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Far-infrared and radio continuum properties of spiral galaxies in clusters

T. N. Rengarajan,[1] A. D. Karnik[1] and K. V. K. Iyengar[2]

[1] *Tata Institute of Fundamental Research, Homi Bhabha Road, Mumbai 400 005, India*
[2] *Indian Institute of Astrophysics, Bangalore 560 034, India*

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ABSTRACT

Data on the far-infrared (FIR) and radio continuum properties of spiral galaxies in several clusters have been collected from the literature. To assess the effect of the cluster environment on the FIR and radio continuum properties of galaxies, the radial distance from the cluster centre in units of Abell radius is used as a parameter, and the correlations of this with normalized luminosities are looked for. It is found that there is no correlation of FIR luminosity with radial distance. The average value of L_{FIR}/L_B is also found to be the same for cluster galaxies and isolated galaxies. However, the radio continuum emission shows a significant correlation with radial distance, the radio emission being stronger in the central region. The correlation for galaxies of type Sc and later is stronger than for the earlier types. From a comparison of FIR, Hα and radio continuum correlations, it is concluded that the enhancement of radio emission is due not to changes in star formation in the cluster environment, but to the enhancement of the magnetic field, and possibly also to the increased residence time of electrons in cluster galaxies.

Key words: galaxies: clusters: general – galaxies: magnetic fields – galaxies: spiral – infrared: galaxies – radio continuum: galaxies.

1 INTRODUCTION

The effect of the environment of galaxies on their properties has been a subject of interest for a long time. It is well known that there is a deficiency of H I, neutral atomic hydrogen in cluster spiral galaxies as compared to isolated field galaxies (Giovanelli & Haynes 1985). There have been several studies of the effect of environment on the global properties of star formation using different indicators of star formation. Bicay & Giovanelli (1987) studied the far-infared (FIR) properties of galaxies in several clusters in relation to the H I gas deficiency and concluded that the FIR properties are generally unaffected. In a series of papers, Gavazzi and coworkers have investigated the radio continuum, Hα line emission, FIR and the H-band properties of cluster galaxies (Gavazzi & Jaffe 1986; Gavazzi & Trinchieri 1989; Gavazzi 1991; Gavazzi, Boselli & Kennicutt 1991; Scodeggio & Gavazzi 1993). They also found that the FIR properties, as well as those of Hα emission, are the same in cluster galaxies and in isolated galaxies. However, the radio continuum emission in cluster galaxies is enhanced as compared to isolated galaxies. The well known radio–FIR correlation (Dickey & Salpeter 1984; de Jong et al. 1985; Helou, Soifer & Rowan-Robinson 1985; Wunderlich, Wielebinski & Klein 1987; Rengarajan & Iyengar 1990) has also been studied in cluster galaxies by Gavazzi (1991) and Niklas, Klein & Wielebinski (1995). Andersen & Owen (1995) studied the same in rich and poor clusters as compared to a field sample. The general conclusion is that cluster galaxies also exhibit the tight correlation, but with an enhanced radio-to-FIR ratio.

The ideal way to study the effect of the environment of galaxies is to compare the distribution and averages of distance-independent ratios, for samples of cluster galaxies and isolated field galaxies. Further, it is necessary that both samples be complete and chosen in the same uniform, unbiased manner. In practice, it is not easy to come by such samples. Even if they are available, unless the two samples cover the same distance range, biases would be introduced. To overcome the lack of a proper field sample, one may compare galaxies belonging to the cluster with those outside it since most of the selection biases will be common. In this

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⋆E-mail: renga@tifrc3.tifr.res.in (TNR)

approach, a lack of difference between the *inside* and *outside* galaxies does not necessarily mean that there is no effect of cluster environment; the environment may be affecting the properties of galaxies even at larger radial distances (with respect to the cluster centre) than are being studied. However, if the study shows that there is a dependence on the radial distance, one can be sure that the cluster environment is the cause. With this in mind, we have, in the present study, collected several samples of cluster galaxies available in the literature and tried to study distance-independent quantities as a function of radial distance from the centre. Following Giovanelli & Haynes (1985), we also combine data for different clusters and analyse them as a function of normalized radial distance, i.e. the projected distance from the cluster centre divided by the Abell radius. This will henceforth be referred to as the radial distance.

In the next section we describe the samples used, and in the succeeding sections we describe the FIR and radio continuum properties. For the FIR study, we also make use of the *IRAS* Bright Galaxy Sample of Soifer et al. (1989) which contains 22 Virgo cluster galaxies. We compare the average values of L_{FIR}/L_B for the isolated and cluster samples and discuss in detail the biases involved. In the final section, we summarize the conclusions of the analysis.

2 THE SAMPLE

For the FIR sample we use the *IRAS* Bright Galaxy Sample 1 (IRBGS1) of Soifer et al. (1989), which is a complete and reliable catalogue of galaxies with a 60-μm flux density >5.24 Jy covering an area of 14500 deg^2. In the present study we confine ourselves to spiral galaxies of morphological type S0 or later only. There are 22 galaxies belonging to the Virgo cluster in this catalogue; the rest of the galaxies are treated as field sample. Distances, whenever needed, are taken from Tully (1988) or computed using the same procedure as in Tully (1988), taking $H_0 = 75$ km s^{-1} Mpc^{-1}. From IRBGS1 we use only those galaxies for which B magnitudes are available in RC3 (de Vaucouleurs et al. 1991). The FIR luminosity is computed using the FIR (W m^{-2}) parameter, defined using *IRAS* F_{60} and F_{100} by Helou et al. (1988) and applying an out-of-band correction assuming a λ^{-1} dust emissivity law, again using the table given by Helou et al. (1988). The corrected face-on blue magnitudes of B_0^T are taken from RC3 or are obtained by applying a similar procedure. The FIR luminosity is expressed in $\mathrm{L}_\odot$, and the B luminosity in units of solar B luminosity using the formula (Bicay & Giovanelli 1987) $\log(L_B/\mathrm{L}_\odot) = 12.148 + 2\log D_{\mathrm{Mpc}} - 0.4B_0^T$. For the FIR data of cluster galaxies we use the compilation by Bicay & Giovanelli (1987) of galaxies in the clusters A262, Cancer, A1367, A1656 (Coma), A2147/2151 and Pegasus. This sample will be referred to as the BG sample. For the Virgo cluster, we use the catalogue of Binggeli, Sandage & Tammann (1985) and use all galaxies for which entries are available in the *IRAS* Faint Source Catalog as obtained from the NASA/IPAC Extragalactic Data Base (NED). The corrected blue magnitudes are again taken from RC3 or are corrected using a similar procedure. This catalogue will be referred to as VCC. The letters M and B are added to denote definite members (or probable ones) and background galaxies, respectively, as defined by Binggeli et al. (1985). The BG and VCC samples have galaxies the FIR thresholds of which are about 20 times fainter than the IRBGS1 sample.

For the radio continuum data we use the compilation of Gavazzi & Trinchieri (1989) and Gavazzi et al. (1991) who list, for a large number of galaxies of the Coma supercluster (A1367 and A1656), 1.4-GHz and 60-μm flux densities normalized to V-band and H-band flux densities as well as Hα equivalent widths. This combined sample will be referred to as the GBKS sample. For all cluster galaxies, the radial distance is computed using the values of the centre coordinate and r_{A}, the Abell radius listed by Giovanelli & Haynes (1985).

3 FAR-INFRARED PROPERTIES

3.1 L_{FIR}/L_B mean

We have computed the mean and median values of the ratio $\log L_{\mathrm{FIR}}/L_B$ for the various samples, and these are displayed in Table 1. For comparison on a similar scale, we have applied small average corrections to the Zwicky magnitude of BG to convert to B_T magnitude. We also show the result for optically selected UGC galaxies taken from Bothun, Lonsdale & Rice (1989). An average out-of-band correction of 0.19 in log units (derived from the average for Virgo galaxies) and a small correction to conform to the same definition as the BG blue luminosity have been made. The errors shown for the mean values are $\sigma/\sqrt{N-1}$ where σ is the dispersion and N the number of galaxies in the sample.

It is seen from Table 1 that, as expected, the brighter IRBGS1 galaxies have a higher mean of $\log L_{\mathrm{FIR}}/L_B$. The mean value for the 22 Virgo galaxies in IRBGS1 is seen to be lower than the mean for the field (non-Virgo) galaxies in the sample. Since the field and Virgo galaxies have been selected with the same criteria, this apparently indicates a deficit of FIR luminosity in the Virgo cluster. However, if we take only those field galaxies which are in the distance range 15–20 Mpc, spanning only a small range on either side of the Virgo cluster distance of 16.8 Mpc, we find that the mean and median values are not different from those for the Virgo galaxies. This effect seems to arise from a scarcity of high-FIR luminosity galaxies in the local volume, defined by the distance <20 Mpc. We find that while there are 108 and 45 galaxies with $\log L_{\mathrm{FIR}} > 10.4$ and 10.8 respectively, out of 250 field galaxies, the corresponding numbers for Virgo galaxies are only 2 and 0 respectively. However, if we confine ourselves to field galaxies in the distance range

Table 1. Mean and median values of $\log(L_{\mathrm{FIR}}/L_B)$.

Sample	N	Mean	Median
IRBGS1 Field	250	+0.036±0.03	+0.04
IRBGS1 Field (15–20 Mpc)	40	−0.22±0.058	−0.23
IRBGS1 Virgo	22	−0.27±0.061	−0.22
VCCM	137	−0.52±0.027	−0.52
VCCB	46	−0.24±0.037	−0.29
UGC	2710	−0.19±0.007	—
BG	167	−0.15±0.028	−0.20
BG (46–66 Mpc)	70	−0.25±0.049	−0.28
BG (90-148 Mpc)	97	−0.04±0.033	−0.03

15–20 Mpc, the numbers are 1 and 0 respectively out of 40 galaxies; for a distance <20 Mpc, they are 4 and 2 respectively out of 86 galaxies. Thus, for bright galaxies there does not seem to be any significant difference between the field and Virgo galaxies either in the average L_{FIR}/L_B or in the luminosity function for large L_{FIR}.

The VCC and BG samples pertain to *IRAS* galaxies much fainter than in IRBGS1; hence, as expected, the average and median values of $\log L_{\mathrm{FIR}}/L_B$ are also lower for these galaxies as seen in Table 1. Further, in contrast to IRBGS1 galaxies, these contain optically selected galaxies with *IRAS* detection. Therefore, we expect that as distance increases, fainter *IRAS* galaxies will be missing and this will, because of the large dispersion in the $\log L_{\mathrm{FIR}}/L_B$ values, lead to an increase in the mean value of the ratio. This effect is also seen in Table 1, wherein it is noted that the mean value is lower for the VCCM galaxies as compared to VCCB, BG and UGC galaxies, which are farther away. The UGC field galaxies and the BG cluster galaxies are at similar average distances and their mean values of $\log L_{\mathrm{FIR}}/L_B$ are also the same. Further, they are the farthest of all the samples and as such show the expected increase in the mean as compared to VCCB galaxies that are at a distance of ≥ 16.8 Mpc. One can see the distance effect even within the BG sample. If we divide it into two samples – A262, Cancer and Pegasus 62–46 Mpc away and A1367, A1656 and A2147/2151 at distances of 90–148 Mpc – the average and median of $\log L_{\mathrm{FIR}}/L_B$ are larger for the latter. Thus, for the fainter *IRAS* galaxies as well, there is no significant difference in the average value of $\log L_{\mathrm{FIR}}/L_B$ of the cluster galaxies and isolated galaxies. Gavazzi (1991) also find that the differential distribution of F_{60}-to-optical ratio in several clusters does not differ from the distribution for non-cluster galaxies. Bicay & Giovanelli (1987) remark that for $\log L_{\mathrm{FIR}} > 10.5$, the luminosity function for the cluster galaxies exhibits a steep drop as compared to field galaxies. However, this is true only with respect to the bump in the luminosity function seen around $\log L_{\mathrm{FIR}} = 10.25$. If we use the smooth curve shown in their fig. 5, there is no significant deficit of high-luminosity BG galaxies as compared to the field samples shown.

3.2 Correlation with r/r_{A}

In this section we investigate the correlation of FIR properties with radial distance for cluster galaxies. For this purpose, we make use of the data from various samples described in Section 2 and use the statistical methods in the IRAF STSDAS package. In particular, we use the BHK method and the Buckley James method (BJM) to estimate the significance of correlation. Both methods can handle censored data. The latter method can also fit a linear function and give the slope and intercept of the best fit. In Table 2, we give the details of the results for the various samples. For the correlation study we have equated $\log r/r_{\mathrm{A}}$ to -1 whenever it is <-1. The number of such galaxies is less than 6. Plots of normalized FIR properties against $\log r/r_{\mathrm{A}}$ are shown in Fig. 1. In Fig. 1(a) we plot $\log \mathrm{FIR}/H$ versus $\log r/r_{\mathrm{A}}$, where H is the 1.6-μm band flux density for the GBKS sample. For the BG and VCCM galaxies, the plots are shown for $\log L_{\mathrm{FIR}}/L_B$. The results of the fits are shown in Table 2 wherein the fitted slope and the values of P_{ncor}, the probability that there is no correlation between the fitted variables, is given. It is seen from Table 2 that no sample shows significant correlation for normalized FIR emission or Hα equivalent width (EW) with r/r_{A}. We have also looked at the correlation for individual clusters in the BG sample. In individual clusters, only the Virgo sample and Coma (A1656) show a mild correlation – lower L_{FIR}/L_B for low r/r_{A} values. The probability of no correlation for individual clusters other than A1656, in the BG sample, is >0.4. From Table 2 it may also be seen that $\log \mathrm{H}\alpha$ EW, which is a measure of recent star formation, also does not show any correlation with r/r_{A}. We have also looked for

Table 2. Results of fits for cluster galaxies: $Y = a + bX$.

Sample	N	X	Y	BHK	Buckley James	
		(log)	(log)	P_{ncor}	Slope	P_{ncor}
GBKS	178	r/r_A	FIR/H	0.849	$+0.01 \pm 0.08$	0.87
GBKS	178	r/r_A	F_{60}/H	0.767	$+0.04 \pm 0.09$	0.62
GBKS	178	r/r_A	$H\alpha(E.W.)$	0.420	-0.07 ± 0.10	0.51
VCCM	147	r/r_A	L_{FIR}/L_B	0.088	$+0.33 \pm 0.11$	0.002
BG : All	171	r/r_A	L_{FIR}/L_B	0.034	$+0.15 \pm 0.08$	0.077
BG : A1656	47	r/r_A	L_{FIR}/L_B	0.005	$+0.41 \pm 0.17$	0.015
BG : All	171	L_{FIR}/L_B	Def HI	0.013	-0.25 ± 0.10	0.0085
BG : A1656	47	L_{FIR}/L_B	Def HI	0.070	-0.31 ± 0.17	0.063
GBKS : All	178	r/r_A	R/H	0.0024	-0.49 ± 0.12	0.00005
GBKS : $X < 0.4$	79	r/r_A	R/H	0.013	-0.65 ± 0.21	0.002
GBKS : $X > 0.3$	117	r/r_A	R/H	0.540	$+0.05 \pm 0.59$	0.94
GBKS : $\leq$ Sbc						
: All X	98	r/r_A	R/H	0.25	-0.2121 ± 0.1806	0.24
: $X < 0.4$	39	r/r_A	R/H	0.167	-0.385 ± 0.2288	0.091
: $X > 0.3$	65	r/r_A	R/H	0.730	-0.1382 ± 0.8813	0.88
GBKS : $>$ Sbc						
: All X	80	r/r_A	R/H	0.0003	-0.7479 ± 0.1181	0.33E-9
: $X < 0.4$	40	r/r_A	R/H	0.0094	-0.9131 ± 0.2613	0.47E-3
: $X > 0.3$	42	r/r_A	R/H	0.8315	-0.4494 ± 0.4635	0.33

P_{ncor} is the probability that there is no correlation.
$\leq$ Sbc is a subsample of galaxies of type Sbc and earlier.
$>$ Sbc is a subsample of galaxies of type later than Sbc.

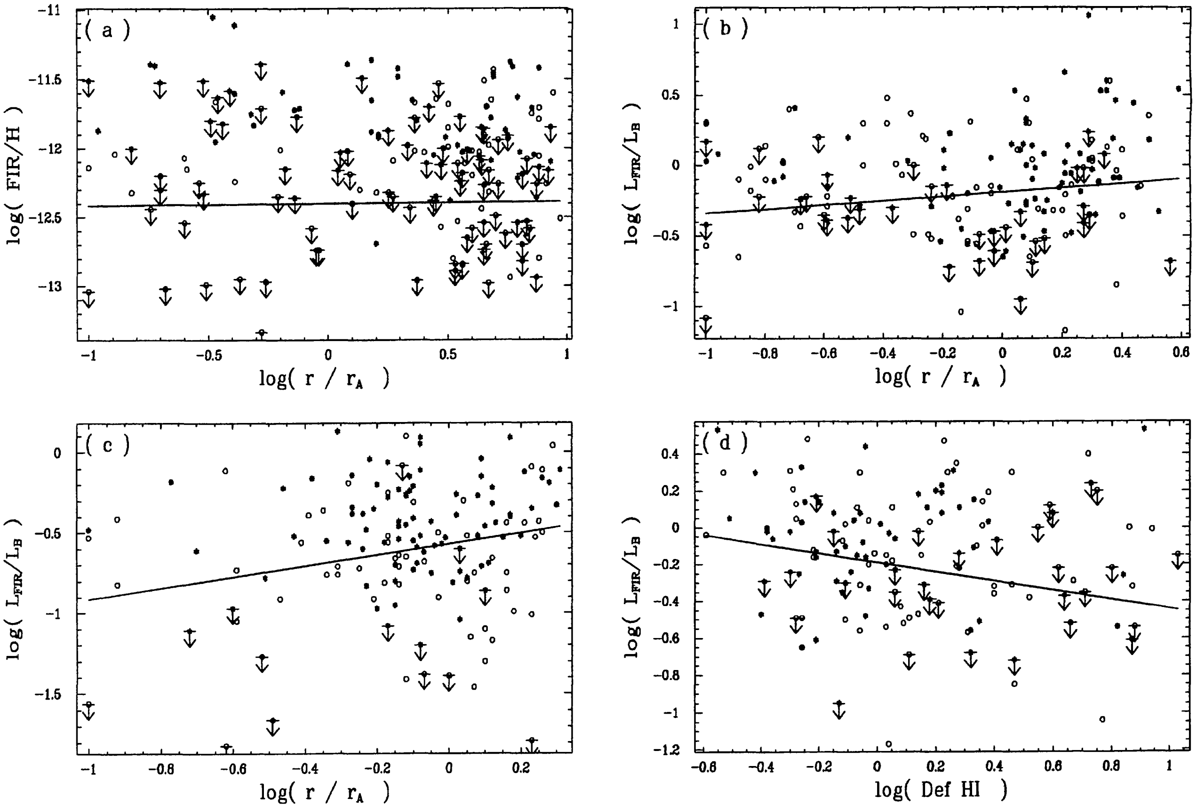

Figure 1. Plot of FIR-related quantities against $\log r/r_{\mathrm{A}}$ where r is the radial distance from the centre and r_{A} is the Abell radius. The ratios plotted are (a) $\log \mathrm{FIR}/H$, GBKS Coma supercluster sample; (b) $\log L_{\mathrm{FIR}}/L_B$ for the BG sample; (c) $\log L_{\mathrm{FIR}}/L_B$ for the VCCM sample and (d) $\log L_{\mathrm{FIR}}/L_B$ against log Def H I for the BG sample. The solid line in all four plots is the best fit to the data obtained using the Buckley James method, which takes into account upper limits also. The downward arrow shows points with upper limits. The open circles represent galaxies of morphological type Sbc or earlier, and filled circles show type Sc and later. Data points with $\log r/r_{\mathrm{A}} < -1$ have been plotted at -1 itself.

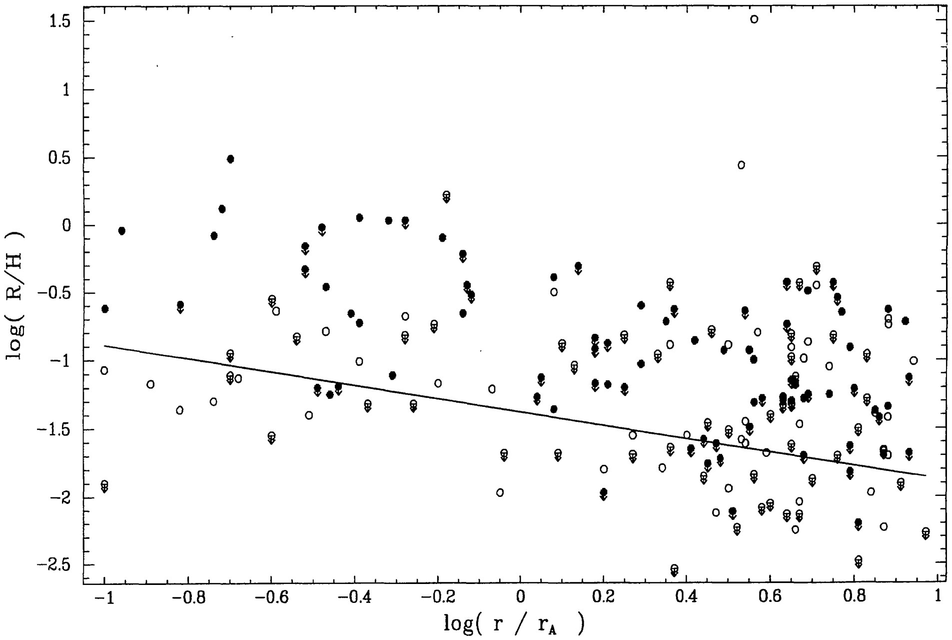

Figure 2. Plot of $\log R/H$, the ratio of radio continuum to H-band flux plotted against $\log r/r_{\mathrm{A}}$. The symbols and line mean the same as in Fig. 1.

correlation between $\log L_{\mathrm{FIR}}/L_B$ and $\log$ Def H I, the deficiency in neutral atomic hydrogen. As noted by Bicay & Giovanelli (1987), there is a mild correlation. Looking at individual clusters, it is again the A1656 cluster that shows a mild correlation, $\log L_{\mathrm{FIR}}/L_B$ decreasing with $\log$ Def H I; all others exhibit no correlation. Since Def H I increases with decreasing r/r_{A}, the mild correlation seen is in the same sense as that seen directly for L_{FIR}/L_B with r/r_{A}.

4 RADIO CONTINUUM EMISSION

In Fig. 2 we show the plot of $\log R/H$ against $\log r/r_{\mathrm{A}}$ for the GBKS sample. Here R is the radio continuum flux density and H the 1.6-μm flux density. The details of the fits and the probability of no correlation are given in Table 2. It is seen that for the Coma supercluster, the normalized radio continuum emission shows a significant correlation with r/r_{A}, the probability of no correlation being < 0.001. If we fit the data for $r/r_{\mathrm{A}} > 2$, i.e. in the outer region of the cluster, there is no correlation at all. For the inner region alone, i.e. $\log r/r_{\mathrm{A}} < 0.4$, the correlation is still good, though the significance is reduced because of the smaller range of r/r_{A} over which the fit is done. In Table 2 we also show the results by dividing the GBKS sample into two groups, early type (Sbc or earlier) and later type (Sc and later). It is seen that the significance of correlation is much larger for the less massive late-type galaxies. It may be noted that for a given r/r_{A} there is a large spread in the values of $\log R/H$. The increase in the radio continuum emission in the inner region of the cluster is statistical. In fact, Scodeggio & Gavazzi (1993) find that only about one-third of the cluster galaxies shows clearly enhanced radio emission. Our analysis shows that the effect of environment is seen up to radial distances of twice the Abell radius. Is the average radio emission at larger distances similar to that for isolated field galaxies? To answer this question, we need a well selected sample of field galaxies spatially far away from the cluster sample, but situated at about the same distance. In the absence of such samples, the answer to the above question will have to await future observations.

5 DISCUSSION AND CONCLUSION

The luminosities in different windows are indicators of global star formation over different time periods (Rengarajan & Iyengar 1988). The Hα EW is clearly a measure of OB star formation and the time-scale involved is $\leq 10^7$ yr. The FIR luminosity is also powered by OB stars; however, part of the luminosity could be powered by older stars formed over a period of $\sim 10^9$ yr. The radio continuum luminosity is powered by cosmic ray electrons presumably accelerated in supernova explosions (Helou et al. 1985). Rengarajan & Iyengar (1990) have argued that the tightness of the FIR–radio correlation implies dominant contribution from Type II supernovae (SN) (high-mass progenitors) and this is consistent with the observation of van den Bergh, McLure & Evans (1987) that Type I SN (low-mass progenitors) are < 50 per cent of the supernovae in spiral galaxies.

The Hα EW was shown not to correlate with r/r_{A} in clusters. Scodeggio & Gavazzi (1993) showed that there is no difference in the distribution of Hα EW between cluster and non-cluster galaxies. The typical time-scale for H I stripping in clusters is $1\text{–}4 \times 10^8$ yr (Lea & de Young 1976; Nulsen 1982; Gavazzi 1989). This being much larger than the OB star lifetime of $\sim 10^7$ yr, it is clear that the cluster environment does not affect the star formation rate (SFR) over this period. The average time-scale implied for FIR and radio continuum could be longer than $\sim 10^7$ yr. The closer the time-scales of two star formation indicators, the tighter will be the correlation between the two. Gavazzi (1991) observes that the R/V versus Hα EW correlation is tighter than the FIR/V versus Hα EW correlation. From this we may infer that the Hα time-scale is closer to the radio time-scale than to the FIR time-scale. The fact that the FIR luminosity is unaffected in cluster galaxies, therefore, implies that it is unlikely that the cluster environment affects the SFR over the 'shorter' time-scale implied for the radio continuum emission.

The radio continuum emission is clearly enhanced in cluster galaxies. Our analysis of correlation with r/r_{A} shows that the effect is significant up to about two Abell radii from the cluster centre. Scodeggio & Gavazzi (1993) find that about one-third of the cluster galaxies show excess radio emission, and these galaxies also show evidence of disturbed morphology. Further, they find that these galaxies stand out on the positive side of the residuals of the $\log R/H - \log \mathrm{H}\alpha$ EW correlation whereas in a similar plot for $\log \mathrm{FIR}/H$, the 'radio excess' galaxies are randomly distributed.

From all the above observations we can confidently conclude that the excess radio emission is not the result of changes in star formation in the cluster environment, but is connected with the radio emission process. The non-thermal radio continuum emission from a galaxy depends linearly on the supernova frequency and the residence time of cosmic ray electrons in the disc of the galaxy, and on the square of the magnetic field. The increase in radio emission could, therefore, be the result of an increase in any of the above three parameters. Very little information is available on the frequency of SN in galaxies in clusters. There are indications that the SN frequency in cluster galaxies is lower as compared to that in isolated galaxies (Barbon 1978; Caldwell & Oemler 1981). This may be partly due to the fact that late-type galaxies are under-represented in such samples. So far, there is no evidence for a substantial increase of SN frequency in cluster samples. As for the residence time of electrons, it could well be affected in the cluster environment. The external pressure associated with the cluster environment could probably inhibit the escape of electrons and increase their residence time. There does not seem to be any study of this aspect in the literature. The cluster environment could lead to an increase in the interstellar magnetic field due to compression arising from the motion of galaxies in the dense medium. Since the synchrotron radio emission depends on the square of the magnetic field, this is probably more effective for increased radio emission. The turbulence associated with the compression process may also lead to more effective confinement of the electrons in the disc, further increasing the radio emission. The increased magnetic field will lead to enhanced radio emission even if the electrons responsible for the radio emission were to be generated by progenitors with a lifetime greater than the typical disturbance time (which is probably the same as the H I stripping time of $1\text{–}4 \times 10^8$ yr). Another noteworthy feature is that the compression of the magnetic field is likely to be more effective for the less massive late-type galaxies in the cluster. This is borne out by the more significant radio–r/r_A correlation for the late-type galaxies as compared to the early-type galaxies.

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