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p. 1

THEORY OF PROTOSTELLAR ACCRETION DISKS.

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I will present an overview of the current paradigm for the theory of gaseous accretion disks around young stars. Protostellar disks form from the collapse of rotating molecular cloud cores. The disks evolve via outward angular momentum transport provided by several mechanisms: gravitational instabilities, thermal convective turbulence, and magnetic stresses. I will review the conditions under which these mechanisms are efficient and consistent with the observed disk evolutionary timescales of several million years. Time permitting, I will discuss outbusts in protostellar disks (FU Orionis variables), the effect of planet formation on disk structure, and the dispersal of remnant gas.

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p. 1

THERMAL CONTINUA OF AGN ACCRETION DISKS.

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We have computed the thermal continuum energy distribution of thermal radiation from the atmospheres of supermassive accretion disks around supermassive black holes, such as may power active galactic nuclei. Non-LTE radiative transfer is combined with a model of the vertical structure at each radius appropriate to the low effective gravities of these disks. Locally, the Lyman edge of H can be in emission or absorption. When the emission is summed over the disk with Doppler and gravitational redshifts taken into account, the observed continuum typically shows little sign of a discontinuity near the Lyman edge. For relatively cool disks, the Lyman edge is in absorption, but it appears as a slope change extending over several hundred angstroms, rather than an abrupt discontinuity. Disks around Kerr black holes can explain the observed range of soft X-ray luminosities of AGN, but disks around Schwarzschild holes are much too faint in soft X-rays.

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p. 2

EVOLUTION OF DYNAMO-GENERATED MAGNETIC FIELDS IN ACCRETION DISKS AROUND COMPACT AND YOUNG STARS.

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Geometrically thin, optically thick, turbulent accretion disks are believed to surround many stars. Some of them are the compact components of close binaries (X-ray binaries, cataclysmic variables), while the others are thought to be single stars (T Tauri stars). These accretion disks must be magnetized objects because the accreted matter, whether it comes from the companion star (binaries) or from a collapsing molecular cloud core (single young stars), carries an embedded magnetic field. In addition, most accretion disks are hot and turbulent, thus meeting the condition for the MHD turbulent dynamo to maintain and amplify any seed field magnetic field. In fact, for a disk's magnetic field to persist long enough in comparison with the disk viscous time it must be contemporaneously regenerated because the characteristic diffusion time of a magnetic field is typically much shorter than a disk's viscous time. This is true for most thin accretion disks. Consequently, studying magnetic fields in thin disks is usually synonymous with studying magnetic dynamos, a fact that is not commonly recognized in the literature.

Progress in studying the structure of many accretion disks was achieved mainly because most disks can be regarded as two-dimensional flows (thin disk approximation) in which vertical and radial structures are largely decoupled. By analogy, in a thin disk, one may expect that vertical and radial structures of the magnetic field are decoupled because the magnetic field diffuses more rapidly to the vertical boundary of the disk than along the radius. Thus, an asymptotic method, called an adiabatic approximation, can be applied to accretion disk dynamo [1]. We can represent the solution to the dynamo equation in the form $B = Q(r)b(r, z)$, where $Q(r)$ describes the field distribution along the radius, while the field distribution across the disk is included in the vector function b, which parametrically depends on r and is normalized by the condition $\max|b(z)| = 1$. The field distribution across the disk is established rapidly, while the radial distribution $Q(r)$ evolves on a considerably longer timescale. It is this evolution that is the subject of this paper. The evolution of Q is dictated by the relative strength of local field amplification and radial diffusion, and is obtained numerically. Each numerical run is started from arbitrary initial conditions and is advanced in time using a numerical code based on the ISLM subroutine MOLCH.

Disks Around Compact Stars: As a first example of how a dynamo-generated magnetic field evolves in a thin accretion disk we have chosen a fiducial case of an accretion α disk around a compact star. A particular simple steady-state solution of disk structure is obtained [e.g., 2] under the assumption that the Rosseland mean opacity is approximated by Kramers' law, and radiation pressure can be neglected in comparison with gas pressure. We assume a disk surrounding a compact star of mass $M_* = 1\ M_\odot$ and radius $r_* = 5 \times 10^8$ cm, with an accretion rate of 10^{16} g s^{-1}, $\alpha = 0.1$, an inner radius of $r_{in} = 2r_*$, and an outer radius of $r_{out} = 10^3 r_*$. We assume that at $t = 0$ the magnetic field is constant and has a magnitude equal to 1% of the equipartition value at the outer radius. In Fig. 1 we show the numerically calculated time evolution of the magnetic field. The nonlinearity of the dynamo equation (so-called α quenching) ensures that the magnetic field equilibrates. At first the field increases sharply at the inner radii and remains unchanged at the outer radii. By the time $t = 10^4$ s, the magnetic field in the innermost portion (up to $r \approx 10r_*$) of the disk achieves equilibrium. By the time $t = 10^5$ s the magnetic field in the region of the disk up to $r \approx 50r_*$ has reached equilibrium, and by the time $t = 10^6$ s the magnetic field in the portion of the disk within $r \approx 300r_*$ is in equilibrium. Finally, at $t = 10^7$ s, the magnetic field in the entire disk ($r < 10^3 r_*$) is already in equilibrium. The final magnitude of the magnetic field approaches about half of equipartition value B_{eq}. We conclude that the evolution of the magnetic field proceeds in such a way that radial transport of the magnetic field is unimportant in comparison with the local amplification, and the evolution of the magnetic field can be considered as a local phenomenon.

Disks Around Young Stars: The typical protoplanetary disk around a 1-$M_\odot$ T Tauri star extends approximately from the star's surface to about 100 AU and is parameterized by $\alpha \approx 0.01$ and an accretion rate of about $10^{-6}\ M_\odot$ per year. At disk locations where the temperature is above about 200 K, the opacity is dominated by grains such as silicate and Fe metal grains, whereas water ice provides the dominant opacity at locations with lower temperature. In general, the temperature in the extended parts of the disk is too cool to thermally ionize the disk's gas; instead, ionization is provided by cosmic rays and radioactive nuclei. For the purpose of our calculations we assume a solar protoplanetary disk to be an α disk with the opacity law taken from Ruden and Pollack [3] and the ionization state taken from Stepinski [4]. We choose $\alpha = 0.08$, and $\dot{M} = 10^{-6} M_\odot$ per year. We assume a disk surrounding a $1\text{-}M_\odot$ star and extending from 0.2 AU up to 40 AU. Figure 2 shows the time evolution of the magnetic field from the initial field $Q(r) = 0.1$ in units of the equipartition value at $r = 40$ AU. At first the field increases sharply at the inner radii, decays at the middle radii, and remains unchanged at the outer radii. By the time $t \approx 10$ yr, the magnetic field in the innermost portion of the disk achieves equilibrium. As time progresses the magnetic field achieves equilibrium at larger and larger portions of the inner disk. At the same time, the field continues to decay at the middle radii, but the decaying region shifts outward as a result of radial diffusion, and the magnetic field in the outer parts starts to show some growth. By the time $t \approx 100$ yr the whole region within 3 AU has reached equilibrium. Radial diffusion from the regions of strong magnetic field stops the further decay of the field within the region where the local growth rate is negative, and the field is now actually growing there. The magnetic field in the outer parts of the disk continues to grow. By the time $t \approx 2000$ yr, the magnetic field in almost the entire disk has reached equilibrium. Total equilibrium is achieved at roughly $t = 4400$ yr. The final configuration of the magnetic field follows closely the distribution of the equipartition value magnetic field, except at the middle radii.

Conclusions: The final configuration of a dynamo-generated magnetic field is independent of unknown initial conditions. However, initial conditions influence the way the magnetic field evolves toward its equilibrium, as well as the time needed to achieve such equilibrium. Evolution from initial conditions without field reversals (presented here) leads to an equilibrium field in a time that is very short in comparison with disk viscous time. Evolution from initial conditions with field reversals (not shown here) leads to an equilibrium in a time $10\text{–}10^2$ times longer, as radial diffusion destroys field reversals. In equilibrium, the field has a magnitude of the order of the equipartition with the kinetic energy of turbulence. Such a field could have a substantial effect on the structure and dynamical evolution of thin disks. From an observational point of view, the magnetic field is concentrated close to the inner disk's radius, so it could be difficult to distinguish it from a stellar magnetic field, provided that a central star has a strong field.

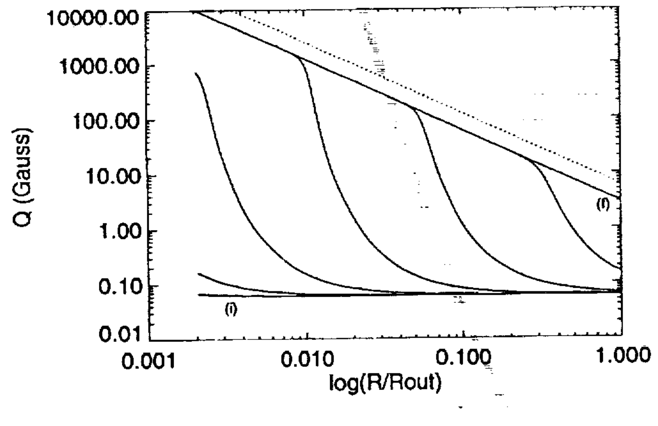

Fig. 1. Radial distribution of magnetic field Q is plotted against dimensionless radius r/r_{out} at various times for the case of an accretion disk around a compact star. The plots (i–f), in order of increasing time, correspond to $t = 10, 10^2, 10^3, 10^4, 10^5, 10^6$, and 10^7 s respectively. The dotted line shows the radial distribution of B_{eq}. After about $t = 10^7$ s the magnetic field equilibrates everywhere in a disk at about half the equipartition value.

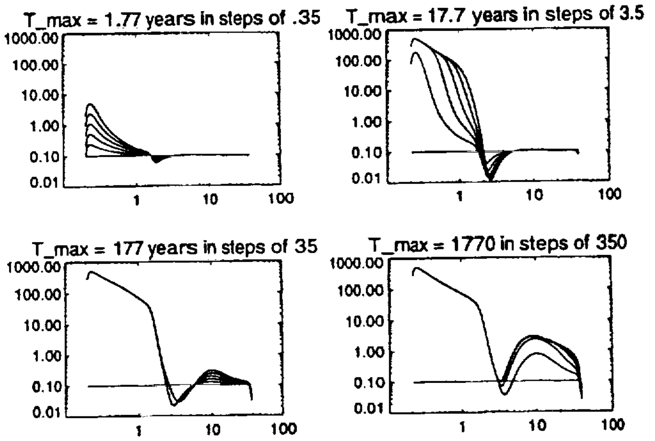

Fig. 2. Time evolution of the magnetic field in a protoplanetary disk from the initial condition $Q = 0.1$ at $t = 0$ represented by the horizontal solid line. Magnetic field Q is measured in units of $B_0 = B_{eq}$ (40 AU). Radial distance from the central star is measured in AU.

References: [1] Stepinski T. F. and Levy E. H. (1991) *Astrophys. J., 379,* 343–355. [2] Frank J. et al. (1985) *Accretion Power in Astrophysics,* Cambridge Univ., Cambridge. [3] Ruden S. P. and Pollack J. B. (1991) *Astrophys. J., 375,* 740–760. [4] Stepinski T. F. (1991) *Icarus, 97,* 130–141.

D– 1

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NONTHERMAL ACCRETION DISK MODELS AROUND NEUTRON STARS.

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We consider the structure and emission spectra of nonthermal accretion disks around both strongly and weakly magnetized neutron stars. Such disks may be dissipating their gravitational binding energy and transferring their angular momentum via semicontinuous magnetic reconnections. We consider specifically the structure of the disk-stellar magnetospheric boundary where magnetic pressure balances the disk pressure. We consider energy dissipation via reconnection of the stellar field and small-scale disk turbulent fields of opposite polarity. Constraints on the disk emission spectrum are discussed.

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GRAVITATIONAL INSTABILITIES IN PROTOSTELLAR DISKS.

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The nonaxisymmetric stability of self-gravitating, geometrically thick accretion disks has been studied for protostellar systems