A New Concept of Transonic Galactic Outflows in a Cold Dark Matter Halo with a Central Super-Massive Black Hole

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We study fundamental properties of isothermal, steady and spherically symmetric galactic outflow in the gravitational potential of a cold dark matter halo and a central super-massive black hole. We find that there are two transonic solutions having different properties: each solution is mainly produced by the dark matter halo and the super-massive black hole, respectively. Furthermore, we apply our model to the Sombrero galaxy. In this galaxy, Chandra X-ray observatory detected the diffuse hot gas as the trace of galactic outflows while the star-formation rate is low and the observed gas density distribution presumably indicates the hydrostatic equilibrium. To solve this discrepancy, we propose a solution that this galaxy has a transonic outflow, however, the transonic point forms in a very distant region from the galactic center (∼127 kpc). In this slowly accelerated transonic outflow, the outflow velocity is less than the sound velocity for most of the galactic halo. Since the gas density distribution in this subsonic region is similar to the hydrostatic one, it is difficult to distinguish the wide subsonic region from hydrostatic state. Such galactic outflows are different from the conventional supersonic outflows observed in star-forming galaxies.

KEYWORDS: galactic outflows, cold dark matter halo, the Sombrero galaxy, ...

1. Introduction

Recent observational cosmology reveals that the primary ingredient of the galactic mass consists of the cold dark matter, and it has an essential role affecting not only to the evolution of galaxies but also to the large-scale structure of the universe. The study of galaxy formation in the gravitational potential of the dark matter halo (DMH) indicates that galactic outflows play significant roles on the evolution of galaxies and the metal enrichment of the intergalactic space. In order to realize galactic outflows, it needs sufficient thermal energy supply to escape from the gravitational potential well of the galaxy. So far, the study mainly assumed supernovae and stellar winds as the thermal energy source. Recently, Tsuchiya et al. (2013) [1] studied the transonic galactic outflow based on the solar wind model assuming the outflow driven by the thermal energy of the interstellar medium itself almost at the virial temperature.

Parker (1958) [13] established the simple model for solar wind as a naturally driven transonic flow (a critical point so-called transonic point connects the subsonic flow and supersonic one). The transonic solution is known as the entropy-maximum solution, and this solar wind model had been confirmed by spacecraft observations. Tsuchiya et al. (2013) extended the Parker’s model and ex-
explored the transonic galactic outflow in a realistic gravitational potential of DMH under isothermal, spherically symmetric and steady assumption. They adopted various models of DMH mass distribution suggested from observations and cosmological simulations. They showed the possibility of a new type of the transonic solution in which the transonic point forms in a very distant region (∼ 100 kpc).

We must note that most galaxies include a central super-massive black hole (SMBH) and it may affect the acceleration process of the outflow in the galactic central region. In this study, we extend our model of the transonic galactic outflow including the SMBH contribution to reproduce a realistic gravitational potential in the central region.

2. The Analytical Model for The Transonic Outflows

We assume isothermal, spherically symmetric and steady outflows without mass injection along flow except the starting point. The basic equations are the conservation of mass and momentum as follows

\[ 4\pi\rho vr^2 = \dot{M}, \quad (1) \]
\[ \frac{\partial v}{\partial r} = -\frac{c_s^2}{\rho} \frac{\partial \rho}{\partial r} - \frac{\partial \phi}{\partial r}, \quad (2) \]

where \( \rho, v, r, \dot{M}, c_s \) and \( \phi \) are gas density, gas velocity, radius from the galactic center, mass flux, sound speed and the gravitational potential, respectively. Note that \( \dot{M} \) and \( c_s \) are constant. Substituting \( \rho \) from equation (1) and (2), we obtain

\[ \frac{\partial M^2}{\partial x} = \frac{4}{x} - \frac{2}{c_s^2} \frac{d\phi}{dx}, \quad (3) \]
\[ N(x) = \frac{4}{x} - \frac{2}{c_s^2} \frac{d\phi}{dx}, \quad (4) \]

where \( M = v/c_s \) is Mach number and \( x = r/r_d \) is non-dimensional radius. \( r_d \) is the scale radius of DMH.

Tsuchiya et al. (2013) adopted the model of the density profile of DMH as

\[ \rho_{DMH}(r; \alpha) = \frac{\rho_d r_d^3}{r^\alpha (r + r_d)^{3-\alpha}}, \quad (5) \]

where \( \rho_d \) represents the scale density. With \( \alpha = 1 \), this density profile represents the NFW model [9]. The density is proportional to \( r^{-\alpha} \) in the limit \( r \to 0 \) in this model.

Integrating the equation (3) with equation (5), we obtain

\[ M^2 - \log M^2 = 4 \log x - 4\phi'(\alpha, K, K_{BH}; x) + C, \quad (6) \]

\[ \phi'(\alpha, K_{DMH}, K_{BH}; x) = \frac{1}{2c_s^2} \phi = K_{DMH} \int \frac{1}{x^2} \left( \int_0^x x^{2-\alpha}(x + 1)^{x-3} dx \right) dx - \frac{K_{BH}}{x}, \quad (7) \]

\[ K_{DMH} = \frac{2\pi G\rho_d r_d^2}{c_s^2}, \quad (8) \]

\[ K_{BH} = \frac{GM_{BH}}{2r_d c_s^2}, \quad (9) \]
where C is the integration constant. $K_{DMH}$ corresponds approximately to DMH mass, while $K_{BH}$ corresponds approximately to SMBH mass. We can reduce outflow solutions from these equations.

We summarise transonic solutions in Figure 1 (for $\alpha = 1$). Transonic solutions for other $\alpha$ are also shown in Figure 2. We find that transonic solutions are categorized into two cases: A) single X-point and B) two X-points with single O-point. In case B), the transonic solution through the inner X-point is referred to as type $X_{in}$ and the transonic solution through the outer one is referred to as type $X_{out}$. In case B-1 (see Figure 1), type $X_{in}$ solution starts from the center, but type $X_{out}$ one does not start from center. In case B-2, type $X_{out}$ solution extends to infinity, but type $X_{in}$ one does not extend to infinity. The inner X-point is formed by the gravitational potential of SMBH, while the outer one is formed by that of DMH.

In B-1 and B-2, two transonic solutions have different mass fluxes and starting points. So, we may expect different influences on the star-formation history and the mass of the gas transported to the intergalactic space.

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**Fig. 1.** Various solutions in the gravitational potential of DMH ($\alpha = 1$) and SMBH. The horizontal axis is $K_{DMH}$ defined in equation (8) and the vertical axis is $K_{BH}$ defined in equation (9). The labels, such as A-1, represent the types of transonic solutions. See Section 2 for details of these solutions. The four thin solid lines in the central diagram represent the range of actual galaxies from $10^{11} M_\odot$ (bottom) to $10^{14} M_\odot$ (top). The three thin solid lines intersecting four solid lines represent $\eta = 0.5, 1$ and 2 from left to right ($\eta$ is defined in section 4.1).
3. Application to the Sombrero Galaxy

The Chandra X-ray Observatory detected a diagnostic feature of the galactic outflow as diffuse hot gas in the Sombrero galaxy [2]. However, the gas density is similar to hydrostatic state and the star-formation rate is lower ($\sim 0.06 M_\odot$/yr) than other early type spiral galaxies [15, 16]. We apply our model to this galaxy to solve this discrepancy.

We add the stellar mass contribution to the gravitational potential to reproduce more realistic mass distribution. We use Hernquist model [6] for the stellar mass distribution,

$$\rho_H(r) = \frac{M_H r_h}{2\pi} \frac{1}{r(r + r_h)^2},$$

where $r_h$ is the scale length of stellar distribution and $M_H$ is the whole mass of the stellar ingredient. The stellar mass contribution modifies the gravitational potential and all X-points move outward while the O-point moves inward. The parameters of stellar mass distribution in the Sombrero galaxy are determined from observation as $(r_h, M_H) = (2.53 \text{kpc}, 1.5 \times 10^{11} M_\odot)$ [3, 4]. The parameters of DMH are determined from the observational data as $(\alpha, r_d(\text{kpc}), \log_{10}(M_{25 \text{kpc}}/M_\odot)) = (1.0, 36.1, 11.95$) [5]. $M_{25 \text{kpc}}$ is the whole mass of DMH inside 25 kpc. The SMBH mass of the Sombrero galaxy is $10^9 M_\odot$ [7, 8], and the averaged temperature of hot gas is about 0.6 keV upto 25 kpc [2].

Figure 3 shows the results of the transonic analysis for the Sombrero galaxy. The upper panels are Mach number radial profiles for (a) $T = 0.6$ keV and for (b) $T = 0.5$ keV, respectively. The bold solid lines indicate the transonic outflows. The lower panels are radial density profiles for (c) $T = 0.6$ keV and for (d) $T = 0.5$ keV, respectively. The dotted-and-dashed curves represent the hydrostatic state, while the the solid curve is for an transonic outflow that passes through the outer X-point. The dashed curves represent the transonic outflow that passes through the inner X-point. Crosses show the data of observation [2]. We suggest that the outflow from the Sombrero galaxy corresponds to type B-1 solution having two transonic solutions (see Figure 1). The transonic solution through the outer transonic point ($\sim 127$ kpc) has similar gas density to the hydrostatic state in the wide subsonic region. Therefore, it is difficult to distinguish the density distribution in the subsonic region from the hydrostatic distribution over the observed region ($< 25$ kpc). Our result provides the new picture of galactic outflows that the slowly accelerated galactic wind may exist even in quiescent galaxies having inactive star formation such as the Sombrero galaxy.

![Fig. 2. Various solutions for (a) : $\alpha = 0$ and (b) : $\alpha = 1.5$. The meaning of colour is the same as Figure 1.](image)
4. Discussion

4.1 Parameters in Actual Galaxies

In actual galaxies, values of parameters \((K_{DMH}, K_{BH})\) should be in a plausible range. Using the virial temperature and results of other studies \([11, 12]\), we estimate the range of these parameters as

\[
K_{DMH} = \eta \frac{c}{2} \left( \int_0^c x^{2-\eta} (x + 1)^{\eta-3} dx \right)^{-1},
\]

\[
K_{BH} = \frac{0.11 \eta c}{2 \times 10^4} \left( \frac{c}{9.7} \right)^{\frac{12\eta-1}{4\eta+3}}.
\]

where \(c\) is the concentration parameter defined as the ratio between the virial radius of DMH and \(r_d\), and \(\eta\) is a fudge factor of the order of unity. We show these actual ranges of \((K_{DMH}, K_{BH})\) in Figure 1. Each of the four long curves extending horizontally in Figure 1 corresponds to different DMH mass. Each of the three curves intersecting these four lines correspond to different temperature. The plausible parameter range covers a region in \(K_{DMH} - K_{BH}\) plane over the types A-1, C-1 and B-1.

4.2 Deduction of Mass Profile from Outflow Velocities

The result in section 2 shows that the mass profile affects strongly the acceleration process of galactic outflows. Thus, we can deduce the mass distribution from the velocity distribution of galactic
outflows if we observe it. In the current technology of the X-ray observation, it is difficult to observe the very slow outflow (∼ 100 km s\(^{-1}\)) of hot gas in details, but future mission like ASTRO-H may enable us to detect it.

If the solution of type B is realized (see Figure 1), the transonic solution of type \(X_{in}\) is mainly accelerated in the central region and the \(X_{out}\) is accelerated in the distant region from the galactic center. Thus, the property of type \(X_{in}\) suggests the mass of SMBH and it of \(X_{out}\) suggests the mass distribution of DMH. Similarly, A-1 and A-2 suggest the mass of SMBH and the mass distribution of DMH, respectively.

5. Conclusion

We have found and categorized all possible transonic solutions of galactic outflows in the gravitational potential of DMH and SMBH using the isothermal, spherically symmetric and steady model. We conclude that the gravitational potential of SMBH adds a new transonic point at the inner region (∼ 0.01 kpc) while Tsuchiya et al. (2013) concluded that the gravitational potential of DMH forms one transonic point in a far distant region (∼ 100 kpc). Because these two transonic solutions have different mass fluxes and starting points, these solutions having different natures may make different influences to the star-formation rate and the evolution of galaxies. In addition, we have estimated the range parameters (\(K_{DMH}, K_{BH}\)) for actual galaxies.

Furthermore, we have applied our result to the Sombrero galaxy and have shown the possibility of slowly accelerated galactic outflows in this galaxy. We have found that the Sombrero galaxy has two transonic solutions. The transonic solution through the outer transonic point (∼ 120 kpc) has similar gas density distribution to hydrostatic state in the wide subsonic region. Therefore, it is difficult to distinguish this solution from the hydrostatic solution inferred by the X-ray observation (< 25 kpc). So far, the studies of the galactic outflows always assume an active star formation, however, our result provides a new picture of galactic outflows from quiescent galaxies.

By using our model, it is possible to estimate the galactic mass distributions of DMH and SMBH from the observed profile of the outflow velocity. Although it is difficult to determine the velocity of hot gas in the galactic halos from the current X-ray observations, but the next-generation X-ray observatory will be able to detect the detailed profiles of outflow velocities.

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