SIGNIFICANT ENHANCEMENT OF H$_2$ FORMATION IN DISK GALAXIES UNDER STRONG RAM PRESSURE

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ABSTRACT

We show for the first time that H$_2$ formation on dust grains can be enhanced in disk galaxies under strong ram pressure (RP). We numerically investigate how the time evolution of H$_1$ and H$_2$ components in disk galaxies orbiting a group/cluster of galaxies can be influenced by the hydrodynamical interaction between the gaseous components of the galaxies and the hot intracluster medium. We find that compression of H$_1$ caused by RP increases H$_2$ formation in disk galaxies before RP rapidly strips H$_1$, cutting off the fuel supply and causing a drop in H$_2$ density. We also find that the level of this H$_2$ formation enhancement in a disk galaxy under RP depends on the mass of its host cluster dark matter halo, the initial positions and velocities of the disk galaxy, and the disk inclination angle with respect to the orbital plane. We demonstrate that dust growth is a key factor in the evolution of the H$_1$ and H$_2$ mass in disk galaxies under strong RP. We discuss how the correlation between H$_2$ fractions and surface gas densities of disk galaxies evolves with time in the galaxies under RP. We also discuss whether galaxy-wide star formation rates (SFRs) in cluster disk galaxies can be enhanced by RP if the SFRs depend on H$_2$ densities.

Key words: galaxies: clusters: intracluster medium – galaxies: evolution – galaxies: ISM – galaxies: star formation – galaxies: structure

1. INTRODUCTION

It is well known that galaxy environments play key roles in the morphological transformation of galaxies, the enhancement and quenching of galaxy-wide star formation, and the cold gas evolution of galaxies (e.g., Dressler 1980; Koopmann & Kenney 2004; Boselli & Gavazzi 2006; Bundy et al. 2010; Villalobos et al. 2014; Pasquali 2015; Cortese et al. 2016). Dynamical and hydrodynamical interactions influence galaxy evolution (e.g., Bekki 2009; Bekki & Couch 2011), and mergers and intracluster medium (ICM) affect fundamental galactic parameters with increasing likelihood in higher-density regions (e.g., Lambas et al. 2012). Star-forming regions peak in merging systems in small and compact groups, increasing star formation rates (SFRs) and have important effects on galaxy morphology and evolution. Hydrodynamical interactions between ICM and cold interstellar medium (ISM) of disk galaxies aid in the quenching of star formation (SF), hence, the reddening of galaxies through “strangulation” (e.g., Peng et al. 2015).

Ram-pressure stripping (RPS) has long been considered to be one of the most important environmental effects, and thus has been investigated by many observational and theoretical astronomers (e.g., Gunn & Gott 1972; Takeda et al. 1984; Vollmer et al. 2001; Kronberger et al. 2008; Book & Benson 2010; Bekki 2014; McPartland et al. 2016). These studies include disk gas stripping (e.g., Roediger & Hollander 2005), halo gas stripping (e.g., Bekki 2009), stripped gas tails (e.g., Irwin et al. 1987; Tonnees & Bryan 2012), and cold gas compression (e.g., Ebeling et al. 2014). The compression of cold gas initially induces SF in the galaxy, while the stripping of the disk and halo gas causes an eventual decrease in SF in the galaxy. RP is an essential physical process that controls SF histories and gas evolution in disk galaxies.

These previous studies have not extensively investigated how RP of ICM in group and cluster environments can influence the evolution of H$_1$ and H$_2$ components of disk galaxies. Yagi et al. (2013) showed that SF occurs in the stripped tails from galaxies under RP; the stripping of H$_2$ from a disk galaxy would cause faster SF-quenching in the galaxy, as it is the direct fuel in the SF process. H$_1$ stripping only aids in the eventual “strangulation” of the galaxy and is a more long-term effect on the galaxy evolution. Compression of the H$_2$ left in the disk galaxy induces SF, due to an increase in density and interactions of H$_2$. Further work into the RP effect on H$_2$ is necessary to understand the formation and evolution of the cold gas in disk galaxies within group and cluster environments.

The purpose of this letter is to show for the first time that strong RP can significantly enhance H$_2$ formation on dust grains in disk galaxies based on the results of numerical simulations. We also show how this enhancement of H$_2$ formation depends on model parameters such as orbits within groups/clusters and disk inclination angles with respect to their orbital planes. H$_2$ is the key parameter in the formation of giant molecular clouds and thus SF; therefore, we discuss the present new results in the context of galaxy-wide H$_2$ formation and SF within dense galaxy environments. In the present work we do not discuss the origin of the shock-excited H$_2$ in disk galaxies, which has been recently discovered by Wong et al. (2014), because the present simulation code does not allow us to investigate H$_2$ formation through gaseous shocks.

2. THE MODEL

To investigate the time evolution of H$_1$ and H$_2$ content of disk galaxies under ram pressure of ICM, we use our original chemodynamical simulation code that can be run on GPU machines (Bekki 2013, B13). This new code enables us to investigate time evolution of dust and formation of H$_2$ on the surface of dust grains in a fully self-consistent manner, though it does not include feedback effects of active galactic nuclei. The most important difference between the present study and previous ones (e.g., Christensen et al. 2012; Hopkins et al. 2014) is the self-consistent time evolution of dust abundances deriving H$_2$ abundances used in the present study,
whereas others used constant dust-to-metal ratios (i.e., no evolution of dust abundances). In the present study, a disk galaxy moves in a cluster with a halo dark matter (DM) mass, \( M_{\text{dm}} \), and an IC temperature, \( T_{\text{ICM}} \), allowing its cold gas to be influenced by RP of the ICM. The RP force is calculated according to the position and velocity of the galaxy with respect to the cluster center (for details see Bekki 2014, B14).

The disk galaxy is composed of a DM halo, a stellar disk, a stellar bulge, and a gaseous disk, similar to the Milky Way (MW-type). The total masses of the DM halo, the stellar disk, the gas disk, and the bulge are set to be \( 10^{12} M_\odot \), \( 6 \times 10^{10} M_\odot \), \( 6 \times 10^9 M_\odot \), and \( 10^9 M_\odot \), respectively. The mass ratio of the DM halo to disk is fixed at 16.7. We adopt the density distribution of the NFW halo (Navarro et al. 1996) suggested from CDM simulations, with \( c \)-parameter and virial radius set to 10 and 245 kpc, respectively. The spherical bulge is represented by the Hernquist model with a scale length of 0.7 kpc and a size of 3.5 kpc. The radial (R) and vertical (Z) density profiles of the stellar disk are assumed to be proportional to \( \exp(-R/R_0) \) with a scale length of \( R_0 = 0.2 R_s \), and \( \csc^2(Z/Z_0) \) with a scale length of \( Z_0 = 0.04 R_s \), respectively. The gas disk, where \( R_g = 2 R_s \), has radial and vertical scale lengths of \( 0.2 R_g \) and \( 0.02 R_g \), respectively. In the present MW-type models, the exponential disk has \( R_s = 17.5 \) kpc and \( R_g = 35 \) kpc and a Toomre’s parameter of \( Q = 1.5 \). SF, chemical evolution, and dust evolution are included in exactly the same way as in B13. The total number of particles used in the MW-type model is 1,033,400, with a gravitational softening length of 2.1 kpc and 200 pc for the disk dark and baryonic components, respectively. The maximum hydrogen density in the present simulation is \( \sim 8 \times 10^3 \) cm\(^{-3} \), which is significantly lower than H2 density of molecular clouds (MCs) cores (\( \sim 10^5 \) cm\(^{-3} \)). This lack of resolution for MCs cores will not be a problem in this study because we focus exclusively on galaxy-scale H2 distribution.

To avoid a large number of gas particles to represent the entire ICM (e.g., Abadi et al. 1999), it is represented by \( 6 \times 10^3 \) SPH particles in a cube with the size of \( R_{\text{ICM}} \) and a disk galaxy is placed in the exact center. The initial velocity of each SPH particle for the ICM is set to be \( (V_r(t = 0), 0, 0) \), where \( V_r \) is determined by the position of the galaxy with respect to the cluster center. The orbit direction is chosen as the \( x \)-axis and disk inclination angles \( \theta \) and \( \phi \) are defined with respect to the \( x \)-\( y \) plane of the ICM cube. \( \theta \) is the angle between the spin axis of the disk and the \( z \)-axis (i.e., \( \theta = 0 \) means the spin axis parallel to the \( z \)-axis), whereas \( \phi \) is the angle between the \( x \)-\( y \) projected spin axis and the \( x \)-axis.

The mass of ICM particle is time-dependent and calculated according to the mass density of ICM at the position of the galaxy at each time step, whereas \( T_{\text{ICM}} \) is assumed to be constant. The ICM is assumed to have a uniform distribution within the cube with \( R_{\text{ICM}} \) set to be \( 6 R_s \) and \( T_{\text{ICM}} \) set to be 5.6 \( \times 10^6 \) K and 2.6 \( \times 10^7 \) K for \( M_\odot = 10^{11} M_\odot \) and \( M_\odot = 10^{12} M_\odot \), respectively; \( T_{\text{ICM}} \) is much higher than the temperature of cold ISM in galaxies. We include periodic boundary conditions (at \( R_{\text{ICM}} \)) for the ICM SPH particles leaving the cube. We mainly described the results of 10 representative models in the present study because these models show typical behaviors of H2 evolution in disks under strong RP and intriguing parameter dependence; see Table 1 for model parameter values.

### 3. RESULTS

Figure 1 shows how RP influences the time evolution of H1 and H2 masses and spatial distributions in a disk galaxy for five models (M1–M5). In the mass distributions of model M1, it can be seen that gas is first strongly compressed and then stripped efficiently form the galaxy. At \( T = 1.41 \) Gyr, just before pericenter passage, the cold gas clumped together with small amounts stripped. The majority of the stripping can, in fact, be seen at \( T = 1.76 \) Gyr, corresponding to the galaxy leaving the cluster central region. This indicates that the gas in the disk galaxy first undergoes compression (a shallower decrease in H1 mass) and is then stripped (a steeper decrease in H1 mass). Compression of the H1 can enhance H2 density significantly, particularly in the central region and thus drives efficient formation of H2 on dust grains in the disk galaxy. As a result, H2 mass can significantly increase with a peak occurring at the pericenter passage. H2 mass begins to decrease after this through stripping of gas and the formation of new stars from H2. The initial decrease of H2 mass at \( T < 0.5 \) Gyr is due to the rapid gas consumption by SF.

As shown in Figure 1, RP effects on H2 differ slightly for the five models (M1–M5) with different disk inclination angles (\( \theta \) and \( \phi \)). Although H2 formation enhancement can be seen in all of these models, the level of this enhancement depends weakly on \( \theta \) and \( \phi \). The more edge-on models (M1, M2, and M5) have a higher rate of H2 loss through H2 stripping and SF (driven by compression of H2). This indicates H2 formation efficiency on dust grains in disks under RP depends on the inclination of the disk to the orbital plane of the galaxy. The models M1 and M5 have higher gas mass losses and RP effects on the disk galaxy than the edge-on model M2, an interesting result that suggests there is a unique angle where RP has the most effect. However, this is beyond the scope of this letter and we will further discuss the origin of this in future papers.
Figure 2 describes how the correlation between gas surface density ($\Sigma_g$) and H$_2$ fraction can change with time in the disk galaxy under RP for the fiducial model M1. In the early phase of disk galaxy evolution ($T = 0.35$ Gyr), the galaxy shows a weak positive correlation between $\Sigma_g$ and $f_{H_2}$ for $\Sigma_g \lesssim 10 M_{\odot}$ pc$^{-2}$. There is an increase in H$_2$ gas fraction between $T = 0.35$ Gyr and $T = 1.41$ Gyr in local gaseous regions, indicating that H$_2$ formation is enhanced in these local regions of the galaxy. There is little stripping of gas between $T = 0.35$ and 1.41 Gyr, as overall surface gas density does not change so significantly. The stripping of gas is evident between $T = 1.41$ Gyr and $T = 1.76$ Gyr by the large drop in the overall surface gas density. These results are consistent with and reinforce what is shown in Figure 1. The move to low mean surface gas density and high H$_2$ fraction in individual gaseous regions of the disk galaxy at $T = 2.47$ Gyr is indicative of H$_1$ being stripped throughout the galaxy and not just its outer disk. The almost horizontal line of average H$_2$ fraction indicates that H$_1$ and H$_2$ are confined to the same pixels (i.e., the same local regions) within the disk galaxy.

Figure 3 demonstrates how different galaxy orbits within clusters of galaxies and different cluster masses ($M_{dm}$) influence the time evolution of H$_1$ and H$_2$ mass in disk galaxies. The peak of H$_2$ mass still corresponds to the pericenter passages of galaxies in these models (M6–M9). Model M6 has a shallower orbit than M1–M5, due to a higher initial galactic velocity, causing less RP to influence the disk galaxy and less gas to be stripped. H$_2$ mass peaks in this model are significantly shallower than those in models with smaller pericenter distances (M1–M5). Similar to models M1–M5 in Figure 1, the most prominent stripping occurs as the galaxy leaves the cluster central region. Model M7, with lower $M_{dm}$ (group-like halo) and an effective tighter orbit of the galaxy, produces more rapid stripping of H$_1$ (a steep slope in H$_1$ mass), resulting in less H$_2$ formation (low H$_2$ mass peak) than in other models (M1–M5). This is likely due to the disk galaxy spending more time in the central-most region of the group, where ICM is has a higher density. In contrast, model M8 has a wide orbit that never passes the central-most region of the cluster. There is little RPS of H$_1$ and no peak in H$_2$ mass, as H$_1$ is not being compressed and not driving the formation of H$_2$.

Model M9, with a very close orbit (due to an initial position closer to the cluster center) and a lower $M_{dm}$ (group-like halo), has two pericenter passes during $\sim 2.8$ Gyr. H$_1$ is rapidly stripped due to the galaxy being in the cluster central region and H$_2$ is formed and stripped during the first pericenter passage. During the second passage little increase in H$_2$ mass is seen, as there is insufficient H$_1$ to compress and form copious amounts of H$_2$.

Figure 4 shows how dust growth can influence time evolution of H$_2$ and SF histories in disk galaxies under RP. H$_2$ mass in the model M10 without dust physics is considerably lower with only a slight peak at the pericenter pass. This indicates that little H$_2$ formation is occurring in the disk galaxy for this model (M10). Owing to consumption of gas and dust by SF, H$_2$ formation on dust grains cannot continue to be effective without dust mass increase through the accretion of gas-phase metals onto dust grains (i.e., dust growth). It is interesting to note that appreciable enhancement of galaxy-wide SF can be seen in these two models with and without dust physics. This SF enhancement cannot last long, owing to H$_2$ consumption by SF and gas stripping during and after pericenter passage. These results imply that dust physics needs to be included in the modeling of H$_2$ evolution of disk galaxies under RP.
4. DISCUSSION AND CONCLUSIONS

Formation and evolution of H$_2$ in galaxies is a fundamental process in understanding SF and evolution of cold gas in disk galaxies. We show how the formation of H$_2$ is influenced through HI compression associated with RP of a disk galaxy in the present study. As the disk galaxy undergoes RP effects, the H$_2$ mass in the galaxy increases due to enhanced H$_2$ formation efficiency; a higher density of compressed gas can significantly enhance the conversion from H I to H$_2$ on dust grains. The present simulation does not have sub-pc resolution, so the evolution of H$_2$ in MCs of disk galaxies under RPS cannot be investigated. Using three-dimensional (3D) MHD simulations of H$_2$ formation within MCs, Valdivia et al. (2015) already investigated (i) how H$_2$ formation in dense MCs occurs rapidly and (ii) how H$_2$ then spreads into more diffuse regions around the clouds. It is our future work to investigate how RP can influence H$_2$ formation and evolution within individual MCs in disk galaxies using more sophisticated high-resolution 3D MHD simulations.

The present study shows that a weak positive correlation exists between H$_2$ gas fraction ($f_{H_2}$) and surface gas density ($\Sigma_g$) in disk galaxies under RP when H I is being compressed (yet not stripped). This result is consistent with observational studies for disk galaxies in the Virgo cluster (Nakanishi et al. 2006), which have revealed a similar $f_{H_2} - \Sigma_g$ relation in NGC 4254 and NGC 4656 (see Figure 3 of Nakanishi et al. 2006). These two galaxies are further from the cluster center, and Nakanishi et al. (2006) conclude that they have not yet been stripped of H I. The other three galaxies in their paper (NGC 4402, NGC 4569, and NGC 4579) are stripped of H I, and the gas fraction and surface density are consistent with our findings after strong RPS. So far, only a few observational

![Figure 2. H$_2$ gas fraction and surface gas density are determined for a 50 by 50 grid points in the x–y plane for model M1, 25 kpc$^2$ from the center. Points represent values for one grid point. H$_2$ gas fraction is H$_2$ mass over H I mass and surface density is total gas mass over the area of the pixel in units of M$_\odot$/pc$^2$. The red squares are the average gas fraction and the average surface density and the blue lines are the average gas fraction over the surface density. Four time steps are shown: $T = 0.35$ Gyr (top left), $T = 1.41$ Gyr (top right), $T = 1.76$ Gyr (bottom left), and $T = 2.47$ Gyr (bottom right).](image)
studies have investigated a $f_{HI} - \Sigma_g$ relation of disk galaxies in cluster environments. Future observations of $HI$ and $H_2$ of disk galaxies in clusters will allow us to discuss the possible influence of RP on $H_2$ formation and evolution in disk galaxies under RP.

The present study reveals that the evolution of $H_2$ in disk galaxies under RP depends strongly on their orbits, disk inclination angles, and cluster/group masses ($M_{\text{dm}}$). For example, models with a more edge-on disk galaxy orientation show more efficient $H_2$ formation by compression from RP. Also, in a lower DM mass cluster halo, the disk galaxy is required to have a closer orbit to the cluster center for RP to be effective, as more time needs to be spent in a higher-density ICM region. These results imply that SFHs of these galaxies can be significantly influenced by these parameters, because galaxy-wide SFRs can be determined by $H_2$ densities. McPartland et al. (2016) recently discussed how a galaxy falling into a cluster at high velocities causes an extreme RPS event and gives rise to the "Jellysh" morphology classification (Ebeling et al. 2014) and would possibly have higher fractions of $H_2$ gas.

$H_2$ formation from a gaseous phase $HI$ is unlikely to occur, as gas particles simply cannot release enough energy when they encounter one another (e.g., Gould & Salpeter 1963; Valdivia et al. 2015). The most commonly accepted solution is for $H_2$ to form on the surface of dust grains in the ISM (e.g., Gould & Salpeter 1963; Duley & Williams 1993; Le Bourlot et al. 2012). Here we have shown for the first time that dust growth is crucial in the rapid enhancement of $H_2$ formation on dust grains in disk galaxies under RP. This implies that large-scale (group/cluster-scale) hydrodynamical effects can influence very small-scale physics of $H_2$ formation on dust grains. This also implies that dust evolution can control the evolution of $HI$ and $H_2$ content of disk galaxies in groups/clusters. Almost all previous galaxy-scale

Figure 3. Galactic orbit and $H_1$ and $H_2$ mass for the models: M6 (top left), M7 (top right), M8 (bottom left), and M9 (bottom right). The orbit of the galaxy is represented as a cluster-centric distance in kpc, and $H_2$ and $H_1$ masses are in units of $M_\odot$. The vertical line represents the galaxy’s pericenter passage ($R_{\text{peri}}$) of the cluster.
and cosmological-scale simulations of galaxy formation and evolution in these dense environments did not include dust physics (e.g., Bekki 2013), and accordingly their predictions on cold gas content are not so robust. Thus, it is our future study to better understand the important roles of dust in evolution of cold gas of group/cluster galaxies using cosmological simulations with more sophisticated models of dust evolution.

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Figure 4. Galactic orbit (top), H2 mass (middle), and the SFR (bottom) are shown for model M1 (red) and model M10 (blue). As in Figures 1 and 3, orbit is represented as a cluster-centric distance in kpc, H2 mass is in units of $M_e$, and SFR is in units of $M_e$ yr$^{-1}$. 