Astron. Astrophys. 226, L13–L16 (1989)

ASTRONOMY AND ASTROPHYSICS

Letter to the Editor

0309+411, an Mpc-sized core-dominated radio galaxy/quasar

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Received June 22, accepted July 7, 1989

Summary: The compact radio source 0309+411, located, in projection, on the periphery of the Perseus cluster of galaxies, is found to possess hitherto unknown very large scale radio emission. WSRT observations at 327 MHz and 608 MHz show that the radio core is straddled by two weak lobes extending over an angular size of 9.5'. Optical spectroscopy of the 18th magnitude galaxy identified with the core shows a quasar-like spectrum with strong broad emission lines with a redshift of 0.136. For an Einstein-de Sitter universe and a Hubble constant of 50 km/sec/Mpc the angular size is equivalent to a linear size of 1.8 Mpc making this the quasar with the largest projected size known to date. In addition to this, the source is remarkable for the fact that the radio core is responsible for about 75% of the total emission at a frequency of 5 GHz. The radio core is variable in flux density, has a slightly inverted spectrum and is known to be less than one milliarcsecond in size. The core properties suggest that the radio axis of the source is inclined by only a small angle to the line of sight, so that the true de-projected size of the radio source could be several times larger still. We briefly discuss the properties of 0309+411 in the context of the "unified scheme" relating compact and extended radio sources.

keywords: giant radio sources, relativistic beaming, unified scheme

1. Introduction

In a 327 MHz study of the Perseus cluster of galaxies with the Westerbork Synthesis Radio Telescope a diffuse radio source with a dominant core was discovered at the periphery of the cluster. The position of the radio core was found to coincide with a red 18th magnitude galaxy which suggested that the source was not in the Perseus cluster, whose members are typically 14-15 magnitude, but considerably more distant. Subsequently it was discovered that the core of this radio source has been the subject of many investigations extending over a decade. Kapahi (1979) first mapped the source with the WSRT at frequencies of 1412 and 4995 MHz in a program to investigate sources in the NRAO-Bonn 'S4' survey; in addition to the dominant radio core he discovered a secondary source displaced by 87" to the north-west. Kapahi identified the object with an 18th magnitude galaxy and gives a finding chart for the galaxy. Some years later Saikia et al. (1984) presented an extensive discussion of observations of the radio core and the secondary feature observed by Kapahi.

In order to determine the nature and distance of the object we obtained an optical spectrum of the galaxy. This spectrum, the 327 MHz data and further radio data acquired by us are described below. The extreme properties found for the source are discussed within the framework of the "unified scheme" of compact and extended extragalactic radio sources.

2. New Optical and Radio Observations

Following identification of the radio core on the Palomar Sky Survey prints we requested an observation of the faint reddish object in the Service Time available on the Isaac Newton Group of telescopes on the Roque de los Muchachos Observatory on La Palma. A spectrum with the Faint Object Spectrograph attached to the William Herschel Telescope was obtained for us by Dr. J. Lub on the 25th of July 1988. This spectrum, a 900 second exposure, is shown in Figure 1; the spectral resolution is about 15 Angstroms. The spectrum shows a strong broad Hα line with a width at zero intensity of about 13000 km/s. The red wing of Hα is partly absorbed by the atmospheric A-band of O_2. Broad Hβ emission can also be discerned at an intensity about one-sixth of that of Hα. Narrow emission lines from [OIII] at 4959/5007 A and [OI] at 6300/6363 A are also visible. The redshift determined from these lines is 0.136. The

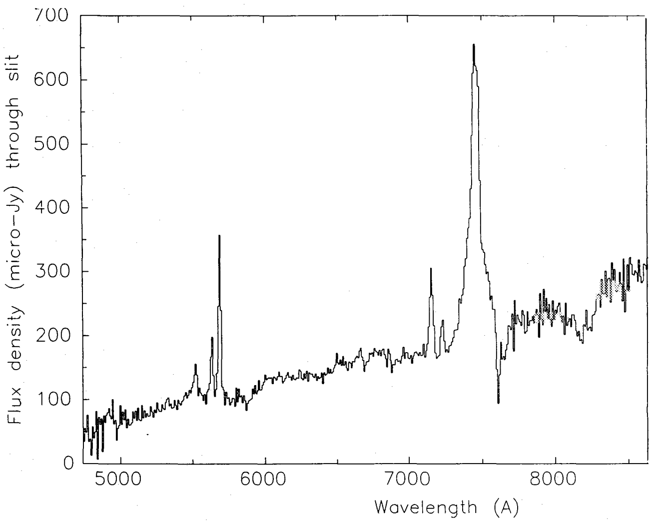

Figure 1: Optical spectrum of the "galaxy" identified with the radio source 0309+411 taken by J. Lub with the Faint Object Spectrograph on the WHT in July 1988.

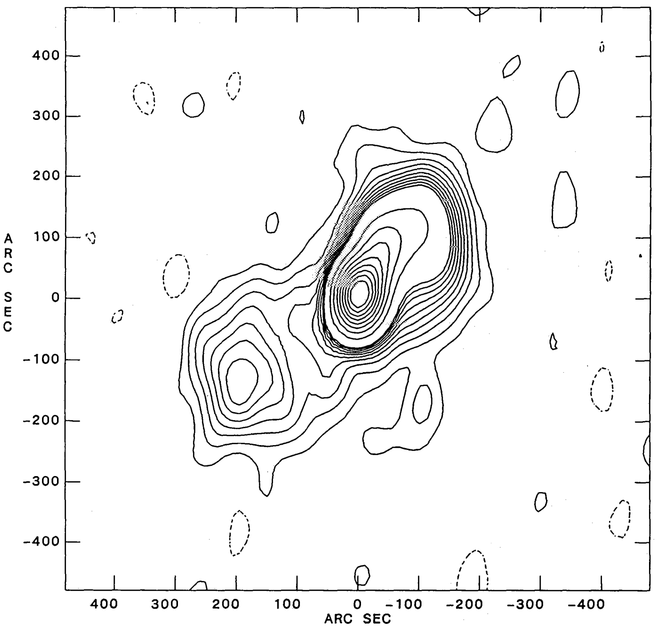

Figure 2: Contour map of the radio source 0309+411 obtained with the WSRT at 327 MHz. The contour levels are 1.6 x (-6,-3,3,6,9,12,15,18,21,24,27,30) and 1.6 x (60,90,120,150,180,210,240,270) mJy/beam. The factor 1.6 corrects for the primary beam attenuation. The peak flux density of the source is 480 mJy. The coordinates are in arc seconds relative to the core of 0309+411. North is up, east to the left.

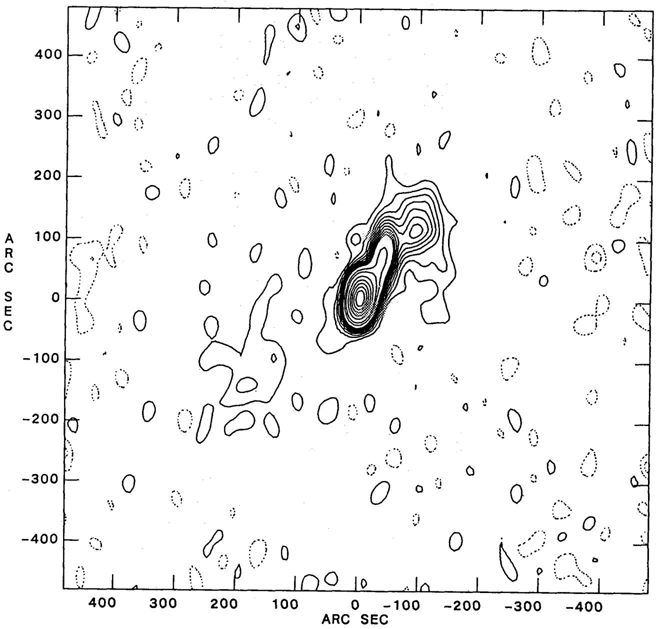

Figure 3: Contour map of the radio source 0309+411 obtained with the WSRT at 608 MHz. Contour levels are 5.9 x (-1.2,-0.6,0.6,1.2,1.8,2.4,3,3.6,4.2,4.8,5.4,6.0) and 5.9 x (9,12,18,24,30,36,42,48) mJy/beam. The factor 5.9 corrects for the primary beam attenuation. The peak flux density of the source is 380 mJy. The coordinates are relative to the core.

continuum emission from the object is rather red, in agreement with the appearance on the Sky Survey prints. This suggests that the spectrum may contain emission from the surrounding galaxy. An absorption feature at an observed wavelength of about 5872 A is at the location expected for the MgIb absorption from stellar emission but higher resolution higher S/N data are required to confirm the presence of galaxian emission in the total spectrum.

Radio observations at a frequency of 327 MHz were obtained with the WSRT in January 1984. A synthesis map was made from data gathered in four periods of 12 hours. The field centre for these observations was located between NGC1265 and NGC1275. The large primary beam width of the WSRT, 2.7° at half-power, enabled a 6° x 6° area to be synthesized. These observations will be described elsewhere (de Bruyn, Brouw and Miley, 1990). About 1° west-south-west of the fieldcentre we detected a diffuse source of angular size 10' with a strong dominant peak. A contour map of this source is shown in Figure 2. The synthesized beam measures 54"x81" in position angle 0°. The peak flux density of the source is 480 mJy, most of which originates in the core. The north-western lobe of the source is about three times more intense than the south-eastern lobe but this is for a large part due to emission from a large-scale jet. The total angular size is 9.5', after correcting for the beam-smearing effects at the extreme edges of the source, in position angle 140° . The transverse size is also considerable, about 4' . The total flux density of the source at 327 MHz is 1.5 ± 0.1 Jy of which about 450 mJy, or 30%, is contained in the core. The WSRT flux scale is based on the Baars et al. (1977) scale and assumes a value of 26.9 Jy for 3C286 at 327 MHz.

As part of a multi-frequency continuum study of the Perseus cluster we also acquired 608 MHz observations in the summer of 1987. These observations form part of a Ph.D. thesis project by D. Sybring and will be reported elsewhere. A contour map of the region surrounding 0309+411 is shown in Figure 3. The resolution at 49 cm equals 29"x44". At 608 MHz the source flux is reduced considerably by the primary beam attenuation which is a factor of 5.9 at the location of the source. The peak flux density in the source at 608 MHz is 380 mJy, almost all of which must come from the core. Due to resolution effects, as well as heavy attenuation, the south-eastern lobe of the source is now only weakly visible. A ridge of emission in the north-western lobe gives the suggestion of a large-scale jet emanating from the core in a position angle of -20° . A 1412 MHz map by Kapahi (1979), with similar resolution as our 49 cm map, also shows a feature in this position angle. In his map, which was made from data with very incomplete UV-coverage, it does appear to be a distinct feature rather than a jet. (Higher resolution observations, obtained when this article went to press, show that this feature is indeed a jet). The low surface brightness and the large primary beam attenuation at the location of the source mean that the lobe flux densities at 49 cm can not be reliably determined from our data.

To determine the precise location of the radio core we also made a short 6 cm observation (4874 MHz) with the WSRT on September 1, 1985. The position of the core was found to agree to within the errors with the more accurate VLA position given by Saikia et al. (1984; we thank P. Shastri for first bringing this reference to our attention) which we quote here:
RA (1950): $03^h09^m44^s.82$, Dec (1950): +41°08'48.9".

Our optical position for the galaxy, determined from the Sky Survey prints is RA (1950): $03^h09^m44^s.86$, Dec (1950): +41°08'48.7", with an estimated uncertainty of about 0.7"; this is in excellent agreement with the position of the radio core.

The 6 cm flux density measured at the WSRT in 1985 was 457±10 mJy which, within the errors, is equal to the 1978 value of 456±30 reported by Kapahi (1979). However, the 6 cm flux density reported by Saikia et al. (1984), which refers to epoch 1980, is 337±17 mJy implying strong variability in a two year timespan. The variability of the core is also evident in the data used to construct the overall radio spectrum of 0309+411 shown in Saikia et al. (1984). The core has been detected at frequencies as high as 100 GHz and shows no indication of becoming optically thin. The source was also monitored by Seielstad et al. (1983) at a frequency of 10.8 GHz and showed a 50% increase in a period of 6 months towards the end of their 4 year monitoring program which ran from 1979 through 1982. Significant variability on time scales less than one year is therefore well established.

3. Discussion

Two properties of 0309+411 make it stand out among the population of extragalactic radio sources. First, the overall linear size is the largest ever found associated with an object with a quasar-like optical spectrum. The angular extent of 9.5' translates to a linear size of 1.8 Mpc for the redshift of 0.136, assuming an Einstein-de Sitter universe with a Hubble constant of 50 km/s/Mpc. This makes 0309+411 about 50% larger than the quasar 4C34.47 (Jägers et al, 1982) which has a linear size of 1.1 Mpc. Very recently several more giant quasars were discovered by Saikia et al. (1989, priv. comm.) and Riley et al. (1988) which have sizes extending up to 1.6 Mpc. A second noteworthy aspect of 0309+411 is the fact that the radio core is extremely dominant. The flux density of the extended emission at 5 GHz is about 125 mJy if we assume a spectral index of -0.8 between 327 MHz and 5 GHz. The core therefore is responsible for about 75% of the total flux density at a frequency of 5 GHz. We further note that the lobe emission is highly aymmetric. This aymmetry is, however, largely due to the one-sided large-scale jet. Such lobe/jet asymmetry is not uncommon in quasars (Owen, 1986; Barthel, 1988; Browne, 1988; Johnston et al. 1987). If the jet emission is beamed the ratio R of core over unbeamed lobe flux would be as high as ten.

The extreme properties of 0309+411 are perhaps best illustrated when we plot it in the f_c - l diagram for a large sample of quasars; here f_c stands for the fraction of the source flux density at 8 GHz coming from the core and l the projected linear size. This is shown in Figure 4, which has been adapted from Saikia (1985). The scarcity of objects in the top-right part of the diagram is thought to be due to alignment of the core-axis and lobe axis: if the angle between the line of sight and this axis is small the core flux is boosted and the projected linear size reduced due to fore-shortening. In this connection it is relevant to discuss the optical emission line properties of 0309+411. The observed full width at half intensity of Hα in 0309+411 is about 2500 km/sec. When applying a, somewhat uncertain, correction to the Hα profile for the strong contribution from the narrow line region we estimate that the FWHM of the proper broad line is closer to 6000 km/sec. This value puts 0309+411 at the upper envelope of the Wills and Browne (1986) diagram which relates the FWHM of the broad emission line to the core dominance. There is, however, very little predictive power in this relation for small FWHM: any value of the inclination of the core radio axis would be possible.

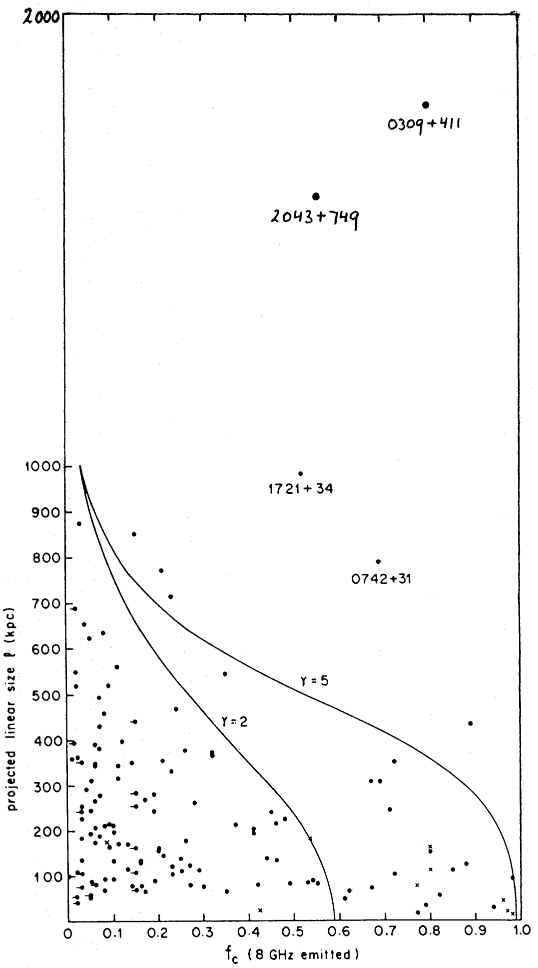

Figure 4: The f_c - l diagram as adapted from Saikia (1985). The relative flux density of the core refers to a frequency of 8 GHz. The extreme position of 0309+411 is indicated at f_c = 0.8 and l = 1.8 Mpc. The dot at location f_c = 0.55 and l =1.6 Mpc refers to the quasar 2043+749 (Riley et al., 1988).

The slightly inverted radio spectrum of the core of 0309+411 at all frequencies up to 100 GHz and the rapid variability at cm wavelengths both suggest that the axis of the radio core of 0309+411 is presently directed close to the line of sight. Only a small amount of VLBI data on the core exists. Van Breugel et al. (1981) observed the source with part of the EVN in 1979 and found the source to be unresolved. Lestrade et al. (1989) have used 0309+411 as a reference source for VLBI observations at 6 cm of Algol, which is about 1° away, and find the source to be essentially unresolved at fringe spacings down to 1.5 milliarcseconds.

The study of large scale radio emission associated with compact radio sources has been the subject of many recent investigations following attempts to unify the optical and radio properties of radio-quiet and radio loud quasars and radio galaxies (Scheuer and eadhead, 1979; Orr and Browne, 1982; Kapahi and Saikia, 1982). In this "unified scheme" the most influential parameter affecting the appearance of a double-lobed radio source with a central core is the orientation of the core axis with respect to the line-of-sight. Due to special relativistic aberration effects a relatively insignificant core flux density can be boosted to very high levels if the outflow attains relativistic velocities. In the most extreme cases, the core-to-lobe flux ratio R can be as high as several thousand to one. In general the theory and observations are in agreement on this count (Browne et al., 1982; Schilizzi and de Bruyn, 1983; Antonucci and Ulvestad, 1985; de Bruyn and Schilizzi, 1986; Murphy, Browne and Perley, 1989). However, this does not mean that there are no problems left. As first pointed out by Schilizzi and de Bruyn (1983) the extended structure of the sub-class of superluminal radio sources appears to be too large, after an "appropriate" de-projection required by the inferred small angles to the line-of-sight, when compared with suitable comparison samples of supposedly unbeamed randomly oriented objects, to maintain the assumption that the sources are drawn from the same population. This result was substantiated when more superluminal sources with large angular sizes were discovered (eg. Barthel et al., 1986).

Browne (1988) has recently reviewed the 'linear size problem' of superluminal and other core dominated radio sources. Although this problem is not a fundamental difficulty for beaming models it does suggest that the unified scheme does need some modification (see also de Bruyn and Schilizzi, 1986). Beam wobbling, as is inferred to be the case in 3C120 (Walker et al., 1987), will reduce the de-projection factors that one should use thereby alleviating the 'linear size problem'. Further study of the VLBI core and the large scale jet, which are presently underway, should clarify whether this is a viable explanation in the case of 0309+411.

An attractive alternative explanation for the 'linear size problem', discarded by Browne (1988) but favoured by Barthel (1989), is that the missing population of sources with large linear extent is to be found among the radio galaxies which have, statistically, larger linear sizes than quasars. Several tens of radio galaxies with sizes over 1 Mpc have now been identified (see, e.g. Saripalli et al., 1986) with the record still standing at 5.7 Mpc for 3C236 (Willis et al., 1974). A small deprojection factor would still be 'acceptable' if 0309+411 would be classified as a radio galaxy. It is therefore intriguing to note that 0309+411 is an intrinsically low-luminosity quasar with $M_V=-21$. In fact, the quasar-nucleus is comparable in brightness to the surrounding galaxy. This absolute magnitude has not been corrected for a possible extinction, but the observed ratio of Hα to Hβ admits at most about 2 magnitudes of visual extinction towards both the broad and the narrow line region. It is therefore unlikely that the optical emission line properties of 0309+411 have been strongly affected by an obscuring torus inferred to be present in all radio galaxies and quasars in the Barthel (1989) viewpoint (see also Chini et al., 1989). If all radio galaxies contain an obscured quasar-nucleus, but also if they have a duty cycle with intermittent phases of optical quasar activity, the distinction between radio galaxies and quasars, as far as the large scale radio structure is concerned, is not very meaningful. Perhaps that is the relevance of the properties exhibited by 0309+411.

Acknowledgements:

We thank Dr. J. Lub for carrying out the service observations at the WHT, Drs. D. Sybring for the use of his 608 MHz data in advance of publication and Dr. R. Schilizzi for comments on the manuscript The WHT is operated by the Royal Greenwich Observatory at the Spanish Observatorio del Roque de los Muchachos of the Instituto de Astrofisica de Canarias. The WSRT is operated by the Netherlands Foundation for Research in Astronomy (NFRA), which receives its financial support from the Netherlands Organization for Scientific Research (NWO).

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