THE ASTRONOMICAL JOURNAL VOLUME 104, NUMBER 2 AUGUST 1992

DOUBLE EMISSION-LINE SYSTEM IN THE RADIO GALAXY 0114+074S

C. E. AKUJOR[1,2]

Nuffield Radio Astronomy Laboratories, Jodrell Bank, United Kingdom and Onsala Space Observatory, S-439 92, Onsala, Sweden

N. JACKSON

Sterrewacht, Postbus 9513, 2300 RA Leiden, The Netherlands

Received 9 March 1992; revised 24 April 1992

ABSTRACT

We report the detection of a double-extended emission-line system in 0114+074S, an asymmetric radio galaxy whose redshift we find to be 0.344. This is one of the few radio galaxies where there is clear evidence of splitting in the nuclear narrow emission lines. The separation of the components in the narrow line is 400 km s^{-1}, and we suggest that this is due either to an intrinsic double nucleus or to expansion of the emitting material around a radio jet. A continuum knot is detected 2.5″–3″ from the central source and nearly coincident with a radio hotspot.

1. INTRODUCTION

It is becoming increasingly clear that the kind of radio and optical structures seen in Seyfert galaxies and radio galaxies are related to one another (Whittle 1989). In high redshift radio galaxies, coincidences between extended radio and optical emission are the rule (McCarthy *et al.* 1987). In low redshift radio galaxies, such coincidences are less frequent (Baum & Heckman 1989a, b) but a number of radio galaxies display evidence for interaction of radio jets and optical emission-line gas when examined by narrowband imaging.

It is of interest to map the velocity fields in these objects, since this provides information about the gas distribution and motion that may be sufficient to rule out simple models of the emitting line region. Additional information from lines of different ionization levels is necessary to distinguish between models in which the emission is produced by photoionization of static emission-line clouds by an ionizing continuum and models in which the gas is excited by a radio jet and photoionized by the central source as it cools.

0114+074 consists of a radio galaxy (0114+074S) 30″ from a redshift 0.861 quasar (0114+074N). Previous radio maps have been published of the field (Akujor 1987, 1989). In this paper we investigate the radio properties further, and publish new optical spectra of the two objects. We find a redshift of 0.344 for the galaxy 0114+074S, and investigate its [O III] emission-line structure.

2. OBSERVATIONS

2.1 Optical Observations

Observations were carried out using the William Herschel Telescope on the nights of 1990 August 16 and 1990 November 10 as part of the service observing program on the La Palma telescopes. The earlier observations were made with a 158 lines mm^{-1} grating and a 1.2″ slit, which gave a resolution of 9 Å, in good seeing (0.9″). An exposure of 1800 s was obtained at a slit position angle of 337°, along the line joining the galaxy and the quasar. The observations in November were of the galaxy only. They were made with a 600 lines mm^{-1} grating and consequently are of higher resolution (2.2 Å). Two integrations of 1000 s each were obtained at position angles of 82° and 352°, parallel and perpendicular to axis of the radio structure of the galaxy, using a 1.2″ slit.

Frames were debiased by subtracting a value derived from an unilluminated part of the chip. No flat fields were available, but from experience with this instrument, we are confident that errors introduced by the lack of flat fields will be much less than the photon noise. Cosmic rays of 3×3 pixels affected the spectra taken at 337° and 352°. The 352° cosmic ray affected the [O III] 5007 Å line and the 337° cosmic ray was slightly off the line. Both were dealt with by replacing data in the affected region by data from the unaffected frame taken at the same position angle.

2.2 Radio Observations

Radio continuum observations of 0114+074S were made with the VLA in A configuration on 1988 November 24 at 327 MHz for 30 min and at 1446 and 4866 MHz for 50 min each. The amplitudes and phases of the observed visibilities were calibrated using 3C48 (Baars *et al.* 1977) and the polarization was measured at 1446 and 4866 MHz using 0146+056 as a zero-polarization calibrator. The data were calibrated at the VLA, while the reduction was done on the Jodrell Bank Alliant computer using the AIPS package.

3. STRUCTURE OF THE SOURCES

3.1 Optical Properties of the Sources

Mg II, [Ne V], [O II], and Hγ are visible in the spectrum of the quasar 0114+074N (Fig. 1). We find a redshift of 0.858±0.003, in agreement with earlier results (Smith *et*

[1]Currently NFR fellow, Onsala Space Observatory, Onsala, Sweden.
[2]On leave from Univ. of Nigeria, Nsukka.

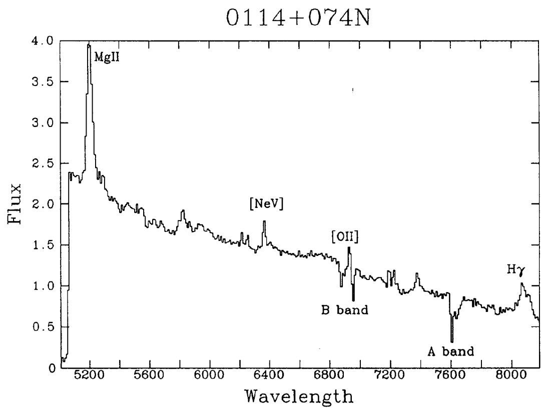

FIG. 1. Spectrum of the quasar 0114+074N.

al. 1977). The quasar also appears on the 408 MHz MERLIN map (Akujor 1989).

Figure 2 shows the spectrum of the Hβ and [O III] 4959, 5007 Å region in the radio galaxy, taken with the slit parallel to the radio jet (P.A. 82°). The sky has been collapsed in the spatial direction and subtracted from the frame (and from all subsequent frames presented), but no attempt has been made to flux calibrate the spectrum. Each spatial pixel represents 0.37″.

Three spectra are presented in Fig. 2, from west to east across the slit. A region of continuum emission is seen about 2.5″–3″ west of the nucleus. The [O III] line in the nucleus shows marginal evidence for splitting, and a region of narrower [O III] emission extends about 2 arcsec to the east.

Figure 3 shows spectra along a line perpendicular to the jet axis. There is clear evidence for splitting of the [O III] line into a strong blue component and a weaker red component. The components are separated by about 400 km s^{-1}. No extended continuum regions are visible along this line. Figure 4 shows the spectra taken along *P.A.* 337° at lower resolution. Again, the splitting is visible although here the lines are only just resolved.

3.2 Radio Structure of the Galaxy 0114+074S

Figures 5 and 6 show the radio structures at 1446 and 4866 MHz. The fractional polarization vectors are superposed on the 1446 and 4866 maps: they are not plotted in regions where the signal-to-noise in polarized flux is less than 3. The noise on the maps of polarized flux is 0.17 mJy at 1466 MHz and 0.11 mJy at 4866 MHz. The rms noises in the total intensity maps are 0.29 and 0.12 mJy at 1446 and 4866 MHz, respectively, corresponding to dynamic ranges of 2700 and 2400.

0114+074S is an asymmetric double source, as was seen in earlier maps made with the 5 km Ryle Telescope at Cambridge and with MERLIN (Akujor 1989). It is well resolved in the 5 GHz map (Fig. 6) showing a weak core of 2.8 mJy. The lobe and the hotspot of the west side of the source are brighter than those on the east side, and have a flatter spectral index. The west lobe has a spectral index [α, where $S(\nu) \propto \nu^{-\alpha}$] of 0.68 and the west hotspot 0.55, whereas the east lobe has a spectral index of 0.85 and the east hotspot 0.75.

There is significant asymmetry in the polarization characteristics of the two sides of the source. The electric field vectors are aligned perpendicular to the axis in the eastern lobe, but the pattern is rather complex in the western lobe. The percentage polarization (and the associated position angle) in the 5 GHz map convolved to the resolution of the 1.4 GHz map are 6% (30°) for the east side and 15% (−34°) for the west side. The corresponding values at 1.4 GHz are 1.3% (−5°) and 0.6% (−27°). The values of the

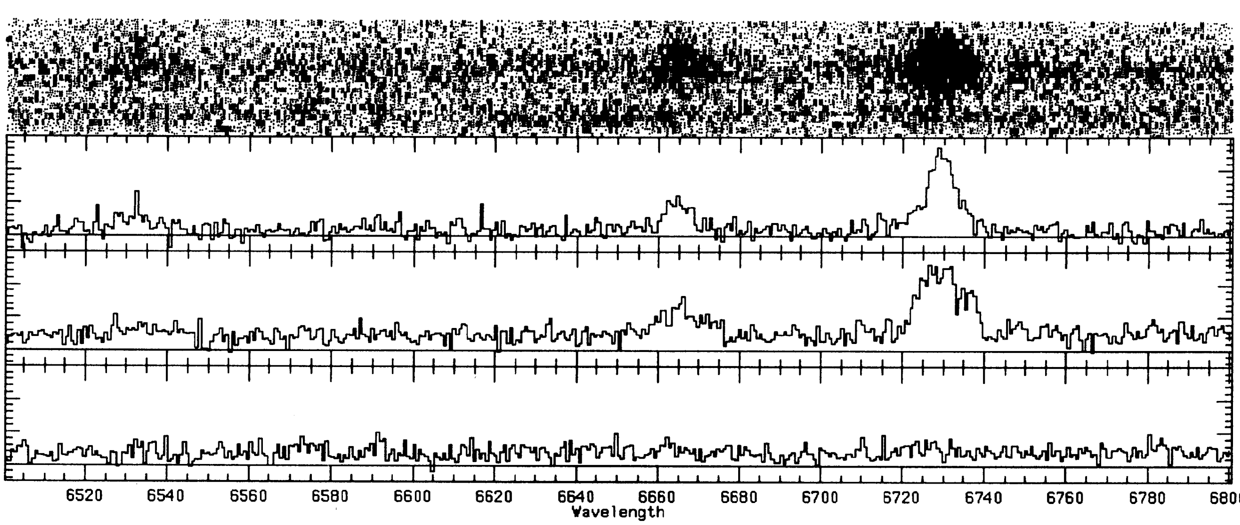

FIG. 2. (Top) Grey scale of the sky-subtracted CCD frame containing the spectrum of 0114+074S at a position angle of 82°. The spectral direction runs from left to right: east is at the top of the plot. Each row represents 0.37 arcsec in spatial extent. (Lower panels) Cuts across the spectrum at (bottom) the western 2″, (middle) the middle 2″, and (top) the easternmost 2″ of the region in the greyscale plot. Note the continuum region 3″(10 pixels) to the west of the nucleus. Note also the narrowing of the [O III] profile between the cut across the nucleus (middle spectrum) and the easterly extension. This narrow component may obscure the split-line effect of Figs. 3 and 4.

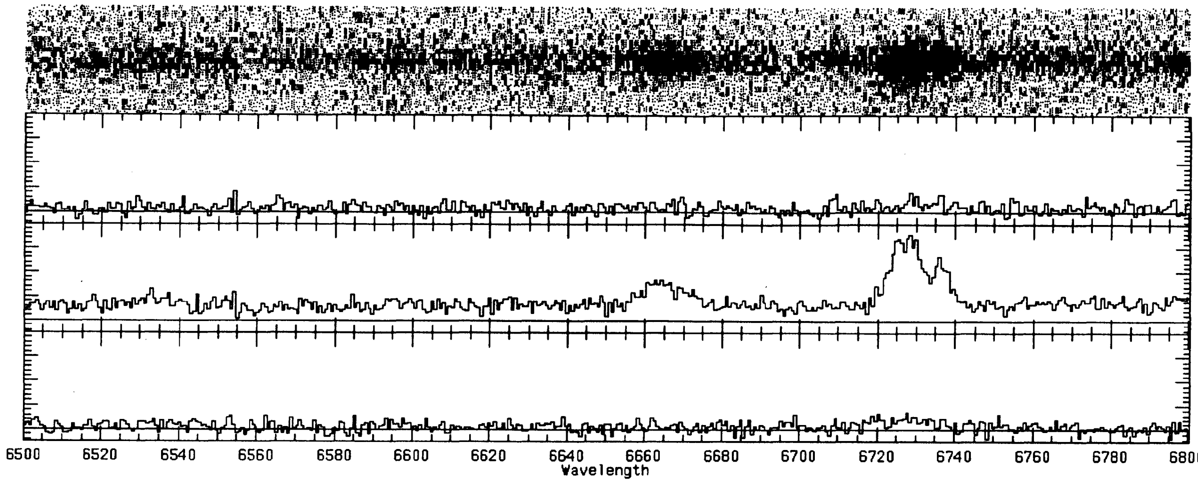

FIG. 3. Grey scale of the CCD frame containing the spectrum of 0114+074S at a position angle of 352°, together with spectral cuts across it as in Fig. 2. Note the lack of extended emission along this direction, and the clear splitting of the emission line (middle spectrum).

depolarization ratio (Garrington *et al.* 1988) of the east and west sides are, therefore, 0.21 and 0.04, respectively. Although both sides of the source exhibit strong overall depolarization at 1.4 GHz, there is less depolarization on the east side. The depolarization is stronger in the hotspots.

4. DISCUSSION

4.1 Line Splitting

Complex emission-line morphologies and velocity systems are quite common in 3C radio galaxies (Baum *et al.* 1990). Baum *et al.* also saw rotation curves offset from the systemic velocity. However, they saw only one possible example of emission-line splitting, along a filament in 3C 433. Moreover, wholescale splitting of the *nuclear* emission lines is rare. Only a few objects with such split [O III] lines are known, such as the Seyfert galaxies Mkn 78 (Pedlar *et al.* 1989) and NGC 5929 (Whittle *et al.* 1986), and the radio galaxies, 3C 159 (Tytler & Browne 1985) and 2010 +614 (Bartel *et al.* 1984). In both of the Seyferts, features in [O III] appear correlated with the radio structure. We do not have the resolution to say whether the splitting is along the radio structure direction.

Unresolved rotation could in principle produce the splitting. However, the splitting is rather larger than the velocities of the rotation curves in low redshift radio galaxies measured by Baum *et al.* (1990), who found velocities between 100 and 325 km s^{-1}. Moreover, the velocity of the rotating material would need to change by 400 km s^{-1} in less than 5 kpc over the slit ($H_0 = 75$ km s^{-1} Mpc^{-1}), and by comparison with the velocity profiles of Baum *et al.* (1990) it appears that such high gradients are rare.

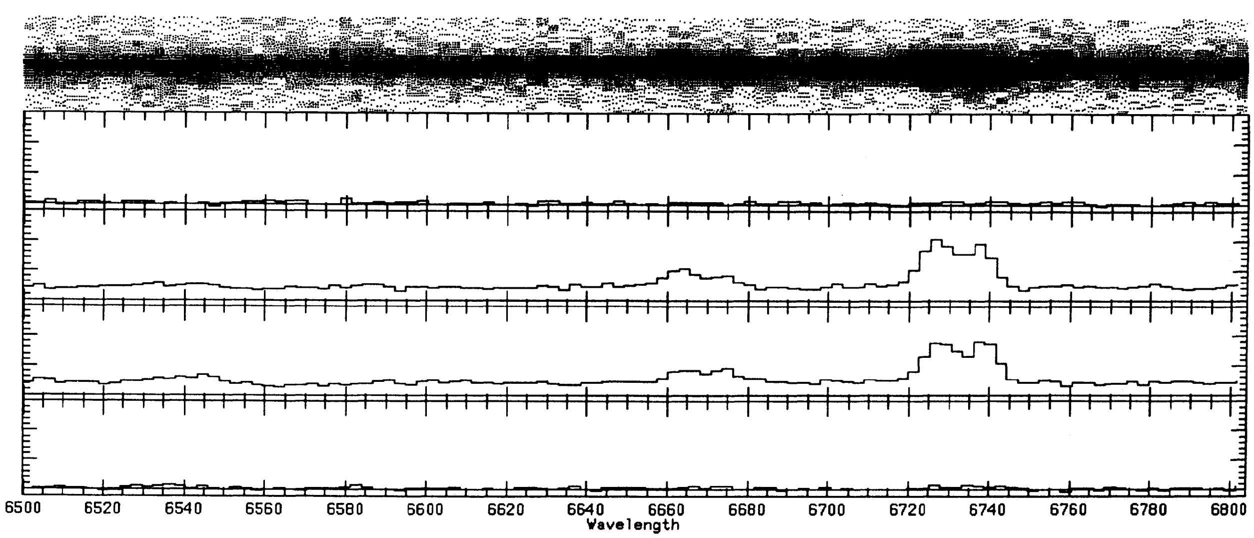

FIG. 4. Grey scale and cuts of the CCD frame containing the spectrum of 0114+074S at a position angle of 337° and lower resolution. Again note the [O III] line splitting.

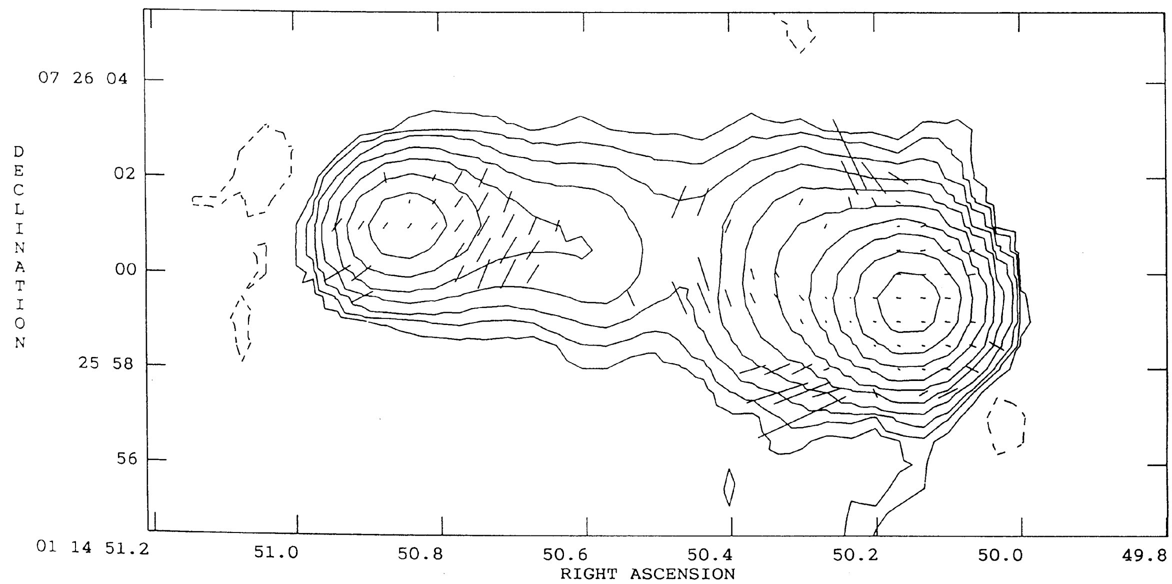

FIG. 5. VLA 1.2″ resolution radio map of 0114+074S at 1446 MHz. Contours are plotted at 1.0 mJy/beam ×(1,2,4,8,16,32,64,128,256). A 1″ vector represents 20% polarization.

This object evidently has a complex velocity field which is made more difficult to investigate by the small size of the line-emitting region. However, we can make some suggestions based on the observations of line splitting. One plausible interpretation (Pedlar *et al.* 1985) is that the radio jet shocks the ambient gas, and forms a cocoon of excited gas around itself which is then photoionized by the central source. Because of the velocity field of this expanding cylinder of gas, we see split narrow emission lines as the gas cools. This model can also be applied to the case of 0114+074, although here the splitting occurs in the whole of the nuclear line. The different strengths of the humps may be explained if the jet is interacting more strongly with the side of its surrounding cylinder that is oriented towards us. Alternatively, we may be seeing two narrow line regions corresponding to two separate active nuclei. Tytler & Browne (1985) made this suggestion in the case of 3C 159, the source most closely analogous to 0114+074S, and speculated that the double hotspot structure in one of the lobes of 3C159 might result from separate radio emission from the two nuclei. However, 0114+074S does not have double hotspot structure in either lobe. Higher-resolution optical imaging is necessary to resolve the question.

In addition to the split nuclear lines, there is also a region of [O III] emission that appears to extend somewhat to the *east* of the nucleus (Fig. 3) at a velocity intermediate between the two humps. This occupies the region between the radio core and the eastern hotspot.

4.2 Continuum Emission

The continuum emission 2.5″–3″ west of the nucleus (see Fig. 7) is just visible on the Palomar Sky Survey red

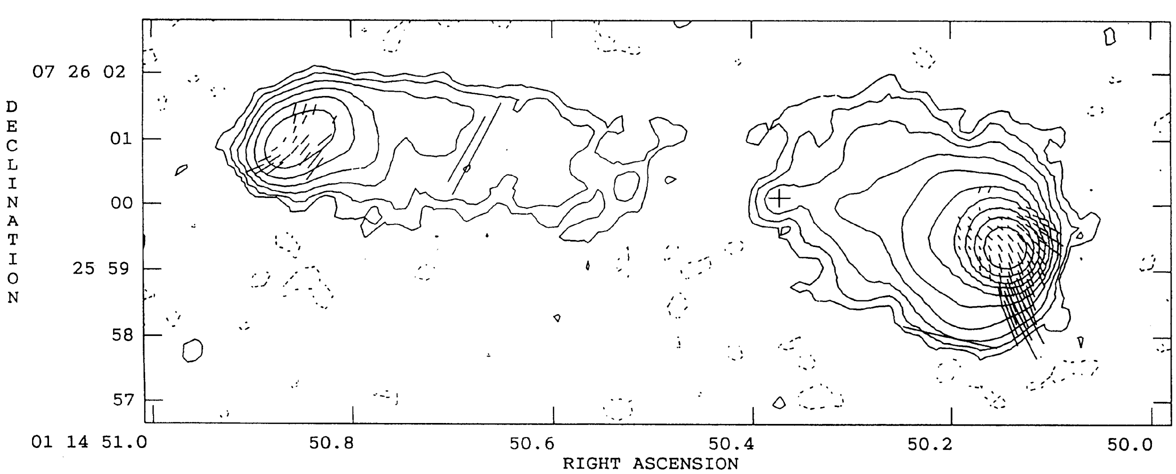

FIG. 6. VLA 0.4″ resolution radio map of 0114+074S at 4866 MHz. Contours are plotted at 0.0464 mJy×(1,2,4,8,16,32,64,128,282). A 0.1″ vector represents 67% polarization. A cross marks the position of the flat-spectrum core.

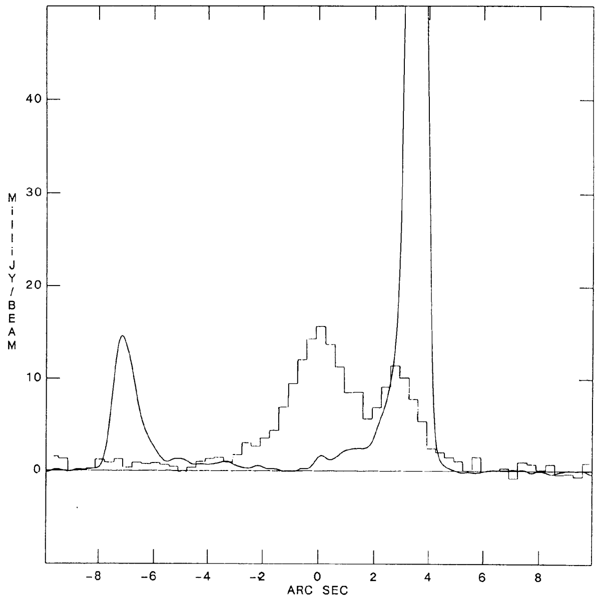

FIG. 7. Plot of slices taken along the radio axis of the optical continuum (steplike) and the radio brightness at 5 GHz (smooth curve). The nucleus is at the center and the vertical axis in mJy refers to the radio brightness.

plate, although not on the blue plate, and is almost equal in brightness to the total continuum emission from the central object. Over the 1000 Å of our spectrum it has approximately the same spectral slope as the nuclear continuum.

Extended continuum of this kind is common. In high redshift radio galaxies alignment of extended continuum with the radio axis (as is the case here) appears to be very common (McCarthy *et al.* 1987). However, at low redshifts ($\leqslant 0.5$) this tendency appears to be very weak (Baum & Heckman 1989a). It is therefore surprising that the optical extended emission should coincide with the radio lobe and there is no evidence of extended emission perpendicular to the radio axis. Coincidences between optical and radio emission in lobes have been seen in 3C 33 (Meisenheimer & Heavens 1986) and Pictor A (Roser & Meisenheimer 1987). In these objects the optical polarization properties of the extended emission indicate a synchrotron origin. A synchrotron model is not impossible here, but would require a rather flat ($\nu^{-0.6}$) overall spectral index between the optical and radio. Moreover, although the optical emission is coincident with the radio lobe, it does not have a peak that coincides with the terminal hotspot (Fig. 7). We note, also that 3C 273 has a synchrotron jet in which the optical peaks before that of the radio (Fraix-Burnet & Nieto 1988). However, optical polarimetry would be necessary to confirm this model.

The alternative explanations for this continuum emission are that it is light scattered from an obscured nucleus, or that it is due to star formation associated with a radio jet. We can argue against scattering by calculating the necessary brightness of the obscured nucleus. Denoting the distance of the scattered emission from the central source by D and its dimension by R, the ratio of scattered to incident light has an upper bound of R^2/D^2 times a geometrical factor not exceeding $3/16\pi$ (Rybicki & Lightman 1981; Eales & Rawlings 1990). Using $R<1''$ and $D=3''$ yields a lower limit on the obscured nucleus of 150 times the total luminosity of the scattered component. From our spectra, we estimate the total flux of the extended continuum as about a third of the total flux of the object, i.e., about 19th magnitude. The obscured nucleus, if viewed directly, would therefore be 12th magnitude or brighter: this is considerably brighter than 3C 273, the brightest low redshift quasar. We therefore regard scattering as unlikely as a production mechanism for the off-nuclear emission in this object. The redness of the extended continuum in 0114+074S suggests that it is not scattered nuclear light as seen in 2152-69 (Tadhunter *et al.* 1987).

Star formation models for the aligned optical continuum emission in high redshift radio galaxies are supported by evidence of stellar absorption visible in some systems (Chambers & McCarthy 1990) and possibly by the detailed shape of the spectrum (Chambers & Charlot 1990). The coincidence with the radio hotspot suggests that interaction may be taking place here.

5. CONCLUSION

We have found an unusual narrow emission line system in the redshift 0.344 radio galaxy 0114+074S. The emission lines are split, and the two velocity components are separated by 400 km s^{-1}. Other single components of [O III] emission are visible, particularly along the jet axis. A region of extended continuum is nearly coincident with the western radio hotspot. We suggest that this is due to an interaction taking place at this point, although optical polarimetry will be necessary to rule out optical synchrotron and scattering models.

The WHT is operated on the island of La Palma by the Royal Greenwich Observatory at the Spanish Observatorio del Roque de los Muchachos of the Instituto de Astrofisica de Canarias. The VLA is operated by Associated Universities, Inc., under contract with the National Science Foundation. We thank Drs. D. Carter and C. Tadhunter for carrying out the optical observations and P. Perley for calibrating the VLA data.

REFERENCES

Akujor, C. E. 1987, AJ, 94, 867
Akujor, C. E. 1989, AJ, 98, 1226
Baars, J. W. M., Genzel, R., Pauliny-Toth, I. I. K., & Witzel, A. 1977, A&A, 61, 99
Bartel, N., Shapiro, I. I., Huchura, J. P, & Kuhr, H. 1984, ApJ, 279, 112
Baum, S. A., Heckman, T., & van Breugel, W. 1990, ApJS, 74, 389
Baum, S. A., & Heckman, T. M. 1989a, ApJ, 336, 681
Baum, S. A., & Heckman, T. M. 1989b, ApJ, 336, 702

Chambers, K. C., & Charlot, S. 1990, ApJL, 348, L1
Chambers, K. C., & McCarthy, P. J. 1990, ApJL, 354, L9
di Serego Alighieri, S., Binette, L., Courvoisier, T. J. L., Fosbury, R. A. E., & Tadhunter, C. N. 1988, Nature, 334, 591
Eales, S. A., & Rawlings, S. 1990, MNRAS, 243, 1P
Fraix-Burnet, D., & Nieto, J.-L., 1988, A&A, 198, 87
Garrington, S. T., Leahy J. P., Conway, R. G., & Laing, R. A. 1988, Nature, 331, 147
McCarthy, P., van Breugel, W., Spinrad, H., & Djorgovski, S. 1987, ApJ, 321 L29
Meisenheimer, K., & Heavens, A. F. 1986, Nature, 323, 419
Pedlar, A., Dyson, J. E., & Unger, S. W. 1985, MNRAS, 214, 463
Pedlar, A., Meaburn, J., Axon, D. J., Unger, S. W., Whittle, M., Meurs, E. J. A., Guerrine, N., & Ward, M. J. 1989, MNRAS, 238, 363
Roser, H. -J., & Meisenheimer, K. 1987, ApJ, 314, 70
Rybicki, G. B., & Lightman, A. P. 1981, Radiative Processes in Astrophysics (Wiley, New York)
Smith, H. E., Burbidge, E. M., Baldwin, J. A., Tohline, J. E., Wampler, E. J., Hazard, C., & Murdoch, H. S. 1977, ApJ, 215, 427
Tadhunter, C. N., Fosbury, R. A. E., Binette, L., Danziger, I. J., & Robinson, A. 1987, Nature, 325, 504
Tytler, D., & Browne, I. W. A. 1985, AJ, 90, 1676
Whittle, M. 1989, in Extranuclear Activity in Galaxies, edited by R. A. E. Fosbury (ESO, Garching bei München), p. 199
Whittle, M., Haniff, C. A., Ward, M. J., Meurs, E. J. A., Pedlar, A., Unger, S. W., Axon, D. J., & Harrison, B. A. 1986, MNRAS, 222, 189