

Frank, J., King, A.R., Raine, D.J.: 1992, Accretion Power in Astrophysics, Cambridge Univ. Press.

Freidberg, J.P.: 1987, Ideal Magnetohydrodynamics, Plenum Press, New York.

Galeev, A.A. and Sudan, R.N., eds.: 1983, Handbook of Plasma Physics, Basic Plasma Physics I, II, North Holland Publ. Cy., Amsterdam.

Galloway, D.J. and Proctor, M.R.E.: 1992, Nature 356, 691.

Ginzburg, V.L.: 1989, Applications of Electrodynamics in Theoretical Physics and Astrophysics, Gordon and Breach Sci. Publ.

Gould, C.M.: 1994, Physica B 197, 472.

Halberstadt, G. and Goedbloed, J.P.: 1993, Astron. Astrophys. 280, 647.

Harwit, M.: 1991, Astrophysical Concepts, Springer-Verlag, Berlin.

IAU Colloquium 142: 1994, Particle Acceleration Phenomena in Astrophysical Plasmas, Astrophys. J. Supplem. Series, 90 Number 2.

Kuijpers, J.: 1992, in The Sun: A Laboratory for Astrophysics, J.T. Schmelz and J.C. Brown (eds.), NATO ASI, Kluwer Acad. Publ. p. 535.

Kuperus, M. and Raadu, M.A.: 1974, Astron. Astrophys. 31, 189.

Melrose, D.B.: 1980, Plasma Astrophysics I, II, Gordon and Breach Publ., New York.

Michel, F.C.: 1990, Theory of Neutron star Magnetospheres, Univ. of Chicago Press, Chicago.

Mikić, Z. and Linker, J.A.: 1994, Astrophys. J. 430, 898.

Parker, E.N.: 1979, Cosmical Magnetic Fields, Clarendon Press, Oxford, UK.

Priest, E.R.: 1982, Solar Magnetohydrodynamics, D.Reidel Publ. Cy., Dordrecht, Holland.

Schramkowski, G.P.: 1994, The Dynamics of Intermittent and Diffuse Magnetic Fields in Accretion Disks, PhD Thesis, Utrecht University.

Sturrock, P.A.: 1994, Plasma Physics, Cambridge Univ. Press.

Thorne, K.S., Price, R.H., Macdonald, D.: 1988, Black Holes: The Membrane Paradigm, Yale Univ. Press.

Torkelsson, U. and Brandenburg, A.: 1994, Astron. Astrophys. 283, 677.

van den Oord, G.H.J., ed.: 1994, Fragmented Energy Release in Sun and Stars, Space Sci. Rev., 68, Nos. 1 - 4.

van Geffen, J.: 1993, Magnetic Energy Balance and Period Stability of the Solar Dynamo, Ph.D. Thesis, Utrecht Univ., p. 155.

van Oss, R.F.: 1994, Space Sci. Rev. 68, 309.

Volwerk, M., van Oss, R.F., Kuijpers, J.: 1993, Astron. Astrophys. 270, 265.

Zeldovich, Y.B., Ruzmaikin, A.A., Sokolov, D.D.: 1983, Magnetic Fields in Astrophysics, Gordon and Breach.