Tidal Triggering of Star Formation and the Butcher-Oemler Effect

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We have calculated the expected level of star formation which would be induced in a disk galaxy falling into the potential well of a cluster of galaxies due to: drag force from the ICM, the radial tidal force from the cluster potential, and the lateral tidal force from the cluster potential. We evaluated these forces for three different cluster mass distributions:

(1) a 250 kpc core radius King distribution, the canonical virialized cluster model, (2) the distribution from an isothermal X-ray gas, (3) the distribution from an adiabatic X-ray gas distribution, which is more centrally peaked than the King model, and (4) that inferred from gravitational lensing, which is the most centrally peaked. The latter two peaked potentials show a progressively more significant lateral compression of the galaxy disk from the tidal field within 250 kpc of the cluster center due to the increase in cluster mass compared to the King function.

For the centrally peaked potentials, inside of approximately 250 kpc, tidal forces from the cluster potential on galaxies will be important and will trigger collisions of neutral Hydrogen clouds which will increase the level of expected star formation in a disk galaxy. Galaxies are very likely to pass within a radius of approximately 250 kpc as a cluster undergoes collapse and tidal triggering should show an increase in the blue fraction at this approximate radius relative to nearby clusters. The lens data (which indicates a centrally concentrated mass profile) comes primarily from clusters at the epoch (redshift) at which the Butcher Oemler effect is observed. Therefore, the lensing potential may be a more realistic potential for the central region of a cluster at this epoch. Compared to nearby clusters with virialized gas distributions, a cluster undergoing initial gravitational collapse is likely to have a lower gas density. Studies of cluster evolution in the X-ray indicate that there may be some increase in the luminosity of clusters between the epoch of the Butcher Oemler effect and the present. Therefore, during collpase, the importance of ram-pressure will be reduced for an infalling galaxy compared to a galaxy in a virialized cluster. For these reasons, tidal triggering is more generally applicable to star formation in a cluster undergoing gravitational collapse than ram-pressure. If ram-pressure were the primary triggering mechanism, then correlations of star formation with the X-ray luminosity should be apparent at some level in all of the clusters showing the Butcher Oemler effect (BOE). However, no clear correlation is seen in the available data. We interpret this as due to the enhanced importance of tidal triggering and the decreased importance of ram- pressure in these clusters.

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1 Cluster Mass Models

Cluster mass profiles in the central region are calculated: two from the X-ray gas density and temperature distributions (isothermal and adiabatic), one from gravitational lensing constraints, and the standard King model.

TABLE 1: Normalized Cluster Mass Distribution from 4 Distributions

Radius (kpc)	King Model	X-ray mass unit is $10^{13} M_{\odot}$	X-ray	Lensing
50	0.07	0.12	0.32	2.1
100	0.5	0.83	2.2	3.9
150	1.1	2.4	5.6	10.5
200	3.3	4.7	9.8	13.6
250	5.6	7.5	13.7	16.2
280	7.8	10.4	15.8	17.4
350	12.3	19.5	19.6	20.0
500	24.	24.	24.	24.

The mass distributions in Table 1 should encompass the range found in clusters and are normalized so that the mass inside of 500 kpc is the same for each distribution.

2 Lateral Tidal Force

Table 2 contains the ratio of the lateral acceleration to the internal centripetal acceleration of the galaxy for the 4 cluster mass distributions.

TABLE 2: Lateral Acceleration from 4 Mass Distributions
10^{-9} cm sec^{-2}

Radius (kpc)	King Model	X-ray ($\gamma = 1$)	X-ray ($\gamma = 5/3$)	Lensing
50	0.45	0.77	2.1	13.4
100	0.4	0.66	1.9	3.1
150	0.26	0.57	1.6	2.5
200	0.33	0.47	1.4	1.4
250	0.29	0.38	0.71	0.83
280	0.28	0.38	0.58	0.63
350	0.23	0.36	0.37	0.37
500	0.15	0.15	0.15	0.15

The centrally peaked lensing distribution results in a larger lateral acceleration for a galaxy passing within 250 kpc of the cluster center than does the other two potentials. For the King model potential which uses the Coma parameters, the lateral compression is negligible at all radii.

3 Radial Forces

3.1 Drag Force

Simulations (Thomas and Couchman 1991) show that the central density of the intracluster medium is approximately 10 times lower 5 Gyr ago (for a cluster formation time of 10 Gyr) relative to the virialized gas density found in a rich cluster such as Coma. If ram pressure is not sufficient to remove the nebular components, the galaxy shoud be treated as a hard shell. The motion of the intracluster medium is then supersonic, laminar flow around the galaxy since the galaxy velocity should be nearly the free fall velocity ($\sim$2000 km s^{-1}). The drag force, the pressure acting on the surface area of a spherical galaxy surface, is shown in Table 3. The drag force will act to accelerate clouds inward and collisions between clouds will induce shocking. The drag force is relatively weak in the central region, but will dominate radially outside of approximately 250 kpc. Over a period of time the drag force may accelerate clouds to supersonic velocities capable of collisionally shocking the most massive clouds to become unstable to gravitational collapse.

3.2 Radial Tidal Force

This acts to resist the drag force and in the central region is dominant so that the drag force is effective only outside of the core. The lateral tidal force is a strong triggering mechanism of star formation through cloud collisions and acts on the entire disk because of the disk's rotation, in only 1/4 of a rotation period. It is one lateral component relative to the galaxy center and is the same on both sides of the galaxy.

TABLE 3: Acceleration from 3 Forces: Lensing Potential

Radius (kpc)	Tidal Radial	Tidal Lateral 10^{-8} cm s^{-2}	Drag
50	20.	5.	0.29
100	2.4	1.2	0.25
150	1.2	0.9	0.21
200	0.4	0.5	0.19
250	0.1	0.31	0.15
350	-0.07	0.14	0.10

The potential for the cluster may be given by a King model (or isothermal gas) in the outer region of the cluster and a central region described by the lensing mass distribution or the adiabatic gas mass distribution. In this case, the radial tidal component will trigger star formation at approximately 825 kpc (Byrd and Valtonen 1990).

4 Likelihood of Star Formation

In our paper, we show that the scenario where star formation results from cloud collisions induced by tidal compression, is plausible. The collision induces an isothermal shock front which traverses the stationary cloud, raising the density above a critical value corresponding to that required for self-gravitation and collapse. Table 4 contains the downstream post-shock critical mass. Comparison to the typical neutral hydrogen cloud (280 $M_{\odot}$) shows that the postshock clouds should be unstable to gravitational collapse when the galaxy is within 200 - 250 kpc of the cluster center.

TABLE 4: Post-shock Critical Mass for Neutral Hydrogen Cloud

Radius (kpc)	a(10^{-8} cm s^{-2})	V(km s^{-1})	Mach Number	m_c
0.	-	2080.	2080.	5.
50.	30.0	201.	201.	55.
100.	1.2	128.	128.	86.
150.	0.92	70.	70.	157.
200.	0.50	38.	38.	290.
250.	0.31	18.	18.	611.
350.	0.14	0.		

5 Discussion, Predictions, and Comparison to Observations

Simple predictions follow as a disk galaxy falls into the cluster. Tidal triggering predicts that star formation should appear at some characteristic radius, 800 kpc where radial tidal forces from a King, or isothermal potential becomes important. If the central distribution of cluster mass is given by the gravitational lensing constraints, as is well established for clusters in this redshift range, then lateral tidal forces will be comparable to the radial tidal forces in the center of the cluster and star formation should increase toward the center, hastening the exhaustion of the gas supply in the disk. This is suggested in the data shown in figure 5 (in Butcher and Oemler 1985). The BOE is an overabundance of blue galaxies in clusters in the redshift range 0.2 - 0.5 *relative* to nearby clusters. In this figure, the data show the BOE at high statistical significance in the cluster center and out to a radius of approximately 1 Mpc. The effect is not statistically significant beyond this distance. Qualitatively, this matches the predictions of tidal stripping if the potential at large radii is given by a King model and at smaller radii by a peaked potential. It is worth noting that the effect reported for Coma (Caldwell et al. 1994) is well outside of this region, suggesting a different triggering mechanism for the star formation episode. The addition of star formation due to lateral compression should appear as an annulus of star formation in the disk in only 1/4 of a rotation period. It is important to study these clusters in the X-ray to measure the gas parameters directly, since strong cluster evolution between the BOE epoch and the present would mean that late infalling galaxies (such as in Coma) see a different gas distribution than would those at an early epoch, when most of the galaxies fall in. X-ray studies imply that there are fewer bright clusters at intermediate redshift (Gioia 1990), suggesting a decrease in the amount of the intracluster gas which has been shocked up to a high density and temperature visible in X-rays is found (e.g., "luminosity evolution"). The hypothesis of star formation triggered by ram-pressure sweeping of the disk on first infall, will only be applicable to the galaxies which fall in late and see a dense ICM. It is important to extend the investigation of the BOE through optical studies of clusters to include clusters with lower X-ray luminosities in the z = 0.2 - 0.5 redshift range. This would clearly separate gas dependent triggering from tidal triggering. We suggest that the processes discussed here, primarily the lateral tidal force from a peaked cluster mass distribution and the drag force of the ICM, may have a more general application to the problem of galaxy evolution in the redshift range of z = 0.2 - 0.5.