Tidal truncation of gas replenishment and global suppression of
galactic star formation in distant clusters

Kenji BEKKI and Warrick J. COUCH

School of Physics, University of New South Wales, Sydney 2052, Australia
bekki@bat.phys.unsw.edu.au, wjc@bat.phys.unsw.edu.au

and

Yasuhiro SHIOYA

Astronomical Institute, Tohoku University, Sendai 980-8578
shioya@astro.tohoku.ac.jp

(Received 2000 November 30; accepted 2001 February 20)

Abstract

Recent spectroscopic observations of galaxies in distant clusters have revealed that the rate of star formation in star-forming galaxies is significantly suppressed with respect to their counterparts in the field at a similar redshift. It is, however, highly uncertain which physical processes are responsible for this suppression. We present the results of a numerical investigation of how the global tidal field of a cluster dynamically influences the reservoir of halo gas surrounding a disk galaxy as it falls into the cluster from the surrounding field. We find that the tidal field of the cluster efficiently removes the halo gas from the galaxy, thereby halting its accretion onto the disk, and thus the fueling of star formation within. This effectively truncates the galaxy’s star formation. We also find that this tidal truncation does not depend very strongly on the orbit of the disk with respect to the center of the cluster. These results suggest that the global tidal field of clusters is capable of causing a widespread and uniform suppression of star formation in galaxies accreted by the cluster. In light of these results, we discuss the importance of this tidal...
Key words: galaxies: clusters — galaxies: star formation — galaxies: ISM — galaxies: formation — galaxies: interactions

1. Introduction

An impressive number of spectroscopic and photometric results have been accumulated which reveal that the star-formation histories of galaxies in clusters are significantly different from those in the field (e.g., Dressler et al. 1985; Balogh et al. 1997; Couch et al. 1994; Dressler et al. 1999; Poggianti et al. 1999). It is, however, still highly uncertain which physical processes specific to cluster environments govern the observed difference. Starbursts triggered by some cluster-related mechanism and the subsequent rapid consumption of gas are suggested to be central to explaining the emission and absorption signatures seen in cluster galaxy spectra (e.g., \([\text{O}_\text{II}]\)\(\lambda 3727\) emission and strong \(\text{H}\delta\) absorption; Dressler, Gunn 1983; Couch, Sharples 1987; Barger et al. 1996; Poggianti et al. 1999). On the other hand, some authors have claimed that if star formation is abruptly truncated when galaxies are accreted by clusters, this is enough to explain the mean strengths of emission lines and any gradients with cluster-centric radius (e.g., Newberry et al. 1990; Abraham et al. 1996; Balogh et al. 2000). Furthermore, Balogh et al. (2000) proposed an even ‘milder’ scenario whereby star formation in cluster galaxies has undergone just a gradual decline owing to the absence of halo gas that is required to fuel star formation in galaxy disks. It remains unclear which of the above three scenarios — starbursts, abrupt truncation of star formation, or gradual decline of star formation — most accurately describes the recent \((z < 1)\) star-formation history of the majority of cluster galaxies.

One of the difficulties in determining unambiguously the global star-formation histories of cluster galaxy populations is that dust extinction greatly affects the spectroscopic properties of star-forming galaxies (e.g., Poggianti et al. 1999). The level of on-going and recent star-formation activity inferred from \([\text{O}_\text{II}]\) emission and \(\text{H}\delta\) absorption can be significantly distorted by dust (Smail et al. 1999; Poggianti, Wu 2000; Bekki et al. in preparation). In contrast to \([\text{O}_\text{II}]\), the \(\text{H}\alpha\) emission line is less affected by dust extinction (Kennicutt 1998), and thus at least comes closer to quantifying the rate of on-going star formation.
formation. Accordingly, Couch et al. (2000) have embarked on a wide-field (∼ 4 \( h^{-1}_{50} \) Mpc) H\( \alpha \) survey of galaxies in 3 optically selected clusters at \( z \sim 0.3 \). Their initial results show that star formation within the members of one of these clusters (AC114) is strongly and uniformly suppressed; within the region studied, at most only 10% of the cluster members are H\( \alpha \)-emitters, and their inferred star-formation rate is no more than ∼ 4 \( M_\odot \) yr\(^{-1} \). Similarly, Balogh and Morris (2000) found that only ∼ 12.5% of the members within the virial radius of Abell 2390 (\( z = 0.23 \)) showed H\( \alpha \) emission with a rest-frame equivalent width greater than 50 \( \text{Å} \), thus arguing that this is consistent with the ‘gradual decline’ model of star formation. Theoretical simulations by Balogh et al. (2000) have also shown that if a galaxy’s star formation undergoes a gradual decline after it has been accreted by a cluster, the observed radial gradients in optical colors and [O\( \text{II} \)] emission line strength can be clearly explained. Kodama and Bower (2001) have also demonstrated that the gradual decline of star formation is consistent with the distribution of galaxies in the color-magnitude diagrams for clusters in the range \( 0 < z < 0.4 \). If the gradual decline of star formation is really the most promising scenario for the history of star formation in the cluster environment, a key issue is which physical processes cause such a decline.

The purpose of this letter is to discuss our numerical investigation of how the cluster environment can lead to a gradual decline in the star-formation rate of its constituent members. In particular, our numerical simulations have focused on the disruption, by the global cluster tidal field, of the gas that is accreted onto galaxy disks from a surrounding gaseous halo, and which fuels their star formation — an effect first suggested by Larson, Tinsley, and Caldwell (1980, hereafter LTC). Because the influence of the cluster tidal field is so widespread, this would seem to be a natural mechanism for producing a significant suppression of star formation over large regions of the cluster. Furthermore, because the starvation of disk galaxies of their gas supply is highly germane to the formation of S0 galaxies (see also LTC), we critically examine the cluster tidal truncation scenario in this context.

The plan of this paper is as follows: In the next section we briefly review our model and the numerical techniques and procedures used. The results of our modeling are then presented in section 3. Finally, we discuss our results and draw our conclusions in section 4.
2. Model

The replenishment of interstellar gas due to sporadic and/or continuous gas infall and acquisition from external environments (e.g., a gaseous halo) has generally been considered to play a vital role in maintaining star formation within disk galaxies up to the present day (LTC). We have investigated, numerically, the effect which the global tidal field of a rich cluster has on this important gas replenishment process in the case of a disk galaxy that has been accreted by the cluster from the surrounding field.

We have modeled the structure of a cluster using the universal density profile predicted by the standard cold dark-matter cosmogony (Navarro et al. 1996). The total cluster mass, represented by $M_{cl}$, the scale (core) radius ($r_c$), and the virial radius ($r_v$) were taken to be $2.0 \times 10^{14} \, M_\odot$, 127 kpc, and 1.16 Mpc, respectively, which are reasonable and realistic values for rich clusters of galaxies such as Coma. The orbit of a disk galaxy accreted onto the cluster was assumed to be influenced by an external fixed gravitational potential resulting from the above-mentioned cluster structure (i.e., the cluster potential is not “live” and thus not represented by collisionless particles in the present simulations). Here, the disk galaxy was represented by Fall and Efstathiou’s (1980) bulgeless, purely stellar disk model. The initial ratio of the dark matter halo mass to the mass of disk stars was taken to be 4:1. Values of $6.0 \times 10^{10} \, M_\odot$ and 17.5 kpc were adopted for the disk mass ($M_d$) and size ($R_d$), respectively. The velocity and time are measured in units of $V_d = (GM_d/R_d)^{1/2} \, (1.21 \times 10^2 \, \text{km s}^{-1})$ and $t_{dyn} = (R_d^3/GM_d)^{1/2} \, (1.41 \times 10^8 \, \text{yr})$, respectively, where $G$ is the gravitational constant, which was assumed to be 1.0 in the present study. The exponential disk scale length and the vertical scale height are 3.5 kpc and 500 pc, respectively. The rotation curve became nearly flat at 0.35 radius with the maximum velocity of $v_m = 1.8$ in our units.

We assumed that the galaxy has a reservoir of halo gas from which gas can be accreted onto the disk. It was assumed that the halo gas was uniformly and spherically distributed with a cut-off radius of $20R_d$ (0.35 Mpc). The halo gas, with a total mass of $0.1M_d$, was represented by particles, each of which...
rotates around the disk with a rotational velocity, $V_{hg}$, satisfying the relation $V_{hg} R_{hg} = V_d R_d$, where $R_{hg}$ is the initial position of each halo particle. By adopting this relation, the specific angular momentum of the halo gas is assumed not to be so remarkably different from that of the disk, accordingly, the halo gas is able to fall onto the stellar disk region in isolated evolution. A halo particle is considered to have been accreted onto the disk if it is within a vertical radius ($z$) of 500 pc. In our halo reservoir model, the accretion rate for the isolated evolution of the disk was estimated to be of the order of $\sim 1 M_\odot$ yr$^{-1}$ (for $T > 4$ Gyr), which is consistent with the value required for maintaining active star formation in disk galaxies (LTC; Blitz et al. 1999). Although the present numerical results depend on the initial size of the halo reservoir, we describe here only the results of the 20 $R_d$ model, since its behaviour is very typical of the effects that the cluster tidal field has on such halo gas reservoirs. The adopted initial size of the halo reservoir is appreciably smaller than the observationally suggested mean distance ($\sim 1$ Mpc from the center of the Galaxy) of the High-Velocity Clouds (HVC) that have been demonstrated to be halo gas reservoirs of the Galaxy (Blitz et al. 1999).

Using this model, we investigated the dynamical evolution of the halo gas reservoir for a variety of different orbits described by the disk galaxy upon its entry into the cluster. We present here the results of three representative models. Figure 1 shows the orbital evolution of the disk with three different initial positions in the cluster. For example, the disk with initial $x$ and $y$ positions equal to 1.73 and 1.15 Mpc, respectively, passes by its pericenter ($x = 0.49$ and $y = 0.42$ Mpc) at $T = 2.06$ Gyr in orbit 1.

The total number used in the simulations is 10000 for the dark-matter halo of the disk, 12000 for the disk galaxy, and 10000 for the halo gas reservoir. In order to demonstrate more clearly the importance of cluster tidal effects on the halo gas reservoir, we treated the halo particles as collisionless ones. Accordingly, the evolution of the halo ‘gas’ reservoir was determined only by purely gravitational evolution (dissipative effects do not play a role at all in the evolution). Here, the softening length was 1.09 kpc for gravitational interactions between the disk stars, the halo gas components, and the dark matter halo surrounding the disk. We used these three different gravitational softening lengths to investigate how the global tidal field of the cluster affects the local dynamical evolution of the halo gas reservoir in an admittedly self-consistent manner. A direct summation method was used in a force
calculation on a GPAPE board (Sugimoto et al. 1990). The energy and angular momentum were conserved within 1% accuracy in a test collisionless GRAPE simulation of an isolated disk model without halo-gas replenishment.

3. Results

As is shown in figure 2, tidal effect of the cluster has a strong dynamical impact on the halo gas reservoir of the disk, and consequently greatly changes the mass distribution of the reservoir. As the disk enters the cluster region ($T = 1.70\,\text{Gyr}$), the halo gas begins to be distorted owing to the tidal field of the cluster. After the galaxy passes the pericenter (640 kpc corresponding to $5r_c$) of the orbit ($T = 2.23\,\text{Gyr}$), the cluster’s global gravitational field dramatically transforms the initially spherical halo into a rather elongated bar-like structure ($T = 2.83\,\text{Gyr}$). As the disk leaves the inner region of the cluster ($T = 3.95\,\text{Gyr}$), the gas reservoir is completely destroyed and dispersed into the intra-cluster regions so that the mean gas density of the halo becomes rather low compared with the initial value. These results demonstrate that the outer halo gas reservoir, which is critically important for continuously supplying fresh gas to the disk, is fragile and thus susceptible to the tidal field of the cluster. We thus confirm here that stripping of the halo gas reservoir is an important physical effect in cluster environments.

As a natural result of this, the accretion rate of halo gas onto the disk is considerably reduced, both for $R \leq R_d$ and for $R_d < R < 2R_d$ (see figure 3). When the galaxy passes the pericenter ($\sim 640\,\text{kpc}$) at $T = 2.23\,\text{Gyr}$, the accretion rate is essentially truncated, particularly, for $R \leq R_d$. The mean accretion rate for $R \leq R_d$ is $0.16\,M_\odot\,\text{yr}^{-1}$ for $T \leq 2.23\,\text{Gyr}$ and $0.42\,M_\odot\,\text{yr}^{-1}$ for $T > 2.23\,\text{Gyr}$ in the isolated disk model. On the other hand, it is $0.05\,M_\odot\,\text{yr}^{-1}$ for $T \leq 2.23\,\text{Gyr}$ and $\sim 0\,M_\odot\,\text{yr}^{-1}$ for $T > 2.23\,\text{Gyr}$ in the galaxy with orbit 1. Although the galaxy does not pass through the cluster core region ($R < r_c$), the accretion rate is drastically reduced. The derived effect is very different from other physical effects thought to operate in clusters, such as ram pressure stripping (Dressler, Gunn 1983; Farouki, Shapiro 1980; Abadi et al. 1999) and the tidal effects of cluster cores (Byrd, Valtonen 1990). Here, the latter two effects are important only for galaxies passing through the cluster core. This is in contrast to the results obtained here, which show that even if disk galaxies are well outside the central region (even
outside the virial radius), star formation in disk galaxies is greatly suppressed due to tidal truncation of the gas-replenishment process.

Figure 4 demonstrates that irrespective of the orbit that the disk galaxy takes through the cluster, the total mass accreted onto the disk is drastically decreased owing to tidal stripping of the halo gas. The ratio of accreted mass in the cluster model to that in the isolated one is estimated to be typically 0.07 (0.20) for \( R \leq R_d \) (\( R_d < R < 2R_d \)). These results imply that as a result of these disk galaxies being ‘starved’ of their gas supply once they are accreted by the cluster, their star formation will be substantially curtailed within a few Gyr, and remain so irrespective of their location within the cluster. Furthermore, figure 4 combined with figure 2 suggests that even if a galaxy is observed to be well outside the virial radius of a cluster, it can show a rather small star-formation rate owing to this abrupt truncation of its gas supply. Gas mass accretion is found to be strongly suppressed not only for the inner-disk regions (\( R \leq R_d \)), but also for the outer ones (\( R_d < R < 2R_d \); see figure 4), which means that the size of the disk does not grow after the disk enters the cluster environment. If we consider that truncation of gas replenishment can also transform late-type disk galaxies into S0s (LTC), the present results suggest that the typical disk size of S0s is appreciably smaller than that of field disk galaxies because of truncation of gas infall onto the outer parts of their disks.

4. Discussion

We have demonstrated that the global tidal field of a cluster can greatly reduce the halo gas-accretion rate in a disk galaxy accreted by the cluster. The implication of this is that the disk rapidly consumes (typically in a few Gyr; LTC) the remaining gas and, as a result, shows a subsequent decline in star formation after this event. Thus, our numerical results have firstly confirmed the earlier suggestion by LTC that the star-formation can be significantly influenced by tidal effects in clusters. It is reasonable to say that star formation rate on a disk with truncation of star formation gradually declines after the truncation owing to no gas replenishment from the halo region.

Cluster tidal fields were previously suggested to drive dramatic morphological transformations of galaxies (Byrd, Valtonen 1990; Moore et al. 1996) and to induce rapid gas consumption of disk gas
The ‘long-term’ and less drastic effects of cluster tidal fields on halo gas derived in this study are in striking contrast to those other ‘short-term’ and rather dramatic effects. In combination, however, they play a vital role in both triggering transient enhancements in the star-formation rate and in reducing the mean star-formation rate in galaxies over a few Gyr.

Tidal effects between galaxies (Moore et al. 1996) and ram pressure stripping of halo gas (Bekki et al. in preparation), both of which were not modelled in the present study at all, are also suggested to efficiently remove the halo gas reservoirs surrounding disk galaxies in clusters. We, accordingly, suggest that the present study, investigating only cluster tidal fields, gives only a partial account of how the cluster environment truncates gas replenishment, which leads to a substantial reduction in the rate of star formation within its galaxies.

Abrupt truncation of gas replenishment from halo regions in disks is suggested to transform gas-rich spiral galaxies into S0s (LTC). If this truncation is a dominant mechanism for S0 formation, the present study would provide the following three implications concerning the nature of S0 galaxies in clusters. Firstly, the color gradients within S0s can be appreciably shallower than those in disk galaxies, if metallicity gradients within the disk are their main cause. The radial dependence of chemical evolution driven mainly by star formation is considered to be responsible for the metallicity gradients within disk galaxies (e.g., de Jong 1996). Accordingly, if truncation of gas infall onto a disk galaxy strongly suppresses the star formation, and thus the chemical evolution, the galaxy should show smaller color (metallicity) gradients after its transformation into an S0. Secondly, the disk size could be smaller for an S0 that has been transformed from a disk galaxy after its accretion by the cluster at an earlier epoch (or higher redshift). The present numerical simulations demonstrate that gas infall onto the outer part of a disk ($R_d < R < 2R_d$) is strongly suppressed, and thus any growth in disk size is prevented. Consequently, the disk size of an S0 would be determined by the epoch when the progenitor spiral galaxy was accreted by the cluster. Therefore, the disk size is smaller for an S0 formed (by truncation) at higher redshift, if the higher redshift spiral galaxies have smaller disks. Thirdly, S0s can be formed by the gas-truncation process even in low-density regions of clusters. This is consistent with the recent observational evidence of Fasano et al. (2000) that the transformation of spirals into S0s must have occurred efficiently even in
Finally, we stress that S0s formed by the above gradual transformation, and which do not involve any ‘starburst’, would have suffered a different fate to those that have been formed by the type of tidal interaction described by Byrd and Valtonen (1990), the galaxy ‘harrassment’ process described by Moore et al. (1996), and unequal-mass merging (e.g., Bekki 1998a), all of which inevitably trigger strong nuclear starbursts and a dramatic morphological change within only several dynamical time scales. The stellar populations in the central bulge components can be different between S0s formed by the ‘gradual’ truncation and those by interaction/merging. In particular, the bulges of S0s formed by the former process will have redder optical colors and weaker Balmer absorption lines than those formed via the latter process. Future imaging/spectroscopy at high resolution will be of much interest in discriminating between these two different evolutionary scenarios.

Y. S. thanks the Japan Society for Promotion of Science (JSPS) Research Fellowships for Young Scientist.

References

Abadi, M. G., Moore, B., & Bower, R. G. 1999, MNRAS, 308, 947
Abraham, R. G., Smecker-Hane, T.-A., Huchings, J. B., Carlberg, R. G., Yee, H. K. C., Ellingson, E., Morris, S., Oke, J. B., & Rigler, M. 1996, ApJ, 471, 694
Balogh, M. L., Morris, S. L., Yee, H. K. C., Carlberg, R. G., & Ellingson, E. 1997, APJ, 488, L75
Balogh, M. L., Navarro, J. F., & Morris, S. L. 2000, (astro-ph/0004078)
Balogh, M. L., & Morris, S. L. 2000, ApJ, in press (astro-ph/0007111)
Barger, A. J., Aragon-Salamanca, A., Ellis, R. S., Couch, W. J., Smail, I., & Sharples, R. M. 1996, MNRAS, 279, 1
Bekki, K. 1998a, ApJ, 502, L133
Bekki, K. 1998b, ApJ, 510, L15
Bekki, K. Couch, W. J., Shioya, Y. 2000, in preparation
Blitz, L., Spergel, D. N., Teuben, P. J., Hartmann, D., & Burton, W. B. 1999, ApJ, 514, 818
Byrd, G., & Valtonen, M., 1990, ApJ, 350, 89
Couch, W. J., & Sharples, R. M., 1987, MNRAS, 229, 423
Couch, W. J., Ellis, R. S., Sharples, R. M., & Smail, I. 1994, ApJ, 430, 121
Couch, W. J., Balogh, M. L., Bower, R. G., Smail, I., Glazebrook, K., & Taylor, M. 2000, ApJ , submitted
de Jong, R. S. 1996, A&A, 313, 377
Dressler, A., & Gunn, J. E. 1983, ApJ, 270, 7
Dressler, A., et al. 1997, ApJ, 490, 577
Dressler, A., Smail, I., Poggianti, B. M., Butcher, H., Couch, W. J., Ellis, R. S., & Oemler, A., Jr. 1999, ApJS, 122, 51
Fall, S. M., & Efstathiou, G. 1980, MNRAS, 193, 189
Fasano, G., Poggianti, B. M., Couch, W. J., Bettoni, D., Kjaergaard, P., & Mariano, M. 2000, preprint (astro-ph/0008195)
Farouki, R., & Shapiro, S. L. 1980, ApJ, 241, 928
Kennicutt, R. C., Jr. 1998, ARAA, 36, 189
Kodama, T., & Bower, R. G., 2001, MNRAS, in press
Larson, R. B., Tinsley, B. M., & Caldwell, C. N. 1980, ApJ, 237, 692 (LTC)
Moore, B., Katz, N., Lake, G., Dressler, A., & Oemler, A., Jr. 1996, ApJ, 379, 613
Navarro, J. F., Frenk, C. S., & White, S. D. M. 1996, ApJ, 462, 563
Newberry, M. V., Boroson, T. A., Kirshner, R. P., 1990, ApJ, 350, 585
Poggianti, B. M., & Wu, H. 2000, ApJ, 529, 157
Poggianti, B. M., Smail, I., Dressler, A., Couch, W. J., Barger, J., Butcher, H., Ellis, R. S., & Oemler, A., Jr. 1999, ApJ, 518, 576
Smail, I., Morrison, G., Gray, M. E., Owen, F. N., Ivison, R. J., Kneib, J.-P., & Ellis, R. S. 1999, ApJ, 525, 609
Sugimoto, D., Chikada, Y., Makino, J., Ito, T., Ebisuzaki, T., & Umemura, M. 1990, Nature, 345, 33
Toomre, A. 1964, ApJ, 139, 1217
Figure Captions

Fig. 1.
Orbital evolution of a disk galaxy accreted onto a cluster with the mass of $2 \times 10^{12} M_\odot$ for three different initial positions of the galaxy. The projected initial $x$ and $y$ positions are 1.73 Mpc (corresponding to 1.5 $r_v$ where $r_v$ is the virial radius of the cluster) and 1.16 Mpc ($r_v$), respectively, for orbit 1, 1.73 Mpc and 0.64 Mpc (5 $r_c$ where $r_c$ is the cluster core radius) for orbit 2, and 1.73 Mpc and 0.13 Mpc ($r_c$) for orbit 3. The initial velocity of the disk is $-8.6 \times 10^2$ km s$^{-1}$ for the $x$ direction and 0 km s$^{-1}$ for $y$ in all three models. Several positions of the disk are indicated by crosses along each of the three orbits for $T = 1.70, 2.23, 2.83, 3.95, \text{ and } 5.66$ Gyr. The small and large dotted circles represent the core (or scale) radius and the virial radius, respectively. The frame measures 7.7 Mpc on a side.

Fig. 2.
Mass distribution of halo gas at each time ($T$) projected onto the $x$–$y$ plane for the disk galaxy that follows orbit 1. Each frame measures 1.75 Mpc on a side. Here, the center of mass of the halo gas is located at ($x,y$) = (0,0) for all time-steps, so that the transformation of the halo gas reservoir can be more clearly seen. Note that the cluster tidal field can completely destroy the disk’s halo gas reservoir and, consequently, strip the gas from the disk.

Fig. 3.
Time evolution of gas accretion rates (in units of $M_\odot$ yr$^{-1}$) onto the region with $R \leq R_d$ (upper) and onto that with $R_d < R < 2R_d$ for an isolated disk (represented by the dotted line) and the disk which passes through the cluster on orbit 1 (a solid line). Note that at $T > 2.5$ Gyr, the gas accretion is abruptly truncated.

Fig. 4.
Time evolution of the total gas mass accreted onto the inner disk region ($R \leq R_d$; upper panel) and that with $R_d < R < 2R_d$ (lower panel) for our three different orbit models (1,2,3). Here, the mass is given in our units ($M_d$ corresponding to $6.0 \times 10^{10} M_\odot$). For a comparison, the results of the isolated disk model are also given (see solid lines). The results of the models for orbits 1, 2, and 3 are represented by the dotted, short-dashed, and long-dashed lines, respectively.
