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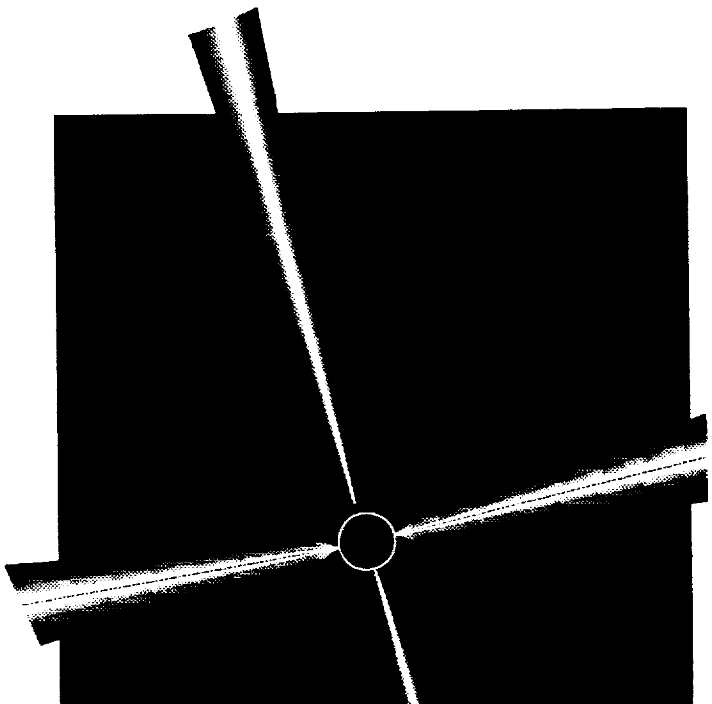
WORKSHOP ON PHYSICS OF ACCRETION DISKS AROUND COMPACT AND YOUNG STARS



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WORKSHOP ON

PHYSICS OF ACCRETION DISKS

AROUND COMPACT AND YOUNG STARS

Edited by

E. Liang and T. F. Stepinski

Held at
Houston, Texas

April 8–10, 1994

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Preface

This volume contains papers that have been accepted for presentation at the Workshop on Physics of Accretion Disks Around Compact and Young Stars, April 8–10, 1994, in Houston, Texas. The Program Committee consisted of co-conveners E. Liang (*Rice University*) and T. F. Stepinski (*Lunar and Planetary Institute*).

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N94-31117

Abstracts

51-90 ABS. ONLY -978

ACCRETION DISKS AROUND BLACK HOLES. M. A. Abramowicz, Gothenburg University, Gothenburg, Sweden.

The physics of accretion flow very close to a black hole is dominated by several general relativistic effects. It cannot be described by the standard Shakura Sunyaev model or by its relativistic version developed by Novikov and Thorne. The most important of these effects is a dynamical mass loss from the inner edge of the disk (Roche lobe overflow). The relativistic Roche lobe overflow induces a strong advective cooling, which is sufficient to stabilize local, axially symmetric thermal and viscous modes. It also stabilizes the non-axially-symmetric global modes discovered by Papaloizou and Pringle. The Roche lobe overflow, however, destabilizes sufficiently self-gravitating accretion disks with respect to a catastrophic runaway of mass due to minute changes of the gravitational field induced by the changes in the mass and angular momentum of the central black hole. One of the two acoustic modes may become trapped near the inner edge of the disk. All these effects, absent in the standard model, have dramatic implications for time-dependent behavior of the accretion disks around black holes.

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A TWISTED DISK EQUATION THAT DESCRIBES WARPED GALAXY DISKS. K. Barker, Department of Physics and Astronomy, Louisiana State University, Baton Rouge LA 70803, USA.

Warped HI gas layers in the outer regions of spiral galaxies usually display a noticeably twisted structure. This structure is thought to arise primarily as a result of differential precession in the HI disk as it settles toward a "preferred orientation" in an underlying dark halo potential well that is not spherically symmetric. In an attempt to better understand the structure and evolution of these twisted, warped disk structures, we have utilized the "twist-equation" formalism originally developed by Petterson [1]. Specifically, we have generalized the twist equation presented by Hatchett, Begelman, and Sarazin [2] to allow the treatment of non-Keplerian disks and from it have derived the steady-state structure of twisted disks that develop from free precession in a nonspherical, logarithmic halo potential. This generalized equation can also be used to examine the time-evolutionary behavior of warped galaxy disks.

Acknowledgments: This work has been supported in part by the U.S. National Science Foundation through grant AST-9008 166 and in part by NASA through grant NAGW-2447.

References: [1] Petterson (1977) *Astrophys. J., 214,* 550. [2] Hatchett et al. (1981) *Astrophys. J., 247,* 677.

53-90 ABS. ON N94-31119

A HETEROGENEOUS COMPUTING ENVIRONMENT FOR SIMULATING ASTROPHYSICAL FLUID FLOWS. J. Cazes, Department of Physics and Astronomy, Louisiana State University, Baton Rouge LA 70803, USA.

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In the Concurrent Computing Laboratory in the Department of Physics and Astronomy at Louisiana State University we have constructed a heterogeneous computing environment that permits us to routinely simulate complicated three-dimensional fluid flows and to readily visualize the results of each simulation via three-dimensional animation sequences. An 8192-node MasPar MP-1 computer with 0.5 GBytes of RAM provides 250 MFlops of execution speed for our fluid flow simulations. Utilizing the parallel virtual machine (PVM) language, at periodic intervals data is automatically transferred from the MP-1 to a cluster of workstations where individual three-dimensional images are rendered for inclusion in a single animation sequence. Work is underway to replace executions on the MP-1 with simulations performed on the 512-node CM-5 at NCSA and to simultaneously gain access to more potent volume rendering workstations.

Acknowledgments: This work has been supported in part by the U.S. National Science Foundation through grant AST-9008166 and in part by NASA through grant NAGW-2447.

54-61 ABS. ON. N94-31120

AN EFFICIENT THREE-DIMENSIONAL POISSON SOLVER FOR SIMD HIGH-PERFORMANCE-COMPUTING ARCHITECTURES. H. Cohl, Department of Physics and Astronomy, Louisiana State University, Baton Rouge LA 70803, USA.

We present an algorithm that solves the three-dimensional Poisson equation on a cylindrical grid. The technique uses a finite-difference scheme with operator splitting. This splitting maps the banded structure of the operator matrix into a two-dimensional set of tridiagonal matrices, which are then solved in parallel. Our algorithm couples FFT techniques with the well-known ADI (Alternating Direction Implicit) method for solving Elliptic PDEs, and the implementation is extremely well suited for a massively parallel environment like the SIMD architecture of the MasPar MP-1. Due to the highly recursive nature of our problem we believe that our method is highly efficient, as it avoids excessive interprocessor communication.

Acknowledgments: This work has been supported in part by the U.S. National Science Foundation through grant AST-9008 166 and in part by NASA through grant NAGW-2447.

55-90 ABS. ONL N94-31121

THE DYNAMICAL SETTLING OF WARPED DISKS AND ANGULAR MOMENTUM TRANSPORT IN GALAXIES. P. Fisher, Department of Physics and Astronomy, Louisiana State University, Baton Rouge LA 70803, USA.

We present results of three-dimensional, hydrodynamic models of gaseous disks settling in a nonspherical potential. As the gas settles, differential precession creates a warped disk similar to the warps seen in spiral galaxies. A logarithmic potential, indicative of a massive halo, seems to induce warps more extreme than those produced by a $1/r$ potential with a quadrupole distortion.

Acknowledgments: This work has been supported in part by the U.S. National Science Foundation through grant AST-9008166 and in part by NASA through grant NAGW-2447.

S6-90 ABS. ONLY N94-31122 70

OBSERVATIONS OF ACCRETION AND ANGULAR MOMENTUM REGULATION IN YOUNG CIRCUMSTELLAR DISKS AND THE IMPLICATIONS FOR PLANETARY FORMATION. P. Hartigan, University of Massachusetts, Amherst MA 01003, USA.

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Accretion disks around young stars produce excess infrared continuum associated with the disk, and excess optical and ultraviolet continua associated with the boundary layer or "hot spot" as material falls from the disk onto the stellar photosphere. When we subtract the excess continuum and photospheric contributions to the total spectrum, we can obtain high-quality emission line profiles of the Balmer lines as well as permitted lines from other elements. These emission lines often exhibit redshifted absorption, indicative of infalling material. Remarkably, objects with large accretion rates tend to rotate *slower* than their counterparts that lack accretion disks. Hence, there must be some process, probably involving magnetic fields, that allows the star to accrete large amounts of material from the disk without increasing its rotational velocity. Young stars typically do *not* have optically thick inner disks that do not accrete. Hence, either planets form within accretion disks, or the timescale for planetary formation is considerably shorter than $\sim 3\times10^6$ yr, the duration of the classical T Tauri star phase of young stellar evolution.

S7-90 ABS. ONLY N94-31123

DISK INSTABILITY AND THE SPECTRAL EVOLUTION OF THE 1992 OUTBURST OF THE INTERMEDIATE POLAR GK PERSEI. S.-W. Kim[1], J. C. Wheeler[1], F. C. Bruhweiler[2], M. Fitzurka[2], K. Beuermann[3], K. Reinsch[3], and S. Mineshige[4], [1]Astronomy Department, University of Texas at Austin, RLM 15.308, Austin TX 78712, USA, [2]Physics Department, Catholic University of America, Washington DC 20064, USA, [3]Göttingen Universitäs-Sternwarte, Geismarlandstrasse 11, 37083, Göttingen, Germany, [4]Astronomy Department, Kyoto University, Sakyo-ku, Kyoto 606-01, Japan.

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The disk instability model can explain the previous history of dwarf-nova-like outbursts in the intermediate polar GK Per, which occur about once every three years. Disk models that reproduce the recurrence time and outburst light curves suggest that GK Per has a large effective inner disk radius (~30–40 white dwarf radii) truncated by a strong magnetic field (10^7 G). In this context, the effective radius is that of the portion of the disk that participates in the disk thermal instability. The radius derived is larger than the corotation radius, which must be an upper limit on the true dynamical inner radius of the disk. Disk instability models with this large effective inner radius predict that the ultraviolet continuum should be rather flat. Here we compare the predictions of the disk instabilty model to IUE observations of the 1981 outburst and to IUE and ROSAT observation of the recent 1992 outburst of GK Per. The model disk continuum spectral evolution is consistent with the observed UV and optical spectra, especially at maximum and in the early decay phase of the outburst. The consistency of the model with the observed UV spectra suggests that the effective inner radius of the disk is almost constant, independent of mass accretion rate, and that whatever structure lies between the effective inner radius and the corotation radius neither participates in the disk instability nor radiates substantially in the UV. The related physics of the inner disk region will be briefly discussed.

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S8-90 ABS. N94-31124

DISK IRRADIATION AND LIGHT CURVES OF X-RAY NOVAE. S.-W. Kim[1], J. C. Wheeler[1], and S. Mineshige[2], [1]Astronomy Department, University of Texas at Austin, RLM 15.308, Austin TX 78712, USA, [2]Astronomy Department, Kyoto University, Sakyo-ku, Kyoto 606-01, Japan.

We study the disk instability and the effect of irradiation on outbursts in the black hole X-ray nova systems. In both the optical and soft X-rays, the light curves of several X-ray novae, A0620-00, GS 2000+25, Nova Muscae 1991 (GS 1124-68), and GRO J0422+32, show a main peak, a phase of exponential decline, a secondary maximum or reflare, and a final bump in the late decay followed by a rapid decline. Basic disk thermal limit cycle instabilities can account for the rapid rise and overall decline, but not the reflare and final bump. The rise time of the reflare, about 10 days, is too short to represent a viscous time, so this event is unlikely to be due to increased mass flow from the companion star. We explore the possibility that irradiation by X-rays produced in the inner disk can produce these secondary effects by enhancing the mass flow rate within the disk. Two plausible mechanisms of irradiation of the disk are considered: direct irradiation from the inner hot disk and reflected radiation from a corona or other structure above the disk. Both of these processes will be time dependent in the context of the disk instability model and result in more complex time-dependent behavior of the disk structure. We test both disk instability and mass transfer burst models for the secondary flares in the presence of irradiation. P. 1

S9-90 ABS. ONLY N94-31125

TIME-DEPENDENT BEHAVIOR OF ACTIVE GALACTIC NUCLEI WITH PAIR PRODUCTION. H. Li[1] and C. D. Dermer[2], Department of Space Physics and Astronomy, Rice University, Houston TX 77251, USA, [2]Code 7653, Naval Research Laboratory, Washington DC 20375-5352, USA.

We study the properties of coupled partial differential equations describing the time-dependent behavior of the photon and electron occupation numbers for conditions likely to be found near active galactic nuclei (AGN). The processes governing electron acceleration are modeled by a stochastic accelerator, and we include acceleration by Alfvenic and whistler turbulence. The acceleration of electrons is limited by Compton and synchrotron losses and the number density of electrons depends on pair production and annihilation processes. We also treat particle escape from the system. We examine the steady, (possibly) oscillatory, and unstable solutions that arise for various choices of parameters. We examine instabilities related to pair production and trapping as proposed by Henri and Pelletier [1] and consider the formation of pair jets.

References: [1] Henri G. and Pelletier G. (1991) *Astrophys. J., 383,* L7. P. 2

S10-90 ABS. ONLY N94-31126 701

OBSERVATIONAL CONSTRAINTS ON BLACK HOLE ACCRETION DISKS. E. P. Liang, Department of Space Physics and Astronomy, Rice University, Houston TX 77215-1892, USA.

We review the empirical constraints on accretion disk models of stellar-mass black holes based on recent multiwavelength observational results. In addition to time-averaged emission spectra, the time evolutions of the intensity and spectrum provide critical information about the structure, stability, and dynamics of the disk. Using the basic thermal Keplerian disk paradigm, we consider in particular generalizations of the standard optically thin disk models needed to accommodate the extremely rich variety of dynamical phenomena exhibited by black hole candidates, ranging from flares of electron-positron annihilations and quasiperiodic oscillations in the X-ray intensity to X-ray novae activity. These in turn provide probes of the disk structure and global geometry. The goal is to construct a single unified framework to interpret a large variety of black hole phenomena. This paper will concentrate on the interface between basic theory and observational data modeling.

S11-90 ABS. ON N94-31127

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NONLINEAR CALCULATIONS OF THE TIME EVOLUTION OF BLACK HOLE ACCRETION DISKS. C. Luo, Department of Space Physics and Astronomy, Rice University, P.O. Box 1892, Houston TX 77251-1892, USA.

Based on previous works on black hole accretion disks, I continue to explore the disk dynamics using the finite difference method to solve the highly nonlinear problem of time-dependent alpha disk equations.

Here a radially zoned model is used to develop a computational scheme in order to accommodate functional dependence of the viscosity parameter alpha on the disk scale height and/or surface density. This work is based on the author's previous work on the steady disk structure and the linear analysis of disk dynamics to try to apply to X-ray emissions from black candidates (i.e., multiple-state spectra, instabilities, QPOs, etc.).

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S12-90 ABS. O N94-31128

EVOLUTION OF VAPORIZING PULSARS. P. McCormick, Department of Physics and Astronomy, Louisiana State University, Baton Rouge LA 70803, USA.

We construct evolutional scenarios for LMXBs using a simplified stellar model. We discuss the origin and evolution of short-period, low mass binary pulsars with evaporating companions. We suggest that these systems descend from low-mass X-ray binaries and that angular momentum loss mainly due to evaporative wind drives their evolution. We derive limits on the energy and angular momentum carried away by the wind based on the observed low eccentricity. In our model the companion remains near contact and its quasiadiabatic expansion causes the binary to expand. Short-term oscillations of the orbital period may occur if the Roche-lobe overflow forms an evaporating disk.

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S13-93 ABS. N94-31129

CAN A VARIABLE ALPHA INDUCE LIMIT CYCLE BEHAVIOR AND EXPONENTIAL LUMINOSITY DECAY IN TRANSIENT SOFT X-RAY SOURCES? C. Meirelles Filho and E. P. Liang, Space Physics and Astronomy Department, Rice University, Houston TX 77251, USA.

There has been, recently, a revival of the stability problem of accretion disks. Much of this renewed interest is due to recent observational data on transient soft X-ray novae, which are low-mass X-ray binaries. It is widely believed that nonsteady mass transfer from the secondary onto the compact primary, through an accretion disk, is the reason for the observed spectacular events in the form of often repetitive outbursts, with recurrence times ranging from 1 to 60 yr and duration time on the scale of months. Though not having reached yet a consensus about the nature of the mechanism that regulates the mass transfer, the disk thermal instability model [1–4] seems to be favored by the fact that the rise in the hard X-ray luminosity is prior to the rise in the soft X-ray luminosity, while the mass transfer instability model [5–7] seems to be hindered by the fact that the luminosity during quiescence is unable to trigger the thermal instability. However, it should be stressed that, remarkably, the X-ray light curves of these X-ray novae all show overall exponential decays ($L_d \approx \exp -t/t_1$), a feature quite difficult to reproduce in the framework of the viscous disk model, which yields powerlike luminosity decay. Taking into account this observational constraint, we have studied the temporal evolution of perturbations in the accretion rate, under the assumption that α is radial and parameter dependent. The chosen dependence is such that the model can reproduce limit cycle behavior (the system is locally unstable but globally stable). However, the kind of dependence we are looking for in α does not allow us to use the usual Shakura and Sunyaev procedure in the sense that we no longer can obtain a linearized continuity equation without explicit dependence on the accretion rate. This is so because now we cannot eliminate the accretion rate by using the angular momentum conservation equation. In other words, the stress now depends upon the surface density, the scale height of the disk, and the accretion rate. If we write the viscosity parameter as

$$\alpha = \alpha_0 f$$

where we have included the r-dependence in α_0 and the parameter-dependence in f, we obtain the linearized angular momentum conservation equation

$$\frac{\delta f}{f_0} = \frac{4}{3} R \frac{\partial}{\partial R}\left(-\frac{\delta \dot{M}}{\dot{M}_0} + u + 2h\right)$$

the linearized continuity equation

$$\Sigma_0 \frac{\partial}{\partial t} u = \frac{1}{2\pi R} \frac{\partial}{\partial R} \delta \dot{M}$$

and the linearized energy equation

$$\left(8 + 51\beta_0 - 3\beta_0^2\right) \frac{\partial}{\partial t} h + 3\left(1 + 3\beta_0 + 4\beta_0^2\right) \frac{\partial}{\partial t} u =$$

$$\frac{2}{3}\left(5 + 18\beta_0 + 9\beta_0^2\right) \alpha_0 \Omega l_0^2 \frac{\partial^2}{\partial R^2}\left(u + 2h - \frac{\delta f}{f_0}\right) +$$

$$3\alpha_0 \Omega \left[2\left(1 + \beta_0\right) u + 2\left(5\beta_0 - 3\right) h - \frac{\delta f}{f_0}\right]$$

This equation only gives us the local response of the disk to these perturbations, and we see that the α r-dependence plays no role, the major role being locally played by the parameter dependence. When we look for the global response of the disk, this equation no longer applies, being substituted by the correct and more complicated set of coupled differential equations, which solution is highly dependent on the α radial dependence.

References: [1] Cannizzo J. K. et al. (1982) in *Pulsations in Classical and Cataclysmic Variables* (J. P. Cox and C. J. Hanson, eds.), Univ. of Colorado, Boulder. [2] Lin D. N. C. and Taam R. E. (1984) in *High Energy Transients in Astrophysics* (S. E. Woosley, ed.), AIP Conf. Proc. 115, 83, New York. [3] Huang M. and Wheeler J. C. (1989) *Astrophys. J., 343,* 229. [4] Mineshige S. and Wheeler J. C. (1989) *Astrophys. J., 343,* 241. [5] Hameury J. M. et al. (1986) *Astron. Astrophys., 162,* 71. [6] Hameury J. M. et al. (1988) *Astron. Astrophys., 192,* 187. [7] Hameury J. M. et al. (1990) *Astrophys. J., 353,* 585.

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514-92 ABS. ONLY 971

CONVECTIVE SOLAR NEBULA. C. Meirelles Filho and M. Reyes-Ruiz, Space Physics and Astronomy Department, Rice University, Houston TX 77251, USA.

p.

Analyzing turbulent flows with rotation, Dubrulle and Valdettaro [1] have concluded that some new effects come into play and may modify the standard picture we have about turbulence. In that respect the value of the Rossby number is of crucial importance since it will determine the transition between regimes where rotation is or is not important. With rotation there will be a tendency to constrain the motion to the plane perpendicular to the rotation axis and as a consequence the horizontal scale will increase as compared to the longitudinal one, which means that the turnover time in this direction will increase. The net effect is that the energy cascade down process is hindered by rotation. As a matter of fact, when rotation is present one observes two cascades: An enstrophy (vorticity) cascade from large scales to small scales and an inverse energy cascade from small scales to large scales. Since the first process is not efficient on transporting energy to the dissipation range, what we see is energy storage in the large structures at the expense of the small structures. This kind of behavior has been confirmed experimentally by Jacquin et al. [2], who observed that, with rotation, $L_{hor} \approx R_o^{-\gamma} L_z$, where γ is a parameter that depends on the Reynolds number and measures the influence of rotation on turbulence and R_o is the Rossby number. For a very large γ we obtain, in the inertial range, a spectrum of k^{-3} instead of the usual Kolmogorov's $k^{-5/3}$ spectrum. In reality, when rotation is dominant, energy gets stored in inertial waves that propagate it essentially in the longitudinal direction. In that case, we can no longer assign just one viscosity to the fluid and, what is most important, the concept of viscosity loses its meaning since we no longer have local transport of energy. According to Dubrulle [1], $R_o = 1$ is the borderline between these two scenarios: For $R_o > 1$ turbulence is not affected by rotation, for $R_o < 1$ it will be greatly affected. It is worth mentioning that compressibility effects will also affect turbulence through the generation of waves, shocks, etc. These aspects have been underestimated by Cabot et al. [3] in their application of the theory of large-structure turbulence developed by Canuto and Goldman [4] for the turbulence generated by convective instability, in the sense that no discussion about the behavior of the characteristic scale lengths in the problem under the influence of rotation is made nor the conditions under which there will be local energy dissipation and an effective viscosity can be assigned to the flow. Also, not apparent in their results are effects such as inverse energy cascade with consequent diminishing of the angular momentum transport efficiency or even how the spectrum in the inertial zone, i.e., Kolmogorov's spectrum, is affected by rotation. In a previous paper [5], employing results from [1], we have shown that even for Rossby number >1 turbulence is affected by rotation, but it succeeds in forming smaller structures, as compared to the case without rotation, in such a way as to overcome rotational effects. As far as the efficiency of angular momentum transport is concerned, the value of the viscosity parameter is highly affected, even if the Rossby number is much greater than 1.

Such results, however, were derived considering a hot disk, in which opacity is mainly given by electron scattering. In the present work we have applied the formulation developed in the previous work for the description of the viscous-stage solar nebula. Following Wood and Morfill [6] we have used two piecewise continuous powerlaws that depend only on the temperature, corresponding to regions in which opacity is provided either by water ice grains or silicate and Fe grains. It should be remarked, however, that by taking into account the z-structure of the disk, there will be, no matter the radius, a region close to the surface of the disk, where the lower-temperature opacity law applies. As we go further out, this region approaches the midplane of the disk. In the outer regions, where the temperature is below the ice condensation point, only the lower-temperature law is applicable. The height of the point separating these regions will be crucial in the determination of anisotropy factor and the viscosity parameter as well as in the possible existence of critical parameters for the flow. Although our results are preliminary compared to other results in the literature, the efficiency for angular momentum transport we have obtained is higher. These high values of α may imply that within this formulation the viscous evolutionary stage of the nebula is shorter. Our formulation also implies a minimum accretion rate to ignite convective instabilities. Since the mass of the disk is related to the accretion rate the main implication of this is related to the age of the nebula.

References: [1] Dubrulle B. and Valdettaro L. (1992) *Astron. Astrophys., 263,* 387. [2] Jacquin L. et al. (1990) *J. Fluid Mech., 220,* 1. [3] Cabot W. et al. (1987) *Astrophys. J., 69,* 387. [4] Canuto V. M. and Goldman I. (1984) *Phys. Rev. Lett., 54-05,* 430. [5] Meirelles C. F. et al. (1993) submitted. [6] Wood and Morfill (1988) in *Meteorites in the Early Solar System,* 329–347, Univ. of Arizona.

N94-31131

515-90 ABS. ONLY 992 p. 2

ROTATIONAL EFFECTS IN TURBULENCE DRIVEN BY CONVECTION. C. Meirelles Filho, M. Reyes-Ruiz, and C. Luo, Space Physics and Astronomy Department, Rice University, Houston TX 77251, USA.

We have treated turbulence with rotation in a thin Keplerian disk. Highlighting implicit assumptions already existent in the α model together with a geometrical but physically reasonable deduction of the degrees of freedom of the largest eddies, which is of paramount importance in our formulation, we were able to obtain relations satisfied by parameters of the turbulence, such as turnover time and α. The effects of rotation in the turbulence we have taken implicitly through an anisotropy factor (x), which is simply related to the Rossby number. Convection is the process assumed to generate turbulence, and we have used Canuto and Goldman's [1] treatment of convective instability, whose characteristic growth time we have assumed equal to the turnover time. We have also used their procedure to obtain the turbulent viscosity. When solving for the convective disk equations assuming electron scattering as the source for opacity, by matching Calluto and Goldman's (1984) prescription for the viscosity with the viscosity we have obtained, we were able to obtain an equation for the anisotropy factor, which is coupled to the solution for the growth rate. By solving for the growth rate in the limit of diverging Rayleigh numbers, the equation for the anisotropy factor is simplified and its structure is such that for m (the size of the convective region in units of the height scale) less than a minimum value there will be no steady solution for the turbulence. For m equal to the minimum value there will be only one solution and for m greater than this minimum value there will be two branches of solutions: the lower branch with anisotropy factor <0.5 and the upper branch with anisotropy factor >0.5. We have studied the nature of the turbulence in these branches using Dubrulle and Valdettaro's [2] approach for turbulence with rotation and have reached the conclusion that for $x < 0.5$, i.e., lower branch, there is an increase of the horizontal scale as compared to the longitudinal scale. In that branch the effects of rotation are such that there will be generation of inertial waves that will transport energy; as the dissipation is nonlocal the concept of effective viscosity loses its meaning. In the upper branch, i.e., $x > 0.5$, the horizontal scale will be smaller than the longitudinal scale and the turnover time is smaller than the Keplerian time: Turbulence manages to overcome the effects of rotation and the generation of waves is negligible. Dissipation of energy is local and we can assign the fluid an effective viscosity. It should be remarked that the structures formed with rotation are much smaller than those that would be formed in the absence of rotation. However, turbulence succeeds in overcoming the effects of rotation only in the upper branch. Using Dubrulle and Valdettaro [2] it is highly suggestive that, in the inertial zone, the spectrum will be $k^{-2.07}$, γ being equal to ≈ 1.3. We have obtained these solutions for both gas-pressure-dominated and radiation-pressure-dominated cases, the solutions being qualitatively similar: decrease of the size of the largest structures as compared to the largest structures formed for turbulence without rotation. The solution in the gas-pressure-dominated case does not depend on the mass of the compact object, nor on the accretion rate, nor on the radial distance. In the radiation-pressure-dominated case the solution will depend on these parameters. The higher the luminosity, the less split the turbulence will be, with higher values for the turbulent mach number and the viscosity parameter, which means higher efficiency for angular momentum transport. Although the rotation rate decreases as we go farther away from the inner radius, the efficiency of angular momentum transport decreases. This is probably due to the assumption of radiation pressure dominance as well as to the kind of opacity law we have used. We should remark that according to Dubrulle and Valdettaro [2] one should expect only one solution with the pattern of turbulence highly dependent on the Rossby number. What we have shown here is that, by a self-consistent calculation of the Rossby number or anisotropy factor, the solution for turbulence generated by convection in a rotation medium is not unique. Both these solutions are affected by rotation.

References: [1] Canuto V. M. and Goldman I. (1984) *Phys. Rev. Lett., 54-55*, 430. [2] Dubrulle B. and Valdettaro L. (1992) *Astron. Astrophys., 263*, 387.

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S16-90 ABS ONLY 493

A CONSTRAINT ON THE PAIR-DENSITY RATIO (Z_+) IN AN ELECTRON-POSITRON PAIR WIND.

M. D. Moscoso and J. C. Wheeler, Department of Astronomy, University of Texas at Austin, Austin TX 78712, USA.

We derive a constraint on the pair density ratio, $z_+ = n_+/n_p$, in an electron-positron pair wind flowing away from the central region of an accretion disk around a compact object under the assumption of a coupling between electrons, positrons, and protons. The minimum rate at which positrons are injected into the annihilation volume is given by the observed annihilation flux per unit volume. This rate is then used to determine a minimum mass loss rate per unit area, $\dot{M}_L$, for a given pair density ratio at the base of the streamline. The requirement that $\dot{M}_L < \dot{M}_{Edd}$ (the mean Eddington mass loss rate per unit area) then places a lower limit on the pair density ratio, $z_{+,min}$.

A positron annihilation line was observed in Nova Muscae 1991 by GRANAT/SIGMA. The narrow width and redshift of the line suggest that the pair production and annihilation regions are physically distinct. We hypothesize that an electron-positron pair wind transports the pairs from the production to the annihilation region and calculate $z_{+,min}$. We then determine constraints on the physical parameters on the pair production region by comparing $z_{+,min}$ with previous studies of two-temperature and one-temperature accretion disks with electron-positron pairs.

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CIRCUMSTELLAR MATERIAL AROUND YOUNG STARS IN ORION.

C. R. O'Dell, Department of Space Physics and Astronomy, Rice University, P.O. Box 1892, Houston TX 77251, USA.

The star cluster associated with the Orion nebula is one of the richest known [1]. Lying at the nearside of the Orion Molecular cloud and at a distance of about 500 pc from us, it contains many pre-main-sequence stars with ages of about 300,000 yr [2]. The nebula itself is a blister type, representing a wall of material ionized by the hottest star in the Trapezium group (member C).

Although this is not the closest star formation region, it is probably the easiest place to detect circumstellar, possibly protoplanetary, material around these solar mass stars. This is because the same process of photoionization that creates the nebula also photoionizes these circumstellar clouds, thus rendering them easily visible. Moreover, their dust component is made visible by extinction of light from the background nebula.

Young stars with circumstellar material were found in Orion on the second set of HST images and were called proplyds, indicating their special nature as circumstellar clouds caused to be luminous by being in or near a gaseous nebula [3]. The brightest objects in the field had previously been seen in the optical [4] and radio [5], and although their true nature had been hypothesized [6,7] it was the HST images that made it clear what they are. The forms vary from cometlike when near the Trapezium to elliptical when further away, with the largest being 1000 AU and the bright portions of the smallest, which are found closest to the Trapezium, being about

100 AU in diameter.

We now have a second set of HST observations made immediately after the refurbishment mission that provides even greater detail and reveals even more of these objects. About half of all the low-luminosity stars are proplyds. The poster paper describes quantitative tests about their fundamental structure and addresses the question of whether the circumstellar material is a disk or shell. One object (HST16) is seen only in silhouette against the nebula and is easily resolved into an elliptical form of optical depth monotonically increasing toward the central star.

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518-90 ABS. C **N94-31134**

p.1

A STUDY OF ANGULAR MOMENTUM LOSS IN BINARIES USING THE FREE LAGRANGE METHOD.

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The evolution of a binary star system depends greatly on the angular momentum losses in the system brought about by gravitational radiation and mass outflow (e.g., evaporating winds and magnetic braking) from the secondary component of the binary. Using a three-dimensional hydrodynamic fluid code based on the free Lagrange method, we study the loss of specific angular momentum from a binary system due to an evaporative wind from the companion of a millisecond pulsar. We consider binaries of different mass ratios and winds of different initial velocities and in particular attempt to model the system PSR 1957+20. We are in the process of incorporating the effect of the radiation force from the pulsar and the magnetic field of the companion on the mass outflow. The latter effect would also enable us to study magnetic braking in cataclysmic variables and low-mass X-ray binaries.

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p.2

EVOLUTION OF PROTOPLANETARY DISKS WITH DYNAMO MAGNETIC FIELDS.

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The notion that planetary systems are formed within dusty disks is certainly not a new one; the modern planet formation paradigm is based on suggestions made by Laplace more than 200 years ago. More recently, the foundations of accretion disk theory where initially developed with this problem in mind by von Weizsäcker [1], and in the last decade astronomical observations have indicated that many young stars have disks around them. Such observations support the generally accepted model of a viscous Keplerian accretion disk for the early stages of planetary system formation. However, one of the major uncertainties remaining in understanding the dynamical evolution of protoplanetary disks is the mechanism, or mechanisms, responsible for the transport of angular momentum and subsequent mass accretion through the disk. This is a fundamental piece of the planetary system genesis problem since such mechanisms will determine the environment in which planets are formed.

Among the mechanisms suggested for this effect is the Maxwell stress associated with a magnetic field treading the disk. Due to the low internal temperatures, and resulting low degree of thermal ionization, through most of the disk, even the question of the existence of a magnetic field must be seriously studied before including magnetic effects in the disk dynamics. On the other hand, from meteoritic evidence it is believed that magnetic fields of significant magnitude existed in the earliest, PP-disk-like, stage of our own solar system's evolution. Hence, the hypothesis that PP disks are magnetized is not made solely on the basis of theory. Previous studies have addressed the problem of the existence of a magnetic field in a steady-state disk and have found that the low conductivity results in a fast diffusion of the magnetic field on timescales much shorter than the evolutionary timescale ($\sim 3 \times 10^6$–10^7 yr from astronomical observations). Hence the only way for a magnetic field to exist in PP disks for a considerable portion of their lifetimes is for it to be continuously regenerated. Levy [2] has suggested this could be accomplished by an α–ω dynamo mechanism working within the disk. Stepinski and Levy [3] derived a criterion to determine the ability of the dynamo to regenerate the magnetic field, and Stepinski et al. [4] have shown that a magnetic field may exist in certain parts of the disk depending on the disk properties. Because the dynamo mechanism depends on the turbulence for its excitation, the generated magnetic field will supplement, rather than replace, the turbulent viscosity in transporting angular momentum. In the present work, we present results on the self-consistent evolution of a turbulent PP disk, including the effects of a dynamo-generated magnetic field.

For our calculations, to include the effects of the large-scale dynamo magnetic field, we redefine the Shakura and Sunyaev dimensionless turbulence parameter, α_{ss}, to

$$\alpha_{eff} = \alpha_{ss}\left(1 + \frac{6}{\beta \alpha_{ss}^{1/2}}\right)$$

where β is the ratio of gas to magnetic pressure and we have assumed that $B \sim B_\phi$ and $B_r \approx \alpha^{1/2} B_\phi$. The magnetic pressure is also taken into account by writing

$$P = P_{gas}\left(1 + \frac{1}{\beta}\right)$$

With these we solve the standard set of time-dependent α disk equations. The opacity of nebular material is considered to be given by the piecewise continuous power laws used by Ruden and Pollack [5]. The self-consistent solution of disk structure in the presence of a magnetic field is calculated as follows. At each timestep, we compute the structure of a uniform α_{ss} nonmagnetic disk. The ionization degree profiles of such disks are calculated from equilibrium between thermal plus nonthermal sources (cosmic rays and radioactive isotopes) and sinks (recombination onto grains or ions). In the present work it is assumed that all grains are the same size, equal to 50 μm. We determine those places in the disk where the dynamo can operate, estimate its magnitude, and compute a new structure using α_{eff}. Such a structure is then evolved to the next timestep using a finite-difference scheme and the operation is repeated.

For the present computations we begin with a disk of mass 0.245 $M_\odot$ and angular momentum 5.6×10^{52} g cm^2 s^{-1}. Such initial conditions may represent a disk coming out of its earliest evolution stage in which, as has been argued by Shu et al. [6], the disk dynamics are dominated by a fast redistribution of angular momentum driven by gravitational waves. The surface density initially obeys $\Sigma(r) = \Sigma_0 [1 + (r/r_0)^2]^{-15/4}$ (it is zero for $r > r_0$), which, with $\Sigma_0 = 10^4$ g cm^{-2} and $r_0 = 15$ AU, gives the initial disk mass and angular momentum. However, after an initial period of less than 10^4 yr the detailed original mass distribution is forgotten. The turbulence parameter α_{ss} is assumed to be 10^{-2}. This value has been found by assuming the turbulence is driven by convection and has been used as a fiducial value in previous disk evolution calculations. The strength of the magnetic field is taken such that the Lorentz force induced by it on the turbulent motions balances the Coriolis force on them, and at this point the dynamo mechanism would be undercut.

As can be seen in Fig. 1, the magnetized disk evolves faster than the purely turbulent one. The increased efficiency in transferring angular momentum in the presence of a magnetic field results in higher accretion rates and hence a faster reduction of the disk's mass. It also results in faster spreading of the disk. As pointed out by Stepinski et al. [4], depending on the degree of ionization, turbulence strength, and disk local properties, the magnetic field can be sustained in different parts of the disk. In most cases, there will be an intermediate region where the dynamo cannot regenerate a seed magnetic field. We call such region the magnetic gap. In Fig. 2 this region is seen as a bulge in the surface-density profile. The bulge is formed as material is transported more easily in the regions where the magnetic field contributes and gets stuck where the viscosity is purely turbulent. The jump in the surface density from outside the gap to its interior can be by as much as a factor of ~4 for this value of β. This contrast is proportional to the strength of the magnetic field. The position and width of the gap varies with time as disk conditions and ionization levels change. As the disk evolves and cools down, the inner boundary moves inward as its position is controlled mainly by thermal ionization. The outer boundary, whose location is initially determined by the ionization from cosmic rays, moves inward as the surface density blocking its passage to the midplane decreases. However, the cooling of the disk implies a reduction in its half thickness, and, because the dynamo regeneration mechanism depends very strongly on this property, when H decreases below a certain value, the magnetic field can no longer regenerate and the outer boundary moves quickly outward. The dynamo can no longer sustain the magnetic field almost anywhere in the disk. From this point on, the dynamics of the disk are controlled mainly by whatever mechanism is responsible for generating the turbulence. For the present disk parameters and initial conditions this happens after 10^6 yr. The viscosity is proportional to the surface density, hence the disk with a magnetic field, which has evolved faster up to this point, now slows its evolution so that the heavier unmagnetized disk catches up to it and the two surface-

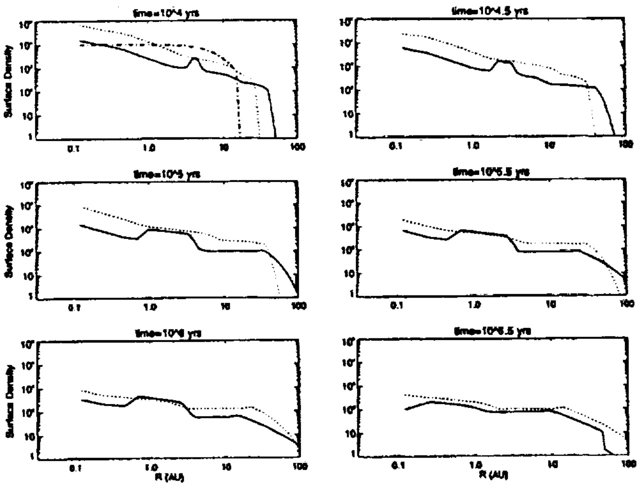

Fig. 1. Time evolution of protoplanetary disk mass, outer radius, and accretion rate onto the protostar for $\alpha_{ss} = 10^{-2}$. The magnetized disk quantities are the solid lines and the dotted lines are for the unmagnetized disk solution.

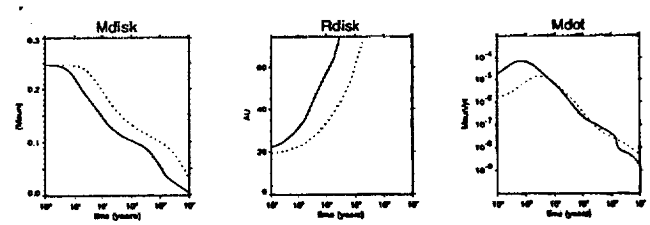

Fig. 2. Radial profiles of the surface density at different times. The solid line corresponds to a magnetized disk with $\alpha_{ss} = 10^{-2}$ and $\beta = 20$. The dotted line is the solution for a solely turbulent disk with the same α_{ss} and the dash-dotted line in the first panel shows the initial condition. The surface density is given in g/cm^2 and the radial distance is in AU.

density profiles are almost the same. This can also be seen in Fig. 1 where the disappearance of the magnetic field results in a sharp decrease in the accretion rate as the disk readjusts itself to the new, solely turbulent viscosity. The rate of decrease of the disk mass also becomes smaller for the previously magnetized disk as the unmagnetized disk tends to catch up to it.

An additional feature of the magnetized disk, which may have important consequences for the assumed planet formation going on in the disk, is the persistence of the surface density bulge, as planetesimal build-up will be facilitated in such a region as compared to its surroundings.

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S20-90 ABS. ONLY **N94-31136**

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.

S21-90 ABS. ONLY **N94-31137**

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.

S22-90 ABS. ONLY **N94-31138**

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 $1\text{-}M_\odot$ 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-$M_{\odot}$ 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 10–10^2 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.

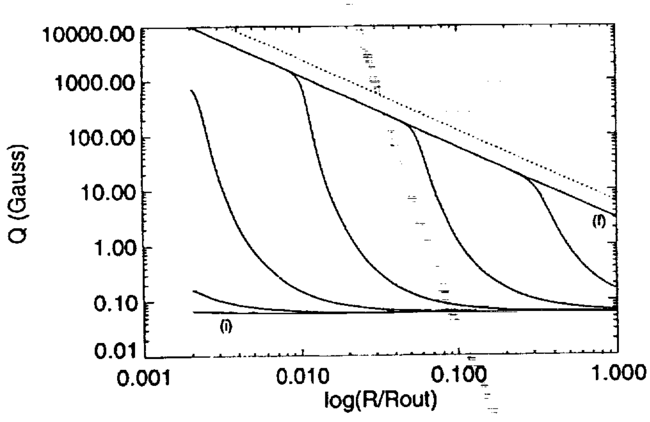

Fig. 1. Radial distribution of magnetic field Q is plotted against dimensionless radius r/r_{out} at various times for the case of an accretion disk around a compact star. The plots (i–f), in order of increasing time, correspond to $t = 10, 10^2, 10^3, 10^4, 10^5, 10^6$, and 10^7 s respectively. The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

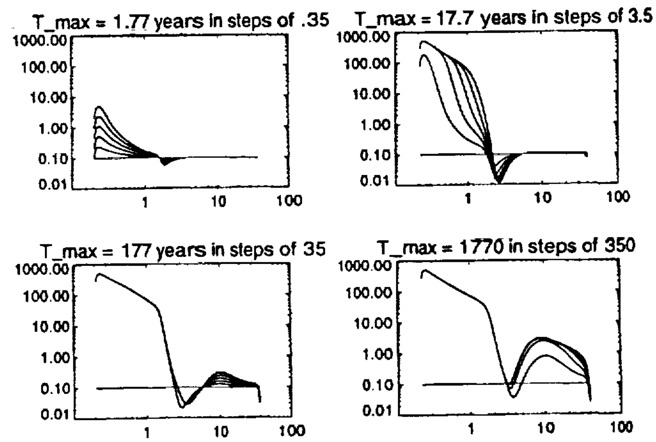

Fig. 2. Time evolution of the magnetic field in a protoplanetary disk from the initial condition $Q = 0.1$ at $t = 0$ represented by the horizontal solid line. Magnetic field Q is measured in units of $B_0 = B_{eq}$(40 AU). Radial distance from the central star is measured in AU.

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.

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D-1

S23-90 ABS. **N94-31139**

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. P. 2

S24-90 ABS **N94-31140**

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 having a wide range of disk-to-central object mass ratios. Global eigenmodes with four distinctly different characters have been identified using numerical, nonlinear hydrodynamic techniques. The mode that appears most likely to arise in normal star formation settings, however, resembles the "eccentric instability" that has been identified earlier in thin, nearly Keplerian disks: It presents an open, one-armed spiral pattern that sweeps continuously in a trailing direction through more than 2-π radians, smoothly connecting the inner and outer edges of the disk, and *requires* cooperative motion of the point mass for effective amplification. This particular instability promotes the development of a single, self-gravitating clump of material in orbit about the point mass, so its routine appearance in our simulations supports the conjecture that the eccentric instability provides a primary route to the formation of short-period binaries in protostellar systems.

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525-90 ABS. **N94-31141**

p. 1

THREE-DIMENSIONAL RADIATIVE TRANSFER CALCULATIONS ON AN SIMD MACHINE APPLIED TO ACCRETION DISKS. H. Vath, Department of Physics and Astronomy, Louisiana State University, Baton Rouge LA 70803, USA.

We have developed a tool to solve the radiative transfer equation for a three-dimensional astrophysical object on the SIMD computer MasPar MP-1. With this tool we can rapidly calculate the image of such an object as seen from an arbitrary direction and at an arbitrary wavelength. Such images and spectra can then be used to directly compare observations with the model. This tool can be applied to many different areas in astrophysics, e.g., HI disks of galaxies and polarized radiative transfer of accretion columns onto white dwarfs. Here we use this tool to calculate the image and spectrum of a simple model of an accretion disk.

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526-90 ABS. **N94-31142**

p. 8

DYNAMICS OF FLUX TUBES IN ACCRETION DISKS. E. T. Vishniac and R. C. Duncan, Department of Astronomy, The University of Texas, Austin TX 78712, USA.

The study of magnetized plasmas in astrophysics is complicated by a number of factors, not the least of which is that in considering magnetic fields in stars or accretion disks, we are considering plasmas with densities well above those we can study in the laboratory. In particular, whereas laboratory plasmas are dominated by the confining magnetic field pressure, stars, and probably accretion disks, have magnetic fields whose β (ratio of gas pressure to magnetic field pressure) is much greater than 1. Observations of the Sun suggest that under such circumstances the magnetic field breaks apart into discrete flux tubes with a small filling factor. On the other hand, theoretical treatments of MHD turbulence in high-β plasmas tend to assume that the field is more or less homogeneously distributed throughout the plasma [1].

Here we consider a simple model for the distribution of magnetic flux tubes in a turbulent medium. We discuss the mechanism by which small inhomogeneities evolve into discrete flux tubes and the size and distribution of such flux tubes. We then apply the model to accretion disks. We find that the fibrilation of the magnetic field does not enhance magnetic buoyancy. We also note that the evolution of an initially diffuse field in a turbulent medium, e.g., any uniform field in a shearing flow, will initially show exponential growth as the flux tubes form. This growth saturates when the flux tube formation is complete and cannot be used as the basis for a self-sustaining dynamo effect. Since the typical state of the magnetic field is a collection of intense flux tubes, this effect is of limited interest. However, it may be important early in the evolution of the galactic magnetic field, and it will play a large role in numerical simulations. Finally, we note that the formation of flux tubes is an essential ingredient in any successful dynamo model for stars or accretion disks.

We will consider an idealized situation in which there exists a turbulent cascade with a scale L and a turbulent velocity, on the scale of V_T. We will assume that the magnetic field has an rms Alfvèn speed V_A where $V_A \sim V_T$. We will also assume that the typical scale of curvature for the field lines is L. These assumptions are less restrictive than they may appear. If the turbulent cascade actually extends to larger length scales and higher velocities, then the magnetic field is dynamically insignificant on these larger scales and we can still confine our attention to scales of size L or smaller. If the magnetic field is in a shearing flow, surrounded by turbulence of its own creation, then the near equality of V_T and V_A is guaranteed, as well as the curvature of the magnetic field lines on the scale L.

The field lines will tend to stretch at a rate $\sim V_T/L$. If the plasma is highly conducting then the same amount of matter will be entrained on a progressively longer and longer flux tube. In a stationary state this stretching will be balanced by the pinching off of closed loops. These loops will have a radius ~L and a longitudinal compressive force $\sim \rho V_A^2/L$. This tension will be opposed, usually by turbulent stretching with a force of $\sim V_T^2/L$. Some large fraction of the time the loops will collapse. Regardless whether the internal pressure of the loop is dominated by the magnetic field or gas pressure the magnetic tension will decrease more slowly than the turbulent stretching force and the loop will collapse to a plasmoid ball, whose energy is slowly lost to microscopic dissipation. This process will tend to remove matter from the flux tubes at a rate of $\sim V_T/L$, which is rapid and will produce largely evacuated flux tubes under almost any circumstances. If we start from a uniform or nearly uniform field, this process will end when the same amount of flux is divided into some number of intense flux tubes with a magnetic pressure equal to the ambient pressure and a local β of order unity or less. The final rms Alfvèn velocity will be the geometric mean between its initial value and the local sound speed. This increase will occur at a rate comparable to V_T/L, in agreement with the results of numerical experiments [2,3].

What will be the typical radius of the individual flux tubes? A single flux tube with an internal Alfvèn speed of $V_{At} \sim c_s$, and exposed to an ambient turbulent velocity of V_T, will remain coupled to the fluid provided that $r_t < (V_T/V_{At})^2 L$. On the other hand, these tubes will impede the flow, and thereby reduce the ambient fluid velocity below V_T, if the total number N is large enough that Nr_t/L is greater than 1. The requirement that the magnetic energy be divided into N flux tubes is just the requirement that $Nr_t^2 V_{At}^2 \sim V_A^2 L^2$, which implies that the flux tubes will not impede the flow if r_t is comparable to, or greater than, $L(V_A/V_{At})^2$. We conclude that the

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favored size for intense local flux tubes with $V_{At} \sim c_s$ is just $L(V_A/c_s)^2$ and we expect there to be roughly $(c_s/V_A)^2$ of them per turbulent cell. Each flux tube will be surrounded by a local turbulent wake of size r_t and a large-scale eddy velocity of V_T. This implies that different parts of the tube will tend to diffuse out to a radius at which the turbulent drift is just balanced by attractive effects due to the winding up of the magnetic flux tube. This radius turns out to be $L(V_A/c_s)^2$ so these flux tubes are relatively stable structures. A similar argument, applied to larger-scale, correlated assemblages of such flux tubes, implies that on a scale R one expects to find $(\tilde{V}_A/V_A)^2$ flux tubes, of strength $\tilde{V}_A \sim V_A(L/R)^{1/2}$.

How quickly will a single flux tube rise? Each flux tube will feel an upward acceleration of g, the local gravity, since each will be significantly underdense relative to the surrounding medium. They will tend to drift upward as fast as allowed by their coupling to the surrounding turbulent medium. Since each is embedded in a local wake with local eddy speed of V_T, and since the buoyant upward rise is slow compared to V_T, we have

$$V_b(V_T / r_t) \sim g$$

or

$$V_b \sim r_t g / V_T \sim \frac{L_t}{V_T}\left(\frac{V_A}{c_s}\right)^2$$

In other words, the tiny flux tubes rise at the speed one would have obtained for the diffuse field. For an accretion disk $L \sim V_A/\Omega$, $g \sim Hc_s$, $c_s \sim H\Omega$, and $V_T \sim V_A$, where H is the disk thickness and Ω is the local Keplerian frequency. Consequently one predicts that magnetic flux is lost from the disk at a rate of $V_A^2/(c_sH)$, in accord with previous estimates based on the assumption of a diffuse field.

In spite of this lack of obvious effect the existence of these small flux tubes turns out to be important for two reasons. First, the separation of magnetized and unmagnetized volumes in the plasma allows us to see how highly conducting dense plasmas can apparently violate the flux-freezing condition and allow nearly independent motion of the magnetic field and the bulk of the fluid. This in turn allows for the possibility of turbulent diffusion and effective dynamo action. This point is extremely important given that recent work in two-dimensional turbulence has cast doubt on the possibility of reconciling dynamo action with flux-freezing [3]. (We note in passing that in two dimensions the formation of flux tubes does not allow large-scale relative motions between the fluid and the magnetic field due to topological constraints.) Second, in radiation-pressure-dominated environments the diffusion of photons into flux tubes will prevent the magnetic field pressure from ever dominating even small volumes in the plasma. This implies large and weak flux tubes that, if effectively evacuated of matter, will be much more buoyant than a diffuse field would be. Consequently the magnetic dynamo in a radiation-pressure-dominated disk will saturate at a lower level, giving rise to a smaller effective viscosity.

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THE PHYSICS OF BLACK HOLE X-RAY NOVAE. J. C. Wheeler[1], S.-W. Kim[1], M. D. Moscoso[1], and S. Mineshige[2], [1]Astronomy Department, University of Texas at Austin, RLM 15.308, Austin TX 78712, USA, [2]Astronomy Department, Kyoto University, Sakyo-ku, Kyoto 606-01, Japan.

X-ray transients that are established or plausible black hole candidates have been discovered at a rate of about one per year in the galaxy for the last five years. There are now well over a dozen black hole candidates, most being in the category of X-ray novae with low-mass companions. There may be hundreds of such transient systems in the galaxy yet to be discovered. Classic black hole candidates like Cygnus X-1 with massive companions are in the minority and their census in the galaxy and magellanic clouds is likely to be complete.

The black hole X-ray novae (BHXN) do not represent only the most common environment in which to discover black holes. Their time dependence gives a major new probe with which to study the physics of accretion into black holes. The BHXN show both a soft X-ray flux from an optically thick disk and a hard power law tail that is reminiscent of AGN spectra. The result may be new insight into the classical systems like Cyg X-1 and LMC X-1 that show similar power law tails, but also to accretion into supermassive black holes and AGN.

The basic properties of the outbursts of the BHXN can be explained by the same accretion disk thermal limit cycle instability that accounts for dwarf novae. The large orbits and low-mass transfer rates qualitatively account for the longer recurrence and outburst timescales. Disk instability models give a good basic representation for the outburst light curves in both the optical and soft X-rays. The basic models do not account for secondary features such as the reflare that has been seen at 50–75 days after outburst in A0620-00, GS 2000+25, Nova Muscae 1991, and GRO J0422+32. These and other minor but systematic features may result from the effects of irradiation [1]. Other phenomena that require exploration are the unique light curve of V 404 Cyg that showed only the power law tail and rapid time variability and may indicate luminosity near the Eddington limit, resulting in disruption in the inner disk and the series of postoutburst flares displayed by GRO J0422+32.

The basic disk models do not account for the hard power law continuum. The fact that the apparent inner radius is fixed during the outburst of the soft X-ray BHXN, independent of the variation of the luminosity and hence the mass flow rate, strongly suggests that the optically thick, geometrically thin disk extends down to very near the last stable circular orbit. Thus models invoked for the hard power law in Cygnus X-1 that rely on an inner corona that subtends a substantial portion of the inner disk are not applicable to these systems. Observations show that the flux in the hard power law does not vary in simple proportion to the soft flux and hence is not simply powered by the mass flow rate through the inner disk. The power law can be approximated by emission from a Comptonized thermal plasma in some cases, but simple single-temperature models are inadequate in other cases. In addition, BHXN outbursts are commonly associated with radio outbursts requiring nonthermal particles and magnetic fields. There is thus a serious question as to whether nonthermal mechanisms contribute substantially to the observed power law spectra.

Two black hole candidates, the 1E Galactic Center source and Nova Muscae 1991, show transient narrow redshifted annihilation lines. These observations suggest that the annihilation region must be deep in the gravitational potential, but cannot be at the site of the positron production. This suggests that electron-positron pair winds may play a role in transporting the positrons from the site of production to that of annihilation [2]. The suggestion that there are quasi-steady-state flows from within the inner disk in turn suggests that the site of the origin of the hard power law radiation may be the same as that of the positrons, but that it is not a static corona, but rather associated with a steady flow from the inner disk.

Another special aspect of the BHXN is that two of them, V 404 Cyg and A0620-00, have revealed enhancements in Li in the atmosphere of the dwarf companion. This is also seen in Cen X-4, a neutron star transient, so the Li is not a unique signature of black hole systems. Nevertheless, the Li represents an important clue to the evolution of the system and to the physical processes that occur there. Two interesting possibilities are spallation in the disk or the companion star requiring energetic particles, or a precursor phase with a Thorne-Żytkow object, a buried neutron star in which the deep hot-bottom convective envelope may generate Li and mix it to the surface.

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GAS DYNAMICS FOR ACCRETION DISK SIMULATIONS.
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The behavior of accretion disks can largely be understood in terms of the basic physical processes of mass, energy, and momentum conservation. Despite this, detailed modeling of these systems using modern computational techniques is challenging and controversial. Disturbing differences exist between methods used widely in astrophysics, namely Eulerian finite-difference techniques and particle codes such as SPH. Therefore neither technique is fully satisfactory for accretion disk simulations. This paper describes a new fully Lagrangian method designed to resolve these difficulties.