Mon. Not. R. astr. Soc. (1984) **208**, 955–959

Very extended ionized gas in radio galaxies – III. [O III] emission along the radio axis of PKS 0634 – 20

R. A. E. Fosbury *Royal Greenwich Observatory, Herstmonceux Castle, Hailsham, East Sussex BN27 1RP*

C. N. Tadhunter *Astronomy Centre, University of Sussex, Falmer, Brighton BN1 9QH*

J. Bland* *Anglo-Australian Observatory, PO Box 296, Epping, NSW 2121, Australia*

I. J. Danziger *European Southern Observatory, Karl-Schwarzschild Strasse-2, D-8046 Garching bei Munchen, Germany*

Received 1983 November 15; in original form 1983 August 8

Summary. Emission lines of [O III] extend at least 70 kpc along the radio axis of the giant radio galaxy PKS 0634 – 20. The non-nuclear emission shows a lower state of ionization than the nucleus. The velocity range covered by the gas is only 200 km s^{-1} and the line-widths outside the nucleus are 60 km s^{-1} (FWHM).

1 Introduction

Papers I and II in this series (Fosbury *et al.* 1982; Danziger *et al.* 1984) discussed the extended distributions of ionized gas around the radio galaxies PKS 2158 – 380 and PKS 0349 – 27. Here we report the discovery of [O III] λλ 5007, 4959 emission extending a total projected distance of 70 kpc (H_0 = 50 km s^{-1} Mpc^{-1} used throughout) along the radio axis of the giant radio galaxy PKS 0634 – 20.

Spectrophotometry of the nucleus of PKS 0634 – 20 (z = 0.056) has been published by Danziger, Goss & Frater (1978) and shows a continuum arising from a late-type stellar population typical of elliptical galaxies. There is, in addition, a strong, narrow emission-line spectrum of high ionization [$I(5007 + 4959)/I(\mathrm{H}\beta) \simeq 17$, although the actual ratio may be slightly smaller than this after correction for underlying Hβ absorption]. Danziger *et al.* (1978) also present a 1415-MHz radio continuum map, with a half-power beamwidth of 50 arcsec, which shows the source to be a giant double with a linear extent of at least 1.3 Mpc. A subsequent 5-GHz observation with the Very Large Array (Ekers *et al.*, in preparation) detected a 12-mJy source, coincident with the optical nucleus of the galaxy and with an angular size of less than 0.4 arcsec (FWHM).

2 Observations

The 25-cm camera of the RGO spectrograph on the Anglo-Australian Telescope was used with the IPCS detector on a partially cloudy night during 1982 November to obtain two

*On leave from Royal Greenwich Observatory and Astronomy Centre, University of Sussex.

long-slit spectra of PKS 0634 – 20 with a total integration time of 2550 s. The dispersion was 66 Å mm^{-1} and the wavelength range covered was 4500–6300 Å. The slit width of 1.5 arcsec on the sky resulted in a spectral resolution of 3 Å (FWHM). There were 90 spatial increments along the slit, each of width 2.4 arcsec (which corresponds to 3.9 kpc at the distance of the galaxy). The position angle of the slit on the sky was 178°, that of the major axis of the radio source measured from the 1415-MHz radio map. A greyscale representation of the calibrated and sky-subtracted data is given in Plate 1.

An examination of the ESO/SERC IIIaJ sky survey shows a faint patch of light about 22 arcsec to the north of the galaxy which coincides in position with the brightest extra-nuclear emission visible on Plate 1. The image of the galaxy itself is peculiar, with evidence of filamentary structure extending particularly into the NW quadrant and also, to a lesser extent, to the south where it again corresponds in scale to the southern [O III] emission.

3 Results and discussion

Due to the non-photometric conditions during the observations, we have had to derive our absolute flux scale from the nuclear Hβ flux measured by Danziger *et al.* (1978). They quote $F(\mathrm{H}\beta) = 1.4 \times 10^{-15}$ erg cm^{-2} s^{-1} for an aperture of 4 arcsec (EW) × 2 arcsec (NS) with no correction for underlying Hβ absorption. If we calibrate our data by comparison with a standard star observed on the previous (clear) night with an identical instrumental configuration, we derive a value of 9.5×10^{-16} erg cm^{-2} s^{-1} in an aperture of similar area but different shape. This implies an average transparency of about 68 per cent for our observation, which appears reasonable for the prevailing conditions. Consequently, all of our flux measurements

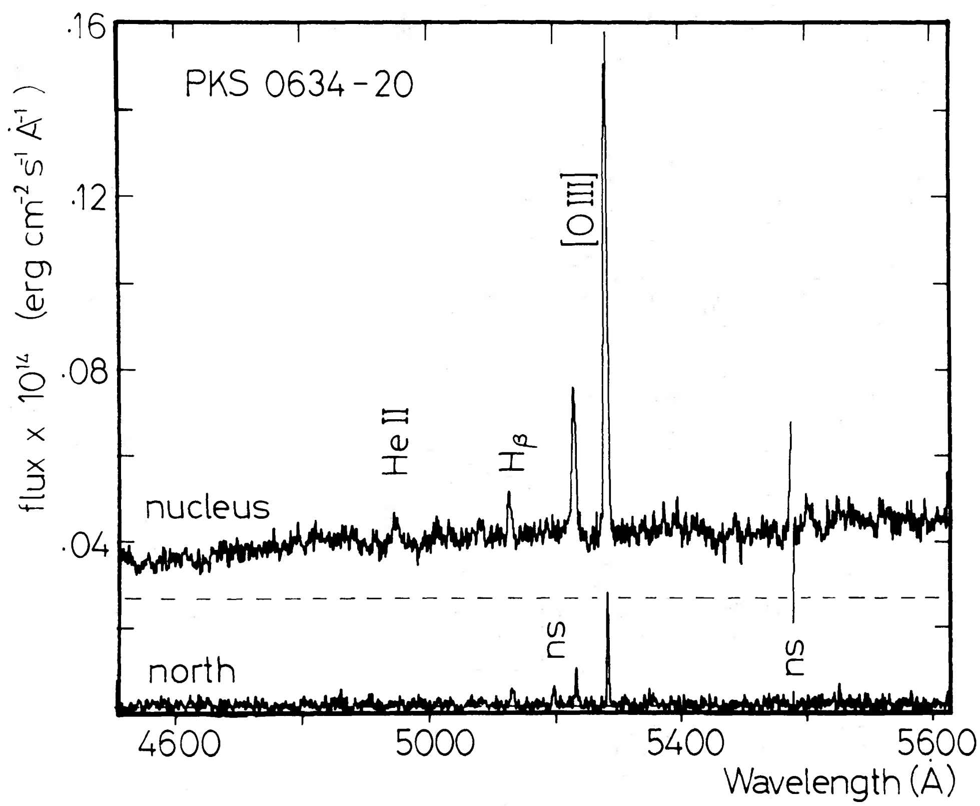

Figure 1. Spectra of the nucleus (1.5 × 4.8 arcsec^2) and of the brightest emission region to the north of the galaxy (1.5 × 7.2 arcsec^2). The flux scale has been corrected for the non-photometric conditions as described in the text. Zero levels for the two spectra are shown by dashed lines.

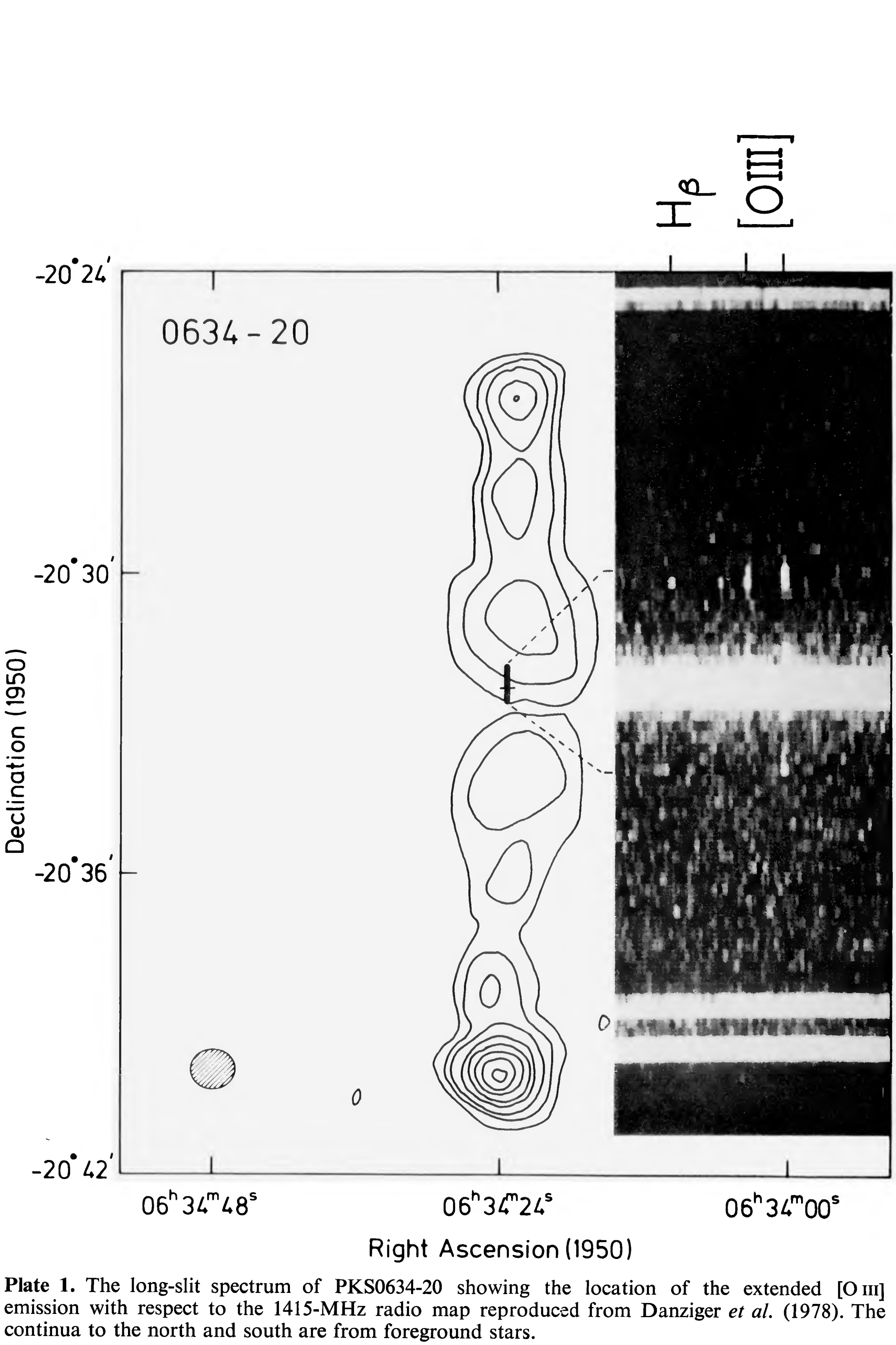

Plate 1. The long-slit spectrum of PKS0634-20 showing the location of the extended [O III] emission with respect to the 1415-MHz radio map reproduced from Danziger *et al.* (1978). The continua to the north and south are from foreground stars.

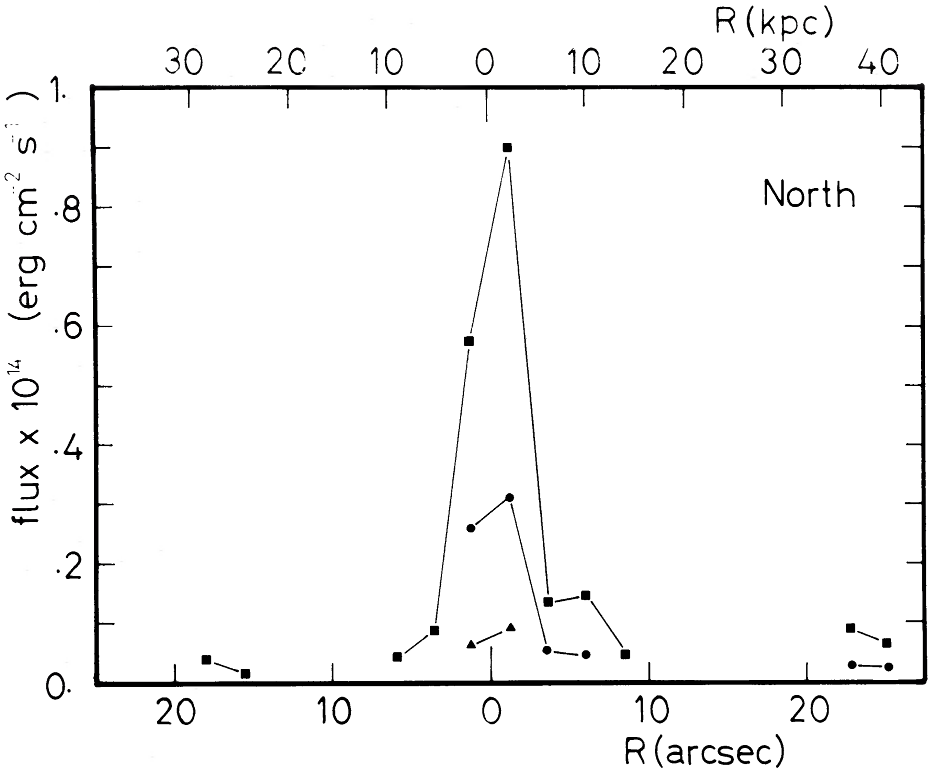

Figure 2. The distribution of line flux along the slit for [O III] λλ 5007, 4959 (■, ●) and Hβ (▲). The scale in kiloparsecs is for $H_0 = 50\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$.

are corrected by this factor. Spectra of the nucleus and the bright northern cloud are shown in Fig. 1 on the corrected flux scale. The flux measurements for the [O III] and Hβ lines in the individual spatial increments are plotted in Fig. 2. The total [O III] λ 5007 + 4959 flux is $2.9 \times 10^{-14}\,\mathrm{erg\,cm^{-2}\,s^{-1}}$, which gives a lower limit on the rest-frame luminosity in these lines of $4.2 \times 10^{41}\,\mathrm{erg\,s^{-1}}$.

Emission-line wavelengths and widths have been measured for all positions where the detections have sufficient S/N ratios. Errors in these quantities have been derived from measurements of nearby, weak night-sky emission lines in each individual spatial increment. The rms error for a single radial velocity measurement is $24\,\mathrm{km\,s^{-1}}$. The heliocentric radial velocities (*cz*) from all the line measurements are plotted in Fig. 3.

The line-widths (FWHM), quadratically corrected for instrumental broadening, range from 300–400 $\mathrm{km\,s^{-1}}$ in the region within ~7 kpc from the nucleus. At larger distances, the lines are only marginally resolved which implies that their widths are ~ 60 $\mathrm{km\,s^{-1}}$. The estimated errors in quadratically corrected FWHM are ~ ± 8 $\mathrm{km\,s^{-1}}$ for the broad nuclear and $\sim^{+15}_{-30}\,\mathrm{km\,s^{-1}}$ for the narrow extended emission lines.

The brightest region to the north has $I(5007 + 4959)/I(\mathrm{H}\beta) \sim 4.5^{+5}_{-2}$ which indicates a lower ionization state than that found in the nucleus, and lower also than that found around the galaxies discussed in papers I and II. The emission spectra of these objects are all well-fitted by photoionization models with power-law spectra extending at least as far as the soft X-ray region. In this case, however, our observations were not sufficiently sensitive to detect important diagnostic lines, e.g. He II λ4686, which would allow a clearer discrimination between ionization mechanisms. We cannot therefore rule out the possibility that the northern emission represents a companion H II galaxy.

The rather low total velocity range of just over 200 $\mathrm{km\,s^{-1}}$ exhibited by the extended gas

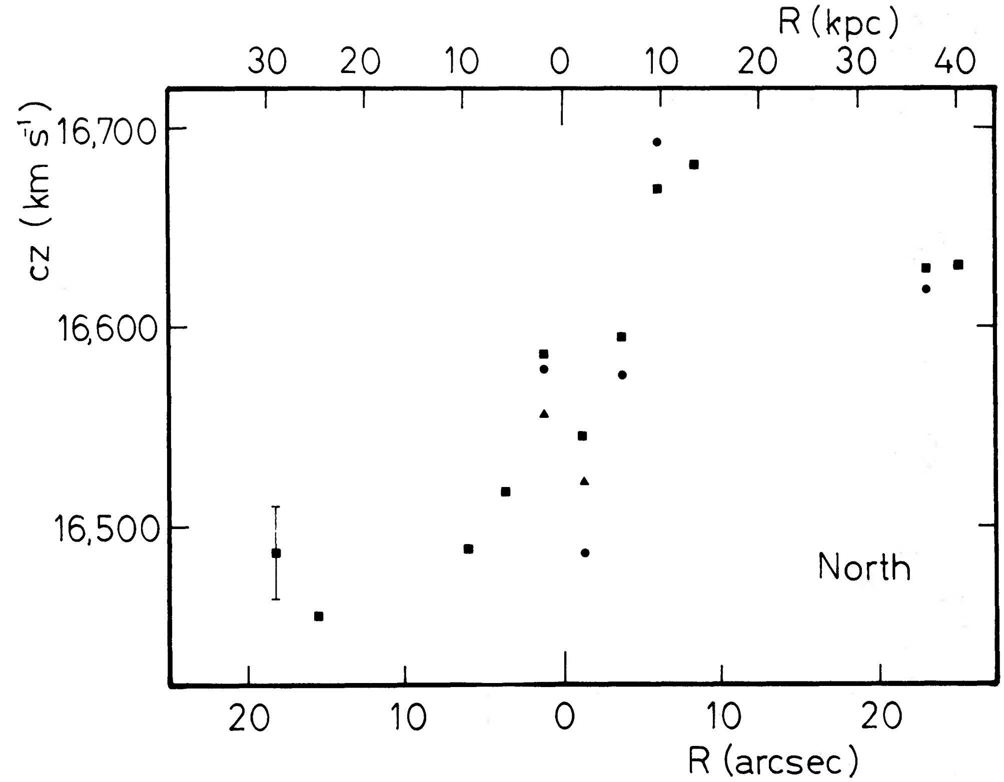

Figure 3. Heliocentric emission-line velocities. The error bar represents the rms from measurements of nearby night-sky lines. We estimate any systematic error to be $\lesssim 10\,\mathrm{km\,s^{-1}}$. Symbols are the same as in Fig. 3.

suggests, but does not prove, that the motions are gravitational in origin, either free infall, rotation or a combination of both. Ejection of gas by the galaxy, perhaps along the beams supplying the extended radio source, is a possible alternative interpretation, as considerably larger velocities could be present but disguised by projection effects.

4 Conclusions

PKS 0634 − 20 is one of a number of radio ellipticals with strong, narrow emission lines which, when examined with an appropriate observational technique, reveal emission from regions some tens of kiloparsecs from the nucleus. Although the statistics are poor as yet, it may be that extensions of this size are common amongst the strong emission-line radio galaxies. This would be in contrast with the spiral Seyfert galaxies where the narrow-line region is typically a few hundred parsecs across. The great differences in the amount and distribution of the interstellar medium in spirals and ellipticals might indeed lead to the expectation that the influence of the nuclear activity would be felt to larger distances in the latter objects: we already know this to be the case for the radio sources. Although the integrated emission-line luminosity is much lower, the closest example of this phenomenon may be the radio galaxy Centaurus A where high-ionization filaments extending along the radio axis have been known for some years (Peterson, Dickens & Cannon 1975; Osmer 1978; Graham & Price 1981; Graham 1983).

In none of the cases is the ionization mechanism for the extended emission clearly established although, in paper I, Fosbury *et al.* have argued that there is sufficient nuclear ultraviolet luminosity to supply the emission lines, provided that a large fraction of the nuclear sky is covered by optically thick clouds. Since the nuclear spectra almost certainly arise from photionization by a non-thermal source and the extended emission usually has a high state of ionization, it is natural to propose that the same mechanism accounts for both. For the larger objects, however, locating the ionizing source at the nucleus can result in such severe geometrical difficulties (e.g. paper II) that it may be necessary to invoke either an extended source of ionization or an anisotropically radiating nuclear source.

Acknowledgments

JB and RAEF thank PATT for the allocation of time on the AAT. We thank Miller Goss and Bob Frater for permission to reproduce their radio map as part of Plate 1. JB and CNT acknowledge support by the SERC in the form of research studentships.

References

Danziger, I. J., Fosbury, R. A. E., Goss, W. M., Bland, J. & Boksenberg, A., 1984. *Mon. Not. R. astr. Soc.,* **208,** 589.

Danziger, I. J., Goss, W. M. & Frater, R. H., 1978. *Mon. Not. R. astr. Soc.,* **184,** 341.

Fosbury, R. A. E., Boksenberg, A., Snijders, M. A. J., Danziger, I. J., Disney, M. J., Goss, W. M., Penston, M. V., Wamsteker, W., Wellington, K. J. & Wilson, A. S., 1982. *Mon. Not. R. astr. Soc.,* **201,** 991.

Graham, J. A., 1983. *Astrophys. J.,* **269,** 440.

Graham, J. A. & Price, R. M., 1981. *Astrophys. J.,* **247,** 813.

Osmer, P. S., 1978. *Astrophys. J.,* **226,** L79.

Peterson, B. A., Dickens, R. J. & Cannon, R. D., 1975. *Proc. astr. Soc. Aust.,* **2,** (6), 336.