THE NATURE OF FAINT RADIO SOURCES

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ABSTRACT. Radio, optical and infrared data are combined to study the nature of mJy-sources found in the 5C12 aperture-synthesis survey. The optical counterparts are QSOs, giant elliptical galaxies of the 3CR type, and blue galaxies. We find that the blue galaxies are a mixed group; the suggestion of a new blue population of evolving spirals at mJy levels is not supported by our data.

1. INTRODUCTION

Statistical studies of faint radio sources address a number of astrophysical and cosmological questions: the form of the cosmic evolution of powerful radio sources; the characteristic time scale for the evolution; whether the crucial parameter in this evolution is luminosity or redshift (Fig 1); and the identification of a redshift cutoff (epoch of creation) for active objects. There is also the prospect of discovering new types of radio-active objects. Above all, there is the incentive to combine improved cosmological mapping of radio source populations with improved optical/radio/X-ray observations of the individual objects to understand the life-cycles of active objects, in turn relevant to the broader questions of galaxy formation

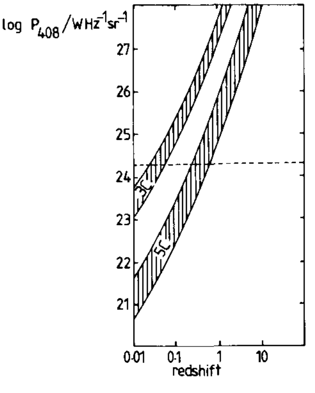

Fig 1. Surveys to different flux-density levels populate strips in the radio-luminosity - redshift plane which are essentially parallel. Together these strips provide a 2D perspective which allows disentanglement of the effects of two key parameters: radio-luminosity and redshift. The dashed line shows P, the luminosity above which the slope of the luminosity function steepens arkedly.*

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and evolution.

The new generation of aperture-synthesis surveys involves several instruments at different frequencies: 0.15 GHz (Cambridge LFT, Baldwin, this volume), 0.41 GHz (Cambridge OMT, e.g. Benn et al 1982), 1.4 GHz (Westerbork SRT, e.g. Windhorst et al 1984; VLA, e.g. Mitchell and Condon 1985), and 5 GHz (VLA, e.g. Fomalont et al 1984). The surveys reach source surface densities substantially higher than previously, and the frequency range covered provides complementary information for different radio populations. We do not intend a review here - instead we present new results from one particular survey, 5C12, whose low selection frequency implies a purer radio spectral content than that of higher-frequency surveys, which detect a mix of flat and steep-spectrum objects. Interpretation may be correspondingly simpler. The new data indicate the nature of the objects hosting faint radio sources, and we consider the preliminary conclusions in relation to those from other investigations. Full details of the present investigation will be reported elsewhere.

2. 5C12

The 5C12 deep radio/optical survey covers an area 4 deg in diameter near right ascension 13^h, declination $+35^o$, close to the North Galactic Pole. The field centre is ~ optimum for extragalactic work: the high galactic latitude ($+82^o$) ensures minimal optical extinction and confusion, Selected Area 57 containing a deep photometric sequence lies a few degrees south, and the field had already been subjected to considerable optical and radio investigation. In our deep radio survey using the Cambridge One-Mile Telescope, 299 sources were detected to a 408-MHz flux-density limit of 9 mJy in a 4^o - diameter field (Benn et al 1982, Paper I). Our deep optical survey is based on a series of 14 sky-limited plates in b, v, r (non-standard) colours from the Palomar 48-in Schmidt. The region (one arcmin square) around each radio source on each plate was digitized and stacked to obtain images of each area in the 3 colours complete to limiting magnitudes of b = 22.4, v = 22.3 and r = 21.3 mag. Calibration was achieved by sky-limited plates of the SA57 region which overlapped the 5C12 region by 1.5 degrees, allowing the photometric magnitudes of the SA57 area to be used via a transfer sequence, to set magnitude scales for the 5C12 region. The optical catalogue from these 299 areas contains positions (to $\pm$ 0.5 arcsec), magnitudes, and colours for a complete sample of 1200 high-galactic-latitude objects (Grueff et al 1984, Paper II).

The catalogue data are augmented at radio wavelengths by low-resolution 151- and 1407-MHz maps from the Cambridge 6C survey and OMT respectively, a low-resolution 5-GHz survey of the entire region carried out with the 100-m Effelsberg telescope of MPIfR, Bonn (Benn et al 1984, Paper III), Cambridge 5-km 5-GHz observations of 30 sources (Fielden et al 1983), and VLA ´B-array´ 1.4-GHz observations of 250 sources. Sources unresolved in the ´B-array´ observations were re-

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observed with the 'A-array' at 1.4/5.0 GHz. Three more 5C surveys overlapping the 5C12 field have been added to the original data, increasing the number of sources detected within the Schmidt-plate area to ~ 800. Structures and accurate positions for most of these extra sources were obtained in 600 snapshot observations, 5-GHz VLA 'C-array', in May 1984.

3. 5C12: A REPRESENTATIVE SAMPLE OF OPTICAL IDENTIFICATIONS

In addition to magnitudes and positions, the optical catalogue of Paper II contains morphological information: half-power widths of the images, and photometry through effective apertures of 5.5, 8 and 11 arcsec. We classified the morphology of each image according to a two-parameter system, diameter and fuzziness, the latter being simply the number of passbands in which significant extra optical flux is integrated in going from the 5.5 arcsec to the 11 arcsec aperture. To examine the nature of objects of different morphologies, we plotted these in the two-colour diagram shown schematically in Fig 2.

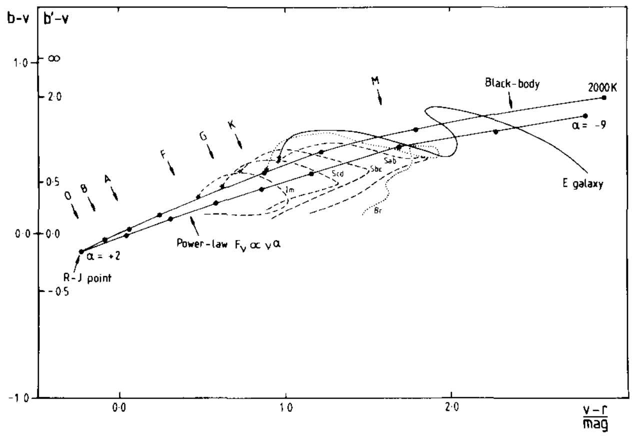

Fig 2. The two-colour diagram, showing colour-colour loci for various objects. Stellar types are marked along the black-body locus, temperatures at the dots representing ∞ (the Rayleigh-Jeans point), 30000, 15000, 10000, 5000, 4000, 3000 and 2000 K. Integer spectral indices (2, 1, 0, -1, -2, -3, -5, -7, -9) are marked as points along the power-law locus. Spectra to the above left of the lines are convex, to the lower right, concave. Galaxy loci run from redshifts of 0 (marked by crosses) to 1.0, using the spectral energy distributions of Pence (1976).

The unresolved objects from the catalogue which are not coincident with 5C12 sources have a bimodal distribution in the diagram, clumps centering near positions predicted for K and M stars. The histogram of such objects in (v − r) is shown in Fig 3, and it is clear that these objects are Galactic stars; the red objects are the nearby M-dwarf disk stars, while the blue are the G − K giant stars of the halo. The result is as found by other workers, and demonstrates the accuracy and reliability of the photometry for the 5C12 optical catalogue.

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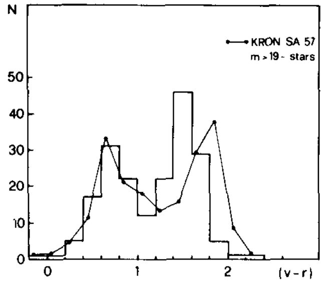

Fig 3. Distribution in (v-r) for stellar objects in the 5C12 optical catalogue which are not associated with 5C12 radio sources. The joined dots are the analogous points in (J-F) from Kron (1980).

From the radio structural information on the VLA maps, a sample of 65 representative and reliable optical identifications with v < 22.0 has been constructed. The sample is formally expected to include 6 misidentifications. The images were classified according to optical morphology as follows:

Q	stellar image	(24)
G	diffuse galactic image	(25)
T	galactic image with bright nucleus	(16)

Fig 4 is the two-colour plot for all images in the sample with measured b, v and r.

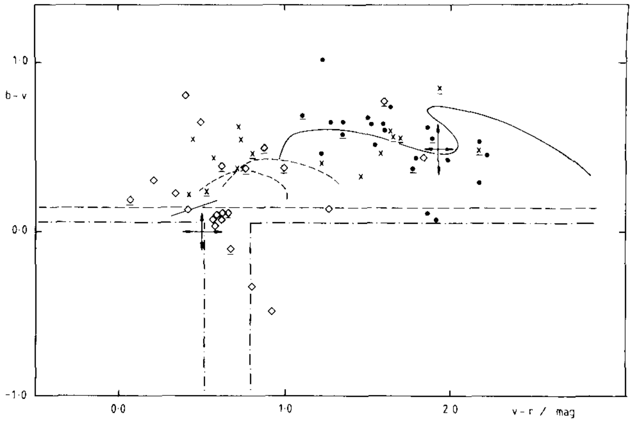

Fig 4. Colour-colour distribution for reliable candidate identifications with v < 22 mag. Most images have reliability p > 90 per cent. Underlined image symbols indicate 70 per cent < p < 90 per cent. The symbols indicate G-images (filled circles), T-images (crosses) and Q-images (diamonds). Power-law, Irr and Scd-galaxy (0.0 < z < 0.5), and E-galaxy (0.0 < z < 1.0) loci are shown (cf Fig 2). The arrowed crosses are error bars for v = 21 mag. The dashed lines mark the triaxon into which would fall the colours of images displaced from the power-law clump at b-v = 0.1, v-r = 0.6 mag, by single emission lines present in one band only.

Class Q, the stellar images: In Fig 4 a compact group of 6 Q images lies at b-v = 0.1, v-r = 0.6, close to the colour expected for an $F_\nu \propto \nu^{-1}$ continuum. They are assumed to be pure power-law QSOs. There is a slight displacement of the group from the expected position of the power-law locus, and a ~ 0.1 mag error in the zero-point of one of the colours is suspected. Of the remaining stellar images, four have red

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(K- or M-star) colours, and identification probabilities below 80 per cent; they may be misidentifications with foreground objects. The colours of the remainder are scattered, and may be affected by emission lines. If a single emission line were to dominate one waveband, the colours would move from the power-law region into the T-shaped region shown in Fig 4. With the exceptions of the possible K- and M-star contaminants, the images displaced from the power-law tend to fall in this region.

For 29 members of the 65-sample, JHK magnitudes were measured with UKIRT, and Fig 5 demonstrates how, in conjunction with optical data, these distinguish power-law from black-body continua. Infrared photometry was carried out for 7 of the blue stellar images and 2 of the red stellar images. The optically blue objects show power-law continua from optical to IR wavelengths, while the red images appear to represent Galactic stars.

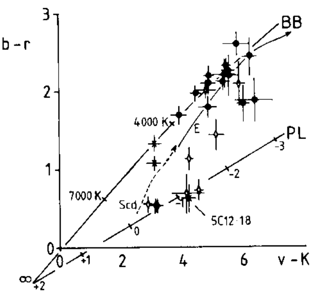

Fig 5. The two-colour diagram b-r vs v-K (2.2μ) provides a strong differentiation between black-body (BB) and power-law (PL) objects, unlike Fig 4. Filled circles represent G-galaxies, diamonds represent Q-objects, and crosses represent T-galaxies. Loci for elliptical and late-type spirals are shown. 5C12.18 appears to be a power-law object, and may well be a Seyfert galaxy.

Savage & Peterson (1983) pointed out that the highest-redshift QSOs have radio spectra which show strong curvature and peak in the spectral range 0.4 - 3 GHz. They suggested that radio QSOs with $z > 4$ might have the curved portions of their radio spectra shifted so far to long wavelengths as to produce a mJy-population at cm-wavelengths with apparently steep radio spectra at the higher frequencies. However, if such sources were to exist in substantial numbers, spectral-index distributions compiled over short and long baselines in frequency should look very different. In particular the long-baseline distribution should show a bump at small spectral indices due to

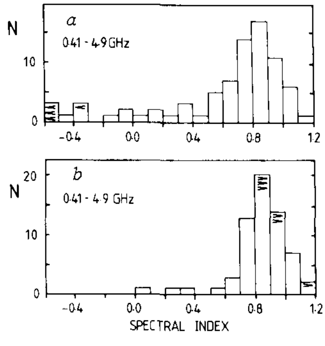

Fig 6. (a) The distribution of two-point spectral indices (0.41 - 4.85 GHz) for 5C12 sources with $S_{4.85}$ > 20 mJy, and (b) the distribution for 5C12 sources with $S_{0.41}$ > 150 mJy. Spectral index is defined in the sense $S_\nu \propto \nu^{-\alpha}$.

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spectral-peak sources. The distributions of spectral indices, defined in terms of the complete 5C12 surveys at both 0.41 GHz and 4.85 GHz, are shown in Fig 6; they look very similar to short-baseline spectral distributions from cm-wavelength surveys at similar source densities. There are thus very few peaked-spectrum QSOs of large redshifts hiding among the (predominantly) steep-spectrum sources found at mJy levels.

G - galaxies: The colour-colour distribution of the 25 G images (Fig 4) is consistent with these objects being giant ellipticals. Further confirmation is provided by the colour-magnitude diagram of Fig 7, in which the rms scatter about the computed colour-magnitude curve is 0.14 mag in v-r. With typical errors in colour of 0.1 mag, the rms intrinsic luminosity of 5C12 giant ellipticals is deduced to be ~ 0.3 mag. Fig 7 suggests that the mean absolute magnitude of 5C12 ellipticals is similar to that of 3CR ellipticals. The mean difference in v-r from that predicted is < 0.1 mag, and does not differ significantly from zero; systematic errors in v and r therefore are < 0.1 mag. There is no evidence for colour evolution (bluening, Katgert et al 1979) out to z ~ 0.5.

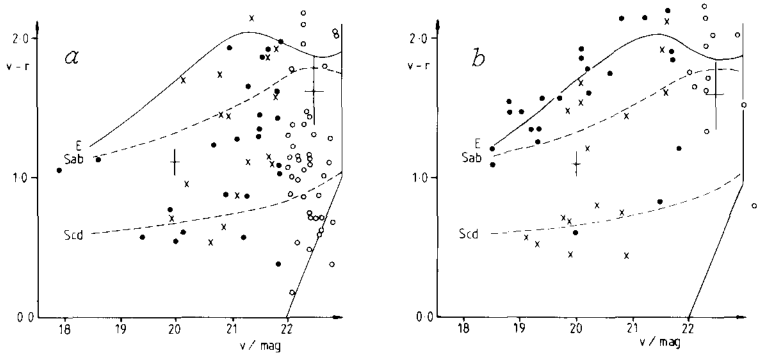

Fig 7. Colour-magnitude distributions for extended images: a) background images, b) reliable identifications. The curves are loci with redshift for first ranked cluster E (0.16 < z < 0.50), Sab (0.07 < z < 0.32) and Scd (0.05 < z < 0.23) galaxies. Filled circles are G-images with v < 22 mag, crosses are T-images with v < 22 mag, and open circles represent all extended images with v > 22 mag. The crooked line is the effective completeness limit (v < 23.0 mag, b < 22.0 mag). Sample error bars are marked.

T - galaxies: The final class of objects we termed T - galaxies (for reasons fortunately lost in the mists of time). There are 16 such images in the restricted sample, and it is clear from the colour-colour and colour-magnitude plots (Figs 4 and 7) that these 16 include a distinct group of blue images. The G/T morphological distinction is not sharp, however, and the colours and magnitudes of the redder T images are consistent with their being ellipticals. Correspondingly, the one G-image with v-r < 1.0 is unlikely to be an elliptical. In summary there are 12 extended images whose colours and magnitudes appear inconsistent with their being giant ellipticals. The colour-colour and colour-magnitude plots, together with the image profiles, are consistent with the hypothesis that these objects are mostly late-type spirals with 0.05 < z < 0.15.

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4. IS THERE A POPULATION OF RADIO-POWERFUL BLUE SPIRALS?

The observations above suggest at first glance that spiral galaxies are a major constituent of the mJy-level source population, the number of such objects exceeding the total of 4 predicted from the local luminosity function for spirals and Seyferts (e.g. Meurs 1982). Optical identifications from the Leiden-Berkeley deep survey also include a surprisingly large number of blue galaxies. This has been interpreted (van der Laan et al 1983, Windhorst 1984) as evidence for a hitherto unknown population of interacting spirals with radio luminosities some 100 to 1000 times in excess of normal spirals, and these luminous spirals are deemed responsible for the flattening of the source count towards faint intensities. To achieve this, significant evolution of their luminosity function by z = 0.4 must take place. However, this interpretation assumes

a) that the sample is not seriously contaminated by misidentifications and misclassified images;

b) that the blue galaxies are predominantly spirals and Seyferts; and c) that the local luminosity function for spirals and Seyferts is well established.

a) For the 5C12 data, we expect contamination of the 65-sample by ~ 6 misidentifications. On the basis of background counts on the plate, about half of these misidentifications will be stellar images, and half extended. It can be seen from Fig 7a that the extended images present in the plate background are predominantly blue for v < 22 mag. When a misidentification is with a galaxy image, it is likely to be a blue galaxy, and we thus expect a few misidentifications with blue field galaxies to be present in the 5C12 sample.

Recently, new VLA observations at 5 GHz have provided better radio positions, and detections of central components in many 5C12 sources: of the 12 images in the restricted sample which are non-G-type, 3 are now known to be misidentifications. When positions of increased accuracy are obtained for sources of the LBDS survey, we suggest that a larger proportion of the blue-galaxy identifications will prove to be erroneous than of the red-galaxy identifications. We also note that misidentifications are more likely to occur in regions of high density, so that misidentifications may appear to be interacting galaxies.

b) A high proportion of powerful radio sources in bright catalogues is identified with 'blue' galaxies. For the most part, these are the broad-line radio galaxies, such as 3C390.3, super-Seyferts or N-galaxies as they used to be called. In the compilation by Laing et al (1983), of 47 3CR galaxies with B-V measurements, no less than 10 have B-V < 1.0. A giant elliptical galaxy is redder than this even at z = 0. Such objects should appear in 5C12, and in fact two radio-bright members of the 65-sample are identified as blue galaxies, with double radio structures.

c) There remains the question of what induces the source-counts to

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flatten at flux densities below $S_{1.4}$ = 2 mJy. It is most plausible that a low-luminosity population is responsible: all investigations have shown how difficult it is to produce pronounced features in the source count with radio sources of high luminosity. Subrahmanya and Kapahi (1983) showed that some such flattening comes about with present data for the radio local luminosity function (RLLF) when no evolution is ascribed to the low-luminosity portion. However, the RLLF is poorly defined at low luminosities, and just how sensitive the counts at faint flux densities are to the form of the RLLF at low luminosities is shown by the illustrative calculation of Fig 8. A new determination of the RLLF (C R Subrahmanya, personal communication) suggests that the previous estimates of space densities are too low, and that the flattening of the source-count predicted by Subrahmanya and Kapahi is underestimated.

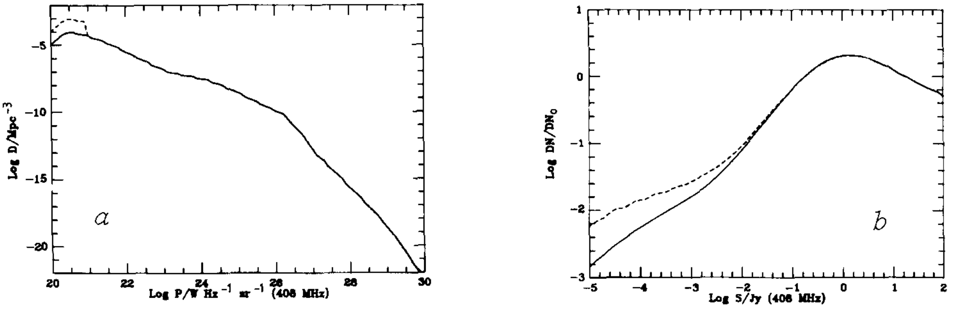

Fig 8. A simple calculation to show the extreme sensitivity of (b) the counts of faint radio sources to (a) the form of the radio local luminosity function (RLLF). In the calculation, the local luminosity function was arbitrary modified by increasing the space density by the dashed bump shown in (a), and the different count which results is shown as the dashed line in (b). The modified space density of the RLLF lies within the present observational errors. The calculation was carried out using evolution models 4 and 5 of Wall et al (1980) which ascribe no cosmic evolution at radio luminosities in question. The solid line in (b) is the source-count prediction from these models and the unmodified RLLF, and it accurately describes the observational data down to $S_{0.41}$ = 0.01 Jy.

5. SUMMARY

We conclude that the blue galaxies found in deep surveys are a mixed bag of misidentifications, misclassifications due to photometric uncertainties, low-z spirals and Seyferts (perhaps more numerous than predicted by the present RLLF), and broad-line radio galaxies. It is most likely that the flattened source count below mJy level is due to a low-luminosity non-evolving population. The prediction is that at the faintest levels, say $S_{1.4}$ < 1 mJy the identifications will be blue (spirals), the redshifts will be $0.2 < z < 0.4$, and the radio structures will be small, representing the cosmic ray structure seen for nearby spiral galaxies. There is some evidence for these small angular sizes (Coleman and Condon 1985). In the intermediate range, that which the current investigation concentrates upon, the mixed bag of blue objects will include low-luminosity spirals, Seyferts, and

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broad-line radio galaxies, and redshifts will range from 0.05 to perhaps 0.6, with a correspondingly large range in excitation level of emission lines in the spectra. It is premature to claim that a new population of interacting and evolving blue galaxies is present.

The primary constituent of faint radio-source populations, at least down to a level of 10 mJy at 0.41 GHz, remains giant elliptical galaxies of the type hosting 3CR radio sources. The present data and the data of Kron et al (1985) show no evidence for optical evolution of these objects out to a redshift of 0.5.

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REFERENCES

Benn, C.R., Grueff, G., Vigotti, M. and Wall, J.V., 1982. Mon. Not. R. astr. Soc., **200**, 747.
Benn, C.R., Wall, J.V., Grueff, G. and Vigotti, M., 1984. Mon. Not. R. astr. Soc., **209**, 683.
Coleman, P.H. and Condon, J.J., 1985. Astron. J., **90**, 1431.
Fielden, J., Downes, A.J.B., Allington-Smith, J.R., Benn, C.R., Longair, M.S. and Perryman, M.A.C., 1983. Mon. Not. R. astr. Soc., **204**, 289.
Fomalont, E.B., Kellermann, K.I., Wall, J.V. and Weistrop, D., 1984. Science, **225**, 23.
Grueff, G., Vigotti, M., Wall, J.V. and Benn, C.R., 1984. Mon. Not. R. astr. Soc., **206**, 475.
Katgert, P., de Ruiter, H.R. and van der Laan, H., 1979. Nature, **280**, 20.
Kron, R.G., 1980. Astrophys. J. Suppl., **43**, 305.
Kron, R.G., Koo, D.C. and Windhorst, R.A., 1985. Astron. Astrophys., **146**, 38.
Laing, R.A., Riley, J.M. and Longair, M.S., 1983. Mon. Not. R. astr. Soc., **204**, 151.
Mitchell, K.J. and Condon, J.J., 1985. Astron. J., **90**, 1957.
Meurs, E.J.A., 1982. PhD Thesis, University of Leiden.
Pence, W., 1976. Astrophys. J., **203**, 39.
Savage, A. and Peterson, B.A., 1983. Proc. IAU Symp. **104**, eds Abell, G.O. and Chincarini, G., D. Reidel: Dordrecht, 57.
Subrahmanya, C.R. and Kapahi, V.R., 1983. Proc. IAU Symp. **104**, eds Abell, G. O. and Chincarini, G., D. Reidel: Dordrecht, 47.
van der Laan, H., Katgert, P., Windhorst, R. and Oort, M., 1983. Proc. IAU Symp. **104**, eds Abell, G.O. and Chincarini, G., D. Reidel: Dordrecht, 73.
Wall, J.V., Pearson, T.J. and Longair, M.S., 1980. Mon. Not. R. astr. Soc., **193**, 683.
Windhorst, R.A., 1984. PhD Thesis, University of Leiden.
Windhorst, R.A., van Heerde, G.M. and Katgert, P., 1984. Astron. Astrophys. Suppl., **58**, 1.

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