Dynamical Behavior of Gaseous Halo in a Disk Galaxy

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Assuming that the gas in the halo of a disk galaxy is supplied from the disk as a hot gas, we have studied its dynamical and thermal behavior by means of a time dependent, two-dimensional hydrodynamic code. Depending upon the temperature and density of the gas at the disk, three types of gaseous halo are formed, that is, a wind-type, a bound-type and a cooled-type halo. In the former two cases, the hot gaseous halo with the temperature higher than $3 \times 10^9$ K is formed, and the X-ray emission of the luminosity $10^{37} \sim 10^{39}$ ergs/s is expected in the 0.3~4 keV region. In the cooled-type halo, the halo gas collapses to the disk plane after a rapid radiative cooling, and this will be observed as infalling, high-velocity clouds. Some discussions on the role of gaseous halo for a disk galaxy are given.

§ 1. Introduction

By observations of diffuse soft X-ray flux and of OVI absorption lines, it has been indicated that a considerable fraction of interstellar space in the vicinity of solar neighborhood is occupied by a hot, tenuous gas. As the origin of this hot gas, the cumulative events of supernova explosions and the strong stellar winds have been proposed. Shapiro and Field have pointed out that if the X-ray emission and the OVI-line absorptions are common in origin, the pressure of this hot gas may be higher than that of general interstellar medium. As a result, this hot gas may flow out from the disk to the halo of the Galaxy.

On the other hand, McKee and Ostriker have studied the global structure of interstellar medium on the assumption of steady state, and concluded that the filling factor of hot gas component with the density $n_h = 10^{2-3}$ cm$^{-3}$ and the temperature $T_h = 10^6$ K will be $f = 0.7 \sim 0.8$. In this case, the pressure scale-height of hot gas attains a few kiloparsecs, so that this gas spreads to the halo. They have argued the possibility that this hot gas will be further heated up by supernova events in the halo and be driven away as a galactic wind. Several other authors have also proposed models of interstellar medium occupied by hot gas component with a substantially large fraction.

From these ideas, the possible gaseous halo has been indicated. Chevalier and Oegerle have studied the energetics of hot galactic corona, considering the supply of energy and gas from the disk and the heating by supernova explosions in the halo. Their treatment for gas motion is insufficient in respect to the angular momentum, and the cooling effects on the gas flow are not fully taken into account. Bregman has numerically calculated the gas motion injected from the disk, and
discussed the observability of hot gaseous haloes as X-ray sources and the origin of intermediate- and high-velocity clouds. In his papers, the relations between the characteristics of gaseous haloes and the gas parameters at the disk are not fully clarified. Particularly, the gas motion in the cooled gaseous halo is not illustrated in Ref. 10.

In the present paper, we study the gas motion in the halo for wider ranges of the gas temperature and density at the disk, and investigate the relations between the structures of gaseous halo and the gas parameters. At the same time, we investigate the observability of various types of gaseous haloes. In § 2, models and fundamental equations are described. In § 3, numerical results of gas motion in the halo are presented for various parameters. In § 4, some discussions on the observability of gaseous halo are given, as well as the roles of gaseous halo on the evolution of galaxies.

§ 2. Models and fundamental equations

2.1. Model of galaxy potential

The mass distribution of a disk galaxy is assumed to be represented by the model proposed by Miyamoto and Nagai, which is expressed in cylindrical coordinate \((r, z, \phi)\) as

\[
\rho_h(r, z) = \sum_{i=1}^{2} \frac{1}{4\pi} b_i^2 M_i \frac{1}{r^2 + (a_i + (z^2 + b_i^2)^{1/2})^{3/2}}. \tag{2.1}
\]

Here, the suffixes 1 and 2 denote the quantities of the bulge and the disk components, respectively. Corresponding gravitational potential becomes

\[
\Phi_P(r, z) = -\sum_{i=1}^{2} \frac{GM_i}{r^2 + (a_i + (z^2 + b_i^2)^{1/2})^{3/2}}, \tag{2.2}
\]

where \(G\) is the gravitational constant. For the parameters in this expression, we adopt those summarized in the following, by which the rotation curve of the Galaxy is well fitted.

<table>
<thead>
<tr>
<th>Bulge component</th>
<th>Disk component</th>
</tr>
</thead>
<tbody>
<tr>
<td>(a_i = 0.0)</td>
<td>(a_t = 7.258) kpc</td>
</tr>
<tr>
<td>(b_i = 0.495) kpc</td>
<td>(b_t = 0.520) kpc</td>
</tr>
<tr>
<td>(M_i = 2.05 \times 10^{10} M_\odot)</td>
<td>(M_t = 2.547 \times 10^{12} M_\odot)</td>
</tr>
</tbody>
</table>

Since the existence of a massive halo is not confirmed in our Galaxy, we have studied both cases with and without a massive halo. As the mass distribution of a massive halo, we adopt the spherical model proposed by Innanen as

\[
M_R(x) = M_{R,0} x^4 (1 + x)^{-4} \quad \text{for} \ R \leq 106 \text{ kpc} \tag{2.3}
\]
with $M_{b,0} = 1.35 \times 10^{13} M_\odot$, $R = (r^2 + z^2)^{1/2}$, $x = R/R_b$ and $R_b = 13$ kpc. Corresponding gravitational potential $R \leq 100$ kpc is given as

$$\phi_h(X) = \frac{GM_{b,0}}{R_b} \left( \ln(1+X) + \frac{1}{1+X} \right) - \phi_0,$$

(2.4)

where $\phi_0$ is $1.4 \times 10^{15}$ cm$^2$/sec$^2$.

The gas in the disk ($z = 0$) will escape from the galaxy potential well if its temperature is higher than the critical temperature where

$$\gamma, \mu, H \text{ and } k \text{ are, respectively, the adiabatic exponent } (\gamma = 5/3), \text{ the mean molecular weight } (\mu = 0.62), \text{ the hydrogen mass and the Boltzmann constant. The gravitational potential is } \Phi = \phi_h + \phi_n \text{ in the case with the massive halo, and } \Phi = \phi_n \text{ in the case without the massive halo. The Keplerian velocity in the disk } v_k(r, 0) \text{ is given as } v_k = \left( \frac{\partial \Phi}{\partial r} \right)^{1/2}. \text{ In Fig. 1, the critical temperature for each distance } r \text{ in the disk is illustrated. The Keplerian velocity } v_k(r, 0) \text{ depends hardly upon the massive halo so long as } r < 10 \text{ kpc, so that the gas motion within 10 kpc is not much affected by the massive halo.}

2.2. Hot gas in the disk

As we consider the halo gas to be supplied from the disk, we must assign the temperature $T_d$ and the density $n_d$ in the disk, as well as its injection region. These should be inferred from the thermal and dynamical investigations of interstellar medium. Here, as the first-step calculation we conveniently suppose the hot gas in the disk as follows:

i) The hot gas with $T_d$ and $n_d$ is uniform at $r = 4 \sim 12$ kpc in the disk.

ii) This hot gas rotates with the stellar disk in the same velocity.

iii) This hot gas will rise vertically from the disk to the $z$-height corresponding to its scale height.

These conditions for the hot gas in the disk are imagined from the model proposed by McKee and Ostriker, and will be verified if the filling factor of the hot gas at $r = 4 \sim 12$ kpc is so large as $f = 0.7 \sim 0.8$. Moreover, we must consider the gas heating by halo supernovae. However, according to the results by Caswell.
and Lernch the scale-height of \( z \)-distributions of supernova remnants is as small as 200 pc and supernovae at \( z > 1.6 \) kpc are not observed. Therefore, the effects of halo supernovae will not be substantial. In the present paper, we conveniently assume that the temperature of hot gas is maintained to be \( T_d \) within the height \( z = 250 \) pc as a result of heating by supernovae near the disk.

2.3. Fundamental equations

The equations of conservation of mass, \( r \)- and \( z \)-momentum and energy are, respectively, written as

\[
\frac{\partial \rho}{\partial t} + \text{div} (\rho \mathbf{v}) = 0, \quad (2.6)
\]

\[
\frac{\partial (\rho u)}{\partial t} + \text{div} (\rho u \mathbf{v}) = -\frac{\partial p}{\partial r} - \rho \frac{\partial}{\partial r} \Phi, \quad (2.7)
\]

\[
\frac{\partial (\rho v)}{\partial t} + \text{div} (\rho v \mathbf{v}) = -\frac{\partial p}{\partial z} - \rho \frac{\partial}{\partial z} \Phi \quad (2.8)
\]

and

\[
\frac{\partial}{\partial t} (\rho e) + \text{div} (\rho e \mathbf{v}) = -\rho \text{div} \mathbf{v} - A \rho^2, \quad (2.9)
\]

where \( \rho, \rho, e \) and \( \mathbf{v} = (u, v) \) are the density, the pressure, the specific internal energy and the velocity, respectively. The cooling function \( A \) in ergs \( cm^3 g^{-2} \) sec\(^{-1}\) is approximated from the results by Raymond et al.\(^{19}\) as

\[
A = 9.4 \times 10^8 T^{8.35} \quad \text{for} \quad 10^4 K \leq T < 10^5 K, \quad (2.10)
\]

\[
= 5.8 \times 10^9 T^{-3.4} \quad \text{for} \quad 10^5 K \leq T < 4 \times 10^7 K, \quad (2.11)
\]

\[
= 1.5 \times 10^8 T^{0.1} \quad \text{for} \quad 4 \times 10^7 K \leq T. \quad (2.12)
\]

For numerical convenience, we neglect the radiative cooling below the temperature \( 10^4 \) K.

The supply of hot gas is set as the boundary condition at the disk. That is, the hot gas on the disk of the radius \( r = 4 \sim 12 \) kpc and in \( z \leq 250 \) pc is always maintained to be \( T_d \) and \( n_d \) although this hot gas tends to flow out to the halo.

Numerical integrations of Eqs. (2.6) \(^\sim\) (2.9) have been performed by means of the beam scheme. In the \( r \)- and \( z \)-direction, we divide the space, respectively, into 22 meshes with the size 1 kpc and 30 meshes with the size 0.5 kpc, except that the first mesh-size in \( z \)-direction is taken to be 0.25 kpc. The effects of magnetic field are not considered in the present paper.

§ 3. Numerical results

Calculated parameters for \( T_d \) and \( n_d \) are summarized in Table I and Fig. 2.
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Gas motion is followed till the time \( t \leq 2 \times 10^8 \text{y} \), which nearly corresponds to the time necessary for the gas with \( T_d = 10^6 \text{K} \) to traverse the distance 15 kpc with the sound speed. This would also be the time necessary for the gas flow to attain a steady state, except for the case when the radiative cooling is efficient.

Depending upon the parameters of hot gas, the resultant gaseous halo can be classified into three types, i.e., a) wind-type, b) bound-type and c) cooled-type. This result is easily understood when the timescales between the radiative cooling \( \tau_r \sim e/4 \rho \) and the transverse time \( \tau_t = R/|v| \) are compared. In the following, we summarize the characteristics of gas motion for each type.

### 3.1. Wind-type gaseous halo

As the wind-type halo, we suppose such a halo that the gas in the halo expands with the velocity higher than the escape velocity, sometimes with the supersonic velocity, and the radiative cooling hardly affects the gas motion. Then, this is similar to the solar wind.

This wind-type halo is realized when the temperature of the disk gas is high enough to exceed the critical temperature, and moreover when the density of the disk gas is small enough for the radiative cooling to be inefficient. As is shown in Fig. 2, the wind-type gaseous halo is realized when \( T_d > T_{cr} \) (at \( r = 12 \text{kpc} \)) and \( \tau_t \gtrsim 10^8 \text{y} \). In these cases, the gas leaves the disk at a subsonic velocity, and then it flows away from the galactic potential well supersonically or subsonically depending upon the parameters at the disk. The gas motion attains a nearly steady state till \( t \sim 2 \times 10^8 \text{y} \).

In Fig. 3, we illustrate the contours of isodensity and isotemperature surfaces at the time \( t = 2 \times 10^8 \text{y} \) for the case \( T_d = 5 \times 10^6 \text{K} \) and \( n_d = 1.0 \times 10^{-3} \text{cm}^{-3} \). Here, we include the potential of the massive halo, but the gas flow near the galaxy is almost the same even if it is not included. The velocity vectors with \( r \) - and \( z \) - components are also plotted. At this stage, the gas motion attains a steady state with supersonically outflowing velocities except for the inner region, i.e.,...
the steady galactic wind is realized.

Although the gravitational force is balanced with the centrifugal force at the disk plane, the former decreases with rising to the halo at the same radius. Therefore, the rising gas is expelled outwardly due to the predominant centrifugal force, and it flows nearly parallel to the disk. Because the initial gas

Table I. Adopted parameters for the hot gas at the disk and the calculated results at the time $t$. $M$, $M_{\text{halo}}$ and $L_x$ are the gas-outflowing rate from the outer boundaries in the present calculations, the accumulated gas mass in the halo and the X-ray luminosity from the halo, respectively. $H_x$ is the scale-height of X-ray intensity at $r=5$ kpc defined in Eq. (4·1).

<table>
<thead>
<tr>
<th>$T_a$ (K)</th>
<th>$n_a$ (cm$^{-3}$)</th>
<th>$t$ (y)</th>
<th>$M$ (M$_\odot$/y)</th>
<th>$M_{\text{halo}}$ (M$_\odot$)</th>
<th>$L_x$ (ergs/s)</th>
<th>$H_x$ (kpc)</th>
<th>Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>$5\times10^6$</td>
<td>$10^{-3}$</td>
<td>$2\times10^8$</td>
<td>$1.0\times10^6$</td>
<td>$5.8\times10^{38}$</td>
<td>4.0</td>
<td>wind</td>
<td></td>
</tr>
<tr>
<td>$3\times10^6$</td>
<td>$10^{-3}$</td>
<td>$2\times10^8$</td>
<td>$1.0\times10^6$</td>
<td>$6.1\times10^{38}$</td>
<td>3.7</td>
<td>wind</td>
<td></td>
</tr>
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<td>$2\times10^6$</td>
<td>$10^{-3}$</td>
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<td>wind</td>
<td></td>
</tr>
<tr>
<td>$2\times10^6$</td>
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<td>$2\times10^8$</td>
<td>$1.4\times10^6$</td>
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<tr>
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<td>wind</td>
<td></td>
</tr>
<tr>
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<td>$10^{-3}$</td>
<td>$2\times10^8$</td>
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<td>$7.4\times10^{37}$</td>
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</tr>
<tr>
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<td>$2\times10^8$</td>
<td>$0.4\times10^6$</td>
<td>$1.5\times10^{37}$</td>
<td>1.2</td>
<td>bound</td>
<td></td>
</tr>
<tr>
<td>$5\times10^6$</td>
<td>$10^{-3}$</td>
<td>$10^9$</td>
<td>$3.3\times10^{14}$</td>
<td>$2.8\times10^{37}$</td>
<td>—</td>
<td>bound</td>
<td></td>
</tr>
<tr>
<td>$2\times10^6$</td>
<td>$10^{-3}$</td>
<td>$7\times10^7$</td>
<td>$2.0\times10^{14}$</td>
<td>$8.0\times10^{37}$</td>
<td>—</td>
<td>c-2</td>
<td></td>
</tr>
<tr>
<td>$10^6$</td>
<td>$5\times10^{-3}$</td>
<td>$8\times10^7$</td>
<td>$0.2\times10^{14}$</td>
<td>$1.9\times10^{37}$</td>
<td>—</td>
<td>c-1</td>
<td></td>
</tr>
<tr>
<td>$5\times10^6$</td>
<td>$3\times10^{-3}$</td>
<td>$1.2\times10^7$</td>
<td>$3.0\times10^{14}$</td>
<td>$1.0\times10^{37}$</td>
<td>—</td>
<td>c-1</td>
<td></td>
</tr>
</tbody>
</table>
temperature $T_d$ at $r \geq 8$ kpc in the disk is higher than the critical one, the hot gas in this region escapes freely with a supersonic velocity. On the other hand, the disk gas within $r \leq 8$ kpc is decelerated and then flows always with a subsonic velocity.

The gas temperature in the halo exceeds $1 \times 10^6$ K, and the $z$-height where the gas density is larger than $10^{-4}$ cm$^{-3}$ is $z \approx 4$ kpc in the inner region and $z \approx 9$ kpc in the outer region. The total gas mass in the halo is $\sim 10^8 M_\odot$ and the mass ejection rate from the galaxy is $\sim 1.0 M_\odot$ yr$^{-1}$ as summarized in Table I.

In the case $T_d=2 \times 10^6$ K and $n_d=10^{-3}$ cm$^{-3}$, the gas flow patterns at $t=2.0 \times 10^8$ yr are almost the same as those shown in Fig. 3 whether the massive halo presents or not. However, this halo gas will not be able to escape away from the galaxy, if the massive halo is considered.

The surface brightness in the soft X-ray region $E=0.28-0.87$ keV is illustrated in Fig. 4 where we use the cooling functions of Raymond et al.\textsuperscript{15} at this energy band. As is seen, the contours of iso-intensity surfaces are parallel to the disk plane, and substantially flattened profiles are expected if the disk galaxy is seen in edge-on. In Table II, the limiting distances $r_x$ and $z_x$, where the X-ray flux $F$ in this energy band is higher than, we say, $10^{-7}$ ergs cm$^{-2}$s$^{-1}$, are summarized. For the case of wind-type halo, this region becomes $r_x \sim 10$ kpc and $z_x \sim 3$ kpc.

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**Table II. Limiting distances $r_x$ and $z_x$, within which the X-ray flux in $0.28-0.87$ keV is higher than $10^{-7}$ ergs cm$^{-2}$s$^{-1}$.**

<table>
<thead>
<tr>
<th>$T_d$ (K)</th>
<th>$n_d$ (cm$^{-3}$)</th>
<th>$r_x$ (kpc)</th>
<th>$z_x$ (kpc)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$5 \times 10^4$</td>
<td>$10^{-4}$</td>
<td>13</td>
<td>3</td>
</tr>
<tr>
<td>$5 \times 10^5$</td>
<td>$3 \times 10^{-3}$</td>
<td>14</td>
<td>11</td>
</tr>
<tr>
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<td>$10^{-3}$</td>
<td>9</td>
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<td>$3 \times 10^6$</td>
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<td>$3 \times 10^{-4}$</td>
<td>13</td>
<td>4</td>
</tr>
<tr>
<td>$10^7$</td>
<td>$10^{-3}$</td>
<td>12</td>
<td>0.5</td>
</tr>
<tr>
<td>$10^7$</td>
<td>$3 \times 10^{-4}$</td>
<td>13</td>
<td>2</td>
</tr>
</tbody>
</table>
3.2. Bound-type gaseous halo

As the bound-type halo, we suppose that the gas velocity in the halo is less than the escape velocity, but the radiative cooling does not affect the gas motion till $t \leq 1 \times 10^8$ y. Therefore, the gas distribution tends to follow the dynamically equilibrium shape, but it is modified due to the angular momentum.

This bound-type halo is realized when the temperature of the disk gas is less than the critical one at $r \approx 12$ kpc and its density is too small for the radiative cooling to be efficient till, at least, $t \sim 10^8$ y. As is shown in Fig. 2, the bound-type halo is expected within a limited region of $T_d n_d$ plane. It is to be noted that the bound-type halo does not mean the static gaseous halo. Since the gas velocity is smaller than the escape velocity and the radiative cooling becomes inefficient before long, the halo gas will return to the disk. Thus, we should rather call this halo the transiently bound-type halo.

In Fig. 5, we illustrate the contours of isodensities and isothermals as well as the velocity vectors at the time $2.0 \times 10^8$ y for the case $T_d = 10^6$ K and $n_d = 10^3$ cm$^{-3}$ without massive halo. In comparison with the wind-type halo in Fig. 3, the isodensity contours become more concentrated and more parallel to the plane. Since the centrifugal force considerably outweighs the pressure force, the gas is rapidly expelled outwardly not so rising to the halo.

The region with the temperature higher than $3 \times 10^6$ K is limited within $r \leq 18$ kpc and $z \leq 7$ kpc, while the region with the density higher than $10^{-3}$ cm$^{-3}$ extends $r > 20$ kpc and $z \leq 6$ kpc. The total gas mass in the halo is $\sim 7.4 \times 10^7$ $M_\odot$. Although the gas escapes from the boundary of calculation at a rate $\sim 0.2$ $M_\odot$ y$^{-1}$, this gas will eventually return to the disk because its velocity is smaller than the...
escape velocity.

The surface brightness in soft X-ray region at the same time as in Fig. 5 is illustrated in Fig. 6. As is seen, the X-ray flux is lower than $10^{-7}$ ergs cm$^{-2}$ s$^{-1}$ except for the disk plane, and the extended X-ray halo cannot be expected. It should be noticed that the results sensitively depend upon the gas temperature at the disk. That is, the X-ray halo with the thickness $\sim 3$ kpc is expected in the case $T_g = 5 \times 10^6$ K as in Fig. 4, but it is not expected in the case $T_g = 10^6$ K for the same density $n_g = 10^{-3}$ cm$^{-3}$.

![Fig. 6. The same as in Fig. 5, but for the iso-intensity contours.](image)

3.3. Cooled-type gaseous halo

In this case, the radiative cooling affects the gas motion substantially. Owing to the radiative cooling, the pressure of cooled gas in the halo becomes lower, and it is compressed to fall onto the disk. Depending upon the parameters of the hot gas in the disk, two distinct flow patterns are realized. One is the case when the temperature of the disk gas is lower than the critical temperature at $r = 12$ kpc and when its density is high enough for the radiative cooling to be efficient. We call this case (c-1) type. The other is the case when the gas temperature is higher than $T_{cr}(r=12$ kpc) but the radiative cooling becomes efficient in a local region. We call this case (c-2) type.

As an example of (c-1) type, we illustrate the results for the case $T_g = 5 \times 10^5$ K and $n_g = 3 \times 10^{-4}$ cm$^{-3}$ at the time $t = 5.2 \times 10^7$ y and $1.15 \times 10^8$ y in Fig. 7. Since the main gas motion is limited to the region $R \leq 20$ kpc, the massive halo does not affect the results. As is seen, once the disk gas expands to the halo, it collapses to the disk within $t \sim 10^8$ y due to the rapid cooling. Because of the centrifugal force, the isodensity contours become nearly parallel to the disk plane. The cooled gas at $r = 9 - 14$ kpc and $z = 2$ kpc will form clouds, and they will fall onto the plane with the velocity $30 - 70$ km s$^{-1}$ according to the present calcula-
Fig. 7. The same as in Fig. 3, but (a) at $t=5.2 \times 10^7$ y and (b) at $1.2 \times 10^9$ y for the case $T_\star=5 \times 10^6$ K and $n_\star=3 \times 10^{-3}$ cm$^{-3}$ without a massive halo. This is a typical (c-1) type halo.

As a result, the gas supplied from the disk $r=4 \sim 9$ kpc is transferred to the ring region $r=7 \sim 14$ kpc. After then, these gas clouds will move along the disk to the original place because the centrifugal force is smaller than the gravitational force if the angular momentum is conserved. In such a manner, a large-scale mixing of matter between the inner and outer regions of disk occurs remark-
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On the other hand, in the case of (c-2) type halo the gas motion is clearly different from the one of (c-1) type halo as shown in Fig. 8, in which the results at the time $7.0 \times 10^7$ y for $T_d=2 \times 10^6$ K and $n_d=10^{-4}$ cm$^{-3}$ without massive halo are illustrated. Since the gas temperature in the disk is higher than $T_d(r=9$ kpc), the gas initially expands extensively and a part of the gas escapes form the galaxy as a wind. Especially, the halo gas near the disk at $r \geq 12$ kpc and $z \leq 4$ kpc escapes freely with a supersonic velocity of $\geq 250$ km s$^{-1}$. With expanding to halo, the radiative cooling becomes efficient for the gas at $r \leq 8$ kpc and it begins to fall towards the outer region of the disk. Since the falling gas and the outflowing gas encounter in the region $r \approx 6$~12 kpc and $z \approx 1$~4 kpc, the compressed and further cooled region extends there. This region corresponds to the area surrounded by the isothermal contour of 10$^4$ K in Fig. 8. If the radiative cooling is included below 10$^4$ K, this region will be further compressed and becomes narrower. Then, the gas in this region would form clouds and fall to the disk. These infalling, cooled gas clouds may be a part of high velocity clouds observed by HI 21 cm line, because the falling velocity would attain $\geq 100$ km s$^{-1}$. The infalling rate would be $2 M_\odot$ y$^{-1}$ in the present model. Moreover, at $z=6$ kpc the cooled gas is flowing outwardly with the velocity $\sim 150$ km s$^{-1}$. This will keep expanding and finally escape from the galaxy as a neutral gas. Eventually, in this (c-2) type halo there coexist three gas flows as the rapidly outflowing hot wind, the expanding cooled wind and the infalling cooled gas. The latter two cooled gas may be confirmed by HI observations.

![Fig. 8. The same as in Fig. 7, but at $t=7 \times 10^7$ y for the case $T_d=2 \times 10^6$ K and $n_d=10^{-4}$ cm$^{-3}$ without a massive halo. This is a typical (c-2) type halo.](https://academic.oup.com/ptp/article-abstract/64/6/1995/1863891)
§ 4. Discussion

As shown in § 3, various types of gas flow in the halo are expected, depending upon the parameters of hot gas in the disk. In the beginning, we discuss the observability of hot gaseous haloes. After then, we consider the effects on the evolution and structure of disk galaxies.

4.1. Observability of hot gaseous haloes

We have already presented the distributions of X-ray surface brightness in Figs. 4 and 6 for the wind-type and bound-type haloes, respectively, when a disk galaxy is seen in edge-on. The iso-intensity contours are nearly parallel to the disk plane, and the gradient to the z-direction is approximated as

\[ I_{\text{x}}(z) \sim I_{\text{x}}(z_0) \exp(-z/H_{\text{x}}), \]

where \( I_{\text{x}}(z_0) \) is the X-ray brightness (ergs cm\(^{-2}\) s\(^{-1}\)) at \( z = z_0 = 250 \) pc and \( H_{\text{x}} \) is the scale-height, which is summarized in Table I for respective models. As is seen, the scale-height of X-ray intensity is (2–4.0) kpc for wind-type halo and <1.0 kpc for bound-type halo at \( r = 5 \) kpc.

In Fig. 9, we illustrate the total X-ray luminosity at \( E = 0.28 \sim 4 \) keV for half of a halo. Naturally expected, since the radiative cooling is not efficient both for the wind-type and bound-type haloes, the results can be scaled as \( n \sim \beta n_0, L_{\text{x}} \sim \beta L_{\text{x}}, \) and \( T \sim T_0 \) if \( n_0 \) is scaled as \( \beta n_0 \). In Fig. 9, the observational data by the Einstein satellite are also indicated. Since the observed luminosity is so small as \( 10^{40} \) ergs s\(^{-1}\) for usual cases, the X-ray halo can be observed when seeing edge-on.

Savage and de Boer have obtained evidence for a hot gas of \( T \sim 10^6 \) K and \( n \sim 3 \times 10^4 \) cm\(^{-3}\) at \( r = 12 \) kpc and \( z = 5 \) kpc by IUE satellite. From the asymmetry of line profiles, they concluded that the hot gas extends from the disk with a scale-height 2 kpc. Since the cooling time of the gas at \( z = 5 \) kpc is so short as \( 3 \times 10^5 \) yr, this hot gas would not be in a steady state. From our calculated models in Fig. 5, we propose that this hot gas would originate in the disk gas of \( T_d \sim 10^4 \) K and \( n_d \sim 3 \times 10^5 \) cm\(^{-3}\) and would be a part of the...
gaseous halo which begins to be cooled. This model will be checked by observing the extension of the hot gas.

The hot gas in the disk proposed by McKee and Ostriker,6 $T_d \sim 5 \times 10^6$ K and $n_d \sim 3 \times 10^{-3}$ cm$^{-3}$, will once rise to the height $z \sim 2$ kpc corresponding to its scale-height with being expelled outwardly, and be cooled within $\sim 10^7$ y. Then, this cooled gas falls onto the disk and moves to the original place. This picture will correspond to the fountain model by Shapiro and Field.5 If this circulation of the matter becomes stationary, cold clouds are to be supplied and the global structure of the interstellar medium will be altered from that by McKee and Ostriker. And it is necessary to consider the role of the gaseous halo in the investigation of the mutual exchange of interstellar media.

4.2. Discussion on the structure of the gaseous halo

In an early epoch of a galaxy, the star formation was active so that the supernova explosions would have occurred frequently. In such a case, the hot gas formed in the disk would flow out to the halo. There are two models depending on whether the hot gas in the halo escapes from the galaxy or is retained within the galaxy. From our present results, when the gas in the disk is heated up to $\geq 5 \times 10^6$ K and $\geq 2 \times 10^6$ K for the cases with and without a massive halo, respectively, and is rarefied to $\leq 10^{-2}$ cm$^{-3}$, the hot gas will escape from galaxies. If these conditions are not satisfied for the case without a massive halo, the gas in the halo will be cooled and return to the disk within $10^7$ y if the gas heating in the halo is negligible. In such a case, it will be difficult to retain the hot gas for a time as long as $10^9$ y. If the disk gas is $T_d = (2-4) \times 10^6$ K and $n_d \leq 10^{-2}$ cm$^{-3}$ for the case with a massive halo, the gas extends to $R \leq 100$ kpc. If this hot gas in the disk is maintained for more than $10^9$ y in the early epoch of a galaxy, the mass of the hot gas within $R \leq 100$ kpc will be more than $10^9 M_\odot$ because of the mass loss rate $\geq 1 M_\odot$ y$^{-1}$ from Table 1. Since its mean density is larger than $10^{-2}$ cm$^{-3}$, it will be cooled and fall to the disk within $10^9$ y.

In rich clusters there must be a hot ($\sim 10^8$ K), dense ($\sim 10^{-5}$ cm$^{-3}$) intracluster gas as indicated by X-ray observations.19 In that case, the hot gas in the halo cannot flow out freely, but is likely to be compressed by the surrounding gas. Then, the radiative cooling will be facilitated if the thermal conduction from the intracluster gas is not efficient. In this case, a radiatively regulated gas accretion will be expected. However, if the random velocity of a galaxy within a cluster is higher than 500 km s$^{-1}$, this picture will be altered. When this galaxy goes in the hot, dense intracluster gas region, the gaseous halo in the upstream side will be compressed and be easily cooled, but that in the downstream side will be drawn out. Accordingly, the wind-type halo will be realized there for a time which is necessary to ablate the gas from the disk and the halo. This will be verified by the observations of asymmetrical features of halo structure such that one half of a halo is characterized by cooled-type halo (probably a filamentary structure) and the other
half is characterized by a tailed X-ray emission. A detailed calculation is now proceeding.

In the present calculations, we have completely ignored the magnetic field which will be also lifted to the halo with the hot gas, if its strength is as small as \(~\sim 10^{-6}\) Gauss. In combination with the differential rotation of a galaxy, this magnetic field will be twisted and annihilated to heat up the halo gas. Moreover, the cosmic rays will also be lifted with the hot gas and the magnetic field. It seems this model is preferable to the convective-diffusion model\(^{19}\) for propagation of cosmic rays. These problems in relation to the hot gaseous halo will be attacked in succeeding papers.

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**References**