SUPPRESSED STAR FORMATION IN CIRCUMNUCLEAR REGIONS IN SEYFERT GALAXIES

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ABSTRACT

Feedback from black hole activity is widely believed to play a key role in regulating star formation and black hole growth. A long-standing issue is the relation between star formation and the fueling of the supermassive black holes in active galactic nuclei (AGNs). We compile a sample of 57 Seyfert galaxies to tackle this issue. We estimate the surface densities of gas and star formation rates in circumnuclear regions (CNRs). Comparing them with the well-known Kennicut-Schmidt (K-S) law, we find that the star formation rates (SFRs) in the CNRs of most Seyfert galaxies are significantly lower than the rates predicted by the Kennicut-Schmidt law. We find that the star formation rates in Seyfert galaxies are suppressed in this sample. Feedback is suggested to explain the suppressed SFRs.

Subject headings: galaxies: active — galaxies: Seyfert — galaxies: starburst

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1. INTRODUCTION

The implications of the well-known relation between black hole mass, bulge magnitude (Magorrian et al. 1998), and velocity dispersion (Gebhardt et al. 2000; Ferrarese & Merritt 2000) show a coevolution of black holes and their host galaxies. However, questions as to how black holes know which evolutionary stage their host galaxies are in and how the growth of the black holes is controlled are still under study via feedback from black holes (Silk & Rees 1998; Croton et al. 2006; Schawinski et al. 2006). Numerical simulations show that there are two roles that feedback plays in black hole activity: (1) modulating the star formation rates and (2) heating the medium and finally quenching the black hole activity (Di Matteo et al. 2005). The direct evidence for the presence of the feedback from active black holes has yet to be shown from observations.

The main goal of the present Letter is to show one piece of evidence for the role of feedback in active galaxies. We show the AGN feedback domain, where starbursts should be suppressed. We find that the star formation rates in Seyfert galaxies are significantly lower than the rates predicted by the Kennicut-Schmidt’s law. We use the cosmological parameters $H_0 = 75 \text{ km s}^{-1} \text{ Mpc}^{-1}$, $\Omega_m = 0.3$, and $\Omega_\Lambda = 0.7$ throughout.

2. AGN FEEDBACK DOMAIN

When the CNR medium is optically thick, namely, the optical depth $\tau = \kappa_{\text{abs}} \Sigma_{\text{gas}} \geq 1$, where $\kappa_{\text{abs}}$ is the opacity and $\Sigma_{\text{gas}}$ is the gas surface density, the radiation from black hole activity will continuously heat the medium and blow the gas away so as to lower the star formation rates. The condition of $\tau = 1$ yields a critical density

$$\Sigma_{\text{gas}}^{\tau=1} = 9.0 \times 10^5 (\kappa_{\text{abs}}/5)^{-1} M_\odot \text{ pc}^{-2}, \quad (1)$$

where $\kappa_{\text{abs}}$ has a mean value of 5 for the CNR medium (Semenov et al. 2003). This is feedback driven by AGN radiation. We note that the outflows from the Seyfert active nucleus have much lower kinetic luminosities, typically ~10^{-15} L_{\text{bol}} = 10^{-15} L_{\text{bol}} based on warmer X-ray absorbers (Blustin et al. 2005), where $L_{\text{bol}}$ is the bolometric luminosity. Thus, feedback from outflows could be neglected. When $\Sigma_{\text{gas}} > \Sigma_{\text{gas}}^{\tau=1}$, the AGN radiation-driven feedback will suppress star formation.

On the other hand, AGN feedback reaches its maximum when an AGN radiates at the Eddington limit $L_{\text{AGN}} = L_{\text{Edd}} = 1.3 \times 10^{39} (M_*/M_\odot)$ ergs s^{-1}. In the case of $L_{\text{Edd}} \leq L_{\text{SFR}}$, AGNs have inefficient feedback to star formation. With the help of $\text{SFR} = 4.5(L_{\text{IR}}/10^4 \text{ ergs s}^{-1}) M_\odot \text{ yr}^{-1}$, $\Sigma_{\text{gas}}$ is given by using the K-S law

$$\Sigma_{\text{gas}}^{\tau=1} = 8.2 \times 10^4 M_\odot^{0.7} R_{\odot}^{-1.4} M_\odot \text{ pc}^{-2}, \quad (2)$$

where $\Sigma_{\text{SFR}} = \text{SFR}/4\pi R^2$ is the surface density of the star formation rate, $A = 2.5 \times 10^{-4}$, $\gamma = 1.4$, $M_\odot = M_\odot/10^5 M_\odot$ is the black hole mass, and $R_{\odot} = R/200 \text{ pc}$ is the size of the circumnuclear star-forming region. When $\Sigma_{\text{gas}} \geq \Sigma_{\text{gas}}^{\tau=1}$, the gas is so dense that the luminosity from star formation dominates over the AGN. We call

$$\Sigma_{\text{gas}}^{\tau=1} \leq \Sigma_{\text{gas}} \leq \Sigma_{\text{gas}}^{\tau=1} \quad (3)$$

the AGN feedback domain, as shown in Figure 1, in which the K-S law is broken.

The strong radiation pressure from the black hole accretion disk at the Eddington limit is $P_{\text{AGN}} \approx 1.0 \times 10^4 M_\odot R_{\odot}^2$ dyn cm^{-2}, where $M_\odot = M_\odot/10^5 M_\odot$. The pressure from a supernova explosion is $P_{\text{SN}} = \epsilon_{\text{SN}} \Sigma_{\text{SFR}} c^2 = 2.0 \times 10^4 \text{ dyn cm}^{-2}$, where $\Sigma_{\text{SFR}} = \sum_{\text{SFR}}/10^5 M_\odot \text{ yr}^{-1} \text{ kpc}^{-2}$ and $\epsilon_{\text{SN}} = \epsilon/10^3$ is the efficiency converting the mass into radiation (Thompson et al. 2005). We find $P_{\text{AGN}} \geq 5P_{\text{SN}}$ within CNRs of radius ~100 pc for typical values of the parameters of $\epsilon$, $M_\odot$, and $\Sigma_{\text{SFR}}$. This indicates that the radiation from an AGN dominates over the local feedback from a supernova explosion. After an AGN switches on, star formation is suppressed, and thus feedback from supernovae is further weakened. The timescale of the AGN feedback to the starburst regions can be estimated by $t_{\text{FB}} \approx \Sigma_{\text{gas}}/f_{\text{FB}} C_{\text{AGN}}$, where $C_{\text{AGN}}$ is the AGN luminosity, $C = \Delta \Omega/4\pi$ is the covering factor, the thermal energy $E_{\text{gas}} \approx k T M_{\text{gas}} m_p$, $k$ is the Boltzmann constant, $m_p$ is the proton mass, $T$ is the gas temperature, $M_{\text{gas}} = \pi R^2 \Sigma_{\text{gas}}$ is the gas mass, and $f_{\text{FB}}$ is the feedback efficiency. We have

$$t_{\text{FB}} \approx 2.6 \times 10^4 f_{\text{FB}}^{-1} R_{\odot}^2 T_{\odot} \Sigma_{\text{gas}} C_{\text{AGN}}^{-1} \text{ yr}, \quad (4)$$

where $\Sigma_{\text{gas},4} = \Sigma_{\text{gas}}/10^4 M_\odot \text{ pc}^{-2}$, $T_{\odot} = T/2 \times 10^3$ K, $f_{\text{FB},-2} = f_{\text{FB}}/10^{-2}$, $L_{\text{AGN}} = L_{\text{AGN}}/10^4$ ergs s^{-1}, and $C_{\text{AGN}} = \sigma/0.5$ is the covering factor of the CNRs. Such a short timescale indicates that the AGN feedback is very efficient. This is sup-
ported by a large fraction of the poststarburst AGNs in a large Sloan Digital Sky Survey sample (Kauffmann et al. 2003). The physics behind the K-S law is not sufficiently understood (Thompson et al. 2005; Krumholz & McKee 2005). It is beyond the scope of the present Letter to give a quantitative description of the suppressed star formation rates. Comparing Seyfert galaxies with the K-S law, a universal rule of cosmic star formation, we may get at the underlying physics of the CNRs.

We have to point out here that the short feedback time does not mean the same timescale as the starburst. The present t_{FB} means that the starburst rates will be suppressed once the AGN is triggered and that they will make it possible for the AGN and the starburst to coexist.

3. APPEARANCE OF FEEDBACK IN SEYFERT GALAXIES

For the goal of testing the above scenario, we compile 57 Seyfert galaxies (Imanishi 2002, 2003; Imanishi & Wada 2004).

The star formation rates in CNRs of Seyfert galaxies can be traced by several indicators, particularly, polycyclic aromatic hydrocarbon (PAH) features at 3.3, 6.2, 7.7, 8.6, and 11.2 μm, which radiate from vibration of PAH grains containing about 50 carbon atoms. Among the features, 3.3 μm emission is intrinsically strong and less affected by broad silicate dust absorption (Imanishi 2002). We choose 3.3 μm emission as an indicator of the star formation rate. We convert the PAH emission into IR luminosity via the relation with a3

\[
\Sigma_{\text{SFR}} = 35.8L_{\text{PAH},44}R_{200}^{-2}\left(M_\odot\text{yr}^{-1}\text{kpc}^{-2}\right),
\]

by using the relation between star formation rate and infrared luminosity (see eq. [7] in Kennicutt 1998a), where \(L_{\text{PAH},44} = L_{\text{PAH}}/10^{44}\) erg s\(^{-1}\). On the other hand, the infrared emission from Seyfert galaxies covers the contribution from starbursts, and by reprocessing radiation from AGNs, we have the upper limit of the surface density of the star formation rates,

\[
\Sigma_{\text{SFR}} \leq 35.8L_{\text{FIR},44}R_{200}^{-2}\left(M_\odot\text{yr}^{-1}\text{kpc}^{-2}\right),
\]

where \(L_{\text{FIR},44} = L_{\text{FIR}}/10^{44}\) erg s\(^{-1}\) is the observed far-IR luminosity. We take the geometric average \(\Sigma_{\text{SFR}} = \left(\Sigma_{\text{FIR,44}}\Sigma_{\text{SFR}}\right)^{1/2}\), and the error bars correspond to \(\Sigma_{\text{SFR}}^\prime\) and \(\Sigma_{\text{SFR}}^\prime\). We have to stress that this average only represents the central value of the logarithm of \(\Sigma_{\text{SFR}}^\prime\) and \(\Sigma_{\text{SFR}}^\prime\) and that the upper and lower limits of \(\Sigma_{\text{SFR}}^\prime\) are the most important. Table 1 gives a sample of Seyfert galaxies, which have been observed through IRTF SpeX or Subaru IRCS with a spatial resolution of 0.9\(^{\prime}\)–1.6\(^{\prime}\).

For Seyfert 1 galaxies, we estimate \(L_{\text{Bal}} = 9L_{5100}\), where \(L_{5100}\) is the luminosity at 5100 Å, and then the accretion rate \(M_\bullet = L_{\text{Bal}}/\eta c^2\), where \(\eta = 0.1\) is the accretion efficiency. The black hole masses are estimated from the empirical relation of reverberation mapping (Kaspi et al. 2000) or are directly taken from the mapping (Peterson et al. 2004). We assume that the potential of the total mass within the CNRs controls the massive disk fueling to the black hole, where star formations are taking

| TABLE 1 |
| --- |
| THE SEYFERT GALAXY SAMPLE |

| Seyfert 1 Galaxies |
|-------------------|
| Object | Redshift | FWHM | \(\log \lambda_{\text{Fl}}\) | Repps. | \(\log M_\bullet\) | \(M_\bullet\) | \(\log \Sigma_{\text{SFR}}\) | \(R\) | \(\log \Sigma_{\text{SFR}}\) |
|-------|----------|------|----------------|--------|----------------|---------|----------------|---|----------------|
| IC 120 | 0.033 | ... | 44.17 | 2 | 7.74 | 0.24 | 4.18 | 76 | 0.48 | 0.85 | 1.32 |
| IC 4329 | 0.016 | ... | 43.32 | 2 | 6.99 | 0.03 | 3.70 | 200 | 0.24 | 1.31 | 1.35 |
| MCG −2−33−34 | 0.014 | 1565 | 42.61 | 22, 5 | 6.11 | 0.01 | 3.13 | 54 | 0.24 | 0.70 | 1.21 |
| MCG −5−13−17 | 0.013 | 4000 | 43.44 | 20 | 7.50 | 0.04 | 3.92 | 67 | 0.19 | 0.79 | 1.24 |

Notes.—Table 1 is published in its entirety in the electronic edition of the Astrophysical Journal. A portion is shown here for guidance regarding its form and content. Col. (1): Source name; col. (2): redshift; col. (3): FWHM of H\(\alpha\) for Seyfert 1s or stellar velocity dispersion \(\sigma\) for Seyfert 2s (in km s\(^{-1}\)); col. (4): luminosity of 5100 Å deduced from extrapolation of \(F_\nu \propto \nu^{-0.7}\) or [O m] \(\lambda5007\) (in ergs s\(^{-1}\)); col. (5): references for cols. (3) and (4) are given below, respectively; col. (6): black hole mass (in \(M_\odot\)); col. (7): accretion rate (in \(M_\odot\text{yr}^{-1}\)); col. (8): gas surface density (in \(M_\odot\text{pc}^{-2}\)); col. (9): the scale of the starbursts (in kpc); cols. (11) and (12): the lower \(\Sigma_{\text{SFR}}^\prime\) and upper \(\Sigma_{\text{SFR}}^\prime\) limits of surface density of star formation rates, respectively (in \(M_\odot\text{yr}^{-1}\text{kpc}^{-2}\)).

References.—(1) NED; (2) Peterson et al. 2004; (3) Spinoglio et al. 1995; (4) Doroshenko & Terebey 1979; (5) Kinney et al. 1993; (6) Nelson & Whittle 1995; (7) Dahari & Roberts 1988; (8) Lipari et al. 1991; (9) Corral et al. 2005; (10) Kirhakos & Steiner 1990; (11) Visvanathan & Griessmeier 1977; (12) Cid Fernandes et al. 2004; (13) Gu & Huang 2002; (14) Kaler & Lebofsky 1988; (15) Herasude & Simien 1998; (16) Bassani 1999; (17) Whittle et al. 1988; (18) Whittle 1992; (19) Garcia-Rissmann et al. 2005; (20) Crenshaw et al. 2003; (21) Marzini et al. 2003; (22) Veron-Cetty et al. 2001; (23) Postman & Lauer 1995.

a The black hole mass is directly taken from Peterson et al. 2004.
place. Assuming Keplerian rotation, the surface density of the disk is
\[ \Sigma_{\text{in}} = 2.1 \times 10^5 \alpha_0 M_{\odot} f_{\text{in}}^{-1/3} M_8^{1/5} R_{200}^{3/5} M_\odot \text{pc}^{-2}. \] (7)
given by the disk model (King et al. 2002; Yi & Blackman 1994; Tan & Blackman 2005), where the opacity \( \kappa_{\text{abs}} = 5 \) in this region, \( f_{\text{in}} \) is the ratio of the black hole mass to the total, \( M_{\bullet,1} = M_\bullet / 1.0 M_\odot \) yr\(^{-1} \), and \( \alpha_0 = 0.1 \) is the viscosity (Shakura & Sunyaev 1973). This estimation is the lower limit since we replace the infalling mass rates in CNRs with black hole accretion rates. The gas surface density of the disk, \( \Sigma_{\text{gas}} = f_{\text{gas}} \Sigma_{\text{tot}} \), is
\[ \Sigma_{\text{gas}} = 1.0 \times 10^3 f_{\text{gas}} \alpha_1 M_{\odot} f_{\text{gas}}^{-1/3} M_8^{1/5} R_{200}^{3/5} M_\odot \text{pc}^{-2}, \] (8)
where \( f_{\text{gas},0.05} = f_{\text{gas}} / 0.05 \) is the gas fraction to the total. Considering that the disk is located inside the bulge, we get \( f_{\text{gas}} = M_{\text{gas}} / M_{\text{gas}} > M_{\text{gas}} / M_{\text{bulge}} = (M_{\text{gas}} / M_{\text{disk}}) (M_{\text{disk}} / M_{\text{bulge}}) \), where \( M_{\text{disk}} \) is the total mass of the disk, \( M_{\text{gas}} / M_{\text{disk}} \) is the gas-to-dust mass ratio, and \( M_{\text{bulge}} \approx 10^9 M_\odot \) is the bulge mass (Kormendy & Gebhardt 2001; McLure & Dunlop 2002). It has been found that the dust mass in PG quasars is comparable to the dust mass in Seyfert galaxies (Spinoglio et al. 2002; Haas et al. 2003). The mean value of the gas-to-dust mass ratio is \( (M_{\text{gas}} / M_{\text{dust}}) \approx 250 \) (Haas et al. 2003). We estimated the dust mass from \( M_{\text{dust}} \approx 4.78 f_{\text{dust}} D_{\odot}^2 [\exp (143.38 / f_{\text{dust}} - 1)] M_\odot \), and the dust temperature is estimated as \( T_{\text{dust}} = (1 + z) [0.5--82 / \ln (0.3 f_{\text{dust}} / f_{\text{dust}})] K \), where \( f_{\text{dust}} \) and \( f_{\text{dust}} \) are the fluxes at 100 and 60 \( \mu \)m in unit of janskys, respectively, and \( D_{\odot} \) is the luminosity distance in units of megaparsecs (Evans et al. 2005). We find a mean value of \( (M_{\text{dust}} / M_{\text{tot}}) = 0.2 \pm 0.2 \) in our sample. So we have \( f_{\text{dust}} \geq 0.05 \) as a lower limit in this Letter. Thompson et al. (2005) used \( f_{\text{dust}} = 0.1 \). We note that \( \Sigma_{\text{gas}} \propto f_{\text{gas}}^{-1/3} \), resulting in uncertainties of \( \Sigma_{\text{gas}} \) by a factor of 4 for \( f_{\text{gas}} \approx 0.1 \). The dispersion velocity \( \sigma = \text{FWHM}([\text{O III}]) / 2.35 \), if the dispersion velocity is not available.

Figure 1 shows the \( \Sigma_{\text{gas}}, \Sigma_{\text{SFR}} \) plot of Seyfert CNRs. We find that the CNR gas surface densities of Seyfert galaxies are located within the AGN feedback domain. There are clearly three branches in the figure, separating the Seyfert galaxies, when \( \Sigma_{\text{gas}} > \Sigma_{\text{gas}} > \Sigma_{\text{gas}} \). The Seyfert galaxies that are located in zone I still satisfy the K-S law. Those (Mrk 273, Mrk 938, NGC 5135, and NGC 1068) marked as being in zone II are located between the K-S law and zone III, and are ultraluminous infrared galaxies or are mixed with strong starbursts. The main energy sources in the CNRs are in a transition state from a starburst to an AGN in these galaxies. The fraction of the transiting galaxies is only \( \sim 4/57--1/10 \). Although the completeness of the present sample is uncertain, this fraction implies that the transition is quite short and is indicated by the feedback timescale from equation (4). The Seyfert galaxies in zone III are undergoing suppressed star formation, being 1--2 orders lower than that predicted by the K-S law. The suppressed \( \Sigma_{\text{SFR}} \) is obviously caused by the feedback. Galaxies obeying the K-S law are powered by nuclear energy from stars; however, the gravitational energy released from accretion onto the black holes will power the AGNs if a transition from starbursts to active galaxies happens. With the dissipation of CNR gas due to star formation and accretion onto the black holes, \( \Sigma_{\text{gas}} \) is decreasing, and the galaxies may return to the K-S law once the AGNs switch off. Such behavior is likely the result of the evolution of stellar energy sources in the Hertzprung-Russell diagram.

It has been found that black hole duty cycles follow the history of the star formation rate density (Wang et al. 2006). The above scenario then implies that both the black hole activities and the starbursts are episodic (Davies et al. 2006). The multiple cycles of the black holes and starbursts make it impossible to measure the time delay between the two episodes. However, the stellar synthesis may shed light on the star formation history and thus give us some insight into the history of black hole activity.

4. CONCLUSIONS AND DISCUSSIONS

We find direct evidence of feedback from active black holes in Seyfert galaxies. Once a black hole is triggered, the feedback will significantly suppress the starbursts within quite a short timescale of a few times \( 10^5 \) yr. The duty cycles of Seyfert galaxies strongly indicate that there is an efficient way to frequently trigger black holes and quench starbursts.

The data presented in this Letter are only lower limits of the gas densities. Future VLT (Very Large Telescope) and ALMA (Atacama Large Millimiter Array) measurements of star formation rates and gas densities may finally help us identify the role that feedback from black hole activity plays.

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