Does a Galaxy Fly?

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Abstract

Disk galaxies in a cluster of galaxies are moving in hot gas filling the cluster. Generally, they are moving at transonic or supersonic velocities. If ram-pressure stripping is insufficient to destroy the gas disk, the galaxies should be affected by the wind of the surrounding hot gas similar to an airfoil. In this paper, I consider whether the aerodynamic interaction can be strong enough to force a disk galaxy to deviate from the orbit that it would have been in. I find that while the lift force is not effective, the drag force could affect face-on disk galaxies in poor clusters on long timescales.

Key words: galaxies: spiral — galaxies: clusters: general — galaxies: evolution — galaxies: interactions — galaxies: intergalactic medium — galaxies: ISM

1. Introduction

The hot gas in clusters is often called the intracluster medium (ICM). The typical temperature and density of the ICM are $T_{\text{ICM}} \sim 2$–10 keV and $\rho_{\text{ICM}} \sim 10^{-27}$ g cm$^{-3}$, respectively (Sarazin 1986). While most galaxies are moving at transonic velocities ($V \sim 1000$ km s$^{-1}$) (Sarazin 1986), the galaxies that fall into a cluster from the outside have a Mach number of $\mathcal{M} \sim 2$–3 (Ghigna et al. 1998). So far, the interaction between disk galaxies and the surrounding ICM has been considered mostly in terms of ‘ram-pressure stripping’ (Gunn, Gott 1972; Fujita, Nagashima 1999; Fujita et al. 1999; Goto et al. 2003). The disk of a disk galaxy is composed of stars and gas filling the disk. The latter is called interstellar medium (ISM), and is cold and dense ($T_{\text{ISM}} \lesssim 10^4$ K and $\rho_{\text{ISM}} \gtrsim 10^{-24}$ g cm$^{-3}$) compared with the ICM. The ISM prevents the penetration of the galaxy by the ICM. If the ram-pressure force of the ICM ($\sim \rho_{\text{ICM}} V^2$ per unit area) becomes larger than the gravitational restoring force of the galaxy, the ISM is stripped away from the galaxy (Gunn, Gott 1972). Once the ISM is stripped, the ICM flows through the stellar disk of the galaxy without much resistance. Many numerical simulations have been performed to study this ram-pressure stripping
Another possible interaction between the ICM and ISM may be aerodynamic effects on a galaxy by the flow around the galaxy. In this paper, I discuss a few cases where the aerodynamic forces could operate on the galaxy motion, assuming that a disk galaxy is a thin solid disk for simplicity. Since the aerodynamic effects are available only when the disk ISM is not completely removed, I discuss only the cases where numerical simulations showed that the ram-pressure does not remove the ISM completely. Ram-pressure stripping is ineffective when the attack angle of a galaxy is small, and/or when the galaxy velocity is small. I consider the former in section 2 and the latter in section 3.

2. Lift Force

I consider a disk galaxy that falls into a cluster from the outside. The galaxy should have an almost radial orbit and should be affected by aerodynamical forces when it passes the central region of the cluster. Suppose that a galaxy is moving in the ICM with a velocity of \( V \) (Fig. 1). The angle of attack, \( \alpha \), is defined as the angle between the disk and the traveling direction of the galaxy. If \( \alpha \) is much smaller than 90°, ram-pressure stripping is not strong; the ISM of the galaxy is not completely removed and makes the surface of the disk. The ICM flows on both sides of the (remaining) ISM disk. It is assumed that the ISM disk is thin and its radius is \( r \). If \( \mathcal{M} > 1 \), the lift force on the disk is given by

\[
F_{\text{lift}} \approx 2\rho\text{ICM}V^2S\alpha/\sqrt{\mathcal{M}^2 - 1},
\]

where \( S = \pi r^2 \) is the area of the disk (Landau, Lifshitz 1987). The lift force is not sensitive to the form of the disk cross-section (Landau, Lifshitz 1987). Although this equation is for an infinitely long airfoil, the correction for a finite long one is small. The influence of the wing ends is limited to the inside of the Mach cones with the apexes at the wing ends and the angle of \( \mu = \sin^{-1}(1/\mathcal{M}) \) (Fig. 2). For a disk, its portions included in the cones are small.

For a luminous disk galaxy, the radius of the ISM disk is \( r \sim 25 \) kpc if ram-pressure stripping can be ignored totally. Considering the ram-pressure stripping, \( r \sim 5 \) kpc is taken here (Vollmer et al. 2001; Roediger, Brüggen 2005). For the central region of a rich cluster similar to the Coma cluster, the ICM temperature and density are \( T_{\text{ICM}} \sim 8 \) keV and \( \rho_{\text{ICM}} \sim 2 \times 10^{-27} \text{ g cm}^{-2} \), respectively. Thus, for a disk galaxy passing through the central region with \( \mathcal{M} \sim 2 \), the lift force is

\[
F_{\text{lift}} \approx 3.1 \times 10^{34} \text{ dyn} \left( \frac{\rho_{\text{ICM}}}{2.3 \times 10^{-27} \text{ g cm}^{-2}} \right) \left( \frac{V}{3000 \text{ km s}^{-1}} \right)^2 \\
\times \left( \frac{r}{5 \text{ kpc}} \right)^2 \left( \frac{\alpha}{10^\circ} \right) \left( \frac{4 \left( \mathcal{M} \right)^2 - 1}{2} \right)^{-1/2} .
\]

As a result, the galaxy gains extra velocity perpendicular to its original direction of travel,
\[ \Delta V \sim (F_{\text{lift}}/M) t_{\text{cross}} \sim 25 \text{km s}^{-1} \], where \( M (\sim 10^{11} M_\odot) \) is the galaxy mass, and \( t_{\text{cross}} (\sim 5 \times 10^8 \text{yr}) \) is the time for the galaxy to cross the central region of the cluster. Since this is much smaller than the velocity dispersions of galaxies in rich clusters (\( \sim 1000 \text{km s}^{-1} \)), it can be ignored. It is to be noted that since \( \alpha \) must be small enough to avoid ram-pressure stripping (Roediger, Brüggen 2005) and large enough to lift the galaxy (\( \sim 10^\circ \)), the fraction of galaxies affected by the lift force (\( \Delta V \sim 25 \text{km s}^{-1} \)) is very limited. After the galaxy reaches the apocenter far away from the cluster center, it falls back into the cluster again. However, it is unlikely for the galaxy to have an attack angle of \( \sim 10^\circ \) again.

3. Drag Force

For a poor cluster with a temperature of \( T_{\text{ICM}} \sim 2 \text{keV} \), ram-pressure stripping is almost ineffective for most galaxies regardless of the attack angle \( \alpha \), because the velocity of the galaxies and thus the ram-pressure on them are small. As a result, the radius of a ISM disk is large, and the drag force on a galaxy would be important especially when \( \alpha \sim 90^\circ \). For spherical galaxies, the drag force has been studied, although its influence on galaxy motion has not been discussed (Shaviv, Salpeter 1982; Gaetz et al. 1987). For a given radius, the drag force on a disk perpendicular to wind (\( \alpha = 90^\circ \)) is much larger than that on a sphere (White 1986). Therefore, it is worthwhile to revisit the problem for disk galaxies.

The drag force is given by
\[ F_{\text{drag}} = \frac{1}{2} C_D \rho_{\text{ICM}} V^2 \pi r^2, \]  

(3)

where \( C_D \) is the drag coefficient. For a disk of \( \alpha = 90^\circ \), the coefficient is \( C_D = 1.17 \), while for a sphere with the same radius, the coefficient is \( C_D \approx 0.2-0.47 \) depending on the Reynolds number (White 1986). The values of \( C_D \) are for incompressible fluids \( (\mathcal{M} \lesssim 0.3) \); they rise by a few tens percent at \( \mathcal{M} \sim 0.6-0.8 \) (Henderson 1976).

I consider a disk galaxy \( (M = 10^{11} M_\odot \text{ and } \alpha = 90^\circ) \) orbiting well-inside a poor cluster with a temperature of \( T_{\text{ICM}} = 2 \text{ keV} \) and a density of \( \rho_{\text{ICM}} \sim 1 \times 10^{-27} \text{ g cm}^{-3} \). Since the galaxy is orbiting inside the cluster and the drag force is not as sensitive to the attack angle as the lift force, the galaxy is constantly affected by the drag force from the ICM. Assuming that \( \mathcal{M} = 0.8 \), the drag force is

\[ F_{\text{drag}} \approx 5.4 \times 10^{23} \text{ dyn} \left( \frac{C_D}{1.2} \right) \left( \frac{\rho_{\text{ICM}}}{9 \times 10^{-28} \text{ g cm}^{-3}} \right) \times \left( \frac{V}{580 \text{ km s}^{-1}} \right)^2 \left( \frac{r}{10 \text{ kpc}} \right)^2. \]  

(4)

Considering weak ram-pressure pressure stripping, the disk radius was assumed to be \( r = 10 \text{ kpc} \) (Abadi et al. 1999; Roediger, Hensler 2005). After \( t = 10 \text{ Gyr} \), which is the typical age of poor clusters, the galaxy velocity decreases by \( \Delta V \sim (F_{\text{drag}}/M)t \sim 90 \text{ km s}^{-1} \) and the deviation from the orbit that the galaxy would have been in if it were not for the ICM is

\[ D \sim (1/2)(F_{\text{drag}}/M) t^2 \sim 0.4 \text{ Mpc}, \]

which is comparable to the size of poor clusters \( (\sim 1 \text{ Mpc}) \).

Note that although ram-pressure may distort the ISM disk, it is unlikely that the disk becomes as round as a sphere. Thus, the drag coefficient, \( C_D \), is at least larger than 0.2–0.47.

4. Discussion

I have shown that while the lift force on disk galaxies can be ignored, the drag force could not be ignored for face-on disk galaxies in poor clusters.

Equations (2) and (4) show that the strengths of the lift and drag forces are sensitive to the radius of the ISM disk, \( r \). In the above estimates, gas supply from stars in the galaxy was not considered. If the gas ejected from the stars is added to the ISM, \( r \) should become larger (Gaetz et al. 1987). It is likely that active disk galaxies, in which large amount of gas is being released from the stars, have much larger \( r \) and are more affected by the aerodynamic forces. It is also to be noted that if the velocity or pressure distribution of the ICM around a disk galaxy is measured, the aerodynamic forces can be constrained. The observations of stripped ISM will be useful to obtain the velocity field around a disk galaxy (Yoshida et al. 2004; Chemin et al. 2006). X-ray observations will tell us the pressure distribution around a galaxy (Vikhlinin et al. 2001).

The models presented here are very simple. In an actual galaxy, the situation would be rather delicate. One example is how the lift or drag would operate on the collisionless stars...
and dark matter particles, as required to alter the orbit of the whole galaxy. The connecting force is gravity. If the gas disk is lifted or dragged off the stellar disk, and the center of the dark matter halo, then both will pull back on the gas disk. This would communicate the lift or drag force to all components. Too much separation, and the restoring gravity force will be weakened and the gas will be stripped, too little and nothing will happen. In order to study the process quantitatively, numerical simulations would be required.

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