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An X-ray illuminated circumnuclear disk at the center of NGC 4258

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Abstract. Observations of the angular distribution of the water masers in the nucleus of NGC 4258 reveal the presence of a thin molecular disk in nearly perfect Keplerian orbit (Miyoshi et al. 1995; Greenhill et al. 1995). The observed water maser clumps are distributed in an annulus of inner radius R_{in} =0.13 pc and outer radius R_{out}=0.26 pc. NGC 4258 is also observed to contain a central X-ray source of inferred intrinsic luminosity is 4×10^{40} ergs s^{-1} over the 2–10 keV energy range (Makishima et al. 1994). We suggest that the molecular density is too high within the inner radius R$_{in}$ and the temperature of the gas in the disk is too low to produce maser emission beyond the outer radius of the annulus. This interpretation implies that the accretion rate is $\sim 8 \times 10^{-4}\alpha$ M$_\odot$ yr^{-1}. The possibility that the masing region extends beyond the annulus could be ruled out.

Key words: accretion, accretion disks – galaxies: nuclei

1. Introduction

VLBI observations of water maser emission from the active galaxy NGC 4258 (Miyoshi et al. 1995; Greenhill et al., 1995) have revealed a thin circumnuclear Keplerian disk around a central object of mass 3.5× 10^7 M$_\odot$. The observed water maser clumps originate in an annulus of inner radius R_{in}=0.13 pc and outer radius R_{out} =0.26 pc, which we view nearly edge on. The systematic trends in the declinations of the high velocity features led to the conclusion that the disk is slightly warped (Miyoshi et al. 1995; Herrnstein et al. 1996). NGC 4258 is also observed to contain a central X-ray source of inferred intrinsic luminosity $\sim 4{\times}10^{40}$ ergs s^{-1} over the energy range 2–10keV (Makishima et al. 1994). Neufeld & Maloney (1995) suggest that the warped circumnuclear disk is illuminated obliquely by X-rays from central source. In their model, the disk is required to be flat for $R < R_{in}$, so the disk is no longer directly illuminated by the X-ray source and no water maser emission there.

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In this paper, we propose an alternative explanation of why the observed water maser emission in NGC 4258 only originates in an annulus of inner radius R$_{in}$=0.13 pc and outer radius R$_{out}$=0.26 pc. The physical conditions within the disk illuminated obliquely by a central X-ray source are inferred. In Sect. 2, the basic equations describing an X-ray illuminated accretion disk are listed. We estimate the physical conditions of the disk in Sect. 3. The mass accreting rate and the efficiency f with which the total X-ray flux available to illuminate the disk are resulted. Sect. 4 contains a discussion of our results.

2. A simplified X-ray illuminated accretion disk model

The X-ray flux that reaches the accretion disk at radius R and is absorbed there is

$$F_{x0} = \frac{fL_x}{4\pi R^2} = \frac{f\eta_x L}{4\pi R^2}, \tag{1}$$

where the correction factor f reflects the efficiency with which the X-ray flux available at a given radius R is used to illuminate the disk surface, η_x is the percentage in the X-ray range of the total bolometric luminosity. The intrinsic luminosity of the central X-ray source over the 2-10 keV energy range in NGC 4258 is inferred from the observed X-ray flux by assuming the isotropic emission of the X-ray (Makishima et al. 1994). If the X-rays are emitted from the inner region of the disk near the black hole, the luminosity tends to emerge perpendicular to the disk. Thus, the inferred X-ray luminosity is under-estimated, since the disk is viewed nearly edge on. Fortunately, we only want to know the X-ray flux reaching the accretion disk, so the Eq. (1) is a good approximation, though the assumption that the X-rays are emitted isotropically is used in Eq. (1).

The value of factor f mainly depends on the obliquity μ of the disk at a given radius, usually $f \leq \mu$. The relation $f = \mu$ is satisfied only when the illuminating X-rays are completely absorbed by the disk. The total bolometric luminosity L could be written as $L = x\dot{M}c^2$, where x, the efficiency of luminosity generation due to mass accreting, is $\sim$ 0.05 for Schwarzschild black holes and $\leq$ 0.4 for Kerr Black holes (Thorne 1974, Rees 1984; Frank et al. 1992).

The X-ray illuminated accretion disks have been studied in detail by many workers (van Paradijs 1983, Blair et al. 1984, Ko & Kallman 1991; Raymond 1993). Here we only list the basic equations describing the structure of X-ray illuminated accretion disk

$$2\pi R\Sigma V_r = \dot{M}, \tag{2}$$

$$\frac{H}{2R} = \left(\frac{R}{GM}\right)^{1/2} c_s, \tag{3}$$

$$c_s^2 = \frac{p}{\rho}, \tag{4}$$

$$p = \frac{\rho kT}{\bar{\mu} m_p}, \tag{5}$$

$$\nu\Sigma = \frac{\dot{M}}{3\pi}, \tag{6}$$

$$\nu = \alpha c_s H, \tag{7}$$

$$\frac{4\sigma T_c^4}{3\tau} = F_{x0} + F_{vis} \tag{8}$$

and

$$\tau = \kappa\Sigma. \tag{9}$$

Eqs. (2) and (6) are derived from the conservation of mass and angular momentum. Eq. (3) is the scale thickness of the disk found by solving the isothermal hydrostatic equation. Eq. (5) is the equation of state, $\bar{\mu}$ is the mean molecular weight for which we take the value of 2 here. Eq. (7) is the typical definition for the kinematic viscosity in the standard α-disk. Finally, Eq. (8) is the energy balance equation, from which the temperature of the gas in the disk is estimated. In principle, all cooling processes should be considered in calculating the equilibrium temperature of the gas (Neufeld et al. 1994). Nevertheless, Eq. (8) can give an estimate of the gas temperature, if the temperature of the gas is close to that of the dust in the disk. At least, it would be the low limit of the gas temperature. In fact, the gas temperature derived from Eq. (8) is a good approximation of the numerical results obtained by Neufeld et al. (1994). For simplicity, we apply Eq. (8) as the energy balance equation throughout this paper and we believe it will not affect the main conclusions. Compared to the central X-ray source heating, the viscous dissipation in the disk region $R_{in} < R < R_{out}$ could be neglected. Assuming the gas pressure dominates radiation pressure, we obtain the disk solutions as

$$\rho_c = 2.39 \times 10^{-20}$$

$$\kappa^{-3/10} f^{-3/10} \alpha^{-7/10} \dot{m}^{7/10} R^{-39/20} m^{17/20} L_{41}^{-3/10}\ \mathrm{g\,cm^{-3}}, \tag{10}$$

$$n_c = 7.21 \times 10^3$$

$$\kappa^{-3/10} f^{-3/10} \alpha^{-7/10} \dot{m}^{7/10} R^{-39/20} m^{17/20} L_{41}^{-3/10} \mathrm{cm^{-3}}, \tag{11}$$

$$T_c = 92.5 \kappa^{1/5} f^{1/5} \alpha^{-1/5} \dot{m}^{1/5} R^{-7/10} m^{1/10} L_{41}^{1/5} \mathrm{K}, \tag{12}$$

$$H = 20.2 \kappa^{1/10} f^{1/10} \alpha^{-1/10} \dot{m}^{1/10} R^{23/20} m^{-9/20} L_{41}^{1/10} \mathrm{pc}. \tag{13}$$

$$\Sigma = 1.87 \kappa^{-1/5} f^{-1/5} \alpha^{-4/5} \dot{m}^{4/5} R^{-4/5} m^{2/5} L_{41}^{-1/5}\ \mathrm{g\,cm^{-2}}, \tag{14}$$

where $10^{41}\ L_{41}$ ergs s^{-1} is the 2–10keV X-ray luminosity, $m = M/M_\odot$, $\dot{m} = \dot{M}/M_\odot\ yr^{-1}$, the subscripts c show the quantities in the equatorial plane of the disk.

3. Estimate of the physical conditions in the disk

Neufeld & Maloney (1995) propose that the pump energy of the observed water masers in NGC 4258 is from the nucleus in the form of X-rays heating the molecular gas in the disk. The observed water maser clumps are distributed in an annulus of inner radius R_{in}=0.13 pc and outer radius R_{out} =0.26 pc. The maser action will be quenched if the molecular density is too high as 10^{10} cm^{-3} (Moran et al. 1995). At temperature $\geq$ 300 K, the water abundance is significantly enhanced by chemical reactions of O and OH with H_2, and maser emission in the 22 GHz water transition is efficiently generated (Neufeld et al. 1994). We speculate that the maser action is quenched at the inner edge of the masing annulus due to the high molecular density. Beyond the outer radius of the annulus the gas temperature would be lower than 300 K. So, the gas temperature there is too low to facilitate rapid water production or to excite the 22 GHz water maser transition.

Now, we can estimate the physical conditions in the disk. At the inner edge R_{in}=0.13 pc, the molecular density at the mid-plane of the disk $n_c = n_{crit}$. We adopt the Rosseland mean extinction coefficient κ given by Pollack et al. (1994). From Eq. (11), we have

$$\frac{n_{crit}}{10^{10}} = 76.6 \left(\frac{\dot{m}}{\alpha}\right)^{7/10} f_{in}^{-3/10}, \tag{15}$$

where the correction factor f_{in} is the value at radius R_{in}. From Eq. (12), the gas temperature $T_c = T_{crit}$ at the outer radius R_{out} =0.26 pc gives the other relation

$$\frac{T_{crit}}{300} = 5.17 \left(\frac{\dot{m}}{\alpha}\right)^{1/5} f_{out}^{1/5}, \tag{16}$$

where f_{out} is the value at radius R_{out}. Here, $f_{in} = f_{out}$ is adopted assuming the same obliquity of the disk at different radii R. The critical values of molecular density n_{crit} and gas temperature T_{crit} are required by maser production.

Combining Eqs. (15) and (16), we obtain

$$f_{in} = f_{out} = 0.24 \left(\frac{T_{crit}}{300}\right)^{7/2} \left(\frac{n_{crit}}{10^{10}}\right)^{-1} \tag{17}$$

and

$$\frac{\dot{m}}{\alpha} = 1.1 \times 10^{-3} \left(\frac{T_{crit}}{300}\right)^{3/2} \left(\frac{n_{crit}}{10^{10}}\right). \tag{18}$$

If T_{crit}=300 K, n_{crit}=10^{10} cm^{-3}, we obtain f=0.24 from Eq. (17) and $F_{x0}/F_{vis} \sim 25\ \alpha^{-1}$ at the inner radius R_{in} which is consistent with the assumption $F_{x0} \gg F_{vis}$ in the region $R_{in} < R < R_{out}$. Compared with the low mass X-ray binaries, the correction factor f obtained here is very large. In the case of a normal axial symmetric disk, such large value of f requires the disk there to be geometrically thick which will break the thin disk assumption. The disk at the center of NGC 4258 is warped so that much more X-rays from the central source illuminate the warped part of the disk than the normal flat thin disk. Thus, the value f for the disk in NGC 4258 could be much larger than in the case of low mass X-ray binaries. The disk's warp presented by Miyoshi et al. (1995) implies an obliquity μ which is approximately 0.25 at the outer edge of the observed emission (Neufeld & Maloney 1995), which is in agreement with the value of f derived here. We assume that the thin disk equations could well describe such a slightly warped disk. A more detailed model fit to the warp of the disk is performed by Herrnstein et al. (1996), which indicates that the obliquity of the disk increases steadily with R. It could be inferred from their work that the obliquity at the outer radius R_{out} is about three times of that at the inner radius R_{in}. We assume that the correction factor f has the similar behavior to the obliquity μ varying with radius R, then $f_{in} \sim f_{out}/3$, where f_{in} and f_{out} are the values of correction factor of f at the radii R_{in} and R_{out}, respectively. Similar to the derivation of Eqs (17) and (18), we have

$$f_{in} = 0.11 \left(\frac{T_{crit}}{300}\right)^{7/2} \left(\frac{n_{crit}}{10^{10}}\right)^{-1}, \quad (19)$$

$$f_{out} = 0.34 \left(\frac{T_{crit}}{300}\right)^{7/2} \left(\frac{n_{crit}}{10^{10}}\right)^{-1} \quad (20)$$

and

$$\frac{\dot{m}}{\alpha} = 8.0 \times 10^{-4} \left(\frac{T_{crit}}{300}\right)^{3/2} \left(\frac{n_{crit}}{10^{10}}\right). \quad (21)$$

The obliquity μ at the given radius R could be inferred from Herrnstein et al. (1996), $\mu_{out} \sim 0.32$, at R_{out}=0.26 pc. At the inner edge of the annulus R_{in}=0.13 pc, $\mu_{in} \sim 0.1$. After we obtain the values of $\dot{m}/\alpha$ and correction factor f, the thickness of the disk is available from Eq. (13)

$$H_{in} = 3.4 \times 10^{-4} \left(\frac{T_{crit}}{300}\right)^{1/2} \text{pc, at } R_{in} = 0.13\text{pc} \quad (22)$$

and

$$H_{out} = 8.1 \times 10^{-4} \left(\frac{T_{crit}}{300}\right)^{1/2} \text{pc, at } R_{out} = 0.26\text{pc}, \quad (23)$$

which are consistent with the thin disk assumption. The vertical size of the maser clumps is very small and unable to be measured. The upper limit of it is 0.0003 pc (Moran et al. 1995). We suggest that the thickness of the disk could be larger than the vertical size of the water emission distribution, because the water maser may originate in a certain region of the disk or only part maser emission in the vertical direction is seen.

4. Discussion

We obtain that the mass accreting rate is $\sim 8 \times 10^{-4}\ \alpha$ M$_\odot$ yr^{-1}, if T_{crit} = 300 K and n_{crit} = 10^{10} cm^{-3} is applied. The viscosity coefficient α could not be greater than unity according to accretion disk theory requires that the upper limit of the accretion rate is $\sim 8 \times 10^{-4}$ M$_\odot$ yr^{-1}, which implies that the fractional Eddington luminosity is quite small: $L/L_{Edd} \leq 10^{-3}$ for NGC 4258. The percentage in X-ray range 1–100keV of the total bolometric luminosity η_x is $\sim 3 \times 10^{-3} x^{-1} \alpha^{-1}$. The obvious requirement $\eta_x < 1$ imposes the constraints that $\alpha > 3 \times 10^{-3} x^{-1}$ and $\dot{M} > 2.5 \times 10^{-6} x^{-1}$ M$_\odot$ yr^{-1}. If we assume that the black hole exists at the center of NGC 4258 is a non-rotating black hole, then x, the efficiency of luminosity generation due to mass accretion, is $\sim$ 0.05. So, the low limits on viscosity α and accretion rate $\dot{M}$ are, 0.06 and 5×10^{-5} M$_\odot$ yr^{-1}, respectively. The efficiency η_x is $\sim 0.06\alpha^{-1}$. Assuming that 2–10 keV X-rays account for 10 % of the bolometric flux (Mushotsky et al. 1993), we thus obtain $\dot{M} \sim 1.4 \times 10^{-4}$ M$_\odot$ yr^{-1} and $\alpha \sim$0.18.

The masing region perhaps extends beyond the annulus. The masers outside the annulus could not be seen due to orientation of the maser beam. If T_{crit} = 300 K and n_{crit} = 10^{10} cm^{-3}, we have $f_{in} \sim 0.11$ and $f_{out} \sim 0.34$ at the radii R_{in} and R_{out}, respectively. The results obtained are in agreement with the observation (Herrnstein et al. 1996). It is obvious that the correction factor f should satisfies $f \leq \mu$, μ is the obliquity of the disk. From Eqs. (19) and (20), we find that the values of correction factor f will be greater than the obliquity μ, if the masing region extends beyond the annulus. This implies that the masing region is almost the annulus in which the water masers are seen. The possibility that the masing region extends the annulus could be ruled out.

In this work, we employ the central X-ray source as the pump energy of the observed water masers in NGC 4258 and describe the disk as a single fluid. However, we can not rule out other possibilities, such as the presence of many clouds in the disk that produce the observed individual masers. The discussion of these other possibilities are beyond the scope of this work.

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