Bull. Astr. Soc. India (1982) **10**, 205–210.

Accretion disks—What do we know about them ?*

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Received 1982 June 19

Abstract. This essay briefly describes the present status of research on accretion disks around compact objects—in particular, blackholes—covering both the thin and thick disks. Significant results from various analyses regarding the structure and stability of such disks are presented. It is pointed out that the magnetic field has a very important role to play in the disk structure as it contributes mainly to the turbulent viscosity which has a primary role in the dynamics of disks. Attention is drawn to the fact that a fully detailed analysis of accretion disks should take into account selfconsistent electromagnetic field, which could get enhanced because of spacetime curvature effects, in a fully general relativistic treatment.

Key word : accretion disks

1. Introduction

Accretion disks are undoubtedly one of the oldest of astronomical phenomena; an intensified research on them however is coming of age only now. Thanks to general relativity and the consequent blackhole the study of accretion disks has reached a very important stage as it could be the only source confirming the existence of blackholes. Though it is very difficult to extract evidence for the presence of accretion disks directly from observations, the most likely candidates for their presence vary among a wide variety of objects like quasars, active nuclei of galaxies, elliptical galaxies, tight binaries, galactic x-ray sources and possibly the most enigmatic object SS433. Of these different sources the most promising ones are x-ray binaries, quasars and active galactic nuclei, wherein the total energy output in the form of high energy radiation turns out to be of the order of $10^{45} \sim 10^{48}$ ergs s^{-1}. Whenever one confronts such high energy phenomena the best process of energy extraction is through gravitation. Accretion is synonymous gravitation, as gravitation is always attractive. The efficiency with which the energy release takes place from a system is directly related to the gravitational potential associated with it. If a particle hits the surface of a star of mass M and radius R, the free fall velocity on impact

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*Received 'honourable mention' at the 1982 Gravity Research Foundation essay competition.

is given by $V_{ff} = 2GM/R$, and this impact releases the kinetic energy of the particle which radiates out in the form of increased luminosity of the star as given by $L = \frac{1}{2}MV^2 = \eta_{ff}^2 \dot{M}C^2$, $\dot{M}$ being the rate of accretion. $\eta = GM/RC^2$ is the efficiency factor and is $\sim 10^{-4}$ for a white dwarf and ~ 0.14 for a neutron star. Though by using the radius of a blackhole as $2GM/C^2$, one could get $\eta = 0.5$, this would not be correct as there is no *hard surface* with which the particle can impact. In the case of a blackhole the energy will be radiated out by the accreting material, before it is swallowed by the hole. Such an accretion will be purely radial if the blackhole is at rest with respect to interstellar gas (isolated) or the incoming matter does not possess angular momentum. In such a situation the radiated energy comes essentially from the work done in compressing the gas, which heats up the accreting material thus rendering the environment of the blackhole a very weak source of x-rays, which may or may not be detectable. On the other hand if the infalling gas has angular momentum then because of the possible existence of stable circular orbits, the accretion will no longer be spherical and the gas will form a disk around the blackhole. Such accretion disks are possible to form around other compact objects like neutron stars and white dwarfs, when they are in a binary system. However, the energy release through radiation from such disks would be much more efficient for blackholes, as the accretion rate goes as M^2 and blackholes come with heavy to superheavy masses. Salpeter (1964) was the first to consider the accretion onto supermassive blackholes as an efficient energy release mechanism and Lynden Bell (1969) considered the accretion disk around a Schwarzschild blackhole in the galactic nuclei as a model for quasars. When an accretion disk forms, as the material cannot move radially inwards without losing angular momentum, it will have lot more time to radiate its internal energy released while falling through the enormous gravitational potential of the blackhole. In order to transport angular momentum the disk has to have viscosity, which would ensure the process of mass loss from the disk to be very slow. This in turn would give sufficient time for gas to get thermalised to very high temperatures ($\sim 10^9$K) and thus the interior of the disk becomes a strong source of x-rays. Further the matter in the disk being in an ionized state, the electrons tend to be highly relativistic and this in turn renders the emitted radiation Comptonised (inverse Compton scattering) to give out hard x-rays. Thus the dominant processes of radiation from the disk seems to be (i) bremsstrahlung, and (ii) Comptonisation (Sunyaev 1973).

2. Models

One of the early models considered for compact x-rays sources using accretion disks was due to Pringle & Rees (1972). Subsequently several improvements have been suggested and a detailed review of this may be found in the article of Lightman *et al.* (1978). All these models come under the nomenclature standard accretion disk model (SADM) or α-model as they all assume the same viscosity law namely that the transverse stress $t_{r\varphi} = \alpha p$ where p is the pressure and α is a dimensionless parameter less than unity. Further all these models consider the disk to be made of three regions as given by

(i) inner region $p_r \gg p_g$ $n^{es} \gg n^{ff}$
(ii) middle region $p_r \ll p_g$ $n^{es} \gg n^{ff}$

and (iii) outer region $p_r \ll p_g$ $n^{es} \ll n^{ff}$

wherein p_r and p_g denote the radiation pressure and gas pressure and n^{es} and n^{ff} denote the opacities due to electron scattering (Thomson Scattering) and free-free absorption. Both these characteristics are the ones first suggested by Shakura & Sunyaev (1976). They show that the energy production rate Q^+ is zero at $r = r_i$, the inner edge of the disk, and reaches maxima at $r = (49/36)$m and decreases as r^{-3} for large r. The total luminosity $L = 4\pi \int_{r_i}^{\infty} Q^+ \, r \, dr = \frac{1}{2} \dot{M}_d \, MG/r_i$ is independent of the nature of the dissipative forces and depends only on the accretion rate $\dot{M}_d$ and the inner radius r_i. This shows that increase in luminosity may be obtained by considering disks with inner edge as close to the blackhole as possible. The dynamics of the disk as envisaged in SADM is governed by the laws of conservation of mass, angular momentum, energy, vertical momentum, nature of viscosity and the law of radiative transfer from inside of the disk to its upper and lower faces. The gas is assumed to be supported against the gravitational pull of the central compact object mainly by the rotation with Keplerian angular velocity. Because of the viscous forces the gas loses angular momentum and acquires radial velocity, while in the vertical direction the velocity is assumed to be subsonic so that the vertical structure is governed by the law of hydrostatic balance. Turbulence and smallscale magnetic field contributes to the viscosity and one writes for the integrated viscous stress $t_{r\varphi} = 2\alpha \, ph$, h being the height. The energy produced owing to the friction is transferred to the disk surfaces and the medium is considered to be optically thick with the opacity due to the Thomson scattering and free-free absorption. To discuss the stationary state one also needs an equation of state with the total pressure $(p_r + p_g)$ and an equation connecting the radiation density to the thermodynamical properties of the gas. Stability of such disks was considered by many authors (Shakura & Sunyaev 1976; Shibazaki & Hoshi 1975), and it has been generally found that the inner regions of the disk are secularly and thermally unstable. Though attempts were made to improve and generalize these models it was soon realised that the thin disk model may not be realistic as one neglects pressure gradient forces. The inclusion of pressure gradient forces leads to two main changes in SADM. The motion will no longer be Keplerian and the disk will have a vertical structure with the inner boundary forming a cusp (Abramowicz *et al.* 1978). Also here the accretion rate could exceed the critical value and the non-Keplerian angular momentum distribution could make the disk go farther inside than r_{ms}, the last circularly stable orbit with the inner edge now having the limiting radius at r_{mb} the marginally bound orbit (Paczynski 1980). Several attempts (Wiita 1981) have so far been made to construct thick disks that are dynamically stable in that $(dl/dr) > 0$ and $(d\Omega/dr) < 0$ everywhere, $l(r)$ being the specific angular momentum and $\Omega(r)$ being the angular velocity; however complete satisfaction of all the stability criteria is still to be achieved. Chakraborty & Prasanna (1981, 1982) have made a very general global stability analysis for a class of thick perfect fluid disks (without any dissipative terms being considered) both in Newtonian and Schwarzschildean formulations under radial and axisymmetric perturbations. Though such disks have been found to be stable, it requires to consider these disks with the inclusion of viscous and radiative terms which play an important role in the dynamics of the disks.

As viscosity is the agency to transport angular momentum, convection is likely to be the agency for vertical transport of energy in optically thick steady accretion disks. It has been found (Robertson & Tayler 1981) that for a wide range of viscosity laws disks which are themally unstable have convective instabilities too. Regions dominated by radiation pressure seem to be unstable under convection but convection itself is less likely to occur if the gas pressure is dominant. Though a simple analysis suggests that convection carrying a sufficiently large fraction of energy may remove thermal instability, a more detailed study of disk structure has shown that radiation always carries most of the energy and convection only increases the critical value of radiation pressure for instablity but does not remove the instability.

3. Role of magnetic field

Inspite of all these interesting studies one feature that has been grossly neglected in most of the analyses is the role of electromagnetic field, either external or internal. In fact as pointed out by Lightman *et al.* (1978), at the high temperatures attained close to the blackhole the particle mean free paths are so long that a fluid dynamical treatment is not really selfconsistent unless collective effects are operative. However, the only way to overcome this difficulty is by taking into account the effects of interstellar magnetic field, which if dynamically important at the accretion radius would affect the character of the flow. Even if it is initially negligible the field lines would be stretched radially during the inflow as a consequence of which the magnetic energy density will vary as r^{-4} and will become dynamically important. Attempts to include the dynamical effects of magnetic fields have been made by Bisnovatyi-Kogan Blinnikov (1972) and Ichimaru (1977) who found respectively that the presence of magnetic field in the accreting gas may increase the efficiency of radiation emission, and that the turbulence is generated mainly by the differential rotation of plasma which decays through current dissipation due to anomalous magnetic viscosity. This latter feature when incorporated in the study of disk dynamics has revealed the existence of two physically distinct states in the middle part of the disk which are thermally stable. A more rigorous treatment of the magnetic field generation due to differential motion of conductive media in accretion disk was made by Galeev *et al.* (1979) who found that even the fastest reconnection mechahism is insufficiently rapid to develop effectively in the inner portions of the accretion disk and that the building up of magnetic fields within the disk is instead limited by nonlinear effects related to convection. Further a structured magnetically confined accretion disk corona can form, consisting of many small scale extremely hot coronal loops which could give rise to both soft and hard x-rays depending on the disk luminosity. All these analyses have been mainly Newtonian; whereas it is well known that in the vicinity of a blackhole even a test electromagnetic fleld will get enhanced owing to the contributions from the spacetime curvature effects, and also the stability region for the charged particle orbits increases very much. Detailed analysis of charged particle trajectories in electromagnetic fields superposed on blackhole spacetimes has shown that even a very weak seed magnetic field can support a charged particle in a stable circular orbit very close to the event horizon (Prasanna 1980). Hence it is certainly possible to have accretion disks of plasma around blackholes with inner edge close to the event horizon. In order to discuss the dynamics of such disks it is necessary to consider the equations of disk structure balanced by the gravitational, electromagnetic, centrifugal and pressure forces in a general relativistic framework, self-consistently. Prasanna & Chakraborty (1981) have set up the system of such equations in terms of local Lorentz components of field variables on a general curved background. Further as a specific example they have also considered the stability of pressureless, thin, charged fluid disk centred along the equatorial plane of a Schwarzschild blackhole, for differential as well as rigid rotation. It is now essential to consider such a general system of equations including conductivity and viscosity, the latter arising from a self-consistent turbulent magnetic field as well as from velocities, and look for equilibrium solutions for thick disks and then consider their global stability analysis as has been carried out by Chakraborty & Prasanna (1980), for thick disks without viscous and electromagnetic forces. In fact, Sakimoto & Coroniti (1981) have considered qualitatively the role of magnetic viscosity for the accretion disk models for quasars. Scaling up the SADM parameters to quasar blackhole masses and quasar luminosities they find that one way of avoiding thermal instabilities is to assume the dominance of magnetic viscosity, limited by equipartition of gas and magnetic pressures giving a viscosity law $t_{r\varphi} = \alpha p_g$, proportional to $n_0 T$, in all regions of the disk which leads to optically thick, thermally stable disks.

4. Applications

Most of the models described were developed essentially to describe the spectrum of Cygnus X-1, a very likely candidate for a blackhole. Apart from this another important application can be for the case of SS433* as the possibility of getting two gaseous jets from the thick disk in the form of collimated accelerated beams is very good. However, the state of art regarding accretion disks is far from being in a position to predict any directly verifiable effects. One of the recent attempts (Gerbal & Pelat 1981) at modelling for comparison with observations is the study of the influence of geometry upon the shape parameters of a line profile emitted by an accretion disk, which appear to be asymmetric, two-peaked, blue or red shifted depending on the characteristics of the disk. It will be necessary to reconsider such studies with more realistic disk parameters and possible modulations of frequency and polarization due to the passage through the disk when the emission region is well in the interior.

It is clear that the study of accretion disks around compact objects presents one of the most significant challenges in theoretical astrophysics today as it is in a stage wherein a good understanding of various disciplines of physics like gravitation, electromagnetics, radiation emission and transfer, in short plasma processes on curved background, would be required.

References

Abramowicz, M., Jaroszynski, M. & Sikora, M. (1978) *Astr. Ap.* **63**, 221.
Bisnovatyi Kogan, G. S. & Blinnikov, S. I. (1972) *Ap. Sp. Sci.* **19**, 119.
Chakraborty, D. K. & Prasanna, A. R. (1981) *J. Ap. Astr.* **2**, 421.

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*See *Vistas in Astronomy*, volume 25, parts 1 and 2 (1981) for the proceedings of a symposium on SS433.

Chakraborty,, D. K. & Prasanna, A. R. (1982) *J. Ap. Astr* (in press).
Galeev, A. A., Rosner, J. & Vaiana, G. S. (1979) *Ap. J.* **229**, 318.
Gerbal, D. & Pelat, D. (1981) *Astr. Ap.* **95**, 18.
Ichimaru, S. (1977) *Ap. J.* **214**, 840.
Lightman, A. P., Shapiro, S. L. & Rees, M. J. (1978) in *Physics and Astrophysics of Blackholes and Neutron Stars* (eds : R. Giacconi & R. Ruffini) North Holland, p. 786
Lynden Bell, D. (1969) *Nature Phys. Sci.* **223**, 690.
Paczynski, B. (1980) *Acta Astr.* **30.4**, 347.
Prasanna, A. R. (1980) *Rev. Nuovo Cim.* **3**, 1.
Prasanna, A. R. & Chakraborty, D. K. (1981) *J. Ap. Astr.* **2**, 1.
Pringle, J. E. & Rees, M. J. (1972) *Astr. Ap.* **21**, 1.
Robertson, J. A. & Tayler, R. J. (1981) *M.N.R.A.S.* **196**, 185.
Sakimoto, P. J. & Coroniti, F. V. (1981) *Ap. J.* **247**, 19.
Salpeter, E. E. (1964) *Ap. J.* **140**, 796.
Shakura, N. I. & Sunyaev, R. A. (1976) *M.N.R A.S.* **175**, 613.
Shibazaki, N. & Hoshi, R. (1975) *Prog. Theo. Phys.* **54**, 706.
Sunyaev, R. A. (1973) *Sov. Astr.* **16**, 941.
Wiita, P. (1981) *Comm. Ap.* (in press).