Postprint of the Study on Momentum-Driven Feedback Mechanisms in Active Galactic Nuclei

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Date: 2017-10-20T00:00:00+00:00

Abstract

Observations have revealed tight correlations between the mass of supermassive black holes at galactic centers and either the velocity dispersion or mass of the galactic bulge. Such correlations are generally believed to be caused by active galactic nucleus (AGN) feedback, but the microphysical implementation of the AGN feedback process remains unclear. Even the proposer of AGN feedback (Silk) has questioned its effectiveness. Using observational data from galaxies, we reconsider the AGN feedback process and test its effectiveness. We have assembled a sample of 29 galaxies and, through the observational data of these sample galaxies, have conducted a more accurate investigation of their potential fields and the motion of gas shells driven by momentum feedback within these potential fields, finding that momentum feedback is effective in the vast majority of galaxies.

Full Text

Preamble

Vol. 13 No. 1 Jan. 2016
ASTRONOMICAL RESEARCH AND TECHNOLOGY
53-1189 1672-7673
ChinaXiv Cooperative Journal

Research on the Momentum-Driven Feedback Mechanism of Active Galactic Nuclei

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Abstract

Observations have revealed tight correlations between the mass of supermassive black holes at galaxy centers and the velocity dispersion of galaxy bulges or bulge stellar mass. Such relations are generally believed to be caused by active galactic nucleus (AGN) feedback, but the microscopic physical implementation of AGN feedback processes remains unclear. Even the proposers of AGN feedback have questioned its effectiveness. Using observational data from galaxies, we reconsider the AGN feedback process and test its effectiveness. We compile a sample including galaxies and use observational data to conduct a more accurate study of their potential fields and the motion of gas shells driven by momentum feedback within these potentials, finding that momentum feedback is effective in the vast majority of galaxies.

Keywords: AGN feedback; momentum-driven feedback; outflow; Compton cooling

1. Introduction

Supermassive black holes ubiquitously reside at the centers of galaxies. Observations have discovered tight correlations between supermassive black hole mass (M_{BH}) and galaxy bulge velocity dispersion (σ) or bulge stellar mass (M_{bulge}), indicating that supermassive black holes and galaxies influence each other and co-evolve. These M-σ or M-M_{bulge} relations are generally explained by AGN feedback mechanisms, which include energy-driven feedback and momentum-driven feedback. Energy-driven feedback refers to the total energy released by black hole accretion being effectively transferred to the thermal or kinetic energy of gas in the galaxy, enabling this gas to escape the galaxy' s gravitational binding. This mechanism can produce the M-σ relation. Momentum feedback, on the other hand, refers to winds or outflows driven by black hole accretion transferring momentum to surrounding gas and sweeping it away, thereby terminating black hole accretion and galaxy growth.

However, it remains unclear whether AGN feedback is dominated by energy or momentum mechanisms, and the specific microscopic physics of the feedback process is uncertain. Silk & Nusser (2010) investigated a number of galaxies with observationally determined black hole masses and velocity dispersions using an isothermal sphere model to study the effectiveness of AGN feedback. They estimated that the energy required for gas to escape from galaxies is approximately M_{gas}σ^2, and compared this with the total energy released by black hole accretion, M_{BHc}^{2} (where c is the speed of light, M_{gas} is the total gas mass in the galaxy, and is the mass-energy conversion or radiation efficiency). They found that winds from black hole accretion alone may be insufficient to blow all gas out of galaxies, suggesting that AGN feedback might be ineffective.

The isothermal sphere model describes the mass density distribution and potential field distribution of galaxies. However, the isothermal sphere distribution yields excessively high densities near galaxy centers compared to actual galaxy density profiles, which may overestimate gas escape velocities and escape timescales. Moreover, the density does not converge at galaxy outer boundaries. Since gas escape velocity decreases with distance from the galaxy center, this could lead to overestimation of both the time required for gas to escape the AGN and the energy required.

To address these issues, we have collected a galaxy sample with observationally determined surface brightness distribution data. From these observations, we can obtain galaxy density profiles, estimate host dark matter halo masses and density distributions, and examine galaxy potential fields. This allows us to reconsider the momentum feedback process and test its effectiveness.

2. Sample and Observational Data

We introduce the observational sample and data related to galaxy surface brightness distributions. The Hubble Space Telescope observed the nuclear regions (0.1 -10) of the sample galaxies. The surface brightness distribution I(R) can be fitted by the Nuker law:

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where R is the two-dimensional projected distance to the galaxy center, and β and γ are Nuker law fitting parameters. R_b and I_b are the break radius and surface brightness at the break radius, respectively. Table 1 presents the relevant fitting parameters for the H-band of each sample galaxy.

For regions outside the nucleus, the surface brightness distribution of galaxies can be described by the de Vaucouleurs law. The data in this paper adopt a concordance cosmological model with Hubble constant H_0 = 70 km s^{-1} Mpc^{-1}, matter density parameter Ω_m = 0.27, and dark energy density parameter Ω_Λ = 0.73.

To study the effectiveness of AGN feedback mechanisms, we need to know the central black hole mass. For some galaxies in the sample, the central black hole mass comes from direct measurements, while for others without direct measurements, we estimate the black hole mass through the M-σ relation:

log$_{10}$(M_{BH}/M_) = α + βlog$_{10}$(σ/200 km s^{-1})

with coefficients (8.40 ± 0.09, 5.08 ± 0.7) for classical bulges and (8.52 ± 0.47, 4.69 ± 2.69) for pseudo-bulges.

3. Galaxy Mass Distribution and Potential Field

Galaxy matter includes the central supermassive black hole, stars, gas, and dark matter halo. Assuming spherical symmetry, the mass density distribution inside galaxies can be expressed as:

(r) = _*(r) + _{gas}(r) + _{DM}(r)

where _*(r) is the stellar mass density distribution, _{gas}(r) is the gas density distribution, and _{DM}(r) is the dark matter mass density distribution. Since the gas component may be relatively unimportant compared to stars and dark matter, we ignore its contribution when calculating the potential.

The stellar mass density profile _*(r) can be obtained directly by integral transformation of the galaxy surface brightness distribution I(R):

_*(r) = (1/π) _r^∞ (dI/dR)(R^2 - r^2)^(-1/2) dR

multiplied by the stellar mass-to-light ratio Υ. Figure 1 shows the stellar mass density distribution _*, the total mass density distribution including dark matter _{tot}, and the isothermal sphere model density distribution _{iso} for galaxies in Table 1.

Using the mass density distribution of galaxies and their host dark matter halos, we can obtain their potential field distributions. The escape velocity at different positions r in the galaxy is defined as the minimum speed required for gas or particles to reach the dark matter halo virial radius r_{vir}:

v_{esc}(r) = √[2(Φ(r) - Φ(r_{vir}))]

Figure 2 shows the escape velocity distribution of gas or particles at different radii in galaxies, considering only stellar matter or including the dark matter halo.

4. Momentum-Driven Feedback

Momentum feedback may be the dominant mechanism causing the M-σ relation. Observations indicate that the momentum output of outflows is related to the total momentum of radiation photons from the AGN by f_p 1-5. The momentum from nuclear activity compresses gas in the galaxy core into a shell and drives this shell outward.

If we consider only the influence of stellar matter, momentum conservation gives:

M_{gas}(r) dv/dt = (f_p L(t)/c) - (GM_*(r)/r^2)M_{gas}(r)

where M_{gas}(r) is the gas mass within radius r, M_*(r) is the total stellar mass within radius r, and f_g = M_{gas}/M_* is the gas-to-stellar mass ratio.

Galaxies generally reside in dark matter halos. If we consider the gravitational binding effect of dark matter halos on gas, the momentum equation becomes:

M_{gas}(r) dv/dt = (f_p L(t)/c) - [G(M_*(r) + M_{DM}(r))/r^2]M_{gas}(r)

where M_{DM}(r) is the dark matter mass within radius r.

After nuclear activity is triggered, gas in the galaxy core is pushed into a shell at radius r. The evolution of this shell over time can be described by the above equations. If the shell radius reaches r when nuclear activity ceases, and the shell velocity v exceeds the escape velocity v_{esc} at that location, the gas can be driven out of the galaxy, terminating nuclear activity. Conversely, if v < v_{esc}, momentum feedback is insufficient to expel the gas.

We adopt two forms for the time evolution of AGN luminosity: 1. Constant luminosity: L(t) = L_{Edd} 2. Exponential evolution: L(t) exp(t/τ)

where L_{Edd} = 4πGM_{BHmpc}/σ_T is the Eddington luminosity, m_p is the proton mass, and σ_T is the electron scattering cross-section.

Assuming a gas composition of primordial abundance (hydrogen fraction X = 0.75, helium Y = 0.25), the mean molecular weight 0.61. For a Kerr black hole with spin parameter a = 0.998, the radiation efficiency 0.3. The Salpeter timescale is τ_S 4.3 × 10^8 years.

Through numerical calculations, we obtain the velocity v of gas shells after one AGN evolution cycle and compare it with the escape velocity v_{esc} at the shell location. The ratio v/v_{esc} reflects the strength of momentum feedback in each galaxy.

Figure 3 shows the position of the gas shell when nuclear activity is quenched. Figure 4 shows the ratio of outflow velocity to escape velocity at the time when nuclear activity is quenched. Under the assumption of constant luminosity, 11/29 galaxies have gas shells that can escape when considering only stellar matter, while 27/29 can escape when including dark matter halo. Under exponential luminosity evolution, 23/29 galaxies have v > v_{esc} for the stellar-only case, and 7/29 for the case including dark matter.

5. Compton Cooling

As the gas shell expands outward, it can be heated by shocks. Hot electrons undergo Compton scattering with photons, causing gas cooling. The Compton cooling timescale is:

t_C (3m_{ec})/(4σT) × (E{kin})/($\gamma^2\beta^2$U_{rad})

where E_{kin} is the kinetic energy of electrons in the gas shell, U_{rad} is the radiation energy density, and γ and β are relativistic parameters.

If the Compton cooling timescale is much shorter than the AGN evolution timescale, the gas will be effectively cooled and cannot escape the galaxy. Conversely, if t_C is much longer than the AGN activity timescale, the gas will not be effectively cooled and can escape.

Figure 5 shows the Compton cooling timescale of shock-heated gas shells when nuclear activity is quenched. For most galaxies where gas can escape, the Compton cooling timescale is much longer than the AGN evolution timescale, indicating that Compton cooling does not prevent gas escape.

6. Discussion

We have revisited the momentum feedback process using observational data and found that momentum-driven feedback is effective in most galaxies. Several factors influence the effectiveness of momentum feedback:

1. **Gas-to-stellar mass ratio (f_g)**: Lower gas fractions make it easier for feedback to expel gas.
2. **Momentum boost factor (f_p)**: Higher values of f_p (the ratio of outflow momentum to radiation photon momentum) increase feedback effectiveness.
3. **Dark matter halo**: The gravitational binding from dark matter halos significantly affects whether gas can escape. Some galaxies can overcome stellar gravity but remain bound to the dark matter halo.

The ratio of black hole mass to galaxy stellar mass (M_{BH}/M_*,total) also influences feedback effectiveness. In some cases where feedback appears ineffective, the black hole mass estimate may be 偏低 (slightly lower than the true central value). If we adopt the upper limit of black hole mass (measured value plus one standard deviation), the effectiveness of momentum feedback improves significantly.

Additionally, galaxy and dark matter halo masses at the time of AGN feedback may have been 2–3 times smaller than present-day measured masses due to subsequent growth through mergers and accretion.

7. Conclusions

By incorporating observational data to reconstruct stellar mass density distributions and dark matter halo density profiles, we have revisited the momentum feedback process. We investigated and discussed several factors affecting feedback effectiveness, including the gas-to-stellar mass ratio f_g, the ratio of outflow momentum to central engine radiation momentum f_p, and the gravitational binding from surrounding dark matter halos.

We find that momentum-driven feedback mechanisms are effective during the evolution of most galaxies, revising the conclusion from Silk & Nusser (2010) that momentum feedback is ineffective. Our results support the importance of AGN feedback in establishing the observed correlations between supermassive black holes and their host galaxies.

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