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Extremely Red Objects in the Fields of High Redshift Radio Galaxies

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We are engaged in a program of infrared imaging photometry of high redshift radio galaxies (McCarthy, Persson, Elston, and Eisenhardt, this conference). The observations are being done using NICMOS2 and NICMOS3 arrays on the DuPont 100–inch telescope at Las Campanas Observatory. In addition, Persson and Matthews are measuring the spectral energy distributions of normal cluster galaxies in the redshift range 0 to 1. These measurements are being done with a 58x62 InSb array on the Palomar 5–m telescope. During the course of these observations we have imaged roughly 20 square arcminutes of sky to limiting magnitudes > 20 in the J, H, and K passbands (3 sigma in 3 square arcseconds). We have detected several relatively bright, extremely red, extended objects during the course of this work. Because the radio galaxy program requires Thuan–Gunn gri photometry, we are able to construct rough photometric energy distributions for many of the objects. Table 1 gives a sample of the galaxy magnitudes within 4 arcseconds diameter. All the detections are real; either the objects show up at several wavelengths, or in subsets of the data. The reddest object in the table, 9ab"B" was found in a field of galaxies in a rich cluster at z = 0.4; 9ab"A" lies 8 arcseconds from it.

TABLE 1 – RED "COMPANION" GALAXIES

Name	g	r	i	J	H	K	r-K	age (est)	z (est)	z (target)
0152-209	24.26	23.58	21.99	19.33	18.23	17.35	6.23	3 Gyr	0.8	1.89
+/-	0.45	0.24	0.10	0.06	0.04	0.05	0.25			
2139-292	23.34	23.34	21.93	19.91	18.78	18.18	5.16	2	1.0	2.55
	0.20	0.16	0.14	0.10	0.08	0.09	0.18			
9ab"A"	...	24.7	23.52	20.12	19.59	18.54	6.16	3	1.2	0.40
		0.3	0.15	0.20	0.20	0.10	0.25			
9ab"B"	...	>25.7	25.19	20.21	19.27	18.13	>7.5	3	1.8	0.40
		3σ	0.40	0.40	0.15	0.10				

Although there is insufficient information to show that these objects are galaxies at high redshift, such extreme IR-visible colors are difficult to reproduce without either a lot of reddening, or the large K-corrections associated with redshifts of order 1 or greater. The two extremely red objects in the 9ab field cannot be reproduced by an unreddened spectral energy distribution corresponding to present day galaxies of any Hubble type at the redshift of the 9ab cluster. The red objects found in the fields of the radio galaxies are as red, and often redder, than the radio galaxies themselves. Taking the K-correction explanation as a working hypothesis, we compare the spectral energy distributions with passively evolving single burst models from Bruzual (1985) to make a first estimate of their redshifts and star formation histories. The J-K and H-K colors alone constrain all four objects to have redshifts in excess of 0.5, even for very modest formation redshifts. Our objects fall quite close to the r-K vs. K relation derived for 3CR radio galaxies by Lilly *et al* (1985), suggesting redshifts between 1 and 2.5. Better redshift and age estimates can, in principle, be determined from fitting the entire SED with a Bruzual model, treating both z and the time since the burst (with a fixed 1 Gyr duration) as free parameters. Figure 1 shows a series of model energy distributions, for a burst lasting 1 Gyr, followed by passive evolution of the stellar population. The 4000 A break is the one feature that gives us some confidence in fitting the models to the data points. For both objects in the 9ab field the precipitous drop in the energy distribution between J and I provides a fairly robust lower limit to the redshifts. Lower bounds on z in the range of 0.8 - 1.2 are implied for all of the red companion galaxies.

While we are unable to determine if tne red companions to the radio galaxies are physically associated, and hence at the same redshift as the radio galaxies, their implied luminosities (of order 10L*) suggest that redshifts or order unity may be more likely. Thus our objects appear to be somewhat more extreme examples of the red field galaxies found by Cowie *et al* (1990) and Elston *et al* (1989). The statistics of our detection rate are uncertain, but are roughly consistent with those of the reddest objects of Cowie *et al.*

The combination of the redshift estimate and the stellar evolution timescale implied by the models leads, at face value, to fairly restrictive limits on either the formation redshift, the cosmology, or both. Even without allowing any time for gravitational accretion of material prior to the onset of the starburst, the formation redshifts implied for a a $q_o = 0.1$ and $H_o = 75$ cosmology are in the range 2 - 20. Formally, the onset of the burst responsible for 9ab"B" occurred at a z of 25. **Our basic result is that there do appear to be strong candidates for ordinary (non-radio) elliptical galaxies that have formed at very high redshifts**. This result supports the similar conclusion reached by Lilly (1989) for "1 Jansky" radio galaxies. In Lilly's (1989) K magnitude versus redshift diagram, our objects lie within the distribution, but systematically to the faint side of it. This is consistent with their being ordinary galaxies (i.e. not radio galaxies). Our estimates for z_f are consistent with those of Turner (1991), who argued from the existence of quasars at redshifts of four or greater that at least those quasars had to have formed at very high redshift. It is difficult to reconcile old stellar populations at high redshift with values of H_o near 100, or values of q_o near 0.5.

One possible way out of these conclusions is to invoke reddening to account for some part of the curvature of the SED, thereby lowering the passive evolution time estimates. To drop the age of 9ab"B" from 3 Gyr to 1 (2) Gyr, one would require a dereddening of 2.5 (1.0) magnitudes between rest frame wavelengths of 3000 and 4500 A, corresponding to an Av of 5 (2) magnitudes. For the latter value, and assuming the same redshift estimate, the formation redshift would be of order 5 and the luminosity would increase to 100 L*. Alternatively, the sharp drop in the energy distribution could be accounted for if the IMF of the stellar population were sharply bimodal, and that the galaxy was just old enough that all the high-mass stars have disappeared, leaving only a population of red giants and dwarfs.

With better SED data, it should be possible to further elucidate the nature of the red objects that have been found, and new ones that are certain to be found in the near future. Clearly, spectroscopic redshifts would remove much of the ambiguity in our constraints on z_f. However, on the basis of present data, the spectral energy distributions are consistent with the existence of high redshift quasars and radio galaxies, and provide evidence for galaxy formation at redshifts of order 10.

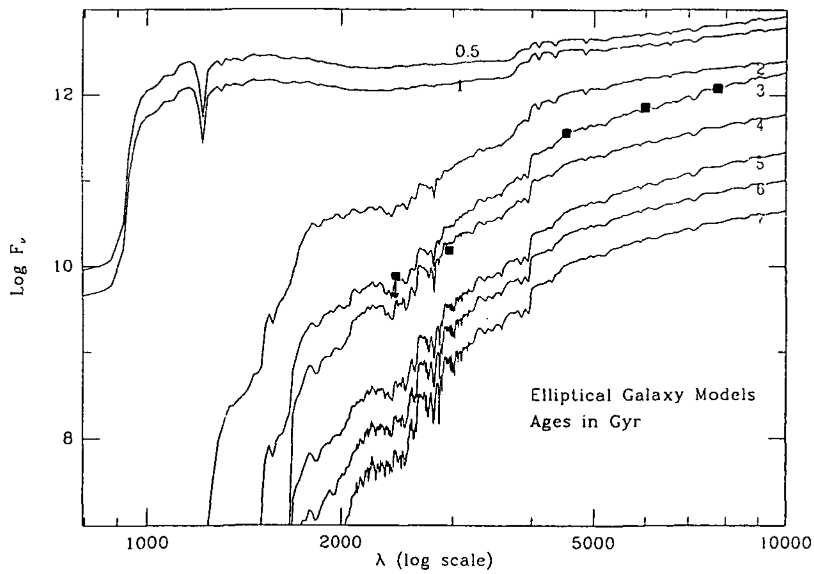

Figure 1. – Family of Bruzual C–model spectral energy distributions, with ages since the beginning of a 1 Gyr starburst indicated. The curves have been vertically shifted by arbitrary amounts for clarity. The data points refer to the reddest object in our sample – 9ab"B"; the data have been shifted horizontally and vertically to achieve a plausible fit to both the redshift and the age of the stellar population. Table 1 gives the resulting values.