CLUSTERS OF GALAXIES AND RADIO SOURCES

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For some time there have been suggestions that there is a special association of radio galaxies with rich clusters of galaxies, and more recently that the radio galaxies in clusters may show different characteristics from those outside. I will discuss the evidence for three types of such differences, in luminosity function, morphology, and occurance of steep spectrum sources. In each case I will try to connect any difference I find to the cluster environment.

A. THE DATA SET

Much of what I will say is of a very tentative nature because of the small amount of relevant data. Table 1 lists the observations which to date have been most useful for cluster studies. These include two types: 1) Large area surveys, which are the most general way to study any extragalactic radio problem, but in which the percentage of cluster galaxies is small. 2) Cluster specific studies which are much more efficient in sampling cluster properties, but which suffer from various special selection effects, and which usually require another, general, survey to provide a baseline.

Survey	Number Abell Clusters Surveyed	Log Typical Luminosities	Number Detected Cluster Galaxies
General:			
3C	~2000	39.5 - 42 erg s^{-1}	10
2d Bologna	~15	38 - 40.5	11
Cluster:			
W4	5	37 - 40	25
4C/cluster	25	39 - 41	17
Owen	~500	40 - 41	130

References: 3C; Macdonald et al 1968, Mackay 1969, Elsmore et al 1970: Bologna; Colla et al 1975; W4; Jaffe and Perola 1975: 4C; Riley 1975: Owen 1975

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B. THE LUMINOSITY FUNCTION

The first question we ask about radio galaxies in clusters is whether they occur more or less often than those outside. Specifically we ask whether the fraction of galaxies of given optical type and absolute magnitude that are radio sources of given luminosity depends on the cluster environment. As Dr. Perola has reviewed, the answer, at least for elliptical galaxies, seems to be that there is no difference (greater than a factor of two or so) in this luminosity function (LF) for galaxies with $-19 \geq M_p \geq -21$ (for $H_o = 100$ kms^{-1} Mpc) and for luminosities of 10^{38} to ^{42} erg s^{-1}.

There is one caveat here and that is the weak end of the LF (10^{38}-10^{40} erg s^{-1}) is determined from a rather small number of clusters, about 5, and could be incorrect if these were unusual in some way. Possible evidence for this comes from Owen's (1975) survey of the total luminosity of a large number of clusters measured with a low resolution telescope. The whole cluster LF he finds, shown in figure 1, shows a well-defined peak at $L \simeq 10^{40.5}$ erg s^{-1} but only accounts for 30% clusters observed. He postulates a second, low luminosity type of cluster, to account for the other 70%.

To explain Owen's result under the hypothesis that the individual galaxy LF is independent of cluster type, we need to assume that the galaxy population of these two types of clusters is drastically different. Since the individual galaxy LF depends very strongly on absolute magnitude, one possibility is that the radio bright clusters contain one superbright cD type galaxy, with $M_p < -21$, which dominates the cluster LF. Figure 1 also shows two whole cluster LF's predicted from the single galaxy LF's for clusters with and without a single superbright galaxy. We see that the inclusion of the one galaxy indeed makes a large difference and that with some mix of the two cluster types we can reproduce the position and amplitude of the peak, but that the faint end

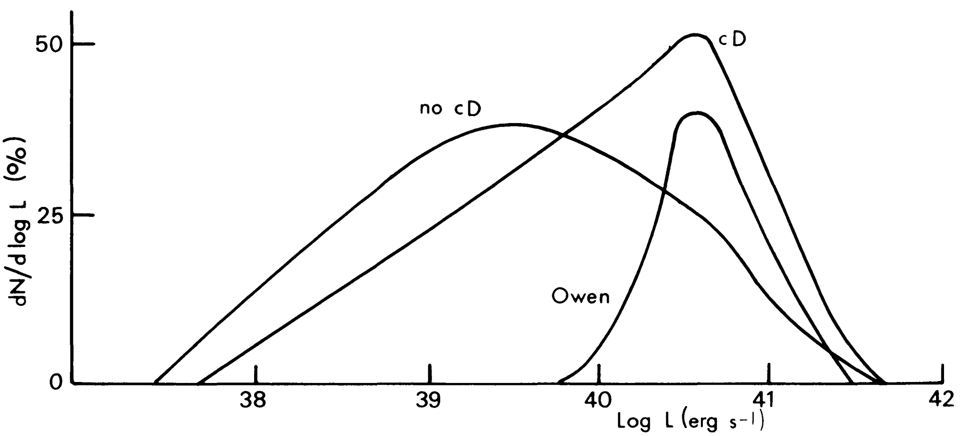

Fig. 1 Whole cluster luminosity function observed by Owen and predicted for clusters with and without a superbright galaxy.

of the LF does not fit that of Owen. It is possible that in this region there may be systematic errors in Owen's data because the clusters detectable in this range were nearby, and resolved into individual galaxies by his telescope. Solving this problem will require high resolution measurements of some of these low luminosity clusters; these I expect will be done soon.

If in fact there is no difference in the cluster/noncluster LF we are in the unexpected position of having to explain this lack of difference. Either the environments of galaxies have no effect on their LF's, or the environments around cluster and noncluster radio galaxies are the same. The second alternative should be taken seriously; present X-ray measurements do not exclude the possibility that giant ellipticals outside clusters carry with them a fairly large, say 100 kpc radius, gas halo of density and temperature similar to that believed to exist in clusters. The X-ray source around M87 might be evidence for this.

If this is not the case, the lack of change of the LF with density puts a restraint on any model of radio sources that involve an external medium. If in a given model the luminosity of a source changes as ρ^{α} then the LF, in one of the regions where it follows a power law, should vary as $\rho^{\alpha(\gamma-1)}$ where γ is the index of the power law. For strong radio sources $\gamma \approx 2.5$ so we can insist that $|\alpha| \log(\rho_{cl}/\rho_{field}) \lesssim 0.2$, or say $|\alpha| \lesssim 0.2$ if we allow at least a factor of 10 variation in ρ between cluster and field.

Whatever the density around isolated galaxies, they do differ from cluster galaxies in that most of the latter move through the surrounding gas at speeds of 1000 km s^{-1} or so, and are probably stripped of their intrinsic interstellar material (Gunn and Gott 1973), while the random velocity of galaxies in small groups or in the field is about 200 km s^{-1} (Geller and Peebles 1973). The similarity of the cluster LF to the field LF seems then to weigh against source models requiring the accretion of interstellar gas by galactic nuclei.

C. SOURCE MORPHOLOGY

Though we find no striking cluster/noncluster differences in terms of luminosity function, we do better when we look at the morphologies of individual sources.

The most spectacular sources specifically associated with clusters are the tailed sources. The two examples in the 3C catalog, 3C129 and 3C82.1B show the defining characteristics of well confined emitting regions extending to one side only from the parent galaxies. In each the radio surface brightness peaks a small distance from the galaxy and decreases irregularly at larger distance. Both also show the double stranded form, and 3C129 the steepening of spectral index with distance from the galaxy that are seen in many tails.

We are beginning to get enough examples of tailed sources to discuss their statistical properties. Studies by Owen (1975) and Rudnick and Owen (1976) of Abell clusters show that the tails make up roughly 10% of cluster radio sources of luminosity $10^{40.5}$ to $10^{41.5}$ erg s^{-1} with few outside this range. Other surveys (Riley 1975, Colla et al. 1975) give consistent numbers, with larger uncertainties. The total number so far detected is about 20. The wide angle tails, intermediate between normal double and true tails may make up another 10%, (Owen and Rudnick 1976), although it is difficult to distinguish them rigorously from somewhat asymmetrical doubles. The wide angle tails tend to be more luminous and associated with more dominant galaxies than the narrow tails.

Are there tails outside clusters? Maybe. Combining the Bologna results with a selection from the 3C (3C radio galaxies with $z < 0.16$ and $|b| > 15°$, for which cluster identification is fairly complete), I find one narrow tail source (B1621 + 38) among 22 noncluster sources in the same luminosity range. The galaxy is however part of the A2197/2199 supercluster, although not in the condensed region of either cluster. A similar case is 1601 + 17w1 from the W4 survey which is a short tail, associated with NGC6034, midway between A2147 and A2151 in the Hercules supercluster. It is not clear whether we should call these cluster sources or not.

In any case there is a clear cut example of a tailed source in a sparse group of galaxies, that associated with NGC7385 in the Zwicky cluster 2247.3 + 1107 (Schilizzi and Ekers 1975) and another in a group that is possibly part of the A2197/2199 association (B1615 + 35).

There may also be cluster induced distortion of higher luminosity sources, but the data is as yet too sparse to tell. In Hooley's (1974) homogeneous subset of the 3C he finds that for monochromatic power $P_{178} > 10^{25.5}$ W Hz^{-1}, 2 out of 6 well resolved sources in Abell type clusters are complex, including 1 wide tail, compared to 2/12 of the sources in poor groups or clusters and 1/4 outside clusters. Hooley also finds no evidence for a size difference between cluster and non-cluster doubles but the statistics are equally poor. From this it is hard to conclude much. Improving on this will require deeper radio and optical data and a lot of work.

The association of tailed sources with clusters probably arises from one of the conditions that seems to be necessary to the formation of tails: that the parent galaxy move through the surrounding medium at a velocity large compared with the ejection velocity of the radiating material. Thus cluster galaxies, which move on the average some five times faster than group or field galaxies, would more likely form tails, at least if the ejection velocity of the material in these low luminosity sources is around 500 km s^{-1}. The absence of tails among more luminous sources could arise either because the ejection velocities in these sources are higher (e.g. the ejection velocity in the very luminous source Cyg A is estimated at 10,000 km s^{-1} by Hargrave and

Ryle, 1974) or because they are associated with more dominant galaxies whose velocities relative to the surroundings are lower, or both.

The tailed sources also tell us that clusters contain something, most likely a hot gas, which prevents the emitting regions from expanding during periods of 10^8 y or more. All the cluster tails found so far have minimum internal pressure of about 1×10^{-11} dyne cm^{-2}, which agrees quite well with the pressure from a gas of density 3×10^{-27} g cm^{-3} and temperature of a few times 10^7K, such as may be responsible for the X-radiation from clusters (Lea et al. 1973). The one poor cluster tailed source shows a lower minimum pressure, about 10^{-13} dyne cm^{-2} (Schilizzi and Ekers 1975) consistent with the lower maximum temperature that the gas could have and still be bound in a low mass group.

We think then that we can understand the tailed source/cluster connection, although the detailed physics of this formation of the tails is uncertain. The few non-cluster tails raise some special questions. Do those in superclusters mean that there is hot gas at long distances from the cluster centers and that the gas, or the galaxies, have high random velocities? And is the one poor cluster tail just a rare case of a high velocity galaxy in such a group?

D. SPECTRAL INDICES

The last cluster radio phenomenon I will discuss is that of steep spectrum sources. In Table 2 I list the fraction of 3C radio galaxies with high frequency spectra steeper than 1.0 (H), and low frequency spectra steeper than 1.0 (L) as a function of cluster membership from the sample I mentioned earlier. Here high frequency means from about 1 GHz upward and low frequency from 100 MHz downward.

	Abell Clusters	Poor Groups or Clusters	Outside Clusters
H	2/9	6/22	1/22
L	5/9	6/22	1/22

Four of the "group" sources are counted in both rows because they have steep spectra at all frequencies. In both rows there seems to be a correlation with cluster memberships. The evidence is stronger for the L types and is confirmed by Slingo's (1974) study of fainter and more rigorously selected L sources (with low frequency spectra steeper than 1.2). Here 12 of the 13 identified sources belonged to Abell clusters.

The conventional explanation for steep spectrum sources involves

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the confinement of relativistic electrons in an emitting region for a period longer than their radiative lifetimes. The L sources, which often have an approximately straight line spectrum down to the lowest frequency observed, about 10 MHz, seem to be cases of a reservoir capable of storing quasi-continuously injected electrons for periods longer than 10^{10} $B^{-3/2}$ y, where B is the source magnetic field in μG. This reservoir need not coincide with the intense "hot spots" seen with high frequency telescopes, but may be a cavity around the intense regions (Scheuer 1974) or may be the entire cluster medium as seems to be the case in the Coma Cluster (Willson, 1970, Jaffe et al. 1976). Some direct observations (Hargrave and Ryle 1974) seem in fact to support the idea that electrons can leak out of the hot spots so quickly that little radiation loss occurs.

The H sources seem to arise from an intermittancy effect, where the source of electrons to an emitting region turns "off" for longer than the radiation lifetimes of the electrons seen at high frequency. This accounts for the features in sources like 3C338 where the source components seem relaxed, without sign of recent motion or injection, and where the source structure in the relaxed regions does not change with frequency (Jaffe and Perola 1974).

The dependence of radiation lifetime on B suggests that the enhanced number of steep spectrum sources in clusters derives from higher magnetic fields in cluster sources, the result of stronger confinement there by the hot gas. This argument is too simple however. In the case of the H sources, for example, it assumes that the old sources do not leak effectively, which may or may not be true. Also this requires that the H sources disappear by some process other than radiation losses. If, to the contrary, radiation losses are responsible for the fading of these sources as well as the spectral changes, shortened lifetimes tend actually to decrease the number found in a given catalog. Without a convincing model of leakage, intermittancy etc. it is difficult to argue in detail along these lines.

A more general, and possibly more important effect is one of luminosity selection. Increasing the magnetic field in remnant emitting regions increases their luminosity and makes them more likely to be included in a catalog. For example, if remnant sources are formed from a cloud of electrons left over from an active source, the luminosity of the remnant will be proportional to $B^{1.7}$ if adiabatic losses are unimportant and to a higher power if they are. As I mentioned in Section B, an increase in source luminosity, due to an external effect, of a factor β increases the LF of such sources by a factor of about $\beta^{1.5}$, so the number of remnant sources found in a given luminosity interval will vary at least as strongly as $B^{2.6}$ due to this effect. This more than compensates the more rapid removal of these sources from view by higher radiation losses.

For the L sources similar luminosity selection applies. Also, as in the H sources, the more rapid aging of the electrons in a higher field would increase the number of L sources observed only if there is a competing, non-radiative electron loss process. Otherwise all halos or cavities would eventually form L type sources, regardless of the value of the magnetic field. If in fact leakage is an important non-radiative loss for the halo sources, then the sheer size of the cluster gas clouds may be instrumental in confining the electrons until they can properly age.

In finishing this section I would like to emphasize that one must be careful in associating a given phenomenon observed in a radio source catalog with a specific physical cause, for example, the occurrence of steep spectrum sources with shorter radiation lifetimes. In addition to the direct physical effect being studied, one must also consider the change in the rate at which sources of a given type enter and leave the luminosity domain being observed.

E. CONCLUSIONS

There are three conditions affecting radio sources which a priori might account for the differences observed in cluster radio sources: the density of the cluster gas, its pressure, and the fast motion of the cluster galaxies through this gas. The last two seem instrumental in explaining the tail-like morphologies of some cluster sources and the higher occurrence of L and H steep spectrum sources in clusters.

We have on the other hand found no effect directly attributable to a higher density about cluster galaxies. This may be because all bright galaxies are in fact surrounded by a high density halo, or it may be that the effects we looked for, principally changes in the luminosity function, are not sensitive to density differences.

We can conclude by asking what all this does and can tell us about radio sources and clusters that we didn't already know from other lines of study. The most concrete fact is the evidence from tailed sources that there is also hot, dense gas in some smaller groups, and between the clusters in supercluster associations. Also some of the galaxies in these associations seem to show high random velocities.

We can also look for signs of cluster phenomenon in quasars and very distant radio galaxies. Those in catalogs like the 3C are so luminous that comparison with the cluster galaxies we have looked at here on the basis of LF or morphology is impossible. The spectral index measurement can be significant even for very luminous sources. At least one (3C 334, Z = .55) of the 50 or so 3C quasars is an L source, and several of the 4C quasars are. This suggests both that some quasars are surrounded by large hot gas halos and that these quasars have been active long enough, 10^{15} s or so, to build up such a spectrum. I look forward to studying these sources in more detail.

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DISCUSSION

Swarup: Do you have any data on comparison of the angular structure of the radio sources associated with the cD galaxies located inside and outside the clusters?

Jaffe: I have no first hand information on this.

Wilson: Vallee, Lari, Parma and I have surveyed Abell clusters A262, A779 and A1314 at Westerbork at 610 MHz to a flux density level of ~ 8 mJy. Comparing our results with those of Jaffe and Perola, we find a radio luminosity function for the E and S_0 galaxies in A779 and A1314 that is in agreement with that for field galaxies and galaxies in richer clusters. In A262, however, which is a spiral rich cluster, both the E + S_0 and the S + Irr seem over luminous. The chance probability of finding as many radio detections as observed is only ~ 1% for both classes. Abell 262 has been suggested as a 3U X-ray identification.

Longair: There used to be a strong correlation between finding a head-tail radio source in a cluster and finding another source in the same cluster. What is the story on that now that you have a much larger sample?

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Jaffe: I think it has disappeared.

OBSERVATIONS OF THE MICROWAVE BACKGROUND RADIATION IN THE DIRECTION OF CLUSTERS OF GALAXIES

S. F. Gull

Northover and I have obtained evidence for the existence of small diminutions in the cosmic microwave background radiation in the directions of several rich clusters of galaxies known to be X-ray sources. We have now accumulated 670 hours of observations on 7 Abell clusters and some control areas of blank sky, using the 25 m telescope at the S.R.C. Chilbolton Observatory. The results are not consistent with the null hypothesis and can best be explained as the Compton scattering of microwave background photons by the hot plasma responsible for the X-radiation.

Cluster	Temperature difference	Cluster	Temperature difference
A 376	- 0.13 mK ± 0.66 mK	A 2218	- 1.94 mK ± 0.54 mK
A 478	+ 0.33 mK ± 0.52 mK	A 2319	- 0.13 mK ± 0.41 mK
A 576	- 0.71 mK ± 0.57 mK	A 2666	- 0.27 mK ± 0.35 mK
Coma	- 1.51 mK ± 0.40 mK	Blank sky	- 0.01 mK ± 0.32 mK

Partridge: For those who like coincidences, how about a comment by Partridge following one by Gull?

During 1975-76, George Lake and I at Haverford have made observations of 8 clusters using a procedure closely resembling that of Gull and Northover. We worked with the 36-foot N.R.A.O. telescope at $\lambda = 9$ mm; the beam width was 4', and the separation between the main and reference beams was 19'. The short wavelength was chosen to reduce as far as possible contamination of the signal by weak sources within the clusters. Our preliminary results are as follows:

Cluster	Temperature difference	Cluster	Temperature difference
A 376	+ 0.54 mK ± 0.80 mK	A 1656 (Coma)	+ 0.60 mK ± 0.81 mK
A 401	- 0.39 mK ± 0.61 mK	A 2079	- 0.35 mK ± 1.24 mK
A 426 (Perseus)	+ 1.91 mK ± 0.82 mK	A 2319	+ 0.27 mK ± 0.77 mK
A 576	- 0.34 mK ± 0.51 mK	A 2666	+ 1.86 mK ± 0.86 mK

We ignore A 426 (Perseus), a known radio source. With this exclusion our data are consistent with the null hypothesis - we have no evidence for the inverse compton cooling of the microwave background. In particular, we do not see the 'dip' in Coma. I should stress, however, that our data analysis is not complete, and that we plan further observations of clusters 1656, 2079 and 2666. In addition, both groups hope to be able to make scans across one or more clusters to attempt to map the radial distribution of hot intergalactic gas.

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Bahcall: Do you point your reference beam well outside the limits of the X-ray extent?

Partridge: Yes, even for the cluster of largest angular extent in our group, Coma.

Webster: Are your quoted temperatures antenna temperatures or surface brightness temperatures corrected for sidelobes?

Partridge: They are sky temperatures, properly corrected for sidelobes, antenna inefficiency, etc., and are thus directly comparable to the results of Gull and Northover.

Shaffer: Are they sky temperatures corrected for the atmosphere, especially at 9 mm?

Partridge: They are sky temperatures, corrected for atmospheric extinction.

A METHOD OF DETERMINING Ω FROM A REDSHIFT SURVEY

E.L. Turner and W.L.W. Sargent

The distribution of galaxies in space is approximated by their distribution in a "redshift space" in which their radial coordinate is cz/H_o. Deviations from a smooth and uniform Hubble expansion, due either to perturbations arising from density fluctuations in the distributions of galaxies or to virial motions in bound groups and clusters, cause characteristic distortions in "redshift space". A method of detecting and measuring these distortions (anisotropies) from the relative redshifts and positions on the sky of pairs of galaxies is proposed. An approximate (covariance function) and a more powerful general method of relating these characteristic distortions to their associated density enhancements (and hence Ω) are presented. The limited data presently available are used to illustrate the approximate method, and a very tentative result of $\Omega \approx 0.07$ is obtained. Redshifts accurate to ~ 20 km s^{-1} for a magnitude limited sample of ~ 4000 galaxies (from which a volume limited sample of ~ 1000 galaxies may be extracted) would be required for a strong test of Ω. These requirements suggest, among other possibilities, a 21-cm redshift survey.

Thuan: It would be nice to extend this treatment to a magnitude limited sample rather than a volume limited sample in order not to waste data.

Turner: Extracting a volume limited sample from an observed magnitude limited one requires throwing out $\geqslant 3/4$ of the data. The analysis could be generalised to avoid this but it would require the assumption of a universal luminosity function with a known form. In the ideal case of plentiful, high quality data, the assumptions can be avoided.

COSMOLOGICAL IMPLICATIONS OF THE ULTRAVIOLET SPECTRUM OF GALAXIES

A. D. Code

Based on OAO-2 ultraviolet photometry of bright galaxies in the spectral region from 1550 - 4250 Angstroms, Code and Welch have found significant variations in the ultraviolet flux for early type galaxies with similar energy distributions longward of 4000 Angstroms.

The energy distribution for most giant ellipticals fall below satellite detection threshold shortward of 2400 Angstroms as they should on the basis of models. However, the energy distribution of the giant elliptical NGC 4486 (M87), which has been measured at 1910 Angstroms is considerably brighter than model predictions. M87 is the only bright radio galaxy in the sample. The jet cannot make a substantial contribution to the total integrated flux at 1910 Angstroms and the result suggests that this excess is due to early-type stars. Sandage (1972, Ap. J. 178, 25) notes that giant ellipticals that are radio sources are often bluer than those that are radio quiet. Van den Bergh (1975, Ann. Rev. of Astron. & Astrop. 13, 217) presents evidence for a burst of star formation accompanying violent events in the nuclei of supergiant elliptical galaxies.

The K-corrections for an energy distribution similar to M87 differ significantly from those for other giant ellipticals and SO galaxies for red shifts in excess of z = 0.4. Finally it is noted that for z > 0.5, in the absence of evolution, the late-type spiral galaxies may become photographically brighter than normal giant ellipticals in distant clusters. The expected increase in the B magnitude relative to the average giant elliptical at z = 1.0 would be $-1\overset{m}{.}50$ for M87, $-1\overset{m}{.}75$ for the average Sb galaxy and $-2\overset{m}{.}0$ for the average Sc galaxy.

Tinsley: The evidence for OB stars in M87 is especially interesting since this is one of the relatively few elliptical galaxies in which a supernova has occurred. Traditionally, the occurrence of supernovae in elliptical galaxies has been taken to mean that very old stars (in particular, white dwarfs) can explode as supernovae, because massive stars are thought to have died out long ago in normal ellipticals. Code's results add further support to the alternative idea that even Type I supernovae (the only type identified in E galaxies) arise from massive stars.

Arp: I am worried about the jet in M87. At 3700 A the photographic image is dominated by the blue jet. Have you removed specifically the effect of the blue jet in your ultraviolet measures?

Code: No I don't think the jet is an important contribution. The photometry field of view was 10' arc which includes essentially all the light from the galaxy. If one extrapolates the contribution of the jet to the total light from the blue to 2000 Angstroms by assuming a flat spectrum the jet contributes only a few per cent. If the jet were to be the principal source of the ultraviolet excess it would have to have a very steep and uncharacteristic spectrum.

Rowan-Robinson: Can you say anything about these young stars?

Code: The type of stars required to produce the flux shortward of 2000 Angstroms in M87 are O or early B stars; certainly earlier than B5.

Tinsley: Evolution of the stellar populations in galaxies is likely to affect their colors significantly in the redshift range ($0 \leqslant z \leqslant 1$) over which Code has predicted K-corrections and broad-band colors. Calculations of color (e.g. B-V) vs. z are presented here, for a typical elliptical and late-type spiral; further details will be published elsewhere (Ap. J. 1977, in press). In the cases without evolution, the usual effects of K-corrections on colors are reproduced (cf Pence, 1976, Astrophys. J., 203, 39): the steep UV spectra of typical elliptical galaxies causes the colors to increase steeply with z, while for late-type galaxies the effects of redshift are much smaller. Evolutionary models lead to the following predictions:

(i) the colors of later-type galaxies are not strongly affected by evolution, because a similar distribution of early-type stars always dominates their light at the relevant wavelengths.

(ii) colors of elliptical galaxies at $z > 0.5$ are significantly affected by the fact that the main-sequence turn-off of a predominantly coeval population is bluer at earlier times. For example, instead of having an observed B-V ~ 2.0 (the approximate value for no evolution) at $z = 0.7$, a normal elliptical galaxy may have B-V ~ 1.5; exact color-redshift observations would help to evaluate a number of uncertain parameters in the elliptical galaxy models.

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