ULTRADEEP OPTICAL IDENTIFICATIONS AND SPECTROSCOPY OF FAINT RADIO SOURCES

Rogier A. Windhorst and Alan Dressler
Mount Wilson and Las Campanas Observatories, Pasadena
Carnegie Institution of Washington

David C. Koo
Space Telescope Science Institute, Baltimore

1. ULTRADEEP CCD IMAGING OF MILLIJANSKY AND MICROJANSKY SAMPLES.

During the last two years we have completed an extensive project of direct CCD imaging with the Palomar 200 inch Four-shooter on several milliJansky and microJansky radio samples, now totaling 200 sources. The purpose is to study the nature and redshift distribution of the radio galaxies that cause the upturn in the milliJansky source counts (WMOKK) and to search for candidates of primeval radio galaxies.

For a complete sample of 70 mJy sources in Hercules accurate VLA positions (0.1", OKSW) are available, yielding about 60% identifications on Mayall 4 m plates (V<23 mag). In 10 minute Four-shooter exposures this fraction increased to 85% down to Gunn r=24.5, while 30 minutes integration in Gunn g and r yielded 97% identifications down to 25.5 mag. The first results are described in W86 and Windhorst and Koo (1986, in prep).

Still, some radio sources refused to show up at r=25.5 mag. These are believed to be the most distant objects, because their angular sizes are very small (expected at high z if $q_0 \ll 0.5$) and their radio spectra are very steep (due to the large radio K-correction at high z). For these sources we finally secured identifications after reaching a limit of r=26.5 mag, obtained in several hours integration, while taking spectra with the Four-shooter for brighter radio galaxies in the same field.

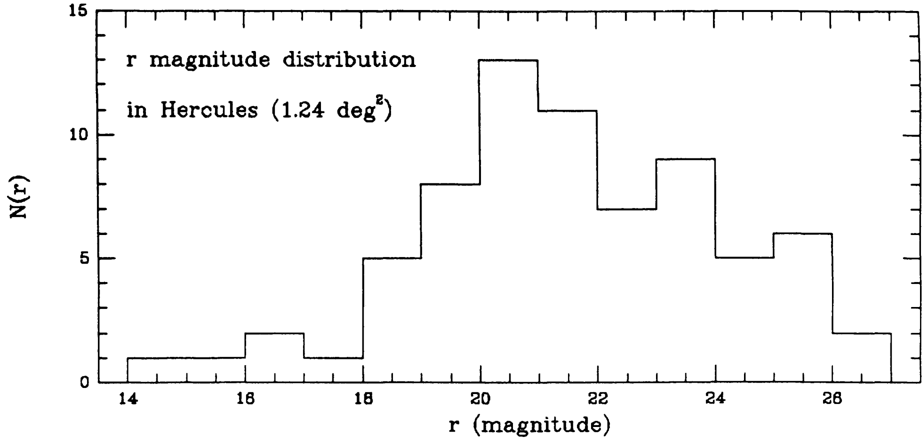
Figure 1 shows the resulting magnitude distribution for our now totally complete sample. The distribution rises strongly for 18<r<21, indicating the cosmological evolution of the mJy radio sources, and gradually declines for 21<r<27, perhaps heralding a redshift cut-off. This is in contrast with the field galaxy counts that continually rise down to r=27 and shows that the accurate VLA positions prevented significant background contamination. Because the identification sample is now 100% complete, optical selection effects are no longer important.

The models of C84 and P85 predict that 10-40% of the milliJansky population extends to z>4, which, if true, means that primeval galaxies must be present in our Four-shooter sample. The 100% complete identifications, and their in general very blue colors, leaves no room for sources that are optically invisible due to dust obscuration at z>3.5. Hence, either the Universe is not significantly obscured by dust at high redshifts, or faint radio sources do not extend to beyond z=3.5, or both.

A. Hewitt et al. (eds.), Observational Cosmology, 573–576.

https://doi.org/10.1017/S0074180900159571 Published online by Cambridge University Press

Figure 1: The r-magnitude distribution of the complete radio source sample in Hercules, which is **100% completely identified down to r=26.5.**



Most of our new Four-shooter identifications (r>22 mag) are clearly extended objects. Their colors are in general fairly blue (-0.5<g-r<1.0), although there exist a few redder identifications. The faint, blue radio objects are possibly actively star forming galaxies at z>0.5, probably the high redshift extension of the blue radio galaxy population discussed in section 2. The reddest radio galaxies are probably very high redshift (z>1) ellipticals with passively evolving spectral energy distributions, like their more nearby counterparts in faint radio samples (KKW, WKS).

It also became clear why the faintest radio sources were not detected before. Although their integrated magnitudes are in the range r=25.0-26.0 mag, they have all very low surface brightness. Some of them are 4-6" in diameter, and show several subclumps in the stacked CCD images. In general these objects showed up in both the deep g,r,i frames with colors in the range -0.5<g-r<0.7 and 0.0<r-i<0.5. (In each exposure the objects were offset and exposed by different pixels to minimize flat field errors). They were more easily recognized in images convolved to a FWHM of 2.5". An example is shown in Figure 2.a and b, which contains 4200 seconds in Gunn g and r added together. While hardly anything is visible at the radio source position in Figure 2.a, an object is clearly visible in Figure 2.b which contains the same data convolved to a FWHM of 2.5". We have detected several of these "fuzzballs". The faintest ones have surface brightness of the order of $<10^{-3}$ x sky.

They have optical colors, morphology and radio structures similar to 3C326.1, although their radio fluxes are a factor 1000 fainter. The radio source 3C326.1 was recently identified by McCarthy et al. (this volume) with an actively starforming gascloud with V~24.0 mag and a size of 10". The object has a low ionization spectrum at a redshift of 1.82, and was tentatively identified as a primeval galaxy. If the "fuzzballs" in our milliJansky sample have the same <u>intrinsic</u> optical brightness and size as 3C326.1, their observed colors and surface brightness suggest that they could be similar galaxies, but at redshifts of 2.5-3.0, due to the $(1+z)^4$ dimming. Spectroscopy will be required to check whether these "fuzzballs" are high redshift radio galaxies in the process of formation.

https://doi.org/10.1017/S0074180900159571 Published online by Cambridge University Press

2. SPECTROSCOPY OF MICROJANSKY RADIO SOURCES.

Since the discovery of the upturn in the 1.4 GHz source counts at milli-Jansky levels (W84, WMOKK), various explanations have been offered for this phenomenon. WMOKK suggested that a population of blue radio galaxies at intermediate redshifts might be responsible, with peculiar optical morphology, sometimes interacting or merging galaxies. C84's model held normal spiral galaxies responsible that underwent very strong cosmological evolution and implied that a large fraction is at very high redshifts. WBGV hypothesized that they are various kinds of unevolving low luminosity galaxies at low redshifts. Here we present the first results of a systematic spectroscopic study with the 100" du Pont CCD spectrograph at Las Campanas. We concentrated on a deep VLA field at 8h+17°, for which we also obtained deep Four-shooter coverage in Gunn g and r.

We obtained good quality spectra with a TI CCD at 20Å resolution for 18 radio sources with B<21.0. Four objects are Galactic stars, mostly of late type. They are usually variable radio sources and the radiation mechanism is possibly gyroresonance or gyrosynchrotron emission (LG). Radio stars do not dominate the sub-milliJansky population but their numbers are sufficiently large that they might induce field to field variations in sub-mJy source counts made at different galactic latitudes.

The sample contained only one QSO (at z=1.92), and four red galaxies with spectra and luminosities of passively evolving giant ellipticals at z=0.2-0.3. The remaining 9 objects were all blue galaxies, some having peculiar optical morphology on the CCD images, like the objects of KKW. Among the 9 blue galaxies, 8 have fairly narrow, and weak to moderately strong emission lines, usually Hα/S[II] and O[III]/Hβ with ~20-30Å equivalent widths. If the galaxies were at high enough redshift we also picked up O[II] 3727. Sometimes Mg b and Na were seen in absorption, as well as H and K and the G-band. These blue radio objects are like actively starforming galaxies, possibly similar to the ones found in spectroscopic studies of distant clusters (DG). For 15<B<21 mag their measured redshift range is 0.05<z<0.3, indicating that sub-mJy radio sources are not local, low-luminosity dwarf galaxies. They have, on the contrary, L^* like optical luminosities. The fact that the emission line fraction is significantly higher than the 30% in a field sample (DTS), combined with their sometimes peculiar optical morphology, makes it unlikely either that they are just normal spiral galaxies.

In conclusion, the blue, actively star forming galaxies constitute the majority group among the sub-mJy identifications and are most likely responsible for the upturn in the 1.4 GHz source counts at milliJansky levels. We expect that the fainter (r>20 mag), blue milliJansky and sub-milliJansky radio galaxies are of the same class, but at z>0.3.

REFERENCES

Condon, J.J.: 1984, Astrophys. J., **284**, 44 (C84).
Dressler, A., Gunn, J.E.: 1983, Astrophys. J. **270**, 7 (DG).
Dressler, A., Thompson, I.B., Shectman, S.A.: 1985, Ap.J. **285**, 481 (DTS).
Kron, R.G., Koo, D.C., Windhorst, R.A.: 1985, A. A., **146**, 38 (KKW).
Linsky, J.L., Gary, D.E.: 1983, Astrophys. J. **274**, 776 (LG).
Oort, M.J.A., et al.: 1986, Astron. Astrophys., submitted (OKSW).

https://doi.org/10.1017/S0074180900159571 Published online by Cambridge University Press

Peacock, J.A.: 1985, MNRAS, **217**, 601 (P85).
Wall, J.V., et al.: 1986, in "Highlights of Astronomy, Vol. VII", ed. J.-P. Swings (Reidel, Dordrecht), pg. 345 (WBGV).
Windhorst, R.A.: 1984, Ph.D. Thesis, University of Leiden (W84).
Windhorst, R.A., et al.: 1985, Astrophys. J., **289**, 494 (WMOKK).
Windhorst, R.A.: 1986, in "Highlights of Astronomy, Vol. VII", ed. J.-P. Swings (Reidel, Dordrecht), pg. 355 (W86).
Windhorst, R.A., Koo, D.C., Spinrad, H.: 1986, in "Galaxy Distances and Deviations from Universal Expansion", ed. B.F. Madore and R.B. Tully (Reidel, Dordrecht), pg. 197 (WKS).

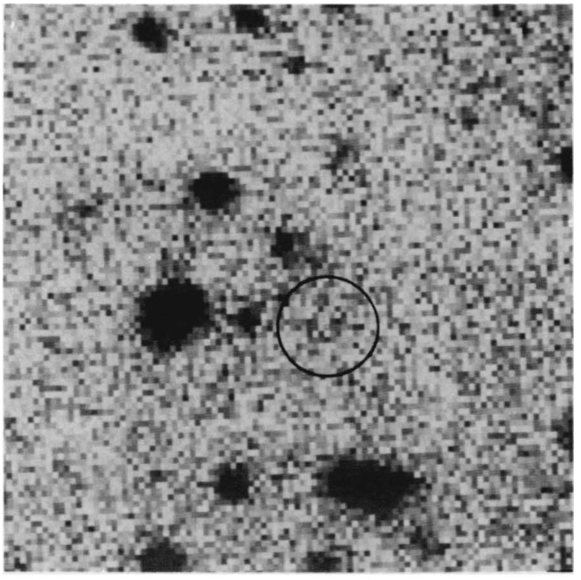


Figure 2.a: Stack of 4200 seconds of Four-shooter exposures in Gunn g and r on a radio source in Hercules. The image shown is 28x28" and has FWHM=1.2". The circle has 3" radius and is centered on the VLA position, which is known to 0.1". There is only marginal signal at the radio position.

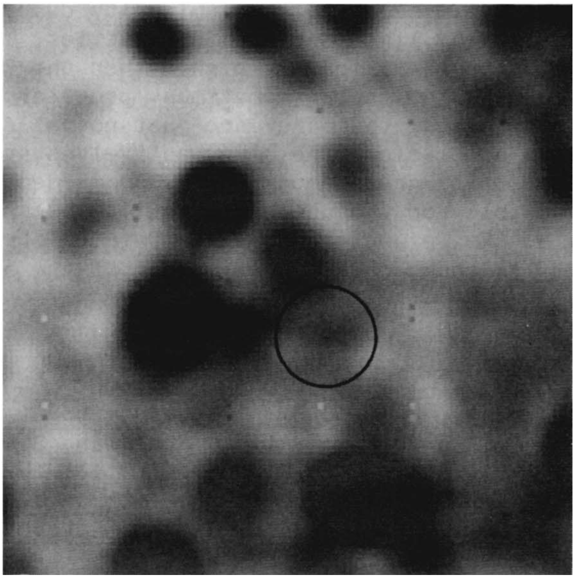


Figure 2.b: The same data convolved to a FWHM of 2.5". A very low surface brightness object now appears at the radio source position, with integrated V=25.7 mag. The grey scale has optimal contrast between -1 and +2σ. Apparently deviant pixel values are due to low level bit errors in the Grinnell.

https://doi.org/10.1017/S0074180900159571 Published online by Cambridge University Press