PASJ: Publ. Astron. Soc. Japan **44**, L23–L26 (1992)

Feeding of Intergalactic Gas Clouds onto Elliptical Galaxies

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(Received 1991 October 9; accepted 1992 January 20)

Abstract

Due to ram-pressure braking, intergalactic H I clouds such as tidal debris from galaxies are captured and accreted by an elliptical galaxy which is embedded in a hot gaseous halo. The captured clouds are rapidly accreted toward the central region along spiral orbits, and play a role in feeding the nucleus.

Key words: Accretion — AGN — Elliptical galaxy — H I clouds —- Hot gas halo — Intergalactic gas — Ram pressure

1. Introduction

The feeding of AGN (active galactic nuclei) in elliptical galaxies is thought to occur either by the infall of intergalactic gas, or by an instability in the central region due to cooling flows followed by infall toward the nulceus (e.g., Fabbiano 1989; Hattori and Habe 1990; Fabian 1991). Increasing evidence of interstellar matter in elliptical galaxies, suggesting clouds of external origin, has been reported (Bertola 1987; Schweizer 1987; Kormendy and Djorgovski 1989; Bettoni et al. 1990; van Gorkom et al. 1986, 1989). Intergalactic H I clouds, such as those observed as debris in interacting galaxy systems (Weilachew et al. 1978; Haynes et al. 1979; Sancici 1987; Smith 1991), could be sources for such clouds of external origin.

Massive objects like galaxies can merge with other galaxies through dynamical friction (e.g., McGlynn and Ostriker 1980; Barnes 1989); this mechanism does not apply to smaller mass objects, like H I gaseous debris. In order for intergalactic gas clouds to be accreted by galaxies, effects other than gravity should play an essential role. It is known that a large fraction of elliptical galaxies have extended hot (X-ray) gaseous halos (Forman et al. 1979; Nulsen et al. 1984; Fabbiano 1989; Fabian 1991). In this paper we point out that a hot halo plays an important role in accreting external gas clouds, and feeding AGN.

2. Ram-Pressure Accretion Model

In our previous paper (Wakamatsu 1990; Sofue and Wakamatsu 1991) we showed that gas clouds orbiting around a galaxy capture and merge due to the gaseous halo around a spiral galaxy through ram-pressure braking. We discuss here a case involving elliptical galaxies which are embedded in extended hot ($\sim 10^7$ K) gaseous halos, which extend to radii much larger than the galaxies' optical radii (e.g., Fabbiano 1989). We consider intergalactic H I gas clouds which are flying about an elliptical galaxy. We trace the orbits of such clouds while assuming a spherical shape for each cloud having a radius (R) of 1 kpc and a mass (m) of $(4\pi/3)R^3\rho_{\rm H\ I}$, where $\rho_{\rm H\ I} \sim 1m_{\rm H}$ cm^{-3} is the cloud's gas density.

Since a cloud feels gravity as a point mass, the galaxy's gravitationl potential is expressed by a Plummer's law,

$$\Phi = GM/\sqrt{r^2 + a^2}, \tag{1}$$

where G, M, and a are the gravitational constant, mass of the elliptical galaxy, and scale radius of the potential, respectively. We take $M = 2.3 \times 10^{11} M_{\odot}$ and $a = 10$ kpc. In addition to the gravitational force, the cloud suffers from ram pressure due to the gaseous halo as well as intergalactic and/or intracluster diffuse gas. We assume that the density distribution of hot gas around the galaxy is

$$\rho(r) = \rho_0(r^2/h^2 + 1)^{-\beta} + \rho_{00}. \tag{2}$$

Here, $\rho_{00} \sim 10^{-3--5} m_{\rm H}$ cm^{-3} is the intracluster (intergalactic) gas density, ρ_0, h, and β are parameters giving the distribution of halo gas; and $m_{\rm H}$ is the mass of hydrogen. We may here take $\rho_0 \sim 0.1 m_{\rm H}$ cm^{-3}, $h \sim 10$ kpc, and $\beta \sim 0.75$ (Fabbiano 1989).

In our model we assume that the initial cloud velocity relative to the galaxy is about 100 to 200 km s^{-1}, and that the hot gas temperature is $\sim 10^7$ K, so that the cloud motion is sub-sonic. The ram-pressure force is therefore given by $-\pi R^2 \rho(r) \Delta V^2$, where ΔV is the relative velocity of the cloud with respect to the halo gas. The equation of motion can be written as

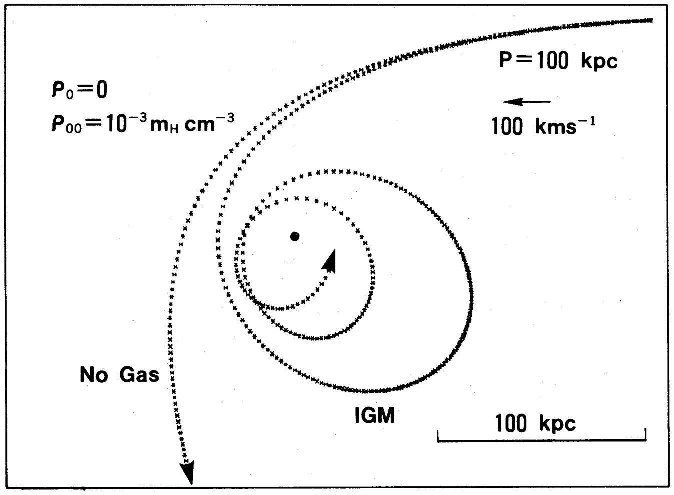

Fig. 1. Accretion of H I clouds by an elliptical galaxy due to ram-pressure by intergalactic gas. Hyperbolic orbits for the case without intergalactic gas is also shown. The cloud position is plotted by dots every 2×10^7 yr interval.

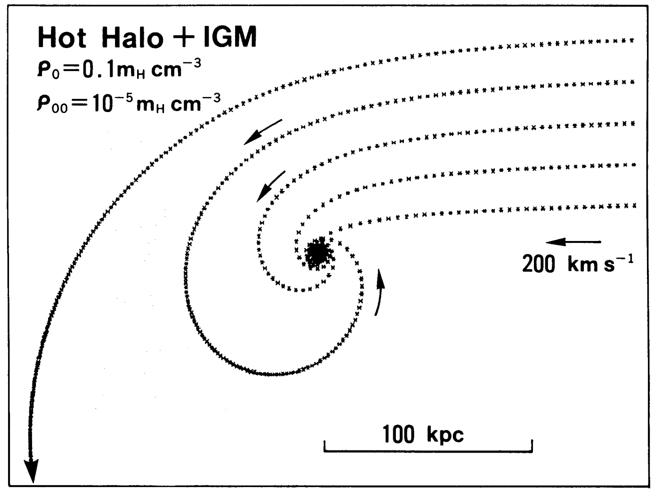

Fig. 2. Ram pressure accretion of an H I cloud by a hot gas halo for various impact parameters ($\rho_0 = 0.1$, $\rho_{00} = 10^{-5} m_{\rm H}$ cm^{-3}).

$$m\frac{d^2\boldsymbol{r}}{dt^2} = m\frac{\partial\Phi}{\partial\boldsymbol{r}} - \pi R^2 \rho(r) \Delta V \Delta \boldsymbol{V}, \tag{3}$$

where $\boldsymbol{r} = (x, y, z)$ is the cloud position with respect to the galaxy center. The velocity difference is given by $\Delta V = \boldsymbol{v} - \boldsymbol{V}$, where $\boldsymbol{v} = d\boldsymbol{r}/dt$ is the cloud velocity and $\boldsymbol{V} = \boldsymbol{V}(\boldsymbol{r})$ is the velocity of diffuse gas.

3. Results

Cloud's Orbits: Figure 1 shows the motion of a cloud encountering an elliptical galaxy on a hyperbolic orbits from inifinity at a speed of 100 km s^{-1} and an impact parameter $p = 100$ kpc. If there exists neither a halo nor intracluster gas ($\rho_{00} = \rho_0 = 0$), the cloud would obviously pass by the galaxy. If intracluster space is filled with diffuse gas of density $\rho_{00} \sim 10^{-3} m_{\rm H}$ cm^{-3}, the orbit changes drastically, and the cloud is trapped by the galaxy's potential, even if the galaxy contains no gas ($\rho_0 = 0$). This result indicates that intergalactic H I clouds are easily captured and merged by galaxies, and can hardly survive as "floating" clouds for a Hubble time.

Figure 2 shows orbits of clouds which approach along hyperbolic orbits at different impact parameters to an elliptical galaxy which is embedded in a hot gas halo at rest, as well as in intergalactic gas, namely for $\rho_{00} = 10^{-5} m_{\rm H}$ cm^{-3} and $\rho_0 = 0.1 m_{\rm H}$ cm^{-3}. As they approach the galaxy, the clouds are attracted by the increasing gravity of the galaxy; as they approach the galaxy, the ram pressure term becomes effective, since both ρ and ΔV increase toward the galaxy. Thus, the clouds change their motion to bound orbits, and are trapped by the galaxy's potential.

Once a cloud is captured, it is rapidly accreted toward the center. The accretion from the r = 50–100 kpc to the $r \sim 10$ kpc region typically occurs in less than one orbital rotation after the perigalactic passage, namely within 10^9 yr. Afterwards, due to increasing gravity and increasing ram pressure, the cloud is further accreted to the central region within an additional few rotations, or within a few 10^8 yr.

Circum-Galactic Gas Bands: We next show the results of a simulation of an ensemble containing many (N) clouds ('N-clouds'), which has a radius (R_N) and velocity dispersion (σ_v) of 5 kpc and 5 km s^{-1} , respectively. Figure 3 illustrates a case without a hot halo ($\rho_0 = 0$), but with intracluster diffuse gas of density $\rho_{00} = 10^{-3} m_{\rm H}$ cm^{-3}. As the N clouds approach the galaxy, they orbit around the galaxy a couple of times before infalling toward the center, forming a band surrounding the galaxy. This could explain the H I band detected around elliptical galaxy NGC 1052 (van Gorkom et al. 1986). The dark lanes found in many elliptical galaxies may also be such accreting clouds (Bertola 1987; Schweizer 1987; Fabbiano 1989). If star formation takes place in these bands during accretion, stellar rings such as those observed in Hoag-type galaxies, would be formed (Schweizer et al. 1987).

"Accretion Spiral" and Nuclear Fueling: Figure 4 shows the result of an N-cloud simulation for an elliptical galaxy embedded in a hot halo, as well as in intergalactic gas for the same parameter as shown in figure 2. In this case the accretion is more rapid, and the clouds are accreted in an open spiral feature. As the N-clouds are accreted into the inner 10 kpc region, they

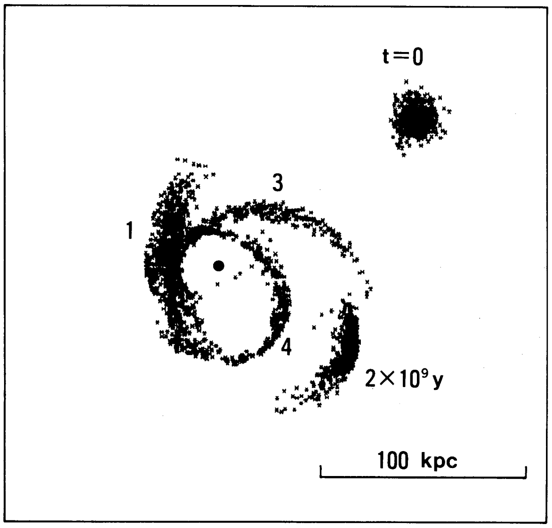

Fig. 3. Ram pressure accretion of an ensemble of N-clouds by an elliptical galaxy without a gas halo located in an intracluster gas of density $\rho_{00} = 10^{-3} m_{\rm H}$ cm^{-3}, for p = 80 kpc and velocity 100 km s^{-1} .

are strongly stretched along the orbit, and attain a one-armed spiral shape. We stress that the clouds are thus accreted toward the nulcear region along such an "accretion spiral." During accretion, the clouds are heated and ionized, which may produce an emission-line gas spiraling toward the nucleus. We mention that similar one-armed spiral features of Hα-line emission have indeed been observed in elliptical galaxy NGC 4696, radio galaxy PKS 0521−36 and in some other elliptical galaxies (Sadler 1987; Danziger and Focardi 1988; Kim 1989).

Effect of Rotation: The present model may be applied to a case in which the halo gas is rotating (Sofue and Wakamatsu 1991), even though rotation of gaseous halos in elliptical galaxies is an open question. We assume that the rotating halo balances gravity in a direction perpendicular to the rotation (z) axis, while it is in pressure balance in the z-direction. Figure 5 shows the result for a "retrograde" encounter of N-clouds, where the halo is in a counter-rotation with respect to the cloud's initial angular momentum. Clouds pass by the central region on S-shaped orbits during accretion, and are then pulled into corotating orbits with the halo; they finally attain an almost perfect ring feature. This may mimick an Hα ring of 20-kpc radius around PKS 1216−10 and its central S-shaped peculiar feature (van Gorkom et al. 1986; Danziger and Focardi 1988).

Confinement, Maintenance, and Cascade of a Cloud: We briefly comment on the confinement and cascade processes of a cloud. We assume that a cloud maintains its structure via a virial balance with the internal motion, such as turbulence and rotation. The cloud is massive

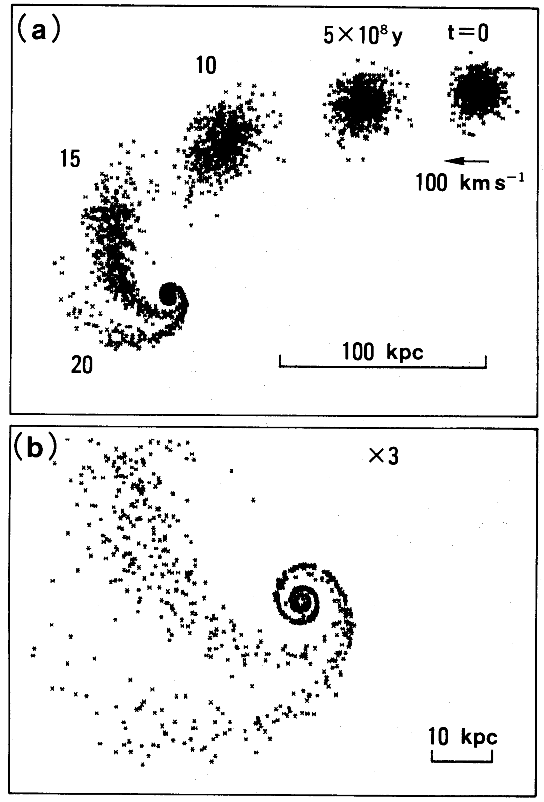

Fig. 4. (a) Ram pressure accretion of an ensemble of N-clouds by a hot gas halo of an elliptical galaxy, for ρ_0 = 0.1, $\rho_{00} = 10^{-5} m_{\rm H}$, p = 100 kpc, and an injection velocity of 100 km s^{-1}. Clouds are rapidly accreted and spiral into the nuclear region within a few rotations. (b) Same as (a) but the central region is enlarged.

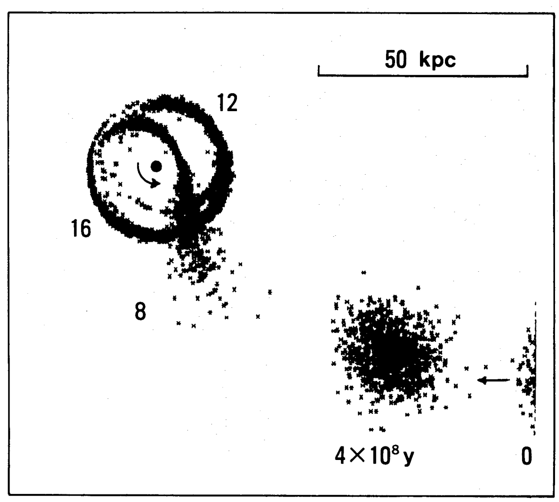

Fig. 5. Retrograde encounter of N-clouds with a rotating hot gas halo. Note the peculiar feature accross the central region.

enough to be gravitaionally bound, unless internal motion exceeds 10–20 km s^{-1}. The ram pressure force at the surface is transmitted to the entire cloud within a time scale of 10^7–10^8 yr of the internal motion. Since the thermal pressure of the H I gas is small compared to the external hot gas pressure, the cloud is thermally stable. Thermal conduction is negligible in heating the cloud, while heating due to turbulence dissipation may take place. However, heating is in balance with radiative cooling, such as that due to molecule (H_2) formation, as is the case for galactic H I clouds. The Rayleigh-Taylor instability (Chandrasekhar 1961) at a stagnation surface of a cloud grows on a time scale of $\tau_{\rm RT} \sim (\lambda/2\pi g_{\rm ram})^{1/2}$. Here, $g_{\rm ram} \sim \rho_0 \Delta v^2/(R\rho_{\rm H\,I})$ is the acceleration and λ is the wavelength. We then obtain $\tau_{\rm RT} \sim (2\rho_{\rm H\,I}/3\pi\rho_0)^{1/2}(\lambda R)^{1/2}/\Delta V \sim 10^9$ yr for $\lambda \sim 1$ kpc. The Kelvin-Helmholtz instability (Chandrasekhar 1961) due to a shearing motion on one side surface of a cloud occurs locally for wavelengths smaller than $\lambda \sim (\rho_0/\rho_{\rm H\,I})(\Delta v^2/g_{\rm cloud})$, where $g_{\rm cloud} \sim Gm/R^2$ is the surface gravity due to the cloud. We thus obtain $\lambda \sim R(\rho_0/\rho_{\rm H\,I})(\Delta v/v_{\rm esc})^2 \sim 100$ pc. The growth of horizontal mode waves is much faster than a transverse mode; its growth time is given by $\tau_{\rm KH} \sim \sqrt{\rho_{\rm H\,I}/\rho_0}\lambda/\Delta v \sim 10^7$ yr. However, in order for the entire structure of the cloud to be changed, it takes about $\tau_{\rm KH} \times (R/\lambda)^2 \sim 10^9$ yr, again comparable to the accretion time scale.

The above-mentioned estimates apply when a cloud moves through the outer halo. However, if the cloud is accreted further, the environment changes and, accordingly, the cloud structure varies and evolves, possiblly being both elongated and compressed. If this compression induces gravitaional and thermal instabilities, followed by fragmentation into denser cloudlets, the cloudlets will be accreted more rapidly. However, if the cloud is stretched along the orbit, the effective cross section decreases, as does the ram. All of these complex processes during accretion are beyond the scope of this paper, and will be discussed separately.

4. Discussion

We have shown that intergalactic H I clouds are easily captured by elliptical galaxies by ram-pressure accretion due to circum-galaxian hot gas. If the galaxy contains a gaseous halo, the clouds are rapidly accreted along spiral orbits, which may play a substantial role in feeding the nuclei. However, our simulation cannot tell more about the details of the gas flow in the central region, since we have not taken into account the variation of sizes, density and physical conditions of individual clouds. Thereby, it may be possible that individual clouds are more condensed and tidally stretched along the orbits, so that the cross sections decrease, which may reduce the effective ram pressure. Therefore, before final accretion onto the nucleus occurs, the clouds would form a circum-nuclear accreting ring. For a detailed modeling of the gas flow near the nucleus, we need a fully hydrodynamical simulation, which is beyond the scope of this paper.

This work was financially supported by the Ministry of Education, Science and Culture under Grant No. 01420001 and 01302009 (Y. Sofue).

References

Barnes, J. E. 1989, *Nature*, **338**, 123.
Bertola, F. 1987, in *Structure and Dynamics of Elliptical Galaxies, IAU Symp. No. 127*, ed. T. de Zeeuw (D. Reidel Publishing Company, Dordrecht), p. 135.
Bettoni, D., Fasano, G., and Galletta, G. 1990, *Astron. J.*, **99**, 1789.
Chandrasekhar, S. 1961, in *Hydrodynamic and Hydromagnetic Stability* (Clarendon Press, Oxford, London), Chap. X, XI.
Danziger, I. J., and Focardi, P. 1988, in *Cooling Flows in Clusters and Galaxies*, ed. A. C. Fabian (Kluwer Academic Publishers, Dordrecht), p. 133.
Fabbiano, G. 1989, *Ann. Rev. Astron. Astrophys.*, **27**, 87.
Fabian, A. C. 1991, *Astron. Astrophys. Rev.*, **2**, 191.
Forman, W., Schwarz, J., Jones, C., Liller, W., and Fabian, A. C. 1979, *Astrophys. J. Letters*, **234**, L27.
Hattori, M., and Habe, A. 1990, *Monthly Notices Roy. Astron. Soc.*, **242**, 399.
Haynes, M. P., Giovanelli, R., and Roberts, M. S. 1979, *Astrophys. J.*, **229**, 83.
Kim, D.-W. 1989, *Astrophys. J.*, **346**, 653.
Kormendy, J., and Djorgovski, S. 1989, *Ann. Rev. Astron. Astrophys.*, **27**, 235.
McGlynn, T. A., and Ostriker, J. P. 1980, *Astrophys. J.*, **241**, 915.
Nulsen, P. E. J., Steward, G. C., and Fabian, A. C. 1984, *Monthly Notices Roy. Astron. Soc.*, **208**, 185.
Sadler, E. M. 1987, in *Structure and Dynamics of Elliptical Galaxies, IAU Symp. No. 127*, ed. T. de Zeeuw (D. Reidel Publishing Company, Dordrecht), p. 125.
Sancisi, R., Thonnard, N., and Ekers, R. D. 1987, *Astrophys. J. Letters*, **315**, L39.
Schweizer, F. 1987, in *Structure and Dynamics of Elliptical Galaxies, IAU Symp. No. 127*, ed. T. de Zeeuw (D. Reidel Publishing Company, Dordrecht), p. 109.
Schweizer, F., Ford, W. K., Jr., Jedrzejewski, R., and Giovanelli, R. 1987, *Astrophys. J.*, **320**, 454.
Smith, B. J. 1991, *Astrophys. J.*, **378**, 39.
Sofue, Y., and Wakamatsu, K. 1991, *Publ. Astron. Soc. Japan Letters*, **43**, L57.
van Gorkom, J. H., Knapp, G. R., Ekers, R. D., Ekers, D. D., Laing, R. A., and Polk, K. S. 1989, *Astron. J.*, **97**, 708.
van Gorkom, J. H., Knapp, G. R., Raimond, E., Faber, S. M., and Gallagher, J. S. 1986, *Astron. J.*, **91**, 791.
Wakamatsu, K. 1990, *Astrophys. J.*, **348**, 448.
Weliachew, L., Sancisi, R., and Guélin, M. 1978, *Astron. Astrophys.*, **65**, 37.