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PKS 0241+011: the largest quasar?

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Abstract. We have made a radio and optical study of the radio source PKS 0241+011 associated with a quasar at z = 1.40. In earlier radio maps this source appears as a large triple radio source with an angular extent of 400 arcsec ($2.4h^{-1}$ Mpc; H_0 = $100h$ km s^{-1} Mpc^{-1}, q_0 = 0.0). If the triple radio structure seen in radio maps represents a single object, PKS 0241+011 would be the largest radio quasar observed so far. We present new radio and optical data, which reveal that this source actually consists of three separate sources. The radio source associated with the z = 1.40 quasar has a linear extent of $65h^{-1}$ kpc.

Key words: quasars: individual: PKS 0241+011 – radio continuum: galaxies – cosmology: distance scale

1. Introduction

Powerful double radio sources of Fanaroff & Riley (1974) class II provide us with the most promising "standard rods" in studying the large scale geometry of the universe. These sources can have linear sizes up to several Mpc and luminosities up to 10^{46} erg s^{-1} and thus be observable from cosmologically significant distances. In addition, they have well-defined outer edges that makes it possible to measure their sizes unambiguously. At first, the luminous double radio sources seemed to be ideal for the so called redshift-apparent size test that seeks to infer the value of the deceleration parameter q_0 from the angular size of a rigid rod at different redshifts (see e.g. Sandage 1988). However, from the first attempts (Miley 1971) it was clear that linear sizes of powerful double radio sources are not constant, but seem to evolve with cosmic epoch in the sense that sources were smaller in the earlier universe. It is still debated whether this apparent evolution is a true effect (Barthel & Miley 1988; Kapahi 1989; Singal 1988) or due to a power-size anticorrelation (Masson 1980; Nilsson et al. 1993), or a combination of both.

While compiling a sample of double radio sources to study the redshift – apparent size diagram of these sources (Nilsson et al. 1993), we encountered a triple radio source with an angular size of 400 arcsec in the complete sample of Downes et al. (1986, see their Fig. 1). The central component of this source coincides with a 20.0 mag quasar for which Arp and Sulentic (1979) have measured a redshift of 1.40 that has been later confirmed by Burbidge et al. (1979). The quasar is embedded in the spiral arm of a nearby spiral galaxy NGC 1073. Two more quasars have been found by Arp and Sulentic (1979) close to the optical disk of NGC 1073. In the redshift–angular size diagram of double radio sources (e.g. Fig. 5 of Nilsson et al. 1993) PKS 0241+011 lies clearly above the upper envelope defined by the largest double radio sources if it is assumed that the observed radio components belong to the same source. The projected linear size of PKS 0241+011 would be 2400 h^{-1} kpc and the radio luminosity between 10MHz and 10GHz would be 6.8×10^{43} h^{-2} erg s^{-1}. If it were a true double radio source, it would rank among the largest double radio sources and the largest double quasar observed so far.

The 1.5 GHz radio map of Downes et al. (1986) with 23 arcsec resolution shows a compact central component coincident with the optical quasar and two continuum sources on both sides of the central source. A 1415 MHz map of similar resolution has been presented by England & Gottesman (1990). Although the appearance of PKS 0241+011 gives an impression a double radio source, it is difficult to decide from these maps if the continuum sources on both sides of PKS 0241+011 represent outer lobes of an extended double radio source or if they are separate sources of their own. We thus decided to undertake a radio and optical study of PKS 0241+011 to determine the nature of the continuum sources on both sides of the central quasar.

2. Observations

2.1. Radio observations

PKS 0241+011 was observed on 18 May 1992 with the VLA[1] in C configuration at 4860 MHz (6 cm) and 8440 MHz (3.6 cm). At both frequencies a total continuum bandwidth of 100 MHz was used. At 6 cm the field was centered at $\alpha_{1950.0} = 2^h\ 41^m\ 10^s$, $\delta_{1950.0} = 1°08'30''$ and integrated for 25 min 20 s. At 3.6 cm the field was separated into two subfields centered at $\alpha_{1950.0} = 2^h\ 41^m\ 04^s$, $\delta_{1950.0} = 1°08'0''$ and $\alpha_{1950.0} = 2^h\ 41^m\ 14^s$, $\delta_{1950.0} = 1°09'15''$, which were combined into one image

[1] The Very Large Array is a facility of the National Radio Astronomy Observatory, operated by Associated Universities Inc., under cooperative agreement with the National Science Foundation.

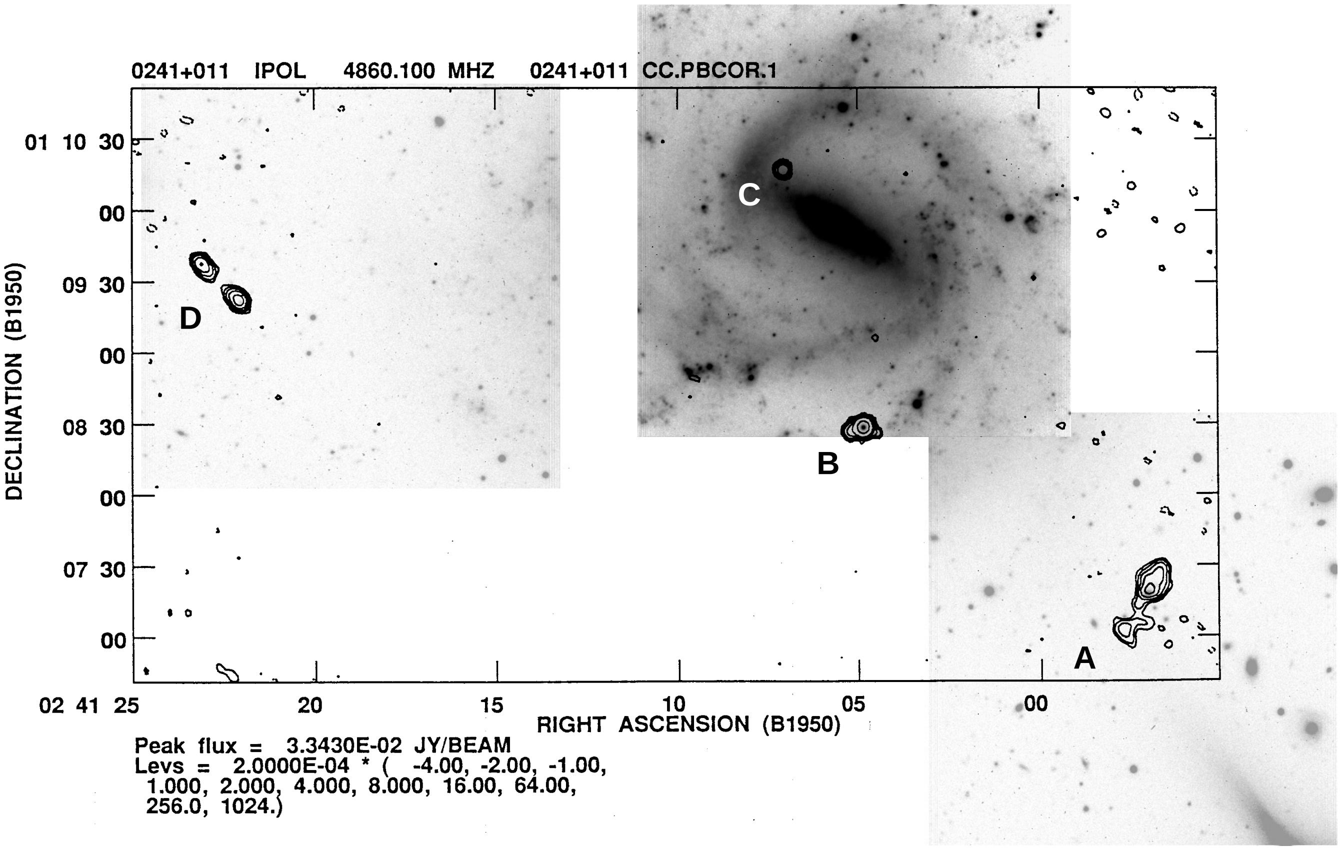

Fig. 1. The optical field around PKS 0241+011 overlaid by the 6 cm radio contours. The beam size is 4.″3 × 4.″0 at PA 21°. The spiral galaxy in the field is NGC 1073. Contours -0.2, 0.2, 0.4, 0.8, 1.6, 3.2, 6.4, 12.8, 25.6 mJy. 1σ rms noise of the map is 67 μJy.

by the AIPS program LTESS before primary beam correction. Both fields were integrated for 17 min 20 s. The fluxes were calibrated to the flux scale of Baars et al. (1977) with 3C 48 for which fluxes of 5.63 Jy (6 cm) and 3.29 Jy (3.6 cm) were calculated by the AIPS task GETJY. A nearby source 0237-027 was used as a phase calibrator. All reductions were done with the AIPS package at Tuorla Observatory. The rms noise in our final maps is 67 μJy and 34μJy at 6 cm and 3.6 cm, respectively.

2.2. Optical observations

The optical observations were carried out at the 2.56 m Nordic Optical Telescope (NOT) on Roque de los Muchachos, La Palma, Canary Islands. Table 1 gives the details of the observations. Direct CCD images were obtained through the R-band filter with a 1024 × 1024 TEK detector that has a gain of 1.7 e^-/ADU and a readout noise of 6.5 e^-. The pixel scale was 0.176″/pixel. The images were de-biased and flat-fielded with IRAF in the standard manner and individual exposures were registered and co-added.

Photometric calibration for each field was obtained by observing the calibration fields by Smith et al. (1985). The calibration exposures were made temporally close to 0241+011 observations and at similar airmass. The weather conditions were not photometric on 04 and 05 September due to dust and thin clouds, but on 06 and 08 September better conditions prevailed. Only the photometric zero point was thus determined from the standard fields with no correction for extinction or color terms. The error from different airmasses for PKS 0241+011 and standard fields is of the order of a few percent. Larger uncertainty results from varying atmospheric conditions and photon noise.

To be able to align radio and optical observations we determined the transformation from CCD pixel positions to equatorial coordinates by using the APM Northern Sky Catalogue (Irwin et al. 1994), which is a digitized version of the Palomar Sky Survey. The accuracy of this transformation depends on the number and quality of objects available in the APM catalogue for each field. The errors of our fits combined with the external accuracy of the catalogue ($\sim$ 0.″5) sum up to a total error of $\sim 1''$ between the radio and optical reference frames in all three optical fields. Note that each optical field used different sets of APM stars and thus the positional errors in one field are independent of the errors in other fields.

3. Discussion

In Fig. 1 we show the optical field close to PKS 0241+011 overlaid with the 6 cm radio contours. The radio field contains four continuum sources that have been labeled A–D. The spiral galaxy in the field is NGC 1073 that lies at a distance of

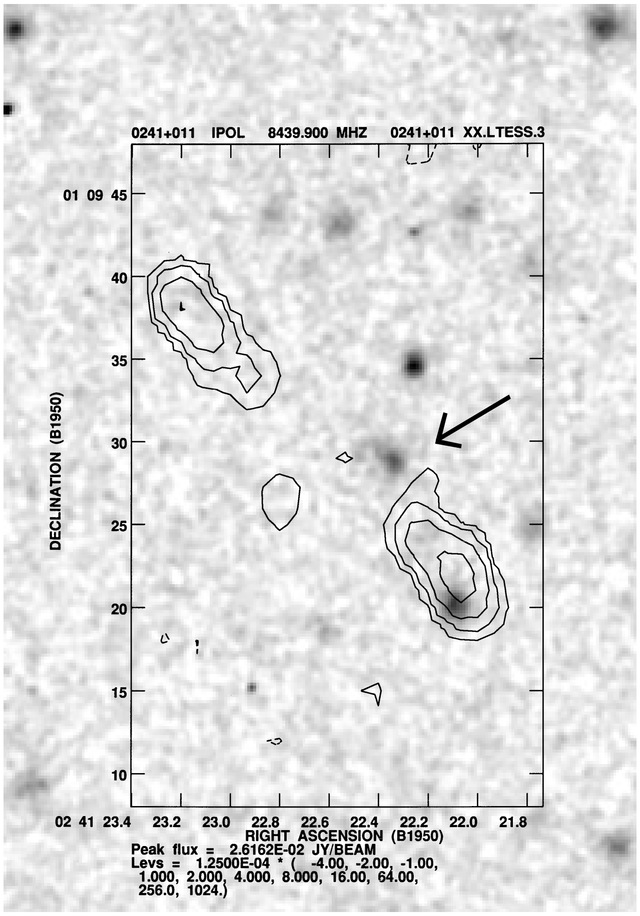

Fig. 2. The optical field around radio source D overlaid with the 3.6 cm radio contours. Light smoothing has been applied to the optical image. The arrow indicates the optical identification. Beam size is 2.6″ × 2.3″ at PA 20°. The radio contours are -0.125, 0.125, 0.25, 0.5, 1.0, 2.0, 4.0 mJy. 1σ rms noise is 34 μJy.

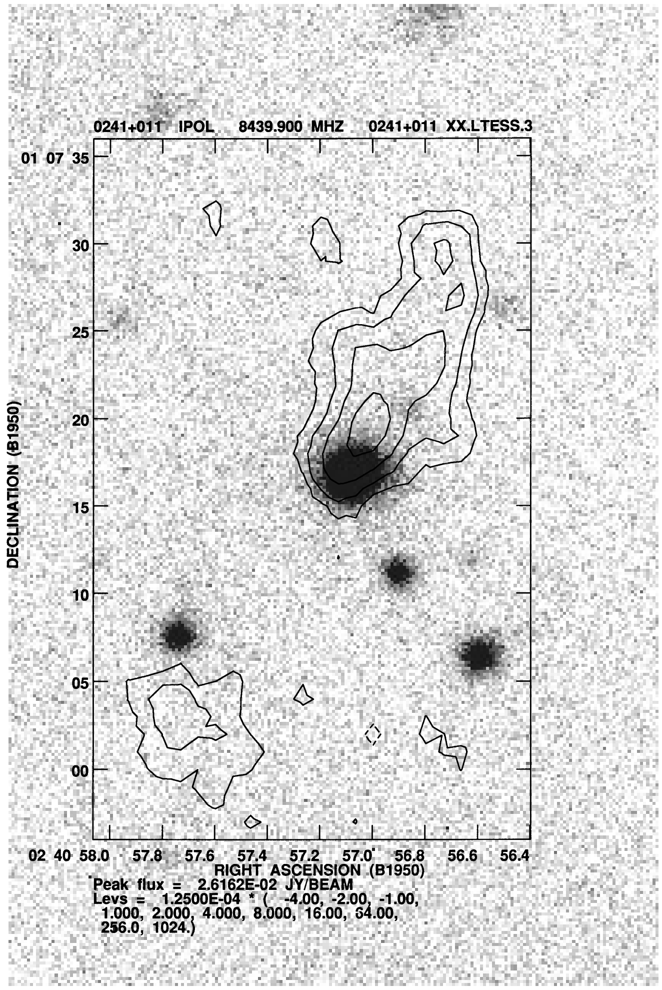

Fig. 3. The optical field around radio source A overlaid with the 3.6 cm radio contours. Beam and contours are as in Fig. 2.

Table 1. Log of optical observations at the NOT.

object	date	filter	exp. (sec.)	FWHM (arcsec)
0241+011 W	04 Sep 1994	R	1050	1.1
NGC 1073	05 Sep 1994	R	900	0.9
0241+011 E	06 & 08 Sep 1994	R	1800	1.0

13.6 Mpc (England & Gottesman 1990). The quasar at z = 1.40 coincides with source B within our positional errors. The two radio-quiet quasars discovered by Arp and Sulentic (1979) lie west of NGC 1073 just outside our northernmost optical image. The radio-optical fields around sources D and A are shown in more detail in Figs. 2 and 3, respectively. Radio fluxes of individual components in sources A–D are given in Table 2.

From Figs. 1 and 2 it appears that source D is an edge-brightened FR II type source identified with a faint optical galaxy. The galaxy has an R-band magnitude of 22.8 ± 0.1 and it lies very close (within 3σ) to the radio centroid of source D. The spectra of both components in source D are steep between 6 cm and 3.6 cm, which is typical for classical edge-brightened double radio sources.

Source A (Fig. 3) has a somewhat peculiar morphology that defies classification into FR I or FR II or any other well-defined category. The optical field contains several objects, but we consider that source A is to be identified with the compact optical object in the field at $\alpha = 2^h\ 40^m\ 57\overset{s}{.}08$, $\delta = 1°07'16\overset{''}{.}6$ and that it is a separate source from source B. This object has an R-band magnitude of 20.3 ± 0.1 and it seems to be the starting point of what appears to be a radio jet that fades from visibility farther away from it. Some faint nebulosity is seen west of the compact object. This nebulosity is better seen when a scaled PSF constructed from stars in the field is subtracted from the compact object (Fig. 4). The clear asymmetry of the nebulosity with respect to the stellar core is visible in the subtracted image. There are several interpretations for the observed morphology: i) a chance coincidence of a foreground star and a background galaxy, ii) a compact galaxy, iii) a quasar with host galaxy and iv) an object in NGC 1073. The last option in the list is unlikely given the radio emission from the region and the fact that the

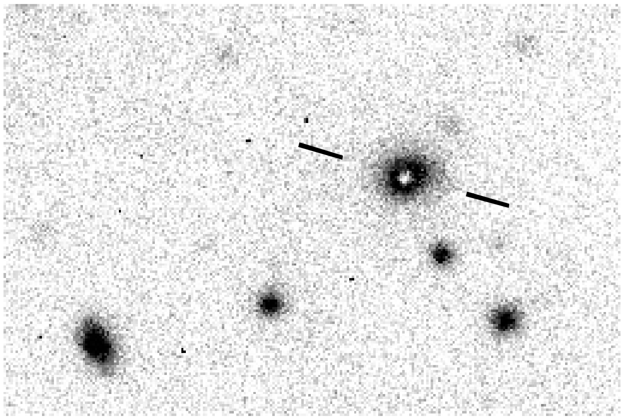

Fig. 4. The group of optical objects close to radio source A. A scaled PSF has been subtracted from the proposed identification to the radio source. Note the asymmetric nebulosity visible after subtraction. Field size is 45″ × 30″.

Table 2. The radio fluxes and spectral indices ($F_\nu \propto \nu^\alpha$) for the continuum sources in Fig. 1

Source	Flux (mJy)		α_{6cm}^{3cm}
	6 cm	3.6 cm	
A north	16.5	8.6	-1.2
A south	4.4	1.6	-1.8
B east	2.4	0.77	-2.0
B center	35.6	31.8	-0.2
B west	0.82	0.33	-1.6
C	3.4	1.6	-1.4
D east	5.3	2.4	-1.4
D west	7.7	3.5	-0.8

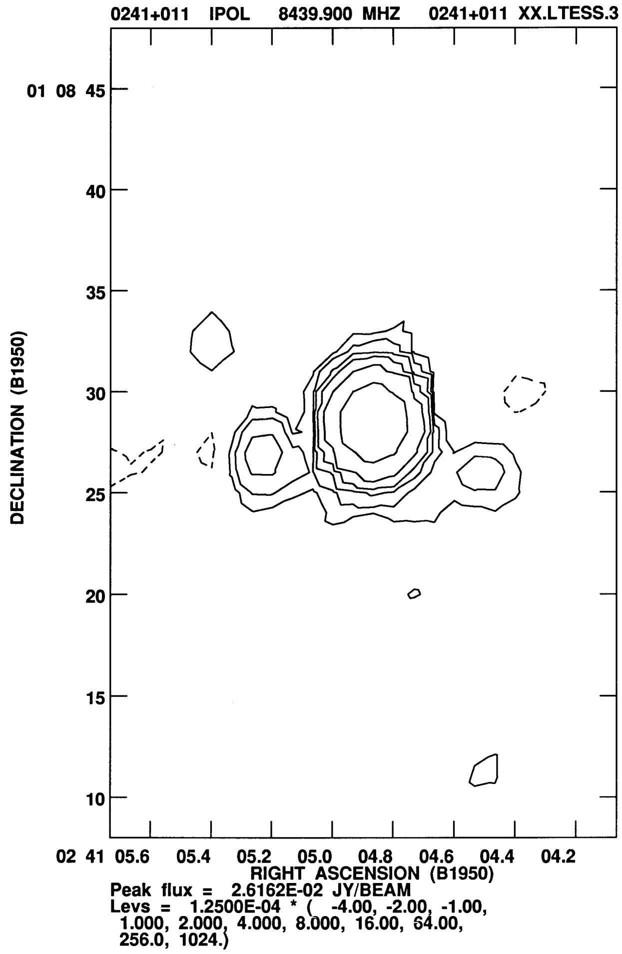

Fig. 5. The radio map of source B (= PKS 0241+011) at 3.6 cm. The quasar at z = 1.40 coincides with the brightest radio component at the center. Beam and contours are as in Fig. 2.

optical disk of NGC 1073 does not extend to the distance of source A (but note that the HI disk does, England & Gottesman 1990). The third option would be particularly interesting since three quasars have already been found very close to NGC 1073. The slight decentering of the nuclear component with respect to the host galaxy could be caused by a nearby companion galaxy that is not resolved from the rest of the system. On the other hand, there is no compact flat spectrum radio source coincident with the proposed optical identification, as would be expected in the case of a radio quasar. Optical spectroscopy is needed to reveal the true identity of the optical counterpart of source A.

Fig. 5 shows the 3.6 cm radio map of source B. A flat spectrum core contains $\sim 95\%$ of the flux at 3.6 cm. Steep spectrum components reside on both sides of the core. Based on earlier discussion source B alone is identified with the quasar at z = 1.40. The angular size of source B is 11 arcsec which translates to a linear size of $65h^{-1}$ kpc. In the redshift–apparent size diagram PKS 0241+011 lies close to the median angular size expected at z = 1.40.

We finally mention the point source in the field (source C) that is embedded deep in NGC 1073. No optical counterpart for this source is seen in our CCD images. We estimate that an object with an R-band magnitude $\lesssim 22.5$ would have been detected.

4. Conclusions

The radio and optical field around the radio source PKS 0241+011 associated with an optical quasar at z = 1.40 has been studied in order to determine whether the observed triple structure is truly a single source or a chance coincidence of two or more unrelated sources. Our main conclusion is that the observed triple structure consists of three independent sources. The eastern radio component is found to be a classical double radio source identified with a faint (R = 22.8) galaxy. The western component displays a complex radio structure identified with a compact optical object that shows a decentered nebulosity around a stellar nucleus. Optical spectroscopy is needed to determine the nature of this object. The central radio component is a core-dominated triple source with a linear extent of $65h^{-1}$ kpc that coincides with the z = 1.40 quasar. No optical object is seen at the location of the fourth unresolved radio source in the field down to limiting magnitude R = 22.5.

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