Star Formation in the Cometary Tails Associated with Cluster Galaxies

Takahiro YAMAGAMI * and Yutaka FUJITA

Department of Earth and Space Science, Graduate School of Science, Osaka University,
1-1 Machikaneyama-cho, Toyonaka, Osaka 560-0043

(Received ; accepted )

Abstract

We investigate the star-formation in cometary tails of galaxies in clusters. In particular, we focus on the evolution of molecular clouds in the tails that generate the stars. Assuming that the gas tails had been derived from the galaxies through ram-pressure stripping, we found that the gas must have been stripped mostly not in the form of molecular clouds, but in the form of H I gas or molecular gas that is not in clouds. Moreover, the molecular clouds are condensed in the tails even away from the host galaxies. We also found that magnetic fields may be required to suppress Kelvin-Helmholtz (KH) instability on the surface of molecular clouds, because otherwise KH instability may destroy the molecular clouds before stars are formed in them.

Key words: galaxies: active — galaxies: clusters: general — ISM: clouds — stars: formation

1. Introduction

Recent observations of nearby clusters of galaxies have shown that some galaxies in the clusters have cometary tails (e.g. Gavazzi et al. 2001; Kenney et al. 2004; Yoshida et al. 2004; Machacek et al. 2005; Wang et al. 2004; Oosterloo & van Gorkom 2005; Sun & Vikhlinin 2005; Chung et al. 2007; Cortese et al. 2007). In the optical band, for example, Yagi et al. (2007) found an long and narrow (∼60 × 2 kpc) tail associated with the galaxy D 100 in the Coma cluster. The relative velocity between the tail and the host galaxy is ∼100–300 km s⁻¹. Yoshida et al. (2008) discovered an unusual complex of the narrow blue filaments derived from the galaxy RB 199 in the Coma cluster and bright knots in these filaments. These knots are found to be young stars. Their masses are ∼10⁶–10⁷ M☉ and their sizes are ∼200 pc. Judging from their colors, they are estimated to be formed ∼10⁸ yr ago. The distance between the host

* Present Address: Graduate School of Engineering Science, Osaka University, 1-1 Machikaneyama-cho, Toyonaka, Osaka 560-0043, email: t-yamagami@mit.eng.osaka-u.ac.jp
galaxy and the knots is $\gtrsim 10$ kpc (Yoshida et al. 2008). In the X-ray band, Fujita et al. (2006) found a comet-like structure around one of the brightest galaxies in Abell 2670. Sun et al. (2010) also found the X-ray tails associated with the spiral galaxy ESO 137-001 in Abell 3627. They confirmed active star-formation in the tails even at positions $\gtrsim 10$ kpc away from the host galaxy. In the infrared band, Sivanandam et al. (2010) discovered a molecular hydrogen tail with an H$_2$ mass of approximately $4 \times 10^7 M_\odot$ extending 20 kpc from ESO 137-001.

It is often believed that the tails are created through ram-pressure stripping of interstellar medium of galaxies, which has been intensively studied (Gunn & Gott 1972; Takeda et al. 1984; Gaetz et al. 1987; Fujita & Nagashima 1999). Recently, detailed numerical simulations of the ram-pressure stripping and formation of the tails have been performed (Abadi et al. 1999; Stevens et al. 1999; Mori & Burkert 2000; Quilis et al. 2000; Schulz & Struck 2001; Bekki & Couch 2003; Roediger & Hensler 2005; Roediger et al. 2006; Kapferer et al. 2009; Tonnesen & Bryan 2010). However, although the resolution of the numerical simulations has increased, it is still difficult to resolve physical processes on a scale of molecular clouds. For example, in current simulations on galactic scales, it would be difficult to resolve Kelvin-Helmholtz (KH) instability, which is expected to develop around a molecular cloud moving along the galactic tail.

In this paper, we study the formation of the galactic tails and star-formation in them. We consider disk galaxies with abundant gas as the host galaxies. We especially focus on the molecular clouds in which the stars were born. We estimate the growth time of KH instability around the clouds and compare it with the time-scale of star-formation in the clouds, which is affected by the ram-pressure on them. For these purposes, we assume that the molecular clouds are gravitationally bound and we use the virial theorem for the clouds.

2. Origin of the Molecular Clouds in Tails

In this section, we discuss the formation process of the tails through ram-pressure stripping. Since we are interested in the star-formation in the tails, we argue whether the molecular clouds that produce stars in the tails were formed in the tails or in the host galaxy.

2.1. Ram-Pressure Stripping

Although the number density of intracluster medium (ICM) is low ($\rho_{\text{ICM}}/m_\text{H} \sim 10^{-3}$ cm$^{-3}$; $m_\text{H}$ is the mass of a hydrogen atom), ram-pressure on a galaxy is relatively large, because the galaxy moves very fast (typically $\gtrsim 1000$ km s$^{-1}$) in a cluster. The ram-pressure is given by

$$P_{\text{ram}} = \rho_{\text{ICM}} v_{\text{gal}}^2 = 1.7 \times 10^{-11} \text{dyn cm}^{-2} \left( \frac{\rho_{\text{ICM}}}{10^{-3} m_\text{H} \text{cm}^{-3}} \right) \left( \frac{v_{\text{gal}}}{10^3 \text{ km s}^{-1}} \right)^2,$$

(1)

where $v_{\text{gal}}$ is the velocity of the galaxy relative to the ICM. On the other hand, the gravity from the galaxy per unit area is given by
where $G$ is the gravitational constant, $\Sigma_s$ is the gravitational surface mass density of the galaxy, $v_{\text{rot}}$ is the rotation velocity, and $R_{\text{gal}}$ is the radius of the disk (Gunn & Gott 1972; Fujita & Nagashima 1999). The column density of the gas we consider is given by $\Sigma_{\text{gas}}$. Most numerical simulations have implicitly considered ram-pressure stripping of HI gas with a density of $\sim 1 \text{ cm}^{-3}$. As their results have been shown, the HI gas can easily be stripped. In fact, if we replace $\Sigma_{\text{gas}}$ by the typical value of the gas column density of the disk, $\Sigma_{\text{HI}}$ (e.g. Binney & Tremaine 1987), it is written as

$$f_{\text{g}} = 2 \times 10^{-11} \text{dyn cm}^{-2} \left( \frac{v_{\text{rot}}}{220 \text{ km s}^{-1}} \right)^2 \times \left( \frac{R_{\text{gal}}}{10 \text{ kpc}} \right)^{-1} \left( \frac{\Sigma_{\text{HI}}}{8 \times 10^{20} \text{ m}_H \text{ cm}^{-2}} \right)$$

and is comparable to $P_{\text{ram}}$ in equation (1). Thus, if $v_{\text{gal}}$ is larger than $\sim 1000 \text{ km s}^{-1}$, the gas is stripped.

Next, we consider the ram-pressure stripping of a molecular cloud in a galaxy, which is expected to be more difficult than that of HI gas, because of its high density (Boselli & Gavazzi 2006). In this case, $\Sigma_{\text{gas}}$ in equation (2) should be replaced by the column density of the molecular cloud. The virial theorem for a molecular cloud gives the relation between the mass $M_c$, the radius $R_c$, and the external pressure $P_c$ of the cloud:

$$\frac{M_c}{R_c^2} = a \left( \frac{P_c}{10^4 \text{ k}_B \text{ cm}^{-3} \text{ K}} \right)^{1/2},$$

where $a = 190 \pm 90 \text{ M}_\odot \text{ pc}^{-2}$ and $k_B$ is the Boltzmann constant (Elmegreen 1989). If we define the column density of the cloud as $\Sigma_c = M_c/(\pi R_c^2)$ and assume that the cloud is affected by the ram-pressure ($P_c = P_{\text{ram}}$), the column density is given by

$$\Sigma_c = 2.6 \times 10^{22} \text{ m}_H \text{ cm}^{-2} \left( \frac{P_{\text{ram}}}{1.7 \times 10^{-11} \text{ dyn cm}^{-2}} \right)^{1/2}.$$ 

Thus, from equation (2) we obtain

$$f_{\text{g}} \sim 6.9 \times 10^{-10} \text{ dyn cm}^{-2} \left( \frac{v_{\text{rot}}}{220 \text{ km s}^{-1}} \right)^2 \times \left( \frac{R_{\text{gal}}}{10 \text{ kpc}} \right)^{-1} \left( \frac{\Sigma_c}{2.6 \times 10^{22} \text{ m}_H \text{ cm}^{-2}} \right).$$

Equations (1) and (6) show that the ram-pressure cannot overcome the gravity from the galaxy ($P_{\text{ram}} \ll f_{\text{g}}$). The larger ram-pressure means the larger column density of a molecular cloud [equation (5)], which tend to prevent ram-pressure stripping of the cloud [equation (6)].

It is to be noted, however, there seem to be galaxies in which molecular clouds have been stripped; NGC 4522 is an example (Vollmer et al. 2008). For this galaxy, Vollmer et al. (2006) indicated that the galaxy might have undergone extremely strong ram-pressure stripping. They
speculated that the relative velocity between the galaxy and the surrounding ICM was larger because of the internal motion of the ICM. For example, if we take $\rho_{\text{ICM}} = 4 \times 10^{-3} m_{\text{H}} \text{cm}^{-3}$ and $v_{\text{gal}} = 3000 \text{ km s}^{-1}$, $P_{\text{ram}}$ is comparable to $f_g$ [equations (1) and (6)]. If this was the case, the clouds could have been stripped. Moreover, smaller gravity of a galaxy ($\propto v_{\text{rot}}^2/R_{\text{gal}}$) makes ram-pressure stripping easier [equation (6)]. Although ram-pressure stripping of molecular clouds is difficult to happen, the observations may suggest that the galaxy has been affected by exceptionally strong ram-pressure.

We also note that equation (4) is not valid when the environment of a cloud rapidly changes. According to the virial theorem for a cloud,

$$\frac{c}{R_c^{1/2}} \sim 0.4 \pm 0.1 \left( \frac{P_{\text{ram}}}{10^4 k_B \text{cm}^{-3} \text{K}} \right)^{1/4} \text{km s}^{-1} \text{pc}^{-1/2}$$

(Elmegreen 1989). For $R_c = 100 \text{ pc}$ and $P_{\text{ram}} = 1.7 \times 10^{-11} \text{dyn cm}^{-2}$, we obtain $c \sim 7.5 \text{ km s}^{-1}$. Thus, the typical time-scale of the evolution of the cloud is $R_c/c \sim 1 \times 10^7 \text{ yr}$. This may be compared with the time-scale of ram-pressure stripping ($< 10^8 \text{ yr};$ e.g. Quilis et al. 2000).

In this subsection, however, we use equation (4) just to check the condition of ram-pressure stripping. For that purpose, equation (4) is appropriate enough, because we do not consider the evolution of the cloud during the stripping. Moreover, extremely large ram-pressure is required to strip the cloud as indicated above. Thus, when the cloud is stripped, interstellar medium with lower density has already been stripped from the galaxy, and the cloud interacts directly with the ICM. Therefore, external pressure on the cloud does not change much during the stripping.

In the following, we also consider molecular clouds in a tail away from the host galaxy. For these clouds, the change of the environment is very slow. For example, the crossing time of the host galaxy in a cluster is $\sim 1 \text{ Mpc}/1000 \text{ km s}^{-1} \sim 1 \times 10^9 \text{ yr}$. Therefore, the change of the environment does not affect the evolution of the cloud and we can use equation (4).

### 2.2. Migration of the Gas

As mentioned in section 1, stars are often found $\gtrsim 10 \text{ kpc}$ behind the host galaxies in clusters. Since each star is very dense, it is obvious that it is not affected by ram-pressure. In other words, ram-pressure cannot decelerate stars and draw them away from the host galaxy. This means that the gas that makes up the stars at present has been drawn from the galaxy not in the form of stars but in the form of diffuse gas. The question is whether the gas was in the form of $\text{H}^1$ gas or molecular clouds when it was migrating from the host galaxy.

First, we consider the migration of $\text{H}^1$ gas. For simplicity, we assume that the $\text{H}^1$ gas in the galactic disk is stripped at one time, because the time-scale of the ram-pressure stripping is very short ($< 10^8 \text{ yr};$ e.g. Quilis et al. 2000). The mass of the $\text{H}^1$ gas blob is

$$M_{\text{H}^1} \sim \Sigma_{\text{H}^1} \pi R_{\text{gal}}^2$$
1. Distance from the galaxy for HI gas (dashed) and a molecular cloud (solid). The ICM density is $\rho_{\text{ICM}}/m_\text{H} = 1 \times 10^{-3}$ cm$^{-3}$ and the initial velocity of the gas is $v_c(0) = v_{\text{gal}} = 2000$ km s$^{-1}$. The mass of the HI gas is $M_{\text{HI}} = 2 \times 10^9 M_\odot$. The result for the molecular cloud does not depend on its mass.

The equation of motion for the gas blob is

$$M_{\text{HI}}\dot{v}_{\text{HI}} \sim -\rho_{\text{ICM}}v_{\text{HI}}^2\pi R_{\text{gal}}^2,$$  \hspace{1cm} (9)

where $v_{\text{HI}}$ is the velocity of the blob relative to the ICM. For given $M_{\text{HI}}$, $\rho_{\text{ICM}}$, and $R_{\text{gal}}$, one can solve equation (9) and obtain the distance between the blob and the host galaxy, if it is assumed that the blob is detached from the galaxy with the velocity of the galaxy, $v_{\text{gal}}$, at $t = 0$. It is to be noted that a galaxy is not decelerated by ram-pressure on a time-scale of $\gtrsim 10^9$ yr (Fujita 2006). For example, if we assume that $M_{\text{HI}} = 2 \times 10^9 M_\odot$, $\rho_{\text{ICM}}/m_\text{H} = 1 \times 10^{-3}$ cm$^{-3}$, $R_{\text{gal}} = 10$ kpc, and $v_{\text{gal}} = 2000$ km s$^{-1}$, the distance between the blob and the galaxy is $\sim 50$ kpc at $t = 1 \times 10^8$ yr (Figure 1). The distance is comparable to the observed length of tails (e.g. Yoshida et al. 2008; Sun et al. 2010). Even at this time, the velocity of the gas is still large ($v_{\text{HI}} \sim 1000$ km s$^{-1}$). In reality, the HI gas blob could decelerate faster than the estimation above, because the blob should be shattered through the interaction with the surrounding ICM, which increases the surface area of the gas per unit mass.

Next, we consider the migration of a molecular cloud. The equation of motion for the cloud is

$$M_c\dot{v}_c \sim -\rho_{\text{ICM}}v_c^2\pi R_c^2,$$  \hspace{1cm} (10)

where $v_c$ is the velocity of the cloud relative to the ICM. From equation (4), it can be easily shown that $\dot{v}_c \propto -\rho_{\text{ICM}}v_c$. Numerically, if we assume that $\rho_{\text{ICM}}/m_\text{H} = 1 \times 10^{-3}$ cm$^{-3}$ and $v_c(0) = v_{\text{gal}} = 2000$ km s$^{-1}$, the distance between the blob and the galaxy is $\sim 1$ kpc even at $t = 1 \times 10^8$ yr (Figure 1). Compared with the HI gas blob, the distance is small, because the cloud is denser and the ram-pressure per unit mass is smaller. Since the maximum age of a molecular cloud is $\sim 10^8$ yr (section 3), this estimation indicates that the cloud cannot travel the distance
between the host galaxy and the positions where star-formation has been observed ($\gtrsim 10$ kpc; e.g. Yoshida et al. 2008; Sun et al. 2010).

In summary, the results we present in sections 2.1 and 2.2 show that in general the molecular clouds that bring forth stars away from the host galaxy were formed neither inside nor close to the host galaxy. In other words, dense part of the HI gas that makes up the galactic tails condenses into molecular clouds even away from the galaxy.

3. Formation of Stars and Destruction of Clouds

3.1. Kelvin-Helmholtz Instability

The gas of the tail has a velocity comparable to that of the host galaxy (e.g. Yagi et al. 2007). Thus, we expect that the molecular clouds that are formed in the tail away from the galaxy also have large velocities. Therefore, the interaction with the surrounding ICM could lead to the development of KH instability around the clouds. Since observations show that stars are born in the tails, KH instability must be suppressed until the clouds turn into the stars. We do not consider thermal conduction for simplicity (see section 3.3).

If the self-gravity of a clouds is large enough, KH instability is completely suppressed. The condition is

$$M_c \gtrsim \frac{6^{1/2}\pi v_c^3}{G^{3/2}(\rho_c/\rho_{ICM})^{1/2}/\rho_{ICM}^{1/2}},$$

where $\rho_c$ is the density of the molecular cloud and is given by $\rho_c = 3M_c/(4\pi R_c^3)$ (Murray et al. 1993). Using equation (4) and assuming that $P_c = \rho_{ICM}v_c^2$, relation (11) can be written as

$$1 - 0.2 \left( \frac{a}{190 \ M_\odot \mathrm{pc}^{-2}} \right)^{-3} \gtrsim 0.$$ (12)

Since $a = 190 \pm 90 \ M_\odot \mathrm{pc}^{-2}$ (Elmegreen 1989), the left hand of relation (12) can vary from -0.4 to 0.9. This means that the cloud is at the boundary between stable and unstable states and that the relation (11) is not a sufficient criterion of stability in our case. Thus, we need to compare the growth time-scale of KH instability ($\tau_{KH}$) with the time-scale of star-formation in the cloud ($\tau_{form}$).

3.2. Comparison of Time-Scales

When KH instability is not completely suppressed, the growth time of the instability is given by

$$\tau_{KH} = \frac{(\rho_c + \rho_{ICM})R_c}{(\rho_c\rho_{ICM})^{1/2}v_c}.$$ (13)

(Murray et al. 1993). Note that $R_c$ is the function of $M_c$ and $P_c$ [equation (4)].

The star-formation in a molecular cloud under external pressure was studied by Elmegreen & Efremov (1997). The equation for the rate of change of gas mass in the cloud is
Fig. 2. Solid lines represent $\tau_{\text{form}}$ and dashed lines represent $\tau_{\text{KH}}$. Each group has three lines corresponding to $v_c = 333, 1000, 3000\,\text{km}\,\text{s}^{-1}$ (from top to bottom).

$$\frac{dM_c}{dt} = -\frac{dM_s}{dt} - \frac{AL}{c^2},$$  \hspace{1cm} (14)

where $M_s$ is the total mass of the embedded stars, $L$ is the luminosity of the stars, $c$ is the velocity dispersion of the gas, and $A$ is dimensionless constant. Equation (14) means that the gas mass decreases because of the star-formation and the evaporation by the stellar radiation. Assuming $L(t)$, and using equation (4) and observational results to determine $dM_s/dt$ and $A$, one can solve equation (14), and obtain the time when $M_c(t) = 0$ for given $M_c(0)$ and external pressure $P_c$ (Elmegreen & Efremov 1997). Since a significant proportion of the molecular gas in the cloud converts to stars in this time-scale, we define this time-scale as the time-scale of the star-formation in the cloud ($\tau_{\text{form}}$).

Figure 2 shows $\tau_{\text{KH}}$ and $\tau_{\text{form}}$ for molecular clouds with various masses $M_c$ [$M_c(0)$ for $\tau_{\text{form}}$] and velocities $v_c$. We fixed $\rho_{\text{ICM}}/m_H = 1 \times 10^{-3}\,\text{cm}^{-3}$ and $a = 190\,M_\odot\,\text{pc}^{-2}$ and gave the external pressure by $P_c = \rho_{\text{ICM}}v_c^2$. The formation time $\tau_{\text{form}}$ in the figure shows that a cloud disappears within $\lesssim 10^8\,\text{yr}$ even if there is no KH instability. The comparison between $\tau_{\text{form}}$ and $\tau_{\text{KH}}$ indicates that the cloud should be destroyed by KH instability before forming stars if $v_c \gtrsim 1000\,\text{km}\,\text{s}^{-1}$ ($\tau_{\text{KH}} < \tau_{\text{form}}$). We have confirmed that the uncertainty of $a$ does not affect the conclusion. On the other hand, although the velocities of stars formed in tails have not been observationally studied well, the relative velocity of the tail gas to the host galaxy is $\lesssim 200\,\text{km}\,\text{s}^{-1}$ in the case of ESO 137-001 (Sun et al. 2010). Thus, it is likely that stars are forming in clouds with velocities of $v_c \gtrsim 1000\,\text{km}\,\text{s}^{-1}$.

One idea to overcome this contradiction is that clouds in tails take a value of $a$ so that they are completely stable against KH instability [equation (12)]. However, there is no solid
ground for that. Moreover, there may be some other uncertainties other than \( a \), because our estimation is simple. Therefore, we consider more persuasive reason for the stability of a cloud in the next subsection.

3.3. Magnetic Fields

It is known that magnetic fields suppress KH instability. The interface between the two magnetized fluids is stable if

\[
B_{\text{ICM}}^2 + B_c^2 \geq 4\pi \frac{\rho_{\text{ICM}} \rho_c}{\rho_{\text{ICM}} + \rho_c} v_c^2,
\]

where \( B_{\text{ICM}} \) is the magnetic field of the ICM and \( B_c \) is the one of a cloud (Landau & Lifshitz 1960). Even if the cloud is almost neutral, minor ionization makes the relation (15) applicable (Spitzer 1978). Since \( \rho_{\text{ICM}} \ll \rho_c \), the relation can be written as

\[
\sqrt{B_{\text{ICM}}^2 + B_c^2} \sim 14 \mu G \left( \frac{\rho_{\text{ICM}}}{1 \times 10^{-3} m_H} \right)^{1/2} \left( \frac{v_c}{1000 \text{ km s}^{-1}} \right).
\]

The typical values of \( B_{\text{ICM}} \) and \( B_c \) are \( \sim 3 \mu G \), and \( \sim 30 \mu G \), respectively (e.g. Sarazin 1986; Spitzer 1978). Thus, it is likely that magnetic fields stabilize the surface of clouds in galactic tails even if their self-gravity alone cannot. Moreover, if the fields are stretched along the surface, thermal conduction will be suppressed (Vikhlinin et al. 2001).

We would like to note that similar phenomena may have been observed in clusters. Vikhlinin et al. (2001) indicated that magnetic fields may suppress the development of KH instability at contact discontinuities (cold fronts) observed in ICM. They also pointed out that the magnetic fields may suppress the thermal conduction across the discontinuity.

Our results show that molecular clouds with small velocities can survive without magnetic fields. However, it is unlikely that only molecular clouds with high velocities have magnetic fields. It may be natural to assume that molecular clouds in the tails have similar magnetic fields regardless of their velocities.

4. Summary

Recent observations have shown that some galaxies in clusters have long tails (> 10 kpc) and stars are forming in the tails. We have studied the formation of the tails and the star-formation in them, using the virial theorem for gravitationally-bound molecular clouds. Our scenario for the tail and star-formation can be summarized as follows.

- H I gas is stripped from a galaxy by ram-pressure from the ICM. On the other hand, molecular clouds in the galaxy are not directly stripped because of the large gravity from the galaxy per unit surface area, unless the ram-pressure is extremely strong (section 2.1).
- While H I gas is easily decelerated by ram-pressure, molecular clouds are not, because they are denser. This means that the overall structure of the long tail is formed by the H I gas, and that molecular clouds that generate stars away from the host galaxy had condensed
in the tail at positions away from the host galaxy. In other words, the clouds have not migrated from the host galaxy or from the neighbor of the host galaxy (section 2.2).

- For KH instability on their surfaces, the clouds are on the boundary between stable and unstable states, if only the self-gravity of the clouds is considered. However, if reasonable magnetic fields exist, they can suppress the development of KH instability (section 3).

Fujita et al. (1999) (see also Fujita 1998) indicated that star-formation is active in galaxies affected by ram-pressure until their interstellar medium disappears. This will be applied to the galaxies with tails. We suppose that the galaxies with tails are the ones that have abundant gas and fall into the central region of clusters for the first time. They may be actively generating stars in the main bodies and the tails. This is consistent with recent observations of galaxies in the Coma cluster (Yagi et al. 2010).

We speculate that the appearance of the tail would change as a galaxy falls toward the cluster center. In the outer region of a cluster, HI gas is stripped from an infalling galaxy and the tail develops. As the galaxy reaches the central region of the cluster, some of the HI gas cools and condenses into molecular clouds. The rest of it will be mixed with the ICM. As the velocity of the galaxy and the ICM density increases, the ram-pressure on the clouds increases. Thus, the star-formation time-scale of the clouds is reduced (Figure 2), and the star-formation becomes more efficient until the clouds are consumed in the star-formation. Hα emission may be observed around this dense gas (Tonnesen et al. 2011). Some of the HI gas that was mixed with the ICM may be compressed by the ambient ICM with high-pressure and may emit X-rays (Tonnesen et al. 2011).

We thank the anonymous referee for useful comments. We are grateful to F. Takahara and T. Tsuribe for useful discussion. This work was supported by KAKENHI (20540269)

References

Abadi, M. G., Moore, B., & Bower, R. G. 1999, MNRAS, 308, 947
Bekki, K., & Couch, W. J. 2003, ApJ, 596, L13
Binney, J., & Tremaine, S. 1987, Galactic Dynamics (Princeton; Princeton Univ. Press), 77
Boselli, A., & Gavazzi, G. 2006, PASP, 118, 517
Chung, A., van Gorkom, J. H., Kenney, J. D. P., & Vollmer, B. 2007, ApJ, 659, L115
Cortese, L., et al. 2007, MNRAS, 376, 157
Elmegreen, B. G. 1989, ApJ, 338, 178
Elmegreen, B. G., & Efremov, Y. N. 1997, ApJ, 480, 235
Fujita, Y. 1998, ApJ, 509, 587
Fujita, Y. 2006, PASJ, 58, 809
Fujita, Y., & Nagashima, M. 1999, ApJ, 516, 619
Fujita, Y., Sarazin, C. L., & Sivakoff, G. R. 2006, PASJ, 58, 131
Fujita, Y., Takizawa, M., Nagashima, M., & Enoki, M. 1999, PASJ, 51, L1
Gaetz, T. J., Salpeter, E. E., & Shaviv, G. 1987, ApJ, 316, 530
Gavazzi, G., Boselli, A., Mayer, L., Iglesias-Paramo, J., Vílchez, J. M., & Carrasco, L. 2001, ApJ, 563, L23
Gunn, J. E., & Gott, J. R., III 1972, ApJ, 176, 1
Kapferer, W., Sluка, C., Schindler, S., Ferrari, C., & Ziegler, B. 2009, A&A, 499, 87
Kenney, J. D. P., van Gorkom, J. H., & Vollmer, B. 2004, AJ, 127, 3361
Landau, L. D., & Lifshitz, E. M. 1960, Electrodynamics of Continuous Media (New York: Pergamon)
Machacek, M. E., Nulsen, P., Stirbat, L., Jones, C., & Forman, W. R. 2005, ApJ, 630, 280
Mori, M., & Burkert, A. 2000, ApJ, 538, 559
Murray, S. D., White, S. D. M., Blondin, J. M., & Lin, D. N. C. 1993, ApJ, 407, 588
Oosterloo, T., & van Gorkom, J. 2005, A&A, 437, L19
Quilis, V., Moore, B., & Bower, R. 2000, Science, 288, 1617
Roediger, E., Brüggen, M., & Hoeft, M. 2006, MNRAS, 371, 609
Roediger, E., & Hensler, G. 2005, A&A, 433, 875
Sarazin, C. L. 1986, Reviews of Modern Physics, 58, 1
Schulz, S., & Struck, C. 2001, MNRAS, 328, 185
Sivanandam, S., Rieke, M. J., & Rieke, G. H. 2010, ApJ, 717, 147
Spitzer L Jr. 1978, Physical Processes in the Interstellar Medium (Wiley Classics Library)
Stevens, I. R., Acreman, D. M., & Ponman, T. J. 1999, MNRAS, 310, 663
Sun, M., Donahue, M., Roediger, E., Nulsen, P. E. J., Voit, G. M., Sarazin, C., Forman, W., & Jones, C. 2010, ApJ, 708, 946
Sun, M., & Vikhlinin, A. 2005, ApJ, 621, 718
Takeda, H., Nulsen, P. E. J., & Fabian, A. C. 1984, MNRAS, 208, 261
Tonnesen, S., & Bryan, G. L. 2010, ApJ, 709, 1203
Tonnesen, S., Bryan, G. L., & Chen, R. 2011, ApJ, 731, 98
Vikhlinin, A., Markevitch, M., & Murray, S. S. 2001, ApJ, 549, L47
Vollmer, B., Braine, J., Pappalardo, C., & Hily-Blant, P. 2008, A&A, 491, 455
Vollmer, B., Soida, M., Otmianowska-Mazur, K., Kenney, J. D. P., van Gorkom, J. H., & Beck, R. 2006, A&A, 453, 883
Wang, Q. D., Owen, F., & Ledlow, M. 2004, ApJ, 611, 821
Yoshida, M., et al. 2004, AJ, 127, 90
Yoshida, M., et al. 2008, ApJ, 688, 918
Yagi, M., et al. 2010, AJ, 140, 1814
Yagi, M., Komiyama, Y., Yoshida, M., Furusawa, H., Kashikawa, N., Koyama, Y., & Okamura, S. 2007, ApJ, 660, 1209