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PKS 0400 – 181: a classical radio double from a spiral galaxy?

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Summary. The radio source PKS 0400 – 181 has a classical edge-brightened double-lobe structure, similar to that of Cygnus A. No radio core has been detected, but the radio centroid is located just 2.8 arcsec from the centre of a 16th mag spiral galaxy. CCD observations reveal the presence of a very red and slightly extended (2.5 × 1.3 arcsec^2) object superimposed on the image of the spiral and 1.5 arcsec from the radio centroid. The properties of this red object and of the radio source are consistent with a powerful radio galaxy at a redshift of ≈ 0.5; the spiral galaxy is probably a foreground object located by chance along the line-of-sight.

1 Introduction

The radio source PKS 0400 – 181 is catalogued in the eleventh part of the Parkes 2700-MHz survey (Wall, Wright & Bolton 1976). Savage & Wall (1976) identified it with a 16th mag spiral galaxy. It was included in a large sample of radio galaxies which we selected to study radio, infrared and optical properties, and in the course of the study was found to have the classical double-lobe structure typical of giant radio galaxies (Plate 1). This came as a

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surprise, because large double-lobed radio sources have invariably been found associated with elliptical galaxies (or quasars), rather than with normal spiral galaxies (Burbidge 1976; Hine & Longair 1979; Ekers 1981). Radio emission associated with spiral galaxies is usually confined within the optical disc, and often within the nuclear region itself (Hummel 1981; Condon *et al.* 1982). Double radio structure is sometimes seen in Seyfert galaxies, but again in these cases the radio emission is confined within the central bulge of the galaxy (Argue, Riley & Pooley 1978; Wilson & Willis 1980; Ulvested, Wilson & Sramek 1981; Wilson 1982).

Any exception to the above picture would clearly be of great interest and improved data were therefore obtained on PKS 0400 – 181 at several wavelengths. CCD observations finally revealed a highly reddened object located 2 arcsec from the centre of the spiral – a plausible candidate for a background elliptical galaxy which may be the correct identification for the radio source. In the following sections we present the observational data on the radio source, the spiral galaxy and the red object; we then discuss the optical identification of the radio source.

2 The radio source

Following the original short VLA observations of the complete sample made in 1979 September (Ekers *et al.* in preparation), further VLA observations of PKS 0400 – 181 were made at 1.4 and 4.9 GHz in 1981 January and May; these are summarized in Table 1. The A-array observations were made in order to search for a nuclear component and to resolve the radio lobes, and the B-array observations to map the more extended structure. Standard VLA calibration and reduction procedures were used. The lobes of PKS 0400 – 181 are

Table 1. Log of VLA observations.

Date	1981 Jan. 11	1981 Jan. 11	1981 May 19
Array	A	A	B
Baseline (km)	0.8–34.4	0.8–34.4	0.2–11.1
Frequency (GHz)	4.885	1.446	1.465
Primary beam HPBW (arcmin)	9	30	30
Bandwidth (MHz)	50	12.5	50
Integration time (hr)	3	1	1
Resolution (arcsec)	0.6	2.0	6.0

≈ 35 arcsec from the field centre. At that distance, attenuation due to the primary beam response and bandwidth smearing is negligible except for the 0.6-arcsec resolution 5-GHz observations where the bandwidth smearing increases the synthesized beamwidth in the radial direction by 8 per cent and reduces the response to a point source by ≈ 8 per cent. Bad seeing can also reduce the point source response, by as much as 10–15 per cent at 5 GHz. These effects are less serious for extended structure. Of greater importance is the fact that large structure is resolved out with these large interferometer spacings; the A-array is only sensitive to structures less than 11 and 38 arcsec at 4.9 and 1.4 GHz respectively, although the B-array at 1.4 GHz is sensitive to structures as large as 2 arcmin.

The resulting 'cleaned' maps are shown in Figs 1 and 2. Owing to the missing short spacings, only half of the flux is represented in Fig 1(a) and (b). Nevertheless the major structural properties of the source are clear from these figures. It is 69 arcsec in length and highly edge-brightened, with 'hotspots' in both lobes, as shown in Fig. 1(a) and enlarged in Fig. 2, with tails diminishing from both lobes back towards the centre, as shown in Fig. 1(c). There is extended emission on the west side of the south-east lobe and an arc-like structure

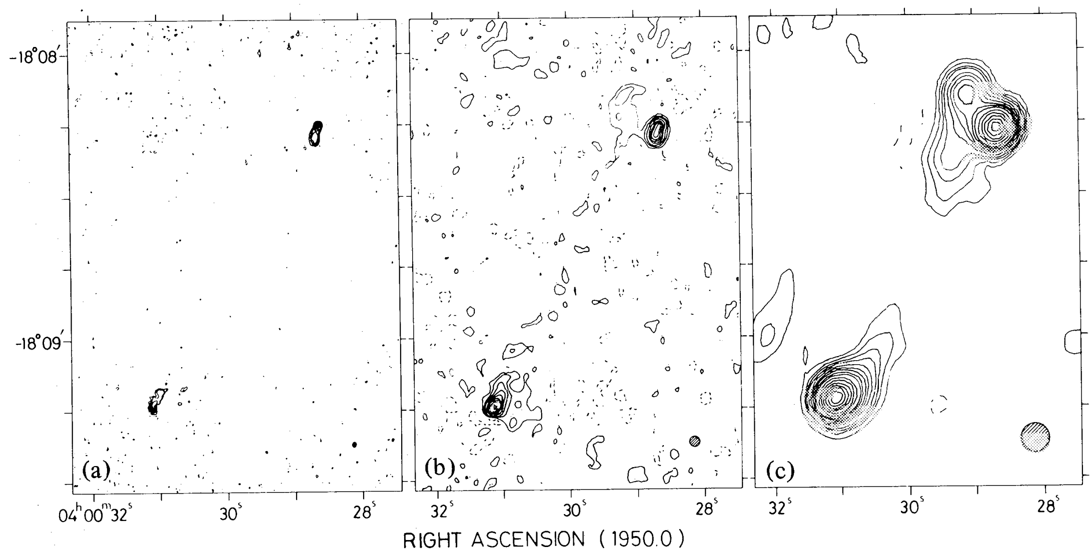

Figure 1. Total intensity contour maps of the radio source PKS 0400 – 181. The half-power beamwidth is indicated by the cross-hatched circle in the lower right-hand corner of each map. (a) 4.9-GHz map of resolution 0.6 arcsec (FWHM); contours are – 3, 3, 5, 10, 20, . . . , 90 per cent of 10.4 mJy per beam area. (b) 1.4-GHz map of resolution 2.0 arcsec (FWHM); contours are – 2, 2, 5, 10, 20, . . . , 90 per cent of 36.0 mJy per beam area. (c) 1.4-GHz map of resolution 6.0 arcsec (FWHM); contours are – 2, 2, 4, 6, 8, 12, 16, 20, 25, 30, 40, . . . , 90 per cent of 106 mJy per beam area.

to the east of the north-west lobe (Fig. 1b and c). The northern lobe is slightly stronger, by ≈15 per cent. No central core source was detected, to a level of 0.6 mJy at 1.4 GHz and 0.3 mJy at 4.9 GHz.

Total flux densities for PKS 0400 – 181 are listed in Table 2. The measurement at 0.61 GHz was made in a short observation with the Westerbork synthesis radio telescope.

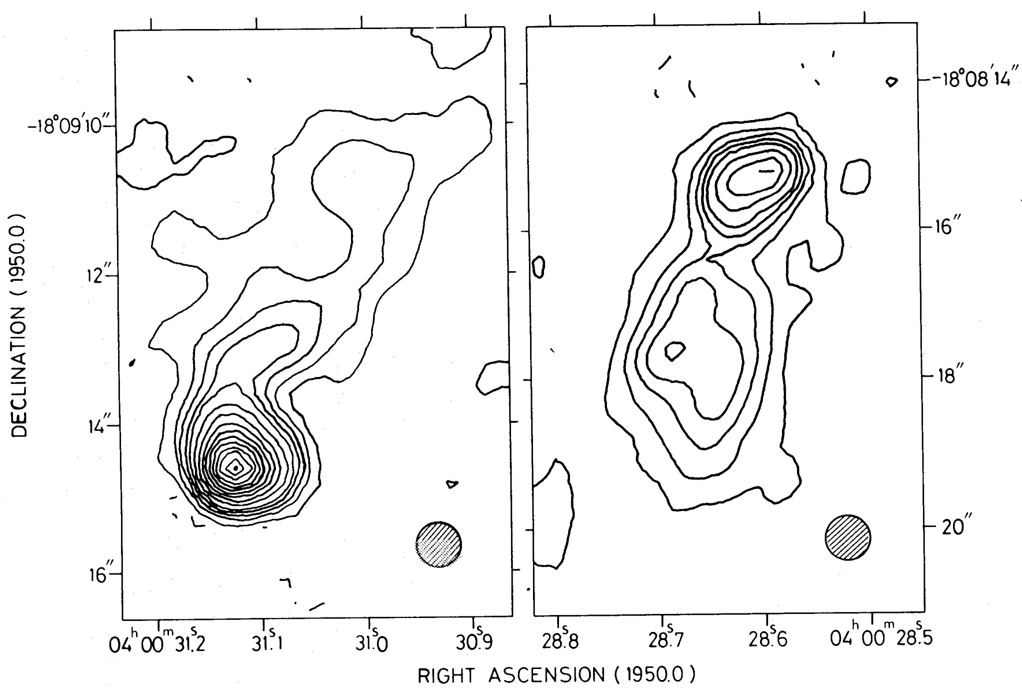

Figure 2. 4.9-GHz contour maps of the lobes of PKS 0400 – 181. The beam (cross-hatched circle) is 0.6 arcsec FWHM, and the contours are – 2, 2, 6, 10, 14, 18, 26, 34, . . . , 98 per cent of 10.4 mJy per beam area.

Table 2. Integrated flux densities of PKS 0400 – 181.

ν (GHz)	S_ν (mJy)	Reference
0.16	2000 ± 500	Slee (private communication)
0.41	970 ± 40	Large *et al.* (1981)
0.61	710 ± 75	Present work
1.65	330 ± 20	Porcas (private communication)
2.70	350 ± 25	Parkes catalogue
5.00	130 ± 20	Parkes catalogue

Aside from the value at 2.7 GHz, which appears to be anomalously high, these flux densities are all consistent with a power-law spectrum with spectral index $\alpha = -0.79$.

Centroid positions for the radio source are given in Table 3. These refer to the mid-point between (a) the two lobes as observed in the original low-resolution VLA observations (HPBW 10×16 arcsec^2) and (b) the hotspots shown in Fig. 2. These two positions agree to within 1 arcsec.

Table 3. Positions.

	(1950) α (h	m	s)	δ (°	′	″)
Radio centroid						
(a) From low-resolution data	04	00	29.93 ± 0.07	– 18	08	44.8 ± 1.0
(b) From hotspots	04	00	29.86 ± 0.03	– 18	08	44.9 ± 0.4
Spiral galaxy						
(a) From ESO/SRC Survey	04	00	29.95 ± 0.06	– 18	08	41.6 ± 0.8
(b) From CCD data	04	00	29.80 ± 0.11	– 18	08	42.6 ± 1.0
The red object	04	00	29.80 ± 0.11	– 18	08	44.2 ± 1.0

3 The spiral galaxy

3.1 DIRECT PHOTOGRAPHY

A 1-hr exposure was made on a IIIa-J plate with a GG 385 filter using the triplet adaptor at the prime focus of the ESO 3.6-m telescope at La Silla. This photograph is shown in Plate 1, with a radio contour map superimposed. The galaxy appears to be a barred spiral inclined at about 60° to the plane of the sky, with arms that form a fairly complete ring about the bar. There is no obvious nucleus.

CCD observations were made at the prime focus of the Anglo-Australian telescope in 1981 September, using a CCD camera built at the Royal Greenwich Observatory. The camera is based on the RCA SID 53612 chip, thinned, back-illuminated, 320×512 pixels, field 2.6×4 arcmin^2. Images of the galaxy from 10-min exposures in V, R and I are shown in both contour and grey-scale representations in Plate 2. Conditions were photometric, and seeing was ~ 1 arcsec FWHM. A red object shows up clearly in the R and I images, 2 arcsec south of the centre of the spiral; it will be discussed in Section 4. Knots indicating individual H II regions are evident along the northern arm, indicating the late-type nature of the spiral galaxy. Integrated magnitudes are given in Table 4. Typical colours for spiral galaxies are $V-R \approx 0.9$ and $R-I \approx 0.7$ (Butcher & Oemler 1978; Burkhead & Hutter 1981; Guidoni, Messi & Natali 1981); the CCD observations suggest that this galaxy is somewhat bluer in $V-R$ and close to normal in $R-I$ (0.5 and 0.6 respectively, corrected for galactic and K reddening), although the differences are of little significance.

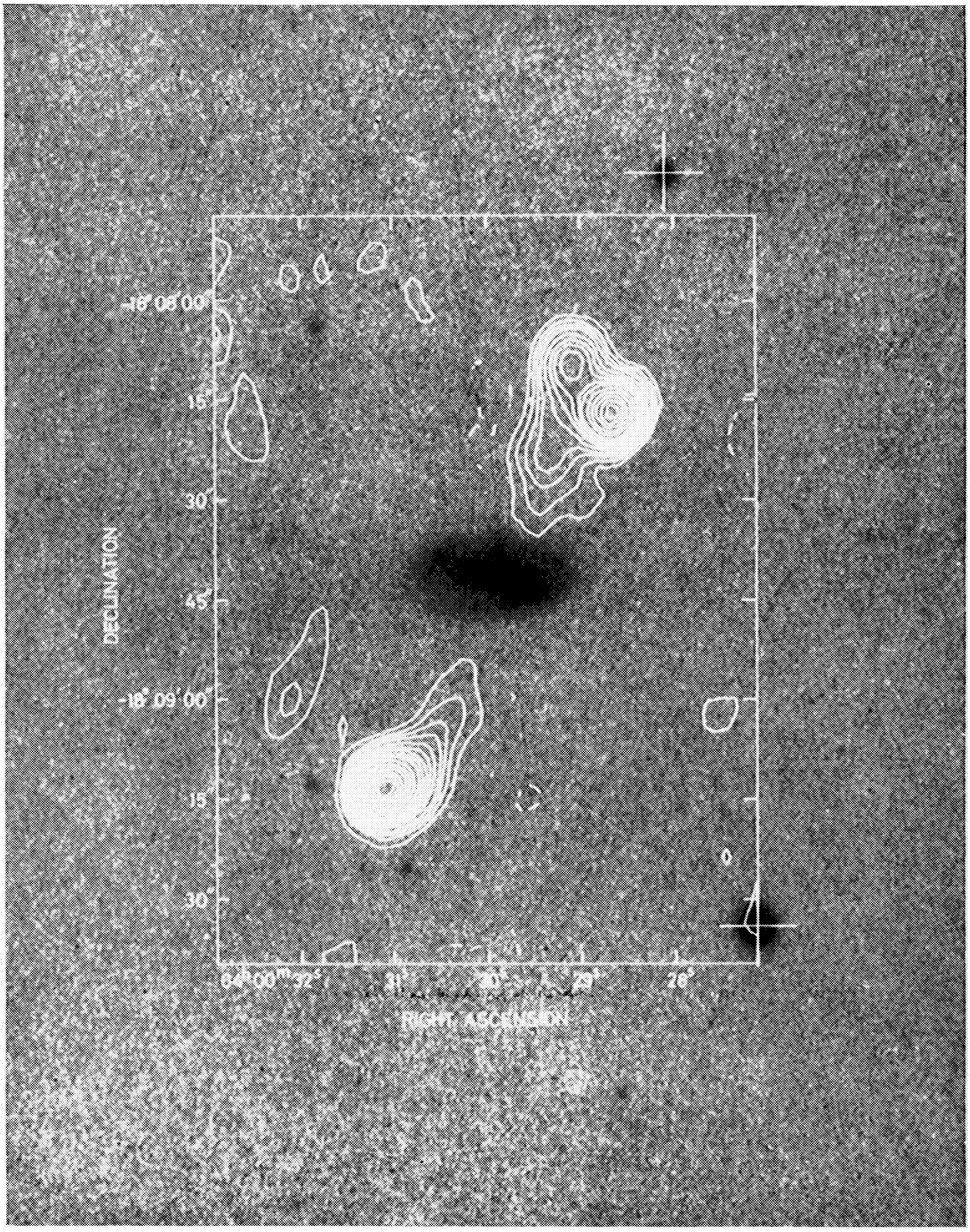

Plate 1. 1.4-GHz contour map of PKS 0400−181 (Fig. 1c) superimposed on a IIIa-J *B* photograph of the field.

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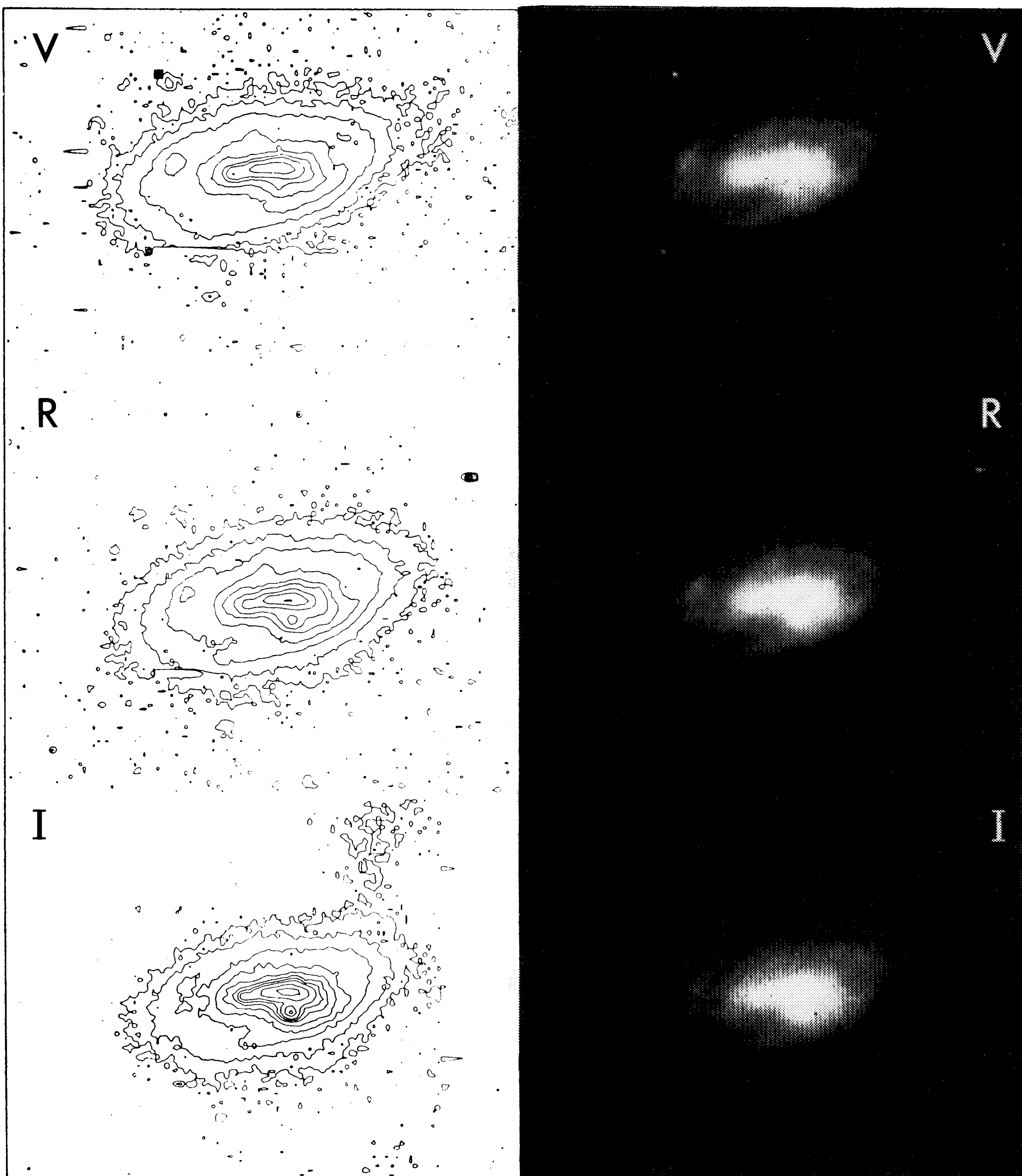

Plate 2. CCD V, R and I contour maps (left) and images (right) of the spiral galaxy and the red object. Exposure times at the AAT prime focus were 600 s, in photometric conditions. North-east is at the top left corner.

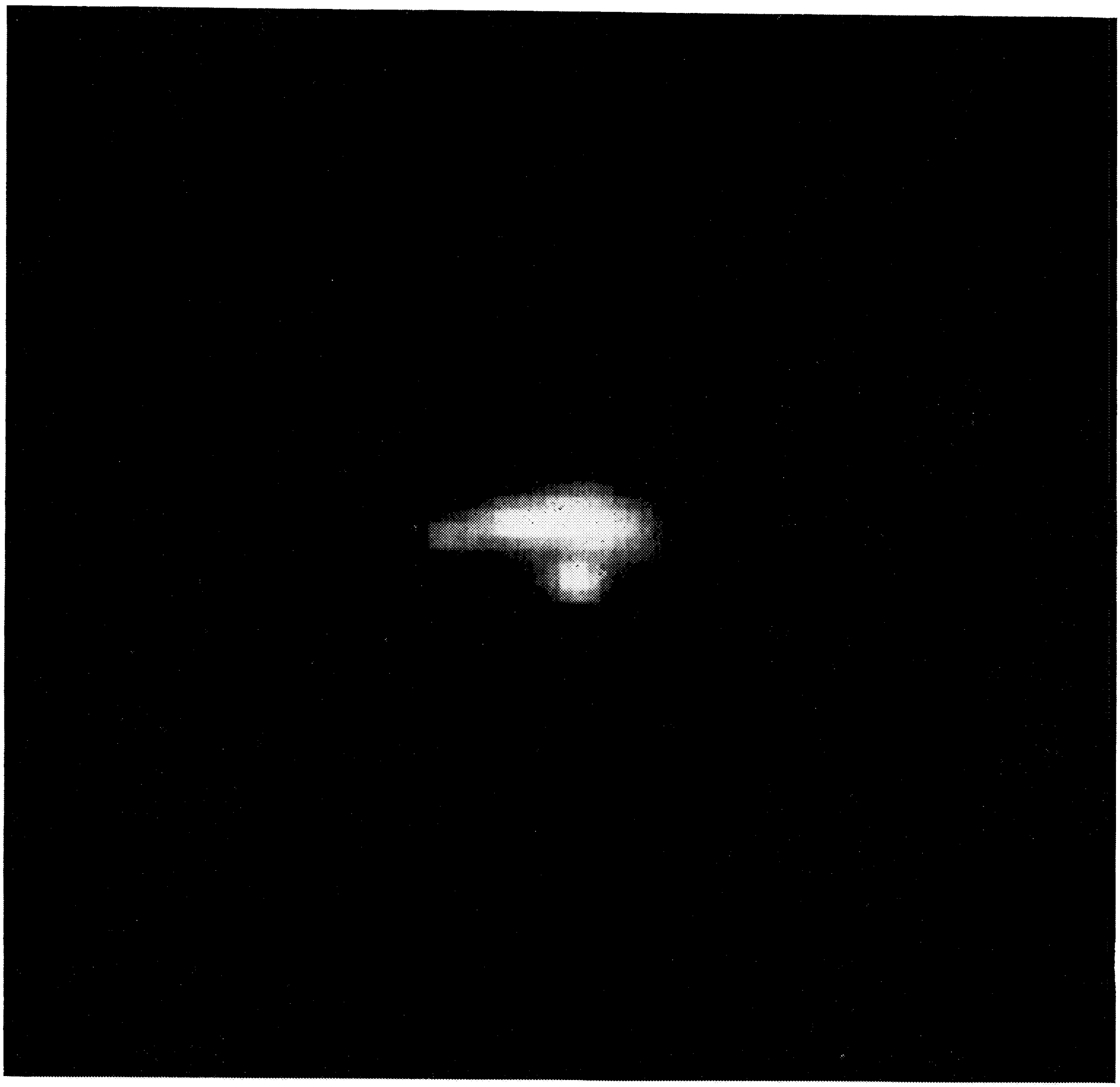

Plate 3. CCD *I*-band image of the spiral galaxy and the red object, with enhanced contrast. North-east is at the top left corner.

Table 4. Optical and infrared photometry.

Band	λ_{eff} (μm)	Observed magnitudes	
		The spiral galaxy	The red object
V	0.55	16.4* ± 0.2	21.8* ± 0.2
R	0.65	15.8* ± 0.2	20.3* ± 0.2
I	0.80	15.1* ± 0.2	19.1* ± 0.2
J	1.20	15.64† ± 0.07	
H	1.65	14.68† ± 0.03	
K	2.20	14.13† ± 0.05	

* Integrated magnitudes, based on the photometric system in Bessell (1976).
† In a 7.5 arcsec aperture.

The position of the centre of the spiral galaxy was measured both from the ESO/SRC survey and from the CCD images. These positions are given in Table 3. The difference between them, 2.4 arcsec, is due largely to the difficulty in defining the centre of the bar.

3.2 OPTICAL SPECTROSCOPY

A flux-calibrated spectrum of the galaxy was obtained with the intensified reticon system attached to the Boller and Chivens spectrograph mounted at the Cassegrain focus of the Las Campanas 2.5-m telescope. Fig. 3 shows the sky-subtracted spectrum resulting from an integration of 100 min through a 4-arcsec aperture, resolution ≈ 4 Å.

Emission lines characteristic of low-excitation late-type spiral galaxies are present (Table 5); these presumably originate in the indigenous H II regions. The weakness of the [N II] lines suggests a galaxy somewhat (3×) underabundant in nitrogen. Absorption features

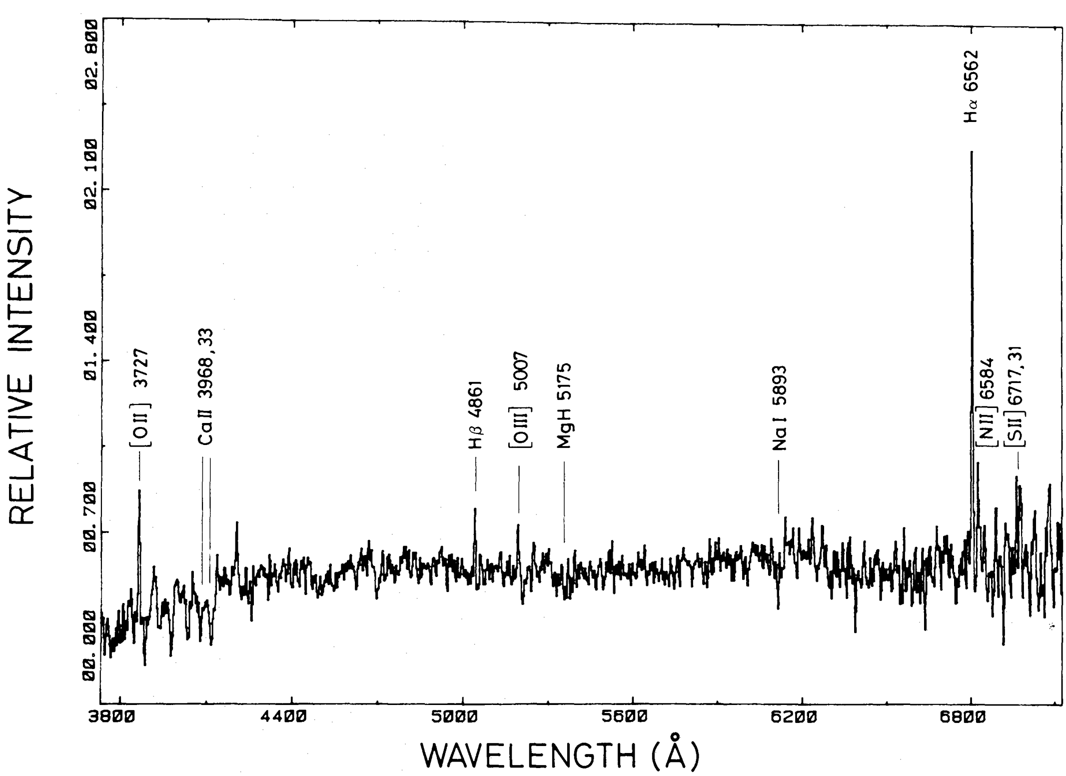

Figure 3. Spectrum of the central part of the spiral galaxy, taken through a 4-arcsec aperture with a resolution of 4 Å.

(MgH, NaD, Ca II) characteristic of late-type stars are present. A quantitative measure of the Mg, CN and CH features in a photometric system simulating that used by Faber (1973) for measuring elliptical galaxies confirms this impression, and suggests that there is a significant contribution from the light of young stars, again consistent with its classification as a late-type galaxy. The visual absorption, $A_V = 2.7$, obtained from the measured Balmer decrement and the Whitford reddening law, is not exceptional for a late-type spiral seen at this inclination. A redshift of $z = 0.0367 \pm 0.0001$ measured from this spectrum corresponds to a distance of 107 Mpc ($H_0 = 100$ km s^{-1} Mpc^{-1}). At this distance the major axis of the galaxy (26 arcsec) is 13 kpc in length, and the absolute magnitude is $M_B = -19.2$.

Table 5. Observed emission line strengths in the spiral galaxy.

[O II] 3727	237
Hβ 4861	100
[O III] 5007	103
Hα 6562	726
[N II] 6584	180
[S II] 6717,31	298

A 30-min long-slit spectrum at a dispersion of 140 Å mm^{-1} was obtained with the Image Photon Counting System (IPCS) attached to the RGO Spectrograph at the Cassegrain focus of the AAT. The resolution was ≈ 2 Å. The pixel separation along the slit was ≈ 4 arcsec, with the slit aligned along the bar of the galaxy. Both the [O II] 3727 and Hα lines extend over the length of the bar. The rotation curve obtained from these lines covers the range ±100 km s^{-1} at most, small but not abnormal for a low-luminosity galaxy such as this (Bosma 1978).

3.3 RADIO SPECTROSCOPY

A 30-min observation of PKS 0400 − 181 was made with the Parkes 64-m radio telescope in 1980 November, to search for H I emission from the spiral galaxy. The system temperature of the cooled FET 21-cm receiver was 52 K on cold sky. No line emission was detected over a range of 2000 km s^{-1} centred at 11070 km s^{-1} ($z = 0.037$); the 3σ upper limit corresponds to $M_{\rm H\,I} < 6 \times 10^9 M_\odot$ for a velocity width of 200 km s^{-1}. This is consistent with the small size, low absolute magnitude and slow rotation of this galaxy, assuming it to be a normal spiral (*cf.* Shostak 1978).

3.4 INFRARED PHOTOMETRY

Infrared *J, H, K* magnitudes were obtained in 1981 November using the infrared photometer/spectrophotometer on the ESO 3.6-m telescope at La Silla. A 7.5-arcsec diaphragm centred on the spiral galaxy, which thus includes the red object, and a beam separation of 15 arcsec, were used. The results are given in Table 4. Although the diaphragm size and sky-subtraction technique preclude a direct comparison with the integrated *V, R, I* magnitudes, it is clear that the spiral galaxy dominates at *J, H, K* and that no useful additional constraints (e.g. redshift) can be placed on the red object. By de-reddening the infrared data taking into account both galactic extinction and the value of $A_V = 2.7$ mag derived earlier, and applying appropriate *K* corrections for the redshift of the spiral galaxy, we obtain colour indices of $J{-}H \approx 0.63$ and $H{-}K \approx 0.25$ which are typical for the stellar populations in normal galaxies.

3.5 X-RAY OBSERVATIONS

A 1-degree field centred on PKS 0400 – 181 was observed for 12 900 s with the IPC on board the *Einstein Observatory* (Giacconi *et al.* 1979; Gorenstein, Harnden & Fabricant 1981) in 1981 February. The strongest X-ray emission found in the vicinity of the galaxy was at the 3σ level, and displaced 1.1 arcmin north-east of the position of the galaxy. As the positional accuracy of the X-ray measurement is better than 30 arcsec, it is unlikely that this X-ray feature is associated with the galaxy (or the radio source). The upper limit for X-ray emission from the spiral galaxy itself is $\approx 2 \times 10^{41}\,\mathrm{erg\,s^{-1}}$; normal galaxies have X-ray luminosities ranging from 10^{38} to $10^{41}\,\mathrm{erg\,s^{-1}}$, and there is thus no evidence that this spiral is exceptional.

4 The red object

The CCD *I*-band images in Plates 2 and 3 clearly reveal the red object, superimposed on the spiral and displaced by just 2.4 arcsec from its centre. It is barely visible in the *V*-image, and not at all in the IIIa-J photograph (Plate 1). It is not stellar – its extent, after subtracting the spiral and correcting for the seeing of ≈ 1 arcsec, is 2.5 arcsec east–west by 1.3 arcsec north–south (FWHM). Thus it is plausible that this may be a background elliptical galaxy.

In fact, a giant elliptical galaxy with $M_V = -23$ at $z = 0.5$ would be consistent with the properties of this object. It would have an apparent *V* magnitude, redshifted approximately into the *I*-band, of ≈ +18, which agrees with the measured *I* magnitude (Table 4) when allowance is made for extinction ($A_V \approx 2.7$) due to the foreground spiral. The geometric mean angular extent of the image (which may in fact be somewhat distorted by gravitational lens effects due to the intervening spiral) corresponds to 7 kpc at $z = 0.5$, consistent with the effective radius for giant elliptical galaxies (≈ 10 kpc) determined by Binggeli, Sandage & Tarenghi (1983, in preparation).

5 Discussion

The radio centroid is 1.5 arcsec from the red object, and 2.8 arcsec from the centre of the spiral galaxy (Table 3). Either of these positional coincidences would satisfy our normal criteria for an identification (even if a core point source were present to better define the radio nucleus – Fosbury *et al.*, in preparation). Indeed, had the spiral galaxy been an elliptical instead, it would probably have been accepted without question as the correct identification. The centroid radio position used here may be somewhat offset from the radio nucleus; the stronger lobe is almost invariably closer than the weaker one (Shaver *et al.*, in preparation). In PKS 0400 – 181 the north-west lobe is slightly stronger, and thus the real radio nucleus may be somewhat to the north of the position given in Table 3, closer still to the positions of the centre of the spiral and the red object. On the basis of positional coincidence alone, then, either the spiral galaxy or the red object could be the correct identification.

The fact that the red object is probably a background elliptical galaxy, and that double radio sources of this type have hitherto always been identified with ellipticals rather than spirals, strongly suggests that the red object is the correct identification. Further support for an identification with a relatively distant object comes from the morphology of the radio source: its well-collimated and edge-brightened structure is typical of radio galaxies of *high luminosity*. If PKS 0400 – 181 is luminous, it must be very distant. At a redshift of 0.5, which was shown in Section 4 to be consistent with an interpretation of the red object as a giant elliptical galaxy, the linear size of the radio source would be 250 kpc and the total power at 6 cm would be $3 \times 10^{24}\,\mathrm{W\,Hz^{-1}\,sr^{-1}}$, typical of 3CR radio galaxies.

What, then, is the probability of an unrelated galaxy being located by chance so close to the line-of-sight to this radio galaxy? The surface density of galaxies with $m_B \leq 17$ (our sample limit) is ~ 6 per square degree (Allen 1973; Shane 1975); counts within a few degrees of PKS 0400 – 181 are consistent with this. The total number of radio sources with flux densities above the sample limit and from which the complete sample of radio galaxies was selected is 1367. The probability of one of these galaxies and one of these radio sources coinciding within 3 arcsec is therefore ≈ 4 per cent. This is not sufficiently small to be compelling, especially as it was computed *a posteriori.*

We conclude that the most plausible identification for the radio source PKS 0400 – 181 is the red object – probably a background giant elliptical galaxy. An identification with the spiral galaxy cannot be completely excluded, but it is less likely; the close positional coincidence is probably a chance superposition of a foreground spiral galaxy and a much more distant radio galaxy. It may prove possible to measure the redshift of the red object, particularly if (like many powerful radio galaxies) it has strong emission lines. Further, more sensitive radio observations may finally reveal a radio core source, which would strongly support the identification if coincident with the red object. However, the detection of the nucleus of a normal spiral would not be unexpected at this level. While at present PKS 0400 – 181 appears to be at worst a difficult problem of identification and at best an unlikely positional coincidence, it may in the future prove to be useful (as it involves an *extended* background object), e.g. in absorption-line studies of the interstellar medium of the spiral.

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