THE ASTROPHYSICAL JOURNAL, 164:L35–L39, 1971 February 15

OPTICAL SPECTRA OF THE NUCLEI OF ELLIPTICAL RADIO GALAXIES

M. J. DISNEY*
Steward Observatory, Tucson, Arizona

AND

R. H. CROMWELL
Optical Sciences Center and Steward Observatory, Tucson, Arizona
Received 1970 October 22; revised 1970 December 7

ABSTRACT

Spectrograms have been obtained of the nuclei of twelve nearby giant E and S0 galaxies that were previously found to be radio sources. Of the three galaxies observed with "normal" radio spectra (spectral indices of about −0.9) none showed unusual optical features; whereas of the eight with definite radio spectral peculiarities (and classified as "active" by Heeschen) seven have emission lines characteristic of low-excitation planetary nebulae. NGC 3078, for which insufficient radio data exist to define it clearly as active or passive, exhibits no optical emission lines. Unlike radio spectra, the present optical spectra of the active elliptical galaxies do not demonstrate any obvious QSO-like properties. This is true of the emission-line spectra and, at least to an accuracy of 0.2 mag, is true of the continuum energy distributions over the region λλ3700–5000.

I. INTRODUCTION

Radio surveys of some 200 or so nearby elliptical and S0 galaxies by Heeschen (1968, 1970*a*) and Rogstad and Ekers (1969) have revealed that twenty-four of them are radio sources. Some, like NGC 4486, are well-known strong sources, but most are relatively weak (<0.5 flux units) at 11 cm.

On the basis of their radio structure and spectra, Heeschen (1970*b*) has divided the sources into two distinct classes which he calls "passive" and "active." The passive sources are extended (more than 1′ in diameter) and have the normal inverse-power-law spectrum associated with nonthermal sources. The active sources, however, are essentially unresolved with diameters less than 1″.5, and they have a variety of more complex spectra that have been found principally in variable QSOs and radio galaxies. Some galaxies, like NGC 4486 and NGC 5077, have both types of source. On the basis of the radio evidence Heeschen (1970*b*) suggested that the active galaxies have miniature QSOs in their nuclei.

Only a few of these galaxies, e.g., NGC 4278 and NGC 4486, have well-studied optical spectra. For most of them spectra have been taken in the course of surveys of bright galaxies (chiefly by Humason, Mayall, and Sandage 1956 and Burbidge and Burbidge 1965), but these surveys have been taken in different spectral regions at different dispersions, through variable effective apertures, and for different reasons. NGC 5444 does not have a published redshift.

We have therefore taken a homogeneous set of spectrograms of the nuclei of twelve of these galaxies. We have concentrated on the galaxies with active sources, but several of the passive objects have also been studied for comparison. In the following we give a preliminary analysis of the plates.

* Present address: Mount Stromlo and Siding Springs Observatories, Australian National University, Canberra.

II. OBSERVATIONS

Some forty spectra were taken in 1970 between February and June with the Carnegie image-tube spectrograph at the f/9 Cassegrain focus of the Steward Observatory 90-inch telescope. To confine the observations to the nuclei and reduce the amount of light received from outlying regions of the galaxies the spectra were not trailed along the slit, but were widened with a moonlight eliminator that admits light over a slit length of only 5″. In most cases the slit width was 3″, though for some observations it was closed down to 1″25. The disadvantage of using the moonlight eliminator is that all knowledge of the spectral structure perpendicular to the dispersion is lost, and such knowledge can be important in elucidating the dynamics.

The spectra were taken in two wavelength regions. The "blue" spectra extend from about 3600 to 5200 Å and were taken with a grating blazed in the second order, giving a dispersion of 95 Å mm^{-1}. The first-order spectrum between 6000 and 7000 Å is also recorded with this grating; and to avoid contamination from the second-order spectrum shortward of 3600 Å a Corning O-52 filter was used. When a 3″ slit is used, the projected slit width is 5.1 Å in the second order. The "red" spectra extend from 4900 to 7500 Å, were taken with a grating blazed in the first order, and have a dispersion of 130 Å mm^{-1}. A Schott GG-14 filter was used to avoid second-order blue light. The projected slit width is 7.0 Å. In nearly all cases the width of the spectra on the plates is 0.37 mm.

The plates used were IIa-O, and on most of them we have also recorded the spectrum of an elliptical galaxy whose absolute spectral-energy distribution has been published by Oke and Sandage (1968). The radio-galaxy spectra will be compared with those of the Oke and Sandage galaxies in order to study their continua.

Exposure times were chosen to give fairly well-exposed continua. All the galaxies are brighter than fourteenth magnitude, but the actual exposure times, which varied between 10 and 90 minutes, depend, of course, only on the brightness distribution close to the nucleus.

III. RESULTS

The best spectrograms in both spectral regions (when available) for each galaxy were measured and microphotometered, and the equivalent widths of the emission lines measured. The redshifts were obtained from the H and K absorption lines and from the G-band, with relative weights assigned as in Humason *et al.* (1956).

Table 1 shows a summary of the results. The morphological types and integrated apparent magnitudes are taken from de Vaucouleurs and de Vaucouleurs's (1964) revised version of the Shapley-Ames catalog. The absolute magnitudes have been calculated from the present radial velocities corrected for galactic rotation (de Vaucouleurs and de Vaucouleurs 1964), and a Hubble parameter of 75 km sec^{-1} Mpc^{-1}. For NGC 4374, 4472, 4486, and 4552, however, the mean distance modulus of the Virgo cluster (Sandage 1968) was used. Only lines that have been clearly identified are included. The measured equivalent widths appear in parentheses following the identification in columns (7) and (8). Where these widths are very uncertain they are not included. It should be remembered that these equivalent widths have usually been measured from only a single plate in each case, and they are therefore probably not very accurate.

IV. DISCUSSION

In Table 1 the galaxies are divided into two distinct classes according to their radio properties: the active and the passive. NGC 3078 is of indeterminate type. Although the statistics are poor, particularly for the passive galaxies, there appears to be a strong correlation between the optical and the radio properties. With the exception of NGC 4552, all eight of the definitely active galaxies have optical emission lines in their

TABLE 1

SPECTRAL PROPERTIES OF ELLIPTICAL GALAXY NUCLEI

(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
NGC No.	Radio source type	Morphological type	Measured redshift uncorrected for galactic rotation (km/sec)	$m_{B(0)}$	$M_{B(0)}$	Clearly identified emission lines. "Blue" spectrogram	"Red" spectrogram	Notes
1052	Active	E4	1430	12.12	-19.3	No spectrum	4861 Hβ (<5,flaw) 4959 [OIII] 5007 [OIII] (4.8) 6563 Hα (5.3), 6584 [N II] (8.0), 6717 [SII] (5.0), 6731 [SII] (5.4)	(1)
2911	Active	SO	3032	13.82	-19.1	3727 [OII] (19.3), 4363 [OIII] (1.4) 4959 [OIII] (2.8), 5007 [OIII] (4.2)	No spectrum	(1)
4278	Active	E1-2	590	11.58	-19.4	3727 [OII] (18.8), 3869 [NeIII](14.6) 4861 Hβ (0.6), 5007 [OIII]	6563 Hα (2.2), 6584 [NII] (4.8) 6717 [SII] (3.2), 6731 [SII] (2.6)	(1)
4552	Active	EO	172	11.30	-19.8	No lines	No lines	(1)
5077	Active and Passive	E3-4	2787	12.66	-20.1	3727 [OII] (10.5), 5007 [OIII] (4.0)	6563 Hα (0.6), 6584 [NII] (1.1)	(1)
5444	Active	E1	3878	13.1	-20.5	3727 [OII] (3.8)	6300 [OI] (1.6), 6584 [NII] (1.6)	(1)
3998	Active and Passive (?)	SO	1173	11.79	-19.4	3727 [OII] (12.1), 4861 Hβ (1.2) 5007 [OIII] (1.8)	5007 [OIII] (1.8), 6563 Hα (9.3) 6584 [NII] (5.1), 6717 [SII] 6731 [SII] (4.2)	(2)
4486	Active and Passive	EO-1	1225	10.30	-20.8	3727 [OII] (11.0), 6584 [NII] (6.7), 6717 & 6731 [SII] blended (total=3.5)	No spectrum	(3)
3078	Active (?)	E2-3	2468	12.51	-19.8	No lines	No spectrum	(4)
4374	Passive	E1	1119	10.82	-19.9	No lines	No spectrum	(5)
4472	Passive	E2	926	9.84	-21.3	No lines	No lines	(5)
7626	Passive	E1	3613	12.90	-20.6	No lines	No spectrum	(5)

NOTES TO TABLE 1

1. Classified as active by Heeschen (1970*b*) on the basis of both radio structure and spectrum.
2. Heeschen (1970*a*) has measured a source of diameter less than 3″. Rogstad and Ekers (1969) report a radio spectrum characteristic of the active sources. It is therefore classified as active here. There is some disagreement over the 11-cm observations, but there may be a passive source present as well.

This galaxy appears to have an exceptionally bright nucleus at the telescope. Demoulin (1970) has taken a low-dispersion spectrogram in the blue, and she reports that the lines are sharply inclined, which would indicate rapid rotation and a massive nucleus.

The galaxy is unique within the sample in having an abnormally broad Hα line.

3. Well-known strong passive source swamps the radio spectrum. However, Hogg *et al.* (1969) have detected two small-diameter sources with 6 percent of the flux at 11 cm.
4. Radio structure unknown. Rogstad and Ekers (1969) report an active spectrum.
5. Classified passive by Heeschen (1970*b*) on the basis of both structure and spectrum.

nuclei, sometimes of considerable strength. In a fair sample of ellipticals only about 18 percent would be expected to show emission (Humason *et al.* 1956). Of the definitely passive nuclei none show significant emission. NGC 3078 has no emission lines—a result first reported by Demoulin (1970). It would be interesting to know what its radio structure is, but on the basis of the optical evidence we might expect it to contain an extended source.

NGC 4552 is the one active galaxy which does not exhibit emission lines, although two good spectra were obtained. Interestingly, this galaxy was shown by Tifft (1969) to have a nucleus which becomes abnormally red toward the center. Possibly its anomalous optical spectrum is therefore explained by obscuration around the nucleus which prevents us from seeing the line radiation.

Heeschen has suggested on the basis of the radio evidence that the active galaxies have miniature QSOs in their nuclei. In general the emission-line spectra do not support this contention. If these spectra are compared with those for QSOs of low redshift (e.g., Burbidge and Burbidge 1967), there appear to be significant differences. Except for NGC 3998, the strong, broad hydrogen lines characteristic of most QSOs are absent. Most of the emission lines are narrower than the absorption lines, and their profiles (which characteristically have a full width at half-maximum of 7–10 Å) are determined largely by the image spread in our image-tube spectrograph. Furthermore, the relative intensity of 5007 [O III] to 3727 [O II] appears to be significantly lower than in most QSOs or Seyfert galaxies and appears to be characteristic of planetary nebulae of excitation class 2 or so (Aller and Liller 1968).

In NGC 3998 the Hα line clearly has an extended, faint wing. The wing profile is confused, however, by the presence of [N II] λ6584, which is easily detected, and by [N II] λ6548, which is barely discernible above the wing and continuum radiation. If one assumes Gaussian profiles and corrects for the image spread in our spectrograph (as evidenced by the nightsky lines), the Hα wing has a full width at half-maximum of 36 Å, corresponding to a velocity of 1600 km sec^{-1}. A wing is not detected in Hβ, but this is presumably due to its weakness relative to the continuum.

It is difficult to calculate accurately the amount of energy in the lines because, unless the brightness distribution close to the nucleus is known, the strength of the continuum is undetermined. In the case of NGC 4278, however, Tifft (1970) has recently made a small-aperture area scan of the nucleus. Use of his scan and earlier photometry with a 36″ diaphragm (Tifft 1961) gives a value for the luminosity in the lines of this galaxy of about 4×10^{39} ergs sec^{-1}.

In making the above calculation we have assumed that all the line radiation of the galaxy arises within the region covered by our 1″.25 × 5″ slit. We also have assumed that the spectral distribution of the continuum in the nuclear region of NGC 4278 is the same as the mean of the nearby giant elliptical galaxies published by Oke and Sandage (1968). Microphotometer traces of our blue spectrograms indicate that this is indeed true. In fact, we find that the continuum distribution in nearly all[1] the galaxies in Table 1 is the same as that of the giant ellipticals, at least to within 0.2 mag over the region λλ3700–5000. It appears, therefore, that there is no strong ultraviolet excess in the active galaxies. This is consistent with the emission-line spectra in failing to show any clear QSO characteristics.

In agreement with earlier observations by Burbidge and Burbidge (1965), all the Hα/[N II] λ6584 ratios for the ellipticals are less than 1, but for NGC 3998, which is of type S0, the ratio is about 2. In view of the strong correlation between the occurrence of emission lines and the presence of a nonthermal source, the problem of whether the variation in this intensity ratio is an abundance effect may have to be reviewed.

We would like to thank D. S. Heeschen and R. D. Ekers for some of their results prior to publication, and W. G. Tifft and R. E. Williams for helpful discussions. We also wish to thank G. Muncaster for his assistance in reducing many of the data presented here.

REFERENCES

Aller, L. H., and Liller, W. 1968, in *Nebulae and Interstellar Matter*, ed. B. M. Middlehurst and L. H. Aller (Chicago: University of Chicago Press), chap. 9.
Burbidge, E. M., and Burbidge, G. R. 1965, *Ap. J.*, **142**, 634.
———. 1967, *Quasi-Stellar Objects* (San Francisco: W. H. Freeman & Co.), chap. 3.
Demoulin, M.-H. 1970, *Ap. J.* (*Letters*), **160**, L79.
Heeschen, D. S. 1968, *Ap. J.* (*Letters*), **151**, L135.
———. 1970*a*, *A.J.*, **75**, 523.
———. 1970*b*, *Ap. Letters*, **6**, 49.
Hogg, D. E., Macdonald, G. H., Conway, R. G., and Wade, C. M. 1969, *A.J.*, **74**, 1206.
Humason, M. L., Mayall, N. U., and Sandage, A. R. 1956, *A.J.*, **61**, 97.
Oke, J. B., and Sandage, A. 1968, *Ap. J.*, **154**, 21.
Rogstad, D. H., and Ekers, R. D. 1969, *Ap. J.*, **157**, 481.
Sandage, A. 1968, *Ap. J.* (*Letters*), **152**, L149.
Tifft, W. G. 1961, *A.J.*, **66**, 390.
———. 1969, *ibid.*, **74**, 354.
———. 1970, in *I.A.U. Symp. No. 44*, Uppsala, Sweden (in press).
Vaucouleurs, G. de, and Vaucouleurs, A. de. 1964, *A Reference Catalog of Bright Galaxies* (Austin: University of Texas Press).

[1] In the case of three of the active galaxies, for which we have obtained only a single "blue" spectrogram, the observed continuum distributions differ from the mean more than 0.2 mag. However, it seems likely that these particular observations are in error due to moonlight contamination (in the case of NGC 2911 and 5444, which appear bluer than the mean), differential refraction, and an unusually large zenith distance (in the case of NGC 3998, which appears redder than the mean).