COLORS OF RADIO GALAXIES AT HIGH REDSHIFTS

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In this paper we present the first results of the Westerbork-Berkeley Deep Survey, the purpose of which is to derive the epoch dependence of the radio luminosity function (RLF) and the optical spectral energy distribution (SED) of elliptical radio galaxies. From calibrated photographic photometry we conclude that no spectral evolution is seen for $z \lesssim 0.4$, but that colors of radio galaxies are $0\overset{m}{.}5-1\overset{m}{.}5$ bluer for $0.4 \lesssim z \lesssim 0.9$ than predicted from classical model spectra for ellipticals (with star formation only during the first 10^9 yrs after formation). First-ranked cluster radio galaxies may be slightly bluer than the average radio galaxy for $z \gtrsim 0.6$. The epoch dependence of the 1.4 GHz RLF is determined in a direct way. We find almost no population evolution for $z \lesssim 0.3$, but strong evolution for $0.3 \lesssim z \lesssim 0.9$ for all radio powers above the break in the RLF, with enhancement factors of ~ 100 at $z \sim 0.8$.

THE OBSERVATIONS

The Westerbork-Berkeley Deep Survey consists of several deep radio surveys of areas in SA 57, SA 68, Hercules and Lynx. For these areas multicolor Mayall 4^m plates are available, taken by two of us for studies of faint galaxies. The 21 cm radio observations were done with the 3 km Westerbork array, with 12" resolution and ~ 100 μJy rms noise in 12^h. About 500 radio sources with $S_{1.4} > 0.6$ mJy were found, of which 297 form a complete sample within 5.3 deg^2. Observations and analysis are described by Windhorst et al (1981).
For most areas we have several high quality prime-focus plates in four passbands, half of them with sub-arcsecond seeing. The plate limits (for stellar objects) are $24\overset{m}{.}0$ in U(3600 Å) and J(4650 Å), $23\overset{m}{.}0$ in F(6100 Å) and $22\overset{m}{.}0$ in N(8000 Å). Absolute photographic photometry was derived, using accurately known photoelectric standards, with magnitude errors of $0\overset{m}{.}05$ for the brightest objects and errors in colors of $\sim 0\overset{m}{.}3$ for objects $\sim 0\overset{m}{.}5$ above the plate limits (see Kron, 1980, for details). Star/galaxy discrimination is done by a -2nd order moment of the object profile.
A complete subsample studied so far contains 150 radio sources, for which
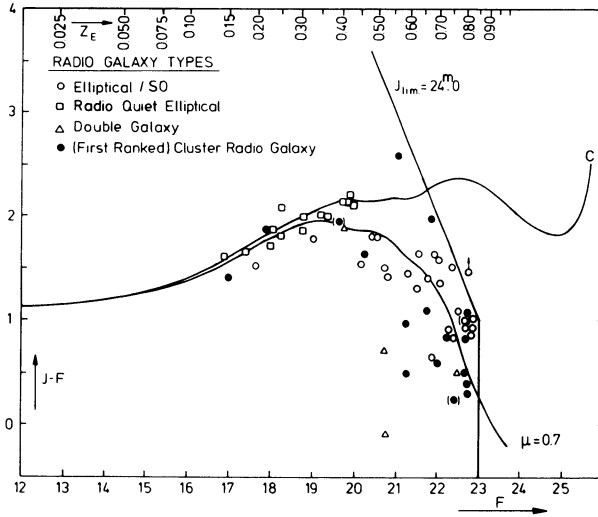
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Fig. 1. The observed color magnitude distribution (J-F) vs F of radio galaxies in the Westerbork-Berkeley Deep Survey.

we found 45% reliable identifications (after correction for contamination) In general the faint identifications were seen on both J and F plates. The U plates gave no new identifications, but the N plates added a few very red radio galaxies. About 85% of all identifications are radio galaxies, predominantly fainter than J = 22^m.0. About a third of all radio galaxies was found in clearly visible clusters, defined as having, within a 40" diaphragm, more than 3 times the general background density.

COLORS OF RADIO GALAXIES

The observed color magnitude distribution (J-F) vs F of elliptical radio galaxies is shown in fig. 1, together with some data for radio-quiet ellipticals (Koo, Kron and Spinrad, unpublished). The radio galaxies appear to become progressively bluer towards fainter magnitudes. This cannot be explained by the shape of the error distribution close to the plate limits (denoted by the lines J = 24^m.0, F = 23^m.0). Note that not many upper limits for J exist for objects visible on F, nor the other way around. Instead, most plate limit objects are visible on both J and F plates, which essentially means J-F $\sim$ 1^m.0. Curve c corresponds with the theoretical colors of an evolving elliptical SED, with constant star formation rate (SFR) during the first 10^9 yrs after formation, and after that SFR = 0 (Bruzual and Kron, 1980, Bruzual, 1981). The μ = 0.7 curve corresponds to an evolving elliptical SED with an SFR that declines exponentially with cosmic time, with 70% of the mass already in stars after the first 10^9 yrs. We conclude that any model with star formation occurring only during the first 10^9 yrs (let alone non-evolving models) do not reproduce the observed color-magnitude diagram of elliptical radio galaxies. The μ = 0.7 model gives a reasonable fit to the data,
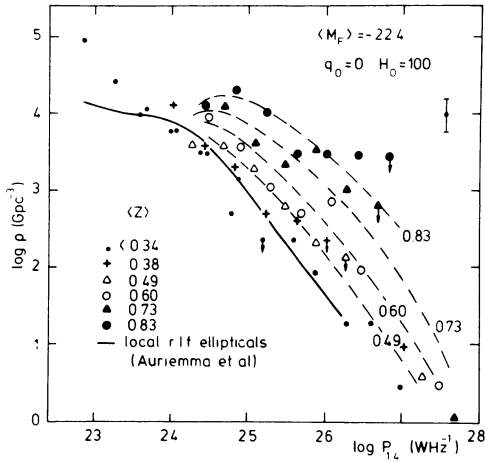
Fig. 2. The 1.4 GHz RLF of elliptical radio galaxies at various epochs. Data from different Westerbork Surveys have been taken together.

but is probably not at all unique. For most radio galaxy identifications we observe, or infer, $U-J \geq 0^{m}.5$. For spirals at all redshifts, as well as for non-thermal nuclei, one expects $U-J \lesssim 0^{m}.0$. This is indeed what we observe for our quasars. So it is likely that all our radio galaxies are ellipticals without a major non-thermal continuum contribution, or rather, that the colors of the radio galaxies are dominated by the stellar population.

Beyond $z \sim 0.6$ there may be a tendency for the first-ranked cluster radio galaxies to be slightly bluer than the other elliptical radio galaxies. A similar trend was observed by Kristian et al. (1978). If this were due to a dependence of star formation history on (cluster) environment one might expect the radio-quiet cluster members to be similarly blue. Radio selected clusters at high redshifts are suitable objects to further study such an effect, which could be similar to that found by Butcher and Oemler (1978).

EPOCH DEPENDENCE OF THE RLF OF ELLIPTICAL RADIO GALAXIES

     The observed color-magnitude distribution of elliptical radio galaxies effectively samples their evolving SED as a function of z. Assuming that the SED evolution manifests itself predominantly in the UV part of the spectrum (as a spectral upturn increasing with redshift) we have derived an evolving SED from the observed colors. This allows us to calculate K-corrections and infer redshifts from apparent magnitudes. Using F magnitudes this procedure should be safe out to $z \sim 0.8 - 0.9$. Of course, one has to assume that the radio galaxy population has the, locally observed, small dispersion in absolute

magnitude at all relevant redshifts. Further, $\langle M_F \rangle$ may depend on z, i.e.
there may be appreciable evolution in the red part of the spectrum as
well. Presently there is however no evidence for such evolution. Using
the SED determined from the observed colors we predicted the Hubble
diagram in V. This turned out to be completely consistent with the
observed diagram, based on spectroscopically measured redshifts of dozens
of 3CR and 4C radio galaxies, out to z $\sim$ 1 (Laing et al 1978, Gunn et al.
1981, Peacock and Wall 1981).
Given the bivariate flux density distribution for the identified radio
galaxies one can derive directly the RLF of elliptical radio galaxies
as a function of redshift. Rather than presenting the results of the
Westerbork-Berkeley Deep Survey separately, we have combined the present
data with those of previous Westerbork surveys (Katgert et al. 1979).
The result is presented in fig. 2, which is based on a total of $\sim$ 200
objects. There appears to be considerable evolution above the break in
the RLF at log $P_{1.4}$ = 24.4 W Hz^{-1}. The magnitude of the increase of the
RLF with redshift does not seem to depend strongly on radio luminosity.
Little or no evolution is seen for z $\lesssim$ 0.3; beyond that redshift there
is a strong increase of the radio galaxy space density, with at z $\sim$ 0.8
enhancement over the local values by factors of 100 or more. It is
interesting to note that the redshift dependence of the RLF as derived
indirectly by Robertson (1980) using a free-form evolution function to fit
source counts and luminosity distributions, also shows the initial flat
part and the steep rise beyond z $\sim$ 0.3 apparent in our direct determi-
nation.

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DISCUSSION

ROBERTSON: What percentage of the radio sample do you estimate are
quasars, and given that quasars have a wide dispersion in absolute
magnitude, what have you done about them in your analysis?

WINDHORST: About 8% of all radio sources down to 2 mJy are quasars,
or 15% of all identifications. Below that level, these functions seem
to increase somewhat. We did not include the quasars in the RLF for
the moment, but their fraction is small anyway. Unlike the radio
galaxies, most quasars are brighter than $J \simeq 21.5^m$, so there is good
hope to get spectra for them somehow.

WALL: I believe that the colors of faint radio galaxies which you
present indicate that the drastic blueing of such galaxies suggested
by Katgert et al. (Nature 280, 20, 1979) is incorrect. Would you like
to comment on this?

WINDHORST: Sure, as Katgert et al. already suggest, the weak point in
their data was, that no photoelectrically calibrated photographic
photometry was available for surveys covering such a large area over
many 48" plates. But still, the blueing is present in their data.
The pure fact that their radio galaxies near the red plate limit did
show up in the blue at all--and often even very clearly--shows
inconsistency with a non-evolving SED. However, with our WBDS colors
and Longair and Lilly's 3CR infrared colors, the controversy is solved
convincingly.

JAFFE: My results differ considerably from yours where they overlap.
This could result from the crudeness of the analysis or it may show a
real cluster/non-cluster difference in evolution.

WINDHORST: Two comments about the differences between our samples:
(1) Our sample is distance limited in the radio out to a redshift of
unity and in the optical out to z = 0.6, which is the redshift at
which we still can see those ellipticals above the break in the
bivariate RLF with the faintest M_F. Our sample in Fig. 2 contains
303 identifications of 1300 radio sources in various surveys, so I
think we have to take the quantitative measure of the evolution
serious out to z = 0.6. Beyond that we are magnitude limited in the
optical, and I am the first one to admit that we really need the
redshifts to see whether we are dealing with a parent population with
the same M_F as locally. It is at the moment impossible to say to what
extent the Malmquist bias or optical luminosity evolution, or both,
play a role for z > 0.6. Your sample might be distance limited in the
optical, but it is not clear to me that this is also true in the
radio. A larger, deeper sample is needed. Note that we find radio
selected faint clusters even below 1 mJy.
(2) But still, the differences could be real indeed. We also found
that several known distant, often extreme rich and red clusters did
not show up as radio sources, while blue ones did show up.