FORMATION OF LARGE-SCALE OBSCURING WALL AND ACTIVE GALACTIC NUCLEUS EVOLUTION REGULATED BY CIRCUMNUCLEAR STARBURSTS

KEN OHSGA AND MASAYUKI UMEMURA

Center for Computational Physics, University of Tsukuba, Tsukuba, Ibaraki 305-8577, Japan

Received 1999 April 28; accepted 1999 June 11; published 1999 July 15

ABSTRACT

By considering the radiative force by a circumnuclear starburst as well as an active galactic nucleus (AGN), we analyze the equilibrium configuration and the stability of dusty gas in the circumnuclear regions. It is found that the radiative force by an intense starburst can support a stable gaseous wall with a scale height of several hundred parsecs. Moreover, by taking the simple stellar evolution in the starburst into account, we find that the covering factor of the wall decreases on a timescale of several times $10^7$ yr. The large-scale wall, if formed, works to obscure the nucleus as a result of the dust opacity. Hence, it is anticipated that the index of AGN type tends to shift from higher to lower in several times $10^7$ yr as the circumnuclear starburst becomes dimmer. On the other hand, if the AGN itself is brighter than the circumnuclear starburst (e.g., the quasar case), no stable large-scale wall forms. In that case, the AGN is most probably identified as type 1. The present mechanism may provide a physical explanation for the putative correlation between AGN type and host properties whereby Seyfert type 2 galaxies are more frequently associated with circumnuclear starbursts than type 1 galaxies, whereas quasars are mostly observed as type 1 regardless of star-forming activity in the host galaxies.

Subject headings: galaxies: active — galaxies: evolution — galaxies: nuclei — galaxies: starburst — quasars: general — radiative transfer

1. INTRODUCTION

Recently, intriguing evidence regarding the host galaxies of active galactic nuclei (AGNs) and quasars (QSOs) has been accumulated. First, it has been reported that the host galaxies of Seyferts are intrinsically unlike between type 1 and type 2 (Heckman et al. 1989; Maiolino et al. 1995, 1997, 1998; Pérez-Olea & Colina 1996; Hunt et al. 1997; Malkan, Gorjian, & Tam 1998; Storchi-Bergmann & Schmitt 1998; Maiolino, Risaliti, & Salvatii 1999). Seyfert 1 galaxies inhabit earlier-type quiescent hosts, whereas Seyfert 2 galaxies are frequently associated with circumnuclear starbursts, which often lie in barred galaxies. The observations may indicate that type 2’s are in an earlier evolutionary stage than type 1’s (Radovich, Rafanelli, & Barbon 1998), whereas in the unified model (see Antonucci 1993 for a review) this dichotomy is simply accounted for by the orientation of the nucleus with an obscuring torus of subparsec scale. Second, the recent Hubble Space Telescope images of nearby QSOs have shown that luminous QSO phenomena occur preferentially in luminous host galaxies, often being elliptical galaxies (McLeod & Rieke 1995b; Bahcall, Kirhakos, & Saxe 1997; Hooper, Limpy, & Foltz 1997). Also, at high redshifts, toward QSO H1413+117 at $z = 2.546$ (“cloverleaf,” a gravitationally lensed quasar) and QSO BR 1202−0725 at $z = 4.69$, a large amount of dust has been detected, i.e., $10^5 M_\odot$ for H1413+117 and $10^6 M_\odot$ for BR 1202−0725 (Barvainis, Antonucci, & Coleman 1992; Omont et al. 1996). Molecular gas of at least $10^8 M_\odot$ is also found for BR 1202−0725 (Ohta et al. 1996a). These suggest that active star formation is ongoing around the quasars.

QSOs, however, are mostly identified as type 1, and only a few type 2 QSOs have been discovered so far (Almaini et al. 1995; Ohta et al. 1996b; Brandt et al. 1997). Hence, a circumnuclear starburst does not seem to indicate type 2 as far as quasars are concerned. QSOs are distinctive from Seyfert galaxies in that the host galaxy is in general fainter than the AGN itself (McLeod & Rieke 1995b; Bahcall et al. 1997; Hooper et al. 1997). These facts regarding the host properties for Seyferts and QSOs suggest a possibility that the AGN type has a close relation to circumnuclear starburst events and the relative luminosity of the starburst to the AGN.

We consider a physical mechanism which may connect circumnuclear star-forming activities with AGN type. Here, attention is concentrated on the radiative force by the circumnuclear starburst. In ultraluminous IR galaxies, the observed IR luminosities (Scoville et al. 1986; Soifer et al. 1986) are comparable to or greater than the Eddington luminosity for dust opacity (Umemura et al. 1998, 1999). Hence, the radiative force is very likely to play an important role in the circumnuclear structure at $\sim 100$ pc. In this Letter, supposing the mass distribution in circumnuclear regions, we analyze the equilibrium configuration and the stability of dusty gas which is supported by radiative force by a starburst and an AGN.

In addition, taking the stellar evolution in the starburst regions into consideration, we investigate the time evolution of gas distributions and attempt to relate the luminosity of the circumnuclear starburst to the evolution of the AGN type.

2. RADIATIVELY SUPPORTED OBSCURING WALL

The circumnuclear starburst regions frequently exhibit ring-like features and have a radial extension of $\sim 10$ pc up to $1$ kpc (Wilson et al. 1991; Forbes et al. 1994; Mauder et al. 1994; Buta, Purcell, & Crocker 1995; Barth et al. 1995; Maoz et al. 1996; Leitherer et al. 1996; Storchi-Bergmann, Wilson, & Baldwin 1996). Thus, here we consider a ring-shaped starburst. (If the starburst regions are anisotropic or clumpy, the effects are expected to be smeared out as discussed later.) We calculate the radiation force and the gravity which are exerted on the dusty gas. Here, the gravitational potential is determined by four components, the galactic bulge, the central black hole, the gas disk, and the starburst ring. We assume the galactic bulge to be an uniform sphere whose mass and radius are $M_{\text{bul}}$ and $R_{\text{bul}}$, the mass of the central black hole to be $M_{\text{bh}}$, the gas disk to be a Mestel disk whose mass and radius are $M_{\text{disk}}$ and $R_{\text{disk}}$, and the starburst ring to be an uniform torus whose mass,
In the vertical directions and cylindrical coordinates, where curvature radius, thickness, and bolometric luminosity are $M_{SB}$, $R_{SB}$, $a_{SB}$, and $L_{SB}$, respectively (see Fig. 1). The observations of IRAS galaxies by Scoville et al. (1991) show that the central regions within several hundred parsecs possess a gas mass of $\lesssim 10^{10} \, M_\odot$. By taking this fact into account, we adopt the mass ratio as $M_{bul} : M_{BH} : M_{disk} : M_{SB} = 1 : 0.01 : 0.1 : 1$.

Also, it is found that the starburst ring often consists of compact star clusters of $\lesssim 10$ pc (Barth et al. 1995; Maoz et al. 1996; Leitherer et al. 1996). The size of these clusters is about a tenth of the radial extension of the starburst ring. Therefore, we assume $R_{bul} : R_{disk} : R_{SB} : a_{SB} = 10 : 1 : 1 : 0.1$. In addition, the nucleus is postulated to be a point source whose bolometric luminosity is $L_{nuc}$.

Here the material is assumed to be subject to the radiative force directly by the starburst radiation. The radiation flux by an infinitesimal volume element, $dV$, of the starburst ring is given by $dF(r, z) = (\rho_{SB} / 4\pi l^2) n dV$, at a point of $(r, z)$ in cylindrical coordinates, where $l$ denotes $r$ or $z$. $\rho_{SB} (= L_{SB} / 2\pi^2 a_{SB}^2 R_{SB})$ is the luminosity density of the starburst ring, $l$ is the distance from $(r, z)$ to this element, and $n$ is a directional cosine. Hence, the radiation flux force by the starburst ring and the nucleus at $(r, z)$ is given by

$$f_{rad}^\circ = \frac{X}{c} \int \frac{\rho_{SB}}{4\pi l^2} n dV + \frac{X}{c} \frac{IL_{nuc}}{4\pi (r^2 + z^2)^{3/2}} ,$$

(1)

where $X$ is the mass extinction coefficient for the dusty gas (Umemura et al. 1998) and $c$ is the light speed. Using equation (1), the equilibrium between the radiation force and the gravity is written as

$$f_{rad}^\circ + f_{grav}^\circ = 0$$

(2)

in the vertical directions and

$$j^3 \frac{r}{z} + f_{rad}^\circ + f_{grav}^\circ = 0$$

(3)

in the radial directions, where $j$ is the specific angular momentum of the dusty gas and $f_{grav}^\circ$ is the gravitational force.

Figure 2 shows that stable branches emerge only for $\Gamma_{SB} \lesssim 1$. This agrees with a naive expectation. If $\Gamma_{SB} > 1$, the radiation force blows out the dusty gas in most regions (e.g., see a dotted curve of $\Gamma_{SB} = 2$). When $\Gamma_{SB} \lesssim 1$, the covering factor of the stable wall is a function of $\Gamma_{SB}$. If $\Gamma_{SB} \sim 1$, the wall surrounds both the nucleus and the starburst ring. When the starburst luminosity is smaller than $\Gamma_{SB} = 0.55$, the wall forms only in the vicinity of the starburst ring and exhibits a torus-like configuration.

In order to achieve the configuration of a finally stable equilibrium, the stability in the radial directions must also be taken into consideration. On the dashed curves, the effective potential in the radial directions turns out to be locally maximal. Thus, the dashed curves are unstable points of saddle type. Finally, only the solid curves are stable branches.

Figure 2 shows that stable branches emerge only for $\Gamma_{SB} \lesssim 1$. This agrees with a naive expectation. If $\Gamma_{SB} > 1$, the radiation force blows out the dusty gas in most regions (e.g., see a dotted curve of $\Gamma_{SB} = 2$). When $\Gamma_{SB} \lesssim 1$, the covering factor of the stable wall is a function of $\Gamma_{SB}$. If $\Gamma_{SB} \sim 1$, the wall surrounds both the nucleus and the starburst ring. When the starburst luminosity is smaller than $\Gamma_{SB} = 0.55$, the wall forms only in the vicinity of the starburst ring and exhibits a torus-like configuration.
The $A_r$ of the wall is expected to be at least several, because the radiative force directly from a starburst can be exerted on such a wall. Then, this large-scale wall of dusty gas would work to obscure the nucleus. When the flux force of scattered diffuse radiation operates efficiently on the wall, a wall of larger optical depth may be supported and therefore $A_r$ could be much larger. (This detail should be investigated by multidimensional radiation hydrodynamics, which will be performed in a future analysis.)

If the $A_r$ of the wall is only several magnitudes, the AGN would be changed to an intermediate type between type 2 and 1, e.g., type 1.2, 1.5, and so on, whereas an $A_r$ greater than 10 mag would result in a perfect shift from type 1 to type 2.

Next, we examine the case that the nucleus is brighter than the circumnuclear starburst (case B). In this case, only vertically stable branches emerge even if $\Gamma_{SB} + \Gamma_{nucl} < 1$ (see Fig. 3). On the dashed curves in Figure 3, in contrast to case A, there is no solution for the radial equilibrium, regardless of the value of starburst luminosity. The gas around the dashed curves is swung away because of the cooperation of radiative force and angular momentum. As a result, the formation of the stable wall is precluded in case B. This implies that the luminous nuclei like QSOs are not likely to be obscured, which are therefore mostly identified as type 1.

Further, for case A, we consider the effects of stellar evolution in the starburst regions on the stable equilibrium branches. We assume a Salpeter-type initial mass function (IMF), $\phi = A(m_*/M_\odot)^{-1.35}$, the mass-luminosity relation $(L_*/L_\odot) = (m_*/M_\odot)^{0.7}$, and the mass-age relation $t = 1.1 \times 10^{10} \text{ yr}(m_*/M_\odot)^{-2}$, where $m_*$ and $L_*$ are, respectively, the stellar mass and luminosity. Recently, it has been revealed that in starburst regions the IMF is deficient in low-mass stars, with the cutoff of about $2 M_\odot$, and the upper mass limit is inferred to be around $40 M_\odot$ (Doyon, Puxley, & Joseph 1992; Charlot et al. 1993; Doane & Mathews 1993; Hill et al. 1994; Brandl et al. 1996). Using the IMF for a mass range of $[2 M_\odot, 40 M_\odot]$ and the above relations, the total stellar luminosity of starburst regions is given by a function of time as $L_* = 1.5 \times 10^{10}(87t_7^{0.87} - 1)(M_{SB}/10^{10} M_\odot)L_\odot$, where $t_7$ is the elapsed time after the coeval starburst in units of $10^7$ yr. Also, if we postulate that stars with masses greater than $8 M_\odot$ are destined to undergo supernova explosions and release the energy radiatively with the efficiency of $\epsilon$ to the rest mass energy, the total supernova luminosity is $L_{SN} = 1.7 \times 10^{11}t_7^{0.87}(M_{SB}/10^{10} M_\odot)(\epsilon/10^{-4})L_\odot$ until $t_7 = 4.0$ and $L_{SN} = 0$ when $t_7 > 4.0$. Hence, the total luminosity of the starburst ring is given by

$$L_{SB}(t_7) = L_* + L_{SN}. \quad (4)$$

Using this dependence on time, the luminosity can be translated into the age of the starburst regions. Therefore, the values of $\Gamma_{SB}$ in Figure 2 represent the evolutionary stage of the circumnuclear starburst. For instance, if we adopt $M_{SB} = 10^{10} M_\odot$, $\Gamma_{SB} = 1$ and 0.55 correspond to $4.2 \times 10^7$ and $8.1 \times 10^7$ yr, respectively.

To summarize, if $\Gamma_{SB} > 1$ in the early evolutionary stage, the dusty gas is blown away by radiative acceleration. Since the blown-out dusty gas would emit strong IR radiation, we may recognize the objects as ultraluminous IR galaxies. When $\Gamma_{SB}$ becomes just below unity, both the nucleus and the starburst ring are surrounded by the dusty wall. Then, the AGN is likely to be type 2. In the later stages, the dusty gas forms a torus-like obscuring wall, which shrinks on a timescale of several times $10^7$ yr. Then, the AGN tends to be identified as type 1 for a wide viewing angle. This implies that the type of AGN evolves from higher to lower in several times $10^7$ yr as the circumnuclear starburst becomes dimmer.

3. DISCUSSION

Here we have assumed that the nuclear activity and the circumnuclear starburst are simultaneous events. A solution, for instance, which links the two events is the radiatively driven mass accretion onto a central black hole due to the radiation drag (Umemura et al. 1997, 1998; Ohsuga et al. 1999). However, in very early luminous phases of the starburst, the mass accretion onto the black hole is prevented because of the super-Eddington radiative force. It results in a radiative blizzard in the nuclear regions. Thus, the nucleus is identified only as an ultraluminous IR galaxy without being accompanied by an AGN. We predict in the present model that ultraluminous IR galaxies evolve into Seyfert galaxies or QSOs in later, less luminous phases of the starburst.

The circumnuclear starburst could not be axisymmetric but clumpy. However, the rotational timescale of the starburst ring is shorter than the shrinking timescale of the obscuring wall. In the present case, the former is around $3.0 \times 10^7$ yr and the latter is several times $10^7$ yr. Therefore, the anisotropies of the starburst are expected to be smeared out by a “wheel effect.”

The stable obscuring wall might be subject to the other local instabilities, i.e., Rayleigh-Taylor or self-gravitational instabilities. The density gradient of the dusty wall is positive inside the equilibrium surface and negative outside the surface. They are in the same directions as the effective acceleration. Thus, the wall would not be subject to Rayleigh-Taylor instabilities. As for the self-gravitational instability, the timescale of the instability could be as short as $\approx 10^6$ yr. So, the wall may fragment on a timescale shorter than the evolutionary timescale.
of the wall. Then, numerous compact gas clouds would form in the wall. They would emit narrow emission lines because they have a velocity dispersion of several 100 km s\(^{-1}\). Also, if the compact clouds are optically thick, the radiative force is less effective for them, so that they fall into the central regions. They also may partially obscure the nucleus.

In this Letter, we do not argue that a conventional obscuring torus of subparsec scale is dispensable. Even if the inner obscuring torus may operate to intrinsically differentiate the type of AGNs, the present large-scale wall can work also to raise further the type index. In particular, the present mechanism may provide a physical solution to account for the tendency that type 2 Seyfert galaxies are more frequently associated with circum nuclear starbursts than type 1's, whereas quasars are mostly observed as type 1 regardless of star-forming activity in the host galaxies.

If we adopt values for size and mass that conform to realistic values, e.g., \(R_{\text{SB}} \approx 100 \text{ pc} \) and \(M_{\text{SB}} \approx 10^{10} M_\odot\), the obscuring wall is extended to several hundred parsecs. Interestingly, it is recently reported that the spectra of a sample of AGNs are more consistent with obscuring material extended up to \(\approx 100 \text{ pc}\) around the nuclei (Rudy, Cohen, & Ake 1988; Miller, Goodrich, & Mathews 1991; Scarrott et al. 1991; Goodrich 1995; McLeod & Rieke 1995a; Maiolino et al. 1995; Maiolino & Rieke 1995), and the hosts of Seyfert 2 galaxies possess more frequently extended dust lanes (Malkan et al. 1998).

Also, the covering factor of a dusty torus around a QSO, M\(0414+0534\), is fairly small (Ohta et al. 1999). These observations are quite intriguing in the light of the present picture.

We are grateful to T. Nakamoto, H. Susa, and S. Oya for helpful discussion. The calculations were carried out at the Center for Computational Physics in University of Tsukuba. This work is supported in part by Research Fellowships of the Japan Society for the Promotion of Science for Young Scientists, 6957 (K. O.) and the Grants-in-Aid of the Ministry of Education, Science, Culture, and Sport, 09874055 (M. U.).

REFERENCES

Almaini, O., et al. 1995, MNRAS, 277, L31
Antonucci, R. R. J. 1993, ARA&A, 30, 705
Bahcall, J. N.,Kirshkos, S., & Saxe, D. H. 1997, ApJ, 479, 642
Barth, A. J., Ho, L. C.,Filipenko, A. V., & Sargent, W. L. W. 1995, AJ, 110, 1009
Barvainis, R., Antonucci, R., & Coleman, P. 1992, ApJ, 399, L19
Brandl, B., et al. 1996, ApJ, 466, 254
Brandt, W. N., et al. 1997, MNRAS, 290, 617
Buta, R., Purcell, G. B., & Crocker, D. A. 1995, AJ, 110, 1588
Charlot, S., Ferrari, F., Mathews, G. J., & Silk, J. 1993, ApJ, 419, L57
Doane, J. S., & Mathews, W. G. 1993, ApJ, 419, 573
Doyon, R., Puxley, P. J., & Joseph, R. D. 1992, ApJ, 397, 117
Forbes, D. A., Norris, R. P., Williger, G. M., & Smith, R. C. 1994, AJ, 107, 984
Goodrich, R. W. 1995, ApJ, 440, 141
Heckman, T. M., Blitz, L., Wilson, A. S., Armus, L., & Miley, G. K. 1989, ApJ, 342, 735
Hill, J. K., et al. 1994, ApJ, 425, 122
Hooper, E. J.,Impey, C. D., & Foltz, C. B. 1997, ApJ, 480, L95
Hunt, L. K., et al. 1997, ApJS, 108, 229
Leitherer, C., et al. 1996, ApJ, 465, 717
Maiolino, R., Krabbe, Thatte, N., & Genzel, R. 1998, ApJ, 493, 650
Maiolino, R. & Rieke, G. H. 1995, ApJ, 454, 95
Maiolino, R., Risaliti, G., & Salvati, M. 1999, A&A, 341, L35
Maiolino, R., Ruiz, M., Rieke, G. H., & Keller, L. D. 1995, ApJ, 446, 561
Maiolino, R., Ruiz, M., Rieke, G. H., & Papadopoulos, P. 1997, ApJ, 485, 552
Malkan, M. A., Gorjian, V., & Tam, R. 1998, ApJS, 117, 25
Maoz, D., et al. 1996, AJ, 111, 2248
Mauder, W., Weigelt, G., Appenzeller, I., & Wagner, S. J. 1994, A&A, 285, 44
McLeod, K. K. & Rieke, G. H. 1995a, ApJ, 441, 96
———. 1995b, ApJ, 454, L77
Miller, J. S., Goodrich, R. W., & Mathews, W. G. 1991, ApJ, 378, 47
Ohsuga, K., Unemura, M., Fukue, J., & Mineshige, S. 1999, PASJ, in press
Ohta, K., et al. 1996a, Nature, 382, 426
———. 1996b, ApJ, 458, L57
Omont, A., et al. 1996, Nature, 382, 428
Oya, S., Iwai, J., Iwamuro, F., & Maihara, T. 1999, in The Universe as Seen by ISO, ed. P. Cox & M. Kessler (ESA SP-427; Noordwijk:ESA), in press
Pérez-Olea, D. E. & Colina, L. 1996, ApJ, 468, 191
Radovich, M., Rafanelli, P., & Barbon, R. 1998, A&A, 334, 124
Rudy, R. J., Cohen, R. D., & Ake, T. B. 1988, ApJ, 332, 172
Scarrott, S. M., Rolph, C. D., Wolkstencroft, R. W., & Tadhunter, C. N. 1991, MNRAS, 249, 16p
Scoville, N. Z., et al. 1986, ApJ, 311, L47
Scoville, N. Z., Sargent, A. I., Sanders, D. B., & Soifer, B. T. 1991, ApJ, 366, L5
Soifer, B. T., et al. 1986, ApJ, 303, L41
Storchi-Bergmann, T. & Schmitt, H. R. 1998, preprint (astro-ph/9812017)
Storchi-Bergmann, T., Wilson, A. S., & Baldwin, J. A. 1996, ApJ, 460, 252
Unemura, M., Fukue, J., & Mineshige, S. 1997, ApJ, 479, L97
———. 1998, MNRAS, 229, 1123
Wilson, A. S., Helfer, T. T., Haniff, C. A., & Ward, M. J. 1991, ApJ, 381, 79