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Circumnuclear obscuration of the Circinus galaxy by a starburst-radiation supported wall

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Abstract. We consider the radiation-hydrodynamical formation of a dusty wall in the circumnuclear regions of the Circinus Seyfert 2 galaxy. We focus on the radiative flux force due to the circumnuclear starburst, the nuclear starburst and the active galactic nucleus (AGN), and analyze the equilibrium configuration and stability of the dusty gas in the circumnuclear regions. The mass distributions used to model the gravitational fields are determined by the observed rotation velocities of the stars and of the gas. Moreover, by using the simple stellar evolution in the circumnuclear starburst, the bolometric luminosity of the starburst is estimated as a function of time. As a result, it is shown that the radiation force by the circumnuclear starburst does play an important role to build up a radiatively-supported dusty wall of $\lesssim$100 pc, which obscures the circumnuclear regions with A_V of a few magnitudes. It is also found that the age of a circumnuclear starburst when the circumnuclear regions are enshrouded by the dusty wall is constrained to be $\lesssim$10^8 yr, which is consistent with the age observationally inferred for the starburst, $4\,10^7$ yr–$1.5\,10^8$ yr.

Key words. galaxies: active – galaxies: individual: Circinus – galaxies: nuclei – galaxies: starburst – radiative transfer

1. Introduction

The structure of the obscuring material around active galactic nuclei (AGNs) is one of the most hotly debated issues. Recently, it has been revealed that circumnuclear regions around AGNs are embedded in obscuring material extending up to $\gtrsim$100 pc (Rudy et al. 1988; Miller et al. 1991; Goodrich 1995; McLeod & Rieke 1995; Maiolino et al. 1995; Maiolino & Rieke 1995; Malkan et al. 1998), although a dusty torus of on the parsec scale is also thought to surround AGNs according to the unified model (Antonucci 1993, for a review). These facts may suggest that the obscuring material around an AGN is distributed not only in nuclear regions, but also in the circumnuclear regions on scales larger than some tens pc. The Circinus galaxy which is a nearby Seyfert 2 galaxy with a circumnuclear starburst is one of the most suitable objects to study the structure of the obscuring material in circumnuclear regions, since the galaxy has been studied on scales down to several tens parsecs. The N_H derived from X-ray observations imply the visual extinction, A_V, to be $\approx$2000 mag in the nuclear region within a few pc (Matt et al. 1999; Risaliti et al. 1999) and A_V inferred by IR and optical observations is a few 10 mag (Marconi et al. 1994; Alexander et al. 2000; Wilson et al. 2000). It should be noted that since the regions of X-ray emission is considerably inner

than those of IR emission, each inferred A_V may correspond to the spatially different obscuring material. On the other hand, A_V in the circumnuclear regions (100 pc scale) of this galaxy is also estimated to be a few mags as based on IR and optical observations (Maiolino et al. 1998; Oliva et al. 1999; Wilson et al. 2000).

Recently, Ohsuga & Umemura (1999) have proposed that the radiation force by a circumnuclear starburst is likely to play an important role in the circumnuclear regions, and it contributes to the obscuration through a large-scale obscuring wall which is radiatively supported by the circumnuclear starburst. The goal of this paper is to study the distributions of dusty gas in the circumnuclear regions of the Circinus galaxy from a radiation-hydrodynamical point of view. With this goal, we carefully treat, based on the recent observational data, the radiation sources and gravitational sources in the circumnuclear regions of the Circinus galaxy. Then, by considering the radiation force exerted both by the circumnuclear starburst and by the nuclear starburst as well as by the AGN, we analyze the equilibrium configuration and the stability of dusty gas in the circumnuclear regions. The paper is organized as follows. In Sect. 2, the radiation fields and gravitational fields are modeled based on the recent observations. In Sect. 3, the formation of a radiatively supported obscuring wall is presented. Section 4 is devoted to conclusions.

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2. Radiation fields and gravitational fields

2.1. Radiation sources

The intrinsic bolometric luminosity of the AGN component in the Circinus galaxy is estimated to be 10^{10} $L_\odot$ (Moorwood et al. 1996), and Hα images revealed that enhanced star formation occurs in nuclear regions (Marconi et al. 1994; Elmouttie et al. 1998a; Wilson et al. 2000). However, the AGN itself of the Circinus galaxy is thought to be surrounded by the obscuring material with an A_V of the order of a few tens to a thousand mags in the vicinity of the nucleus thus reducing its effect on the surrounding regions (Marconi et al. 1994; Matt et al. 1999; Alexander et al. 2000; Wilson et al. 2000). But, the nuclear starburst could exert radiation force on the dusty gas in circumnuclear regions. Maiolino et al. (1998) estimated that the bolometric luminosity of the nuclear starburst is only 20% or less of the AGN. On the other hand, the presence of a starforming ring at a radius of $\sim$200 pc is reported by Marconi et al. (1994), Elmouttie et al. (1998a), and Wilson et al. (2000). Based on the observed K-band luminosity and using stellar population synthesis models, Maiolino et al. (1998) have also argued that the bolometric luminosity of the circumnuclear starburst is $1.1\,10^{10}$ $L_\odot$ and its age is between $4\,10^7$ yr and $1.5\,10^8$ yr. Therefore, we assume two components of radiation sources, a nuclear starburst whose bolometric luminosity (L_{Nuc}) is $2\,10^9$ $L_\odot$ and a starburst ring of 200 pc whose bolometric luminosity (L_{Ring}) is $1.1\,10^{10}$ $L_\odot$ at the present day.

2.2. Gravitational sources

Based on the rotation velocities of stellar components or gaseous components in circumnuclear regions of $\lesssim$300 pc measured by Maiolino et al. (1998), most of the mass is not concentrated into a pointlike object but extended to a few hundred parsecs. The dynamical mass within the starburst ring is assessed to be at least 10^9 $M_\odot$ because the gaseous velocity at 200 pc is around 150 km s^{-1}. Moreover, it is reasonable to suppose that the mass distributions within the ring are uniform since the velocity is roughly proportional to the radius. An upper limit of the mass of a putative black hole is estimated as $4\,10^6$ $M_\odot$ by Maiolino et al. (1998) and Greenhill (2000) has detected a nuclear pointlike dark mass of $1.3\,10^6$ $M_\odot$. Elmouttie et al. (1998a) also reported that the starburst ring has an inclination angle of $40° \pm 10°$ and a rotation velocity of $\sim$350 km s^{-1}. This implies that the dynamical mass within the ring lies between $4\,10^9$ $M_\odot$ and $9\,10^9$ $M_\odot$. (Elmouttie et al. 1998b estimated the dynamical mass of the nucleus to be less than $3.9\,10^9$ $M_\odot$ by the observed rotation velocity of a molecular ring or disk with radius of about 300 pc. Although this conclusion does not agree with the estimate by the rotation velocity of the starburst ring, $\sim$4–9 10^9 $M_\odot$, it is not definitely inconsistent because the radiative flux force is comparable to the gravity in the vicinity of the ring and the net force which works on

the molecular gas could be weaker than the intrinsic gravity by the dynamical mass.) In addition, Jones et al. (1999) discovered that an H I ring or a disk of $\sim$1 kpc is rotating with a speed of at least 200 km s^{-1}, so that the total dynamical mass within 1 kpc is around $\sim$9 10^9 $M_\odot$. Therefore, we consider the gravitational potential that is determined by four components; the galactic bulge, the inner bulge, the starburst ring, and the central black hole. Here, we assume the galactic bulge to be a uniform sphere whose mass and radius are respectively M_{GB} and 1 kpc, the inner bulge to be a uniform sphere whose mass and radius are respectively M_{IB} and R_{IB}, and the mass of the central black hole to be $1.3\,10^6$ $M_\odot$. Here, it is noted that the gravity of the black hole does not play important role outside the central ten pc even if we adopt the upper limit $4\,10^6$ $M_\odot$ as the black hole mass. Taking account of the uncertainties in the modeling, we assume the mass of the inner bulge within 200 pc of between 10^9 $M_\odot$ and $9\,10^9$ $M_\odot$, and R_{IB} of $\gtrsim$200 pc based on the rotation curve given by Maiolino et al. (1998). The difference between the total mass ($\sim$9 10^9 $M_\odot$) within 1 kpc and the sum of other components is ascribed to the galactic bulge, M_{GB}. Although the mass distribution on the several hundred parsec scale is unknown, it does not have much influence on the circumnuclear structure of the dusty gas within a few hundred parsecs. The mass of the starburst ring should be determined by the subtraction of the inner bulge mass from the mass inferred by the rotation velocity at 200 pc. Hence, the mass of the starburst ring, M_{Ring}, is presumed to be between a few 10^8 $M_\odot$ and a few 10^9 $M_\odot$. Also, we adopt a simple starburst model consistent with that of Maiolino et al. (1998) in order to take account of the luminosity evolution of the starburst ring, where a Salpeter-type initial mass function (IMF) for a mass range of [1 $M_\odot$, 60 $M_\odot$], the star formation rate in the starburst regions, SFR $\propto \exp(-t/10^7$ yr$)$, the mass-luminosity relation, $(l_*/L_\odot) = (m_*/M_\odot)^{3.7}$, and the mass-age relation, $\tau = 1.1\,10^{10}$ yr $(m_*/M_\odot)^{-2.7}$, are employed.

3. Radiatively supported obscuring wall

Based upon the model constructed above and taking the effects by the optical depth into account, we calculate the radiative flux force which is exerted on the dusty gas. The radiative flux force exerted by the starburst ring at a point of (r, z) in cylindrical coordinates is given by

$$f_{\mathrm{Ring}}^i = \frac{\chi}{c} \int \frac{\rho_{\mathrm{Ring}}}{4\pi l_{\mathrm{Ring}}^2} \frac{1 - \exp(-\tau/\cos\theta_{\mathrm{Ring}})}{\tau/\cos\theta_{\mathrm{Ring}}} n^i \mathrm{d}V, \qquad (1)$$

where i denotes r or z, χ is the mass extinction coefficient for dusty gas (Umemura et al. 1998), c is the light speed, dV is an infinitesimal volume element of the starburst ring, l_{Ring} is the distance from (r, z) to this element, θ_{Ring} is the viewing angle from this element, ρ_{Ring} is the luminosity density of the starburst ring ($L_{\mathrm{Ring}} = \int \rho_{\mathrm{Ring}}\mathrm{d}V$), τ is the total optical depth of the wall, and n^i is a directional
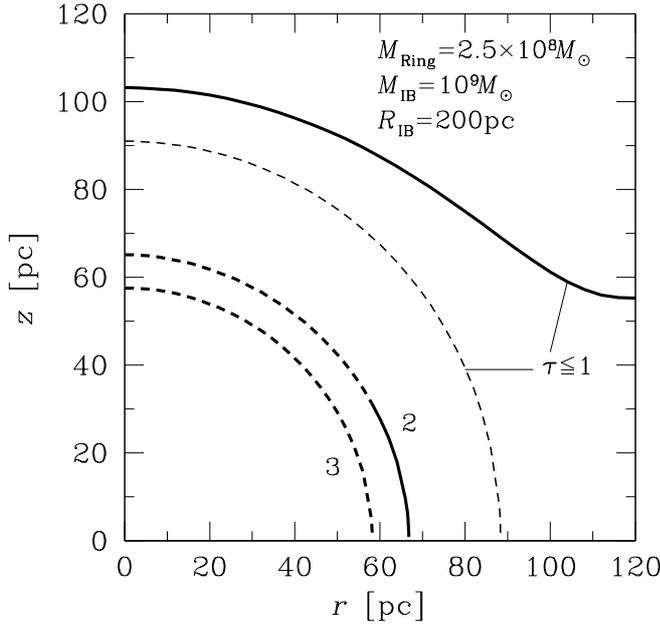
Fig. 1. Equilibrium configuration of dusty gas between the radiation force and gravity is shown in r-z space for $\tau = 3, 2$, and $\tau \leq 1$. Here, $M_{\mathrm{Ring}} = 2.5\,10^8\ M_\odot$, $R_{\mathrm{IB}} = 200$ pc, and $M_{\mathrm{IB}} = 10^9\ M_\odot$ are assumed. The thick and thin curves correspond to $t = 4\,10^7$ yr and $1.5\,10^8$ yr, respectively. In this model, the starburst age at the present time is $4\,10^7$ yr. The solid curves represent stable branches, while the dashed curves are stable in z directions but radially nonequilibrium branches. The solid curves show the final configuration of the stable obscuring wall. The circumnuclear regions are enshrouded by the obscuring wall of $\tau \sim$ a few at $4\ 10^7$ yr
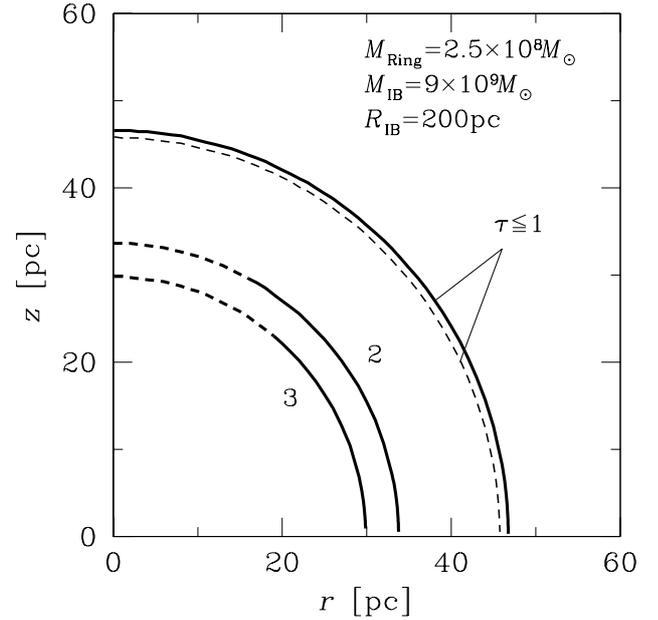

Fig. 2. Same as Fig. 1, but for $M_{\mathrm{IB}} = 9\,10^9\ M_\odot$. The circumnuclear regions are also enshrouded by the obscuring wall at $4\ 10^7$ yr. Thus, it is found that a stable wall forms which enshrouds the circumnuclear regions at $4\ 10^7$ yr regardless of uncertainties on gravitational fields

cosine (Ohsuga & Umemura 2001). Similarly, the radiative flux force by the nuclear starburst is presented by

$$f_{\mathrm{Nuc}}^i = \frac{\chi}{c} \frac{iL_{\mathrm{Nuc}}}{4\pi\,(r^2 + z^2)^{3/2}} \frac{1 - \exp(-\tau/\cos\theta_{\mathrm{Nuc}})}{\tau/\cos\theta_{\mathrm{Nuc}}}, \tag{2}$$

where θ_{Nuc} is the viewing angle from the center.

Using Eqs. (1) and (2), the equilibrium between the radiation force and the gravity is given by

$$-\frac{\mathrm{d}\Phi}{\mathrm{d}z} = f_{\mathrm{Ring}}^z + f_{\mathrm{Nuc}}^z + f_{\mathrm{grav}}^z = 0 \tag{3}$$

in the z (vertical) directions and

$$-\frac{\mathrm{d}\Phi}{\mathrm{d}r} = \frac{j^2}{r^3} + f_{\mathrm{Ring}}^r + f_{\mathrm{Nuc}}^r + f_{\mathrm{grav}}^r = 0 \tag{4}$$

in the r (radial) directions, where Φ is the effective potential, j is the specific angular momentum of dusty gas, and f_{grav}^i is the gravitational force. These equations are simultaneously solved to obtain the equilibrium configuration, by also taking into account of the conditions for the stability,

$$\frac{\mathrm{d}^2\Phi}{\mathrm{d}z^2} > 0, \tag{5}$$

and

$$\frac{\mathrm{d}^2\Phi}{\mathrm{d}r^2} > 0. \tag{6}$$

In Figs. 1 and 2, the resultant equilibrium branches are shown in the r-z space for $\tau = 3, 2$ and $\tau \leq 1$. Here, $M_{\mathrm{Ring}} = 2.5\,10^8\ M_\odot$ and $R_{\mathrm{IB}} = 200$ pc are assumed, and the age of the starburst ring at the present time is $4\,10^7$ yr. In both figures, the thick curves show the branches at the present, although the thin curves represent those at $1.5\,10^8$ yr. Also, owing to the uncertainties in the observational estimation of the inner bulge mass, we consider two extreme cases of $M_{\mathrm{IB}} = 10^9\ M_\odot$ in Fig. 1 and $M_{\mathrm{IB}} = 9\,10^9\ M_\odot$ in Fig. 2. The former corresponds to the case that the inner bulge has the smallest density. Although the inner bulge might extend to over 200 pc, the equilibrium branches of <200 pc are not affected by the size of the inner bulge itself and depend solely on the mass within 200 pc. The latter corresponds to the densest inner bulge. In this case, $M_{\mathrm{GB}} \sim 0$ and most of the mass is concentrated within 200 pc. In Figs. 1 and 2, all curves represent stable equilibrium branches in the z directions. Above the curves, the z component of the gravity, which works to lower the gas, is stronger than that of radiation force, while below the curves the radiation force lifts the gas towards the curves. However, the stable equilibrium states in the z directions do not always show the stable configuration of the obscuring wall. To find it, we need to check force balance (4) and stable condition (6) in the radial directions. In doing so we found that the force by the starburst ring plays an important role. This can be more directly understood by the argument of azimuthal components of the forces, where a unit vector in the azimuthal direction at a point of (r, z) is $(-z, r)/(r^2+z^2)^{1/2}$. Since the nuclear starburst, the bulge components, and the black hole provide spherical forces, they are not

exerted on dusty gas in the azimuthal directions. However, the centrifugal force and the force by the starburst ring have the azimuthal component. Therefore, the centrifugal force can only balance with the ring force. Since, as a result of the numerical integrations, it is found that the azimuthal component of the radiation force by the ring is counterclockwise on these figures and that of the gravity is clockwise in the same way as that of the centrifugal force, the stable wall forms only when the effective radiation force by the ring is stronger than the gravity by the ring at a point of branches. If these components are out of balance, the dusty gas could not be in equilibrium there, and then the branches are of radial nonequilibrium. In Figs. 1 and 2, the dashed curves are branches of radial nonequilibrium, and the solid curves show the stable branches both in the z (vertical) and in the r (radial) directions. Hence, these solid curves give the configuration of obscuring walls which are expected to actually form.

Figures 1 and 2 show that a stable wall forms which enshrouds the circumnuclear regions of several 10 pc–100 pc at $4\,10^7$ yr regardless of uncertainties on gravitational fields, although the size is smaller for a denser inner bulge. Then, the A_V of the wall would be about a few mags in spite of the uncertainties for the dust model, e.g. dust-to-gas mass ratio, the size distribution, and the composition. Near the rotation axis, the effective radiation force exerted on the wall by the ring is weakened due to the large optical depth measured along the light ray (see Eq. (1)), so that the radial equilibrium is not achieved. Thus, an opening forms near the axis. On the other hand, the wall turns to be radially nonequilibrium at $1.5\,10^8$ yr even for $\tau \leq 1$, since the bolometric luminosity of the ring decreases with time due to stellar evolution. (Here we do not take into account the time evolution of the bolometric luminosity of the nuclear starburst, but it does not have an influence on the force balance and stability in the r directions of the dusty gas.) We have found that, also for other sets of parameters, the Eddington ratio for the starburst ring itself gives a good criterion for the formation of a wall which enshrouds the circumnuclear regions, where Eddington luminosity is defined solely by the ring mass, $L_E = 4\pi c G M_{\mathrm{Ring}}/\chi$. A condition for the starburst age for which a stable wall can form is shown in Fig. 3, where we have considered the range of the observationally inferred ages, i.e. $4\,10^7$ yr–$1.5\,10^8$ yr. The condition depends upon the low mass cutoff of the IMF, m_{low}, although almost regardless of a reasonable range of the upper mass limit, m_{up}. As a result, we find a range of the starburst ages compatible with the observation. By taking into account the uncertainty on the IMF, it is concluded that the radiation force regulates the circumnuclear structure of the dusty gas in the Circinus galaxy if the age of the starburst is $\lesssim 10^8$ yr. In this case, the obscuration of the circumnuclear regions (A_V of a few mags) can be attributed to a radiatively-supported dusty wall. Incorporating the present picture with the other observed features, a schematic view of the Circinus galaxy is presented in Fig. 4.
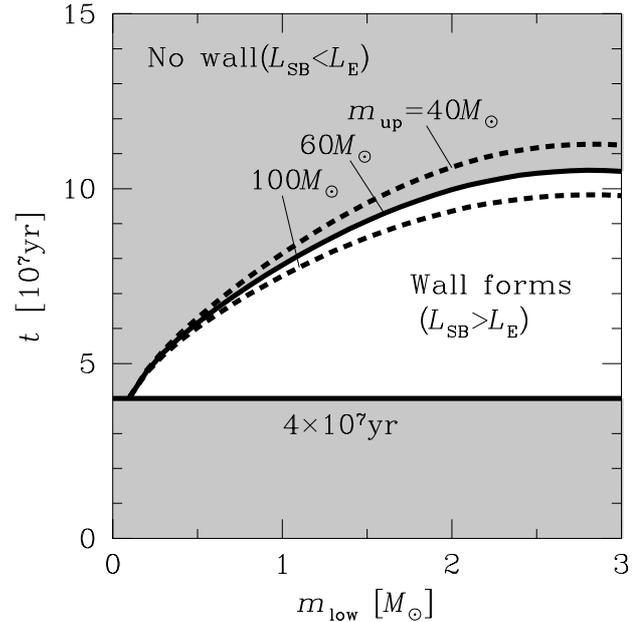

Fig. 3. A condition for the age of a starburst ring on which a radiatively-supported stable wall can form is shown as a function of the low mass cutoff of the IMF, m_{low}. The range of the observationally inferred age, i.e., $4\,10^7$ yr $-1.5\,10^8$ yr, is considered. Here, we assume the high mass cutoff of the IMF, m_{up}, to be 40 $M_\odot$, 60 $M_\odot$, or 100 $M_\odot$. Under the curves, the starburst ring is super-Eddington ($L_{\mathrm{Ring}} > L_E = 4\pi c G M_{\mathrm{Ring}}/\chi$), and then the radiation force supports a stable wall which enshrouds the circumnuclear regions, whereas no stable wall forms above the curves. Hence, the radiation force plays a significant role in the Circinus galaxy, if the age of a circumnuclear starburst ring lies in the white regions

4. Conclusions

To study the distributions of dusty gas in the circumnuclear regions of the Circinus galaxy, we have analyzed the equilibrium configurations and the stability of the dusty gas in the circumnuclear regions by considering the radiation force exerted by the circumnuclear starburst ring as well as by the central radiation source, which consists mainly of a nuclear starburst. As a result, it has been found that, within the observationally inferred age of a circumnuclear starburst ring in the Circinus galaxy, the radiation force can work to build up a dusty wall which enshrouds the circumnuclear regions. The wall may contribute to the obscuration of the region inside the nuclear 100 pc in this galaxy.

The visual extinction A_V of the wall could be a few mags. Also, if dusty gas which was blown away by stronger starburst radiation in earlier phases is afloat in the circumnuclear regions, A_V would ascend further. Although the detail is not given before multi-dimensional radiation hydrodynamics is treated (will be performed in the future analysis), A_V of the circumnuclear regions of the Circinus galaxy would be a few or several mags. In any case, the present picture provides a physical structure of the dusty gas in the circumnuclear regions, which is consistent with
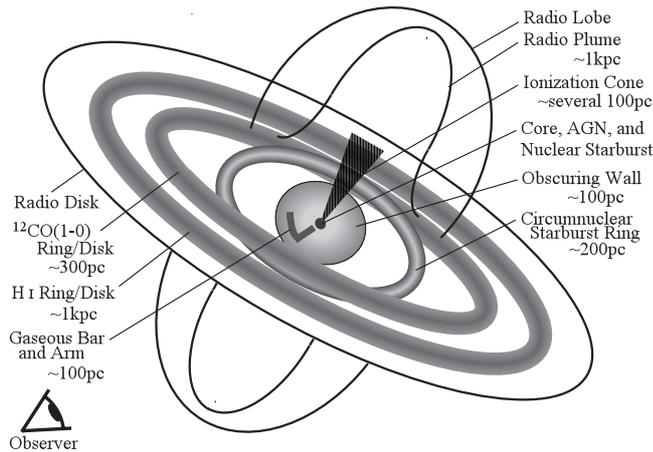
Fig. 4. A schematic view of the nuclear regions of the Circinus galaxy based upon the radiation-hydrodynamical modeling. In the central regions of the Circinus galaxy, there exist a Sy2 nucleus and a core which is observed by visible and near infrared coronal lines (Oliva et al. 1994), as well as Hα, and radio continuum emission (Elmouttie et al. 1998a). Moreover, an inner 100 pc bar and a spiral arm are discovered by Maiolino et al. (2000). It is reported that the ionization cone detected in Hα ($\sim$400 pc) and O[III] (500–900 pc) (Veilleux & Bland-Hawthorn 1997; Elmouttie et al. 1998a; Wilson et al. 2000) lies in the direction of NW. The obscuring wall is supported due to radiation force by the circumnuclear starburst ring as well as the nuclear starburst. Hence, the AGN, the core, and the bottom of the ionization cone would be obscured by the wall. A disk is detected by observations of radio continuum (Elmouttie et al. 1995), H$\,$I (Jones et al. 1999), and ^{12}CO(1–0) (Elmouttie et al. 1998b). These observations also revealed the ring-like features of ^{12}CO(1–0) of $\sim$350 pc and HI of $\sim$1 kpc, respectively. The inclination angle of the starburst ring ($40° \pm 10°$) is very different from the edge-on disk components. In addition, radio lobes and plume are detected by Elmouttie et al. (1995). The radio components are observed to be two-sided, whereas the ionization cone extends to the direction of NW only

the extended obscuring materials in the Circinus galaxy (Maiolino et al. 1998; Oliva Marconi & Moorwood 1999; Wilson et al. 2000).

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