Starburst Galaxies in Clusters

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**Abstract.** The nature of the starburst phenomenon in galaxies is investigated using a narrow band color system designed to study color evolution in distant clusters. Work on zero redshift, luminous far-IR galaxies, calibrated by starburst models, demonstrates the usefulness of this color system in isolating starburst from normal star-forming colors, and also demonstrates a strong correlation with far-IR colors despite reddening effects. The same color system applied to distant clusters finds that a majority of the faint blue cluster population are starburst dwarf galaxies, probably the progenitor of the current population of dwarf ellipticals in nearby clusters.

1. **Introduction**

In a series of papers extending over the last 12 years (Rakos et al. 1988, 1990, 1995, 1996, 1997), we have used a narrow band color system to perform photometry of galaxies in rich clusters at various redshifts in the rest frame of the cluster. Our study approaches this problem through the use of a modified Strömgren system, modified in the sense that the filter set is ‘redshifted’ to the cluster of galaxies in consideration; therefore, no k-corrections. We call our modified system $uz,vz,bz,yz$ to distinguish it from the original Strömgren system ($uvby$). The color indices have been a profitable tool for investigating color evolution and we have demonstrated that the amplitude of the 4000Å break (Dressier and Shectman 1987) in the spectra of galaxies is correlated with the $uz - vz$ color index.

In more recent studies, we have used the high resolution and high S/N ratio spectra of galaxies published by Gunn and Oke (1975), Yee and Oke (1978), Kennicutt (1992), De Bruyn and Sargent (1978) and Ashby et al. (1992) compute synthetic colors. In this fashion, we have constructed a set of templates to establish the relationship between our color indices and the morphology of galaxies. This scheme can be expanded upon using principal component analysis similar to the technique outlined by Lahav et al. (1996) in order to classification of galaxies in high redshift clusters.
For our preliminary work, our sample galaxies are divided into four classes: ellipticals, spirals, Seyferts, and starbursts. Each class is well separated in our color-color diagrams, especially starburst galaxies which have anomalous $mz$ indices ($mz$ is defined in the same manner as the traditional Strömgren $m$ indice, $mz = (vz - bz) - (bz - yz)$). The starburst galaxies all lie below $mz = -0.2$ due to a combination of intrinsic reddening combined with starburst colors from a marginally low metal content population (see Figure 1).

2. Starburst Colors

In our photometric system, there are reddening free expressions, similar to the original relations defined by Strömgren, which can be used to estimate the variable amount of reddening in individual galaxies. The reddening free parameter for $mz$, called $C$, is defined to be:

$$C = mz + 0.39(bz - yz)$$

For $uz - vz$ we define the reddening free variable, $A$, as:

$$A = 1.49(uz - vz) - (bz - yz)$$

Using these variables, our indices become primarily dependent on the age and total mass of the starburst. Calibration is based on theoretical models of
starburst galaxies from Leitherer and Heckman (1995). Figure 2 displays the various models for timesteps of log t = 6.3, 7.0, 7.3, 7.7 and 8.7 years. The initial model at each timestep is for a pure starburst population. Additional models represent a the mixture of an underlying old stellar population that is 1 mag fainter than the starburst, the same total luminosity as the starburst and 1 mag brighter than the starburst as noted in the Figure. Note that the luminosity, rather than burst mass, is used for normalization. The brightness of the burst is taken as the peak luminosity at 5500Å.

As an illustration to the use of these indices, we have compared new data on Mrk325, a clumpy irregular galaxy, and NGC 3277, a normal spiral. Mrk 325 is estimated to contain more than 20,000 very hot stars and is one of the strongest extragalactic far-infrared sources (see Condon and Yin 1990). Its luminosity, size and internal motions are all larger than the typical dwarf irregular galaxies. The position of the two galaxies in the reddening free diagram are shown as open symbols in Figure 2 and indicate that the age of the starburst in Mrk 325 is in the range of 40 Myrs, whereas NGC 3277 displays all the global colors of an old starburst of 0.5 Gyrs ago.
The IRAS infrared index $f(60)/f(100)$ and the narrow band colors are also well correlated despite reddening effects. The IRAS index is a good indicator of the nature of the dust heating sources in galaxies and provides a direct indication of the dominance of the warm component of the interstellar radiation field produced by O and B Stars. We have defined a reddening free color index, $E$ such that:

$$E = (u_z - v_z) + (v_z - y_z) - 2.84(b_z - y_z)$$

Figure 3 shows this correlation between the far-IR colors for starburst galaxies from the literature and new narrow band data. It has been commonly assumed that IRAS colors are poorly correlated to UV and blue optical colors due to the heavy presence of dust responsible for far-IR emission. However, new HST imaging has revealed that, in fact, ultraluminous infrared galaxies display a complex structure of dust lanes and compact knots of star formation (see Surace et al. 1998). A significant amount of the light from these blue star formation regions exists outside the dust-rich core regions to produce the $E$, far-IR relation in Figure 3.

### 3. Starbursts in Distant Clusters

Observations of galaxy clusters with high redshift show an increasing numbers of blue galaxies $(b_z - y_z < 0.2)$ and an increasing number of those blue galaxies
have $mz < -0.2$ with redshift (Rakos and Schombert 1995). One such clusters, CL0317+1521 at $z = 0.583$, has over 60% of its population as blue galaxies and 42% have $mz < -0.2$, the photometric signature for starburst. The deep rest frame Strömgren color photometry of the cluster A2317 ($z = 0.211$, Rakos, Odell and Schombert 1997) shows that the ratio of blue to red galaxies has a strong dependence on absolute magnitude such that blue galaxies dominate the very brightest and very faintest galaxies, shown in the bottom panel of Figure 4. Similar behavior is found in new data on A2283 ($z = 0.183$) also shown in Figure 4. However, the fraction of galaxies displaying the signatures of a starburst only increases towards the faint, dwarf end of the luminosity function (see top panel of Figure 4).

Tidal interactions are frequently invoked as an explanation for the high fraction of starburst galaxies. These starburst systems would have their origin as gas-rich dwarf galaxies who then undergo a short, but intense, tidally induced starburst. It should be noted, however, that the orbits of cluster galaxies are primarily radial, and the typical velocities into the dense cluster core are high. This makes any encounter with another galaxy extremely short-lived, with little impulse being transferred as is required to shock the incumbent molecular clouds into a nuclear starburst.

Recently, a new mechanism for cluster-induced star formation has been proposed. This method, called galaxy harassment (Moore et al. 1996) emphasizes the influence of the cluster tidal field and the more powerful impulse encounters with massive central galaxies. These two processes conspire to not only raise the luminosity of cluster dwarfs, but also to increase their visibility (i.e. surface brightness) and hence their detectability. One of the predictions of galaxy harassment is that galaxies in the cores of clusters will be older (post-starburst) than galaxies at the edges. In terms of star formation history, this is exactly what has demonstrated in A2317 and A2283 (Rakos, Odell and Schombert 1997). That is, the blue population is primarily located in the outer two-thirds of the cluster (see Figure 6 of Rakos, Odell and Schombert 1997).

Regardless of the origin of the blue population, its fate is obvious. These galaxies do not exist in present-day clusters and, therefore, must either be destroyed or reduced to the luminosity (or detectability) of dwarf galaxies. As shown in Figure 4, the blue galaxies dominate the bright and faint ends of the luminosity function. Figure 4 also shows that the blue-fraction of faint galaxies contains a larger number of starbursting galaxies (i.e. ones with $mz < -0.2$) then the bright galaxies. One interpretation is that bright galaxies finished their starburst phase much earlier in the past, and now only display a steady, spiral-like production of new stars. Thus, the scenario proposed here is that the blue galaxies on the bright end of the luminosity function are core galaxies on low orbits involved in high impulse star-forming events. Faint galaxies, on the other hand, are cluster halo objects undergoing harassment style starburst phenomenon. This scenario naturally divides the galaxy population by mass and by distance from the center of the cluster through dynamical processes. Confirmation for this scenario is found from deep HST observations by Koo et al. (1997), Oemler et al. (1997) and Couch et al. (1998) who have shown that the most spectacular starbursts and emission-line galaxies tend to be low mass objects, whose final state is likely to be that of a dwarf galaxy.
Figure 4. The fraction of blue galaxies in A2317 ($z = 0.211$) and A2283 ($z = 0.183$) as a function of absolute magnitude, $M(5500)$ and the fraction of starburst galaxies as a function of apparent magnitude in A2317.
4. Conclusions

The colors of faint blue cluster galaxies in clusters are consistent with a simple starburst phenomenon and indicates that there exists a bursting population of dwarf galaxies in clusters which rises in visibility at earlier epochs, then fades to become the current population of dwarf elliptical and nucleated galaxies. This becomes a parallel issue to the faint blue galaxy problem in the field, except in clusters the bursting dwarf population does not distinguish itself sharply from other cluster galaxies by color alone. Only through a mixture of filter indices does the reddened nature of the bursting dwarf population reveal itself as unique in color and luminosity from the Butcher-Oemler population common in most distant clusters. The fraction of blue galaxies (in A2283 and A2317) increases on both ends of the luminosity function. The bright end is dominated by post-starburst and merger objects identified in HST images of the Butcher-Oemler population. The faint end is dominated by the dwarf population, temporarily enhanced in visibility probably caused by galaxy harassment mechanisms.

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