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Equilibria of self-gravitating gaseous disks

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Abstract. The equilibrium of the self-gravitating gaseous disk in a galactic nucleus is discussed. We solve the force-balance equation perpendicular to the disk plane at arbitrary radius. We, thus, calculate the mass density ρ, and pressure p as functions of z for given central temperature T_c. Implications of the result for active galactic nuclei are discussed.

Key words : galaxies : general-galaxies : nuclei-galaxies : active

1. Introduction

The repeatedly active role of the nuclei of galaxies has excited the astronomical community, primarily because a tiny (~ 100 astronomical units ; A U) central region (as compared to the overall galactic dimension) gives rise to spectacular and energetic phenomena. Already in 1943, Seyfert discovered that many spiral galaxies show violent nuclear activity and have bright nuclei with strong high-excitation emission-line spectral features. In fact, broad hydrogen emission lines show Doppler motions of several thousand km s^{-1}. Incidentally, these velocities correspond to supernova-explosion velocities. The enormous energy budget ($\geq 10^{62}$ ergs) of these objects (for a power of 10^{46} erg/s during an active cycle, of duration several 10^8 yr) may be understood in terms of synchrotron emission from relativistic particles and significant magnetic fields (Burbidge 1958). Theoretical problems to explain such an energy requirement became more apparent during 1962-63 when the radio source 3*C*273 was discovered giving testimony to a new class of astronomical object the QSOs (Schmidt 1963). Optical variations on timescales of years and shorter, originating in sub-parsec regions, have been detected (see also Smith and Hoffleit 1963, Sandage 1964). The overall supply of a huge energy from such a small region remained a challenge for quite some time.

Unknown is the nature of the central engine (CE). We follow Kundt's suggestion (1987, 1996a) that a common type of CE is operative for both the stellar case and the extragalactic objects. Most of the literature assumes a black hole at the centre of AGNs. In fact, recent results (Kormendy and Richstone 1995; among others) have shown that dynamical searches

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suggest but do not prove the existence of supermassive black holes as the CE. Current studies of galaxies using the HST Data, e.g. for NGC 3115 (Kormendy et al. 1996a), NGC 4594 (Kormendy et al. 1996b), NGC 4486B (Kormendy et al. 1997), and NGC 4261 (Ferrarese et al. 1996) conclude at the existence of a massive dark object (of mass ~ $10^8\ M_\odot$ to $10^9\ M_\odot$) at the centre of a galactic nucleus at radii of $\leq 10^{18}$ to 10^{19} cm. This massive dark object may well be the supermassive gas disk with ringlike thickenings including dust.

The gas distribution in our Galaxy was originally described by Oort (1965). Güsten (1989) has shown that inside 500 pc of galacto-centric radius of the Galaxy, the gas component is composed of giant molecular complexes (size ~ 100 pc). The mass of the central gas layer of size $450pc \times 40pc$ is ~ $10^{7.9\pm0.25}\ M_\odot$. The mass distribution in our Galaxy is asymmetric with respect to the centre. Kundt (1990a) concludes that the core of our Galaxy, Sgr A East ($r \leq 5$ pc), is an electron-positron pair plasma bubble (generated in localised discharges in the corona of the innermost disk), poured out from the central engine. Accordingly, Sgr $A*$ ($r \leq 10^{-5}$ pc) is regarded as the rotating supermassive core of mass ~ $10^{6.4}\ M_\odot$ (Eckart and Genzel 1996a, 1996b), radius $R \sim 10^{13}$ cm, surface temperature $T \leq 3.6 \times 10^4$ K, surrounded by a low-luminosity near-Keplerian accretion disk with angular velocity $\Omega \leq 10^{-4}\ s^{-1}$.

One finds a high concentration of ionized hydrogen near few kpc of many galaxies where the neutral component is deficient. A large H_I concentration appears between 5 kpc and 15 kpc. There is an inhomogeneous distribution of gas primarily lying in a thin layer in a planar configuration. The 21-cm line observations with the 91-m telescope at NRAO (Roberts (1967) show strikingly (supporting Oort's (1965) suggestions) that central contours in $M31$ and $M33$ depict ring-like distributions (see also Kennicutt 1989, Elmegreen 1993, Wang and Silk 1994, Marston and Appleton 1995). Observations of many spiral galaxies (e.g. NGC 2403, NGC 5055, NGC 5457, IC 342 and our Galaxy) also display a ring-like pattern for the hydrogen distribution. For the distribution in our Galaxy one may refer to Kerr and Westerhout (1965), Einasto (1979), Elmegreen (1979), Cowie (1981), Ikeuchi et al. (1984) and Kundt (1990a).

It is thus tempting to think that a balance primarily between gravitational force and centrifugal force persuades the neutral hydrogen distribution to assume a disk pattern. Self-gravitating gaseous disks may exist in all active galactic nuclei (Bower et al. 1997). Even our Galactic centre belongs to the class of mildly active Seyfert nuclei which account for ~ 10% of all spiral galaxies (Mezger et al. 1996). Our aim is to discuss some of the characteristics of gaseous disks in galactic nuclei. The whole galactic disk is practically infinite in extent. We deal with its innermost part. A schematic view is shown in Fig. 1. The disk of a galaxy contains stellar and gaseous components, the latter typically contributing ~ 10% of the mass of a late-type galaxy. It has been established that all massive galaxies contain highly flattened disk-like gaseous systems. The flat character of our Galaxy may be observed through its bright strip across the night sky, which is strongly broadened by warping. Flatness in other galaxies has also been observed (see e.g. Sandage 1961). In fact, this emerges as a natural consequence. With this view, we present the basic equations of disk equilibrium and their solution in section 2. Implications of the result are discussed in the last section.

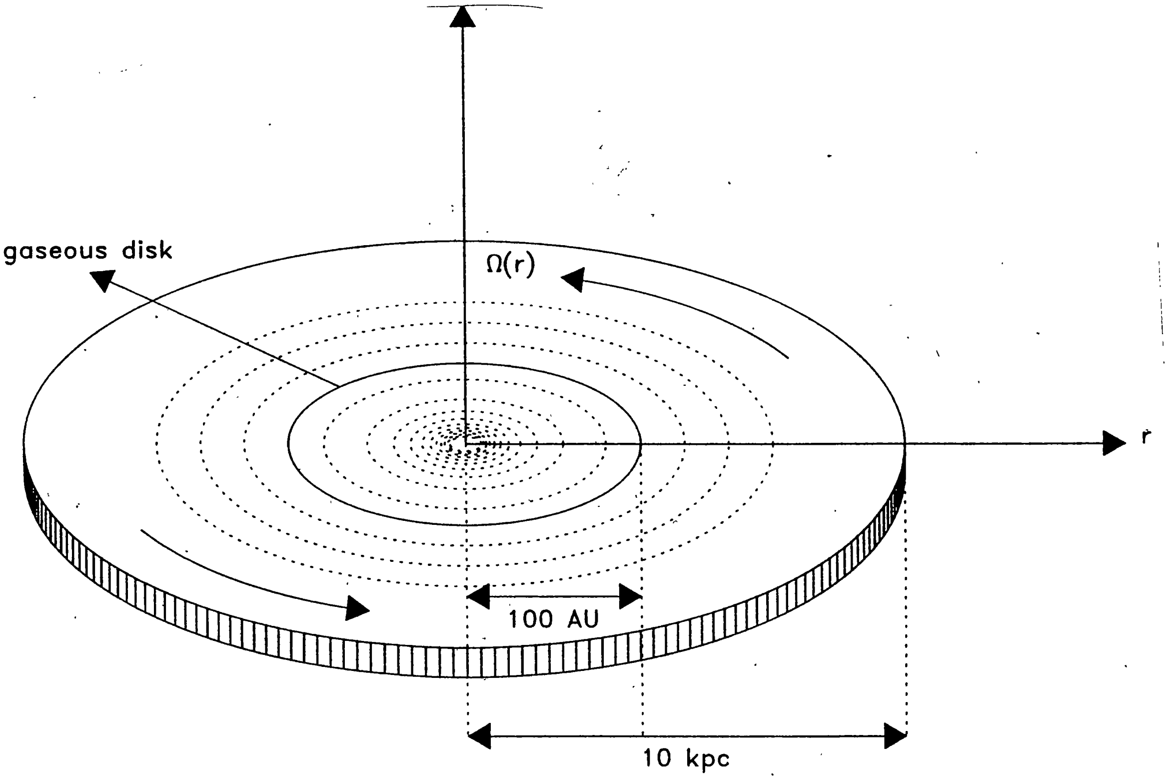

Figure 1. A schematic sketch of a gaseous disk in a galactic nucleus. Practically, the disk may extend upto infinity, however, the central active region has a radius of $r \sim 10^2$ AU. Nuclear burning starts above $\sigma \approx 10^{11.2}$ g/cm^2. Large fluctuations inside of $r = 1$ *kpc* manifest a variety of nuclear phenomena in AGNs (cf. e.g. Figure 1 by Kundt 1996b for more detailed information)

2. Basic equations and solutions

Let us assume that the disk is in hydrostatic equilibrium along z. The two dimensional (r,z) gaseous disk geometry is shown in Fig. 1 (z varying perpendicular to the disk plane). Matter spirals into the disk and gets hotter as it reaches the centre, thereby also increasing the central temperature T_c where $T_c := T$ (z = 0). Two basic equations of stellar structure are written as

$$\frac{dp}{dz} = g\rho \tag{1}$$

$$\frac{dg}{dz} = -4\pi G\rho \tag{2}$$

where p is the pressure and g is the gravity acceleration at z. We write eq. (1) as

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$$g = \frac{1}{\rho}\frac{dp}{dz} = \frac{dp}{d\rho}\frac{d\ln\rho}{dz} = v_{th}^2\,\tau' \tag{3}$$

where

$$\tau := \ln\frac{\rho}{\rho_c}\,, \tag{4}$$

and $v_{\rm th}^2 := dp/d\rho = kT/m\beta \approx$ square of thermal velocity, $\beta := p/p_{gas}$, $\rho_c := \rho(z = 0)$ and a prime denotes differentiation with respect to z. With the help of eqs. (2) and (3) one gets

$$\tau'' = -\,\frac{4\pi G\rho_c}{v_{\rm th}^2}\,e^{\tau}. \tag{5}$$

In order to get a closed-form solution, we assume $v_{\rm th}^2$ = constant. Eq. (5) can then be integrated, after multiplication with $2\tau'$, to get

$$\tau' = \Big[\frac{8\,\pi G\rho_c}{v_{\rm th}^2}\,(1 - e^{\tau})\Big]^{1/2}. \tag{6}$$

Further integration yields

$$\frac{z}{z_c} = \int\frac{dy}{y\,\sqrt{1-y}}\,, \tag{7}$$

$$z_c := \frac{v_{th}}{\sqrt{8\pi G\rho_c}} = 10^{10.6}\,cm T_8^{1/2}\,\rho_0^{-1/2} \approx R_\odot \tag{8}$$

where $\rho_0 := \rho_c/10^0\ g/cm^3$ is ρ_c in units of g/cm^3, T_8 is T_c in units of 10^8 K, and $y := e^{\tau}$. Thus, the scale height z_c of variation in the disk is of the order of the solar radius for a central mass density ρ_c like that of the sun and a somewhat higher central temperature T_c.

It is now straight forward to integrate eq. (7) using standard integrals (see e.g. Gradshteyn and Ryzhnik 1965). One gets

$$\frac{z}{z_c} = \ln\left|\frac{\sqrt{1-\frac{\rho}{\rho_c}} - 1}{\sqrt{1-\frac{\rho}{\rho_c}} + 1}\right|\,, \tag{9}$$

since $\rho \le \rho_c$ and $\sqrt{1-\frac{\rho}{\rho_c}} \le 1$. Eq. (9) may be simplified to obtain

$$\frac{\rho}{\rho_c} = \frac{1}{cosh^2(z/2z_c)}\ . \tag{10}$$

Thus, near the central plane (z = 0) of the disk, ρ has a plateau, and falls exponentially at large heights.

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The surface mass density σ of the gaseous disk is calculated as

$$\sigma = 2 \int_0^\infty \rho dz = 4\, \rho_c z_c \;|tanh(z/2z_c)|_0^\infty = 4\rho_c z_c = 10^{11.2}\ g/cm^2. \tag{11}$$

Because of our assumption v_{th}^2 = constant, we also get

$$\frac{p}{p_c} = \frac{1}{cosh^2(z/2z_c)}\,, \tag{12}$$

where from eq. (8) and (11)

$$p_c = \frac{\pi G \sigma^2}{2}\,. \tag{13}$$

The disk's 'central' temperature T_c can be estimated following Kundt (1996b). For a radiatively cooling disk, the central temperature T_c is related to the 'surface' temperature T_s through diffusive photon flow. In this case,

$$\kappa \nabla T_c \approx \frac{u_\gamma c}{3\tau} \approx \frac{\sigma_{SB} T_c^4}{\tau} \tag{14}$$

with κ = opacity, u_γ = photon energy density and τ = optical depth. Blackbody radiation from the surface is $\sigma_{SB} T_s^4$, yielding $T_c/T_s \approx \tau^{1/4}$. For effective optical depth $\tau = 10^{9\pm3}$, $T_c/T_s \gg 10$.

3. Discussion

We present the equations for a self-gravitating, gaseous disk in galactic nuclei. The gaseous components of the mass of a late-type galaxy being ~ 10% of its mass, gains prime significance with regard to the dynamics, and physical properties presumably in the early phases of their evolution, before significant star formation has taken place. We derive expressions for the variation of mass density ρ, and the pressure p under the simplifying assumption of constant thermal velocity. One may construct models of the nuclear gaseous disk by appropriately selecting two quantities out of the central mass density ρ_c, the surface mass density σ, the pressure p, the scale height z_c and the temperature T_c in the central-plane regions, whereupon the others are determined by eqs. (8), (11) and (13).

It has been found that when matter in a galactic disk spirals in towards its centre - average rate $M_{in} \geq 1\ M_\odot yr^{-1}$; cf. Kundt 1990b - small fluctuations may produce huge oversupply of matter in the central regions. Kundt (1996b) has explained that the mass density σ grows largely beyond σ_{Jeans}, giving rise to a spike in the inner rotation curve, and most likely resulting in an outburst. After 10^8 yrs or so, densities of the nuclear disk may grow again to stellar values, converting the nucleus into a 'burning disk' : an alternative model for active galactic nuclei.

Low-ionization-nuclear-emissionline region (LINERs) activities are nonthermal in character (Osterbrock and Mathews 1986). These are described as 'coronal activity' leading to stellar flares via magnetic reconnections (Benz 1994). It seems appropriate to conclude that starbursts, LINERs, and other forms of nuclear activity at the centres of galaxies might be attributed to instabilities of a self-gravitating gaseous disk with various manifestations triggered due to different initial conditions prevailing inside the disk.

In order to provide a self-consistent picture of self-gravitating gaseous disks, among several issues to be addressed are : (i) relaxation of the strong assumption of a constant thermal velocity, (ii) discussion of the stability of the disk under small and large scale perturbations. One must also explain (among others) the following properties of AGN.

1. Narrow and broad emission lines of Seyfert galaxies of types I and also narrow lines of type II with luminosities ~ 10^{44} erg/s and accretion rates ~ $10^{-2}\ M_{\odot}/yr$.

2. Quasars : broad and narrow emission lines, UV bump, high luminosities in the range 10^{44} to 10^{48} erg/s with accretion rates $10^{-2}\ M_{\odot}$ per year to $10^{+2}\ M_{\odot}$ per year and rapid variability timescales of high-energy emission.

3. Radio galaxies : with powerful jets, steep-spectrum radio lobes and flat-spectrum compact cores; narrow emission lines in the optical spectrum.

4. Blazars : variable and non-thermal (synchrotron) emission from a compact core (BL Lacs), highly polarized quasar, optically violently variable (OVV) sources and high-energy ($\geq GeV$) emission, even ≥ TeV emission.

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