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LETTER TO THE EDITOR

Broad H I absorption in the candidate binary black hole 4C37.11 (B2 0402+379)

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ABSTRACT

We report the discovery of extremely broad 21-cm H I absorption ($FWZI \sim 1600$ km s^{-1}) detected with the Westerbork Synthesis Radio Telescope in the radio source 4C37.11 (B2 0402+379). This object has been claimed to host a supermassive binary black hole (Rodriguez et al. 2006). The main features in the absorption profile are two components, separated by ~1100 km s^{-1}. The H I absorption in 4C37.11 is unusual because it is the first case where broad absorption is found to be *centred* on the systemic velocity of the host galaxy and not asymmetric and blueshifted as seen in all other galaxies with broad H I absorption. Given the large width of the absorption, we suggest that a possible explanation for the extreme properties of the H I absorption is that it is the kinematical signature of a binary black hole. If this interpretation is correct, the combined black-hole mass derived from the absorption profile is consistent with that derived from the luminosity of the spheroid. If the broad absorption is indeed due to a binary black hole, this finding confirms the importance of the gaseous component in the merging process of supermassive black holes.

Key words. galaxies: active – galaxies: individual: 4C37.11 (B2 0402+379) – galaxies: ISM

1. Introduction

Galaxy mergers and accretion are common phenomena, even in our nearby Universe. Early-type galaxies, and in particular those hosting an active galactic nucleus (AGN), are believed to form through mergers or accretion events. Because most early-type galaxies are known to host a black hole (e.g., Ferrarese & Ford 2005), it is therefore natural to expect that the two black holes (BH) from the progenitor galaxies will sink to the centre of the merger remnant where eventually they will merge. During this process, a binary black-hole system is expected to exist in the centre of the newly created galaxy. Recent numerical simulations (see e.g., Mayer et al. 2007, and references therein) have emphasised that this process is influenced profoundly by the presence of a gaseous component, because the orbital evolution of merging supermassive BHs is affected strongly by friction against this gaseous background. Gas is indeed commonly present in the nuclear regions of galaxies with AGN. This gas often exhibits complex kinematics due to the effects of the AGN on the ISM (e.g., gas outflows, Morganti et al. 2005; Holt et al. 2008, and references therein). Even more extreme kinematics could be expected in the case of binary black holes, where the gas in the nuclear region may be strongly disturbed and kinematical signatures of this might be observed.

Identifying binary black holes is not easy because the distance between the two black holes can be quite small and high spatial resolution is required. Indirect evidence for spatially unresolved binary black holes can be found, e.g., from the morphology of the radio emission and radio jets, or from semi-periodic signals in lightcurves (see Komossa 2003, for a review). However, a few cases of spatially resolved systems are known. These include NGC 6240 (Komossa et al. 2003) and 3C 75 (Owen et al. 1985). One candidate recently proposed is the supermassive binary black-hole system in the radio galaxy 4C37.11 (B2 0402+379). This radio source is classified as a compact symmetric object (CSO), although it has some properties that are unusual for a CSO. Interestingly, it is one of the few CSOs to possess a kiloparsec-scale radio structure. On VLBA scales, it has *two* compact, variable, flat-spectrum active nuclei, separated by only 7.3 pc. From one of them, two relatively symmetric radio lobes with a total extent of ~40 pc emanate. Because of this morphology, 4C37.11 has been considered to be a candidate binary black hole (Rodriguez et al. 2006).

H I absorption was earlier detected in 4C37.11 against one of the radio lobes by Maness et al. (2004). Here we present new H I observations revealing that the absorption is much broader than that found by Maness et al. (2004), and showing two components separated by ~1100 km s^{-1}. The characteristics of the broad absorption in 4C37.11 differ from other, previously detected broad H I absorption systems, and we discuss whether the absorption in 4C37.11 could indicate the existence of a binary black-hole system in this galaxy. We also present optical spectra to investigate the kinematics of the ionised gas, and confirm the value of the systemic velocity, which is important to the interpretation of the H I absorption.

2. The broad H I absorption

H I observations of 4C37.11 were performed using the westerbork synthesis radio telescope (WSRT) on 1 Nov. 2003 (duration 5 h) and were repeated on 4 Jun. 2005 (duration 11 h) to confirm the detection of the broad absorption profile. We used two bands

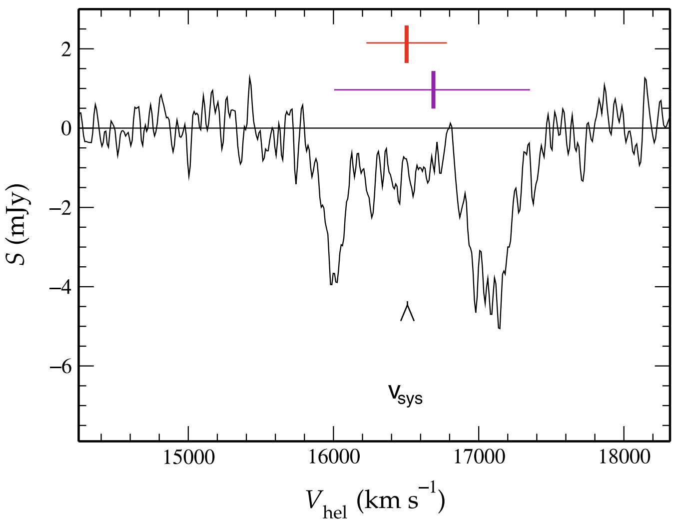

Fig. 1. H I absorption profile of 4C37.11. The kinematics of the optical [N II] emission-line are indicated in color; the thick vertical colored bars indicate the central velocity of the narrow (red) and broad (magenta) component of [N II], while the thin horizontal colored bars indicate the FWHM of the narrow and broad component. The systemic velocity ($v_{\rm sys}$) derived from the optical emission lines is also shown.

of 20-MHz bandwidth each, both centred on 1346 MHz and with 512 channels. The data were reduced using the MIRIAD software (Sault et al. 1995). The source 4C37.11 is unresolved at the resolution of the $WSRT - L$ band system (about 12 arcsec). A noise level of 0.39 mJy beam^{-1} was achieved for a velocity resolution of 36 km s^{-1} (after Hanning smoothing). The continuum flux density of 4C37.11 is 1.43 Jy.

The observed H I absorption profile is shown in Fig. 1. The extremely broad profile is detected in both observations. The H I absorption profile covers about 1600 km s^{-1} (full width zero intensity – FWZI) and is dominated by two peaks: one centred on ~16 000 km s^{-1} and a deeper, broader one centred on ~17 100 km s^{-1}. Fainter absorption is also detected between these two peaks. Despite the relatively similar bandwidth used, our H I detection is much broader than that found by Maness et al. (2004). While the deep H I absorption centred on ~17 100 km s^{-1} is detected in their VLBI observations, the remaining absorption does not appear in the profiles presented by them, although no integrated profile is presented by Maness et al. (2004), so a direct comparison with our data cannot be done. This means that for the deeper absorption we know that it is located against the southern radio-lobe/hot-spot and extends to about 20 pc, while the remainder of the absorption may have been resolved out by the high resolution of the VLBI data. Part of the H I absorption could be against the more extended continuum emission (on scales ~500 pc) that appears in the 0.3 GHz VLBI image (Rodriguez et al. 2006). Another possibility is that part of the absorption is against the kpc-scale radio lobes described by Maness et al. (2000). However, as we see in the next section, our optical spectra indicate that the H I absorption occurs closer to the AGN. As discussed for the case of Cygnus A by Conway & Blanco (1995), velocity widths of the H I absorption broader than ~150 km s^{-1} suggest that the absorption is unlikely to be due to gas located at large distances from the nucleus (i.e. the limited spatial scale of the continuum background would imply an overly large velocity gradient of the gas associated with a large-scale dust-lane). This argument appears to be even more valid in the case of the broad absorption detected in 4C37.11.

At the low resolution of our WSRT observations, 4C37.11 is unresolved and, therefore, the low optical depth that we derive for the absorption centred on ~17 100 km s^{-1} (peak $\tau \sim 0.005$) is a lower limit because the VLBA data of Maness et al. (2004) show that the covering factor is less than 1. Indeed, Maness et al. (2004) derived an higher value for the peak optical depth of this component of $\tau \sim 0.0179$ (and a column density of 1.8×10^{20} cm^{-2} for $T_{\rm spin} = 100$ K).

3. The broad optical lines

In order to compare the kinematics of the neutral and ionised gas, we performed new optical observations. An optical spectrum of 4C37.11 was taken with the william herschel telescope (WHT) on 13 January 2004 using the ISIS long-slit spectrograph with the 6100 Å dichroic, the R300B and R316R gratings in the blue and red arm respectively, and the *GG*495 blocking filter in the red arm to cut out second-order blue light. This resulted in a wavelength coverage from about 3500 to 8400 Å. A slit width of 1.3 arcsec was used, which was aligned along the parallactic angle of the observations (PA 120°), i.e. almost perpendicular to the PA of the radio source on VLBA-scales. The observations were done at an airmass of 1.04–1.08 and the seeing was approximately 1.9 arcsec. The total integration time was 1800 s for both the blue and red arm. Here, we present results for the red arm (6000–8400 Å), because [O I], [N II]+Hα and [S II] are the only identifiable emission lines in the spectrum (see also Stickel et al. 1993). We used the image reduction and analysis facility (IRAF) to perform a standard data reduction. The accuracy of the wavelength calibration is 0.3 Å. The spectral resolution derived from night sky-lines is 4.2 Å.

To analyse the kinematics of the emission-line gas, we fitted the profile of the [N II]+Hα emission lines. This was done by using Starlink software to create 1D spectra and fit Gaussian profiles to the emission lines. Figure 2 shows the [N II]+Hα profile across an aperture of 1.6 arcsec in the central part of the host galaxy. Following atomic physics, the Gaussian fit to the [N II]+Hα triplet was done by constraining the width of the [N II] doublet components to be the same and their intensity ratios to be 3.0, while leaving all other parameters free. A good fit was only obtained by using two Gaussian components (see Fig. 2 – top). The second component is much broader and is slightly redshifted with respect to the first, narrower one, in agreement with Rodriguez et al. (2006). This result is also confirmed by fitting the [S II] doublet using a similar procedure (see Fig. 2 – bottom).

The [N II]+Hα triplet is spatially extended to a radius of at least 4 arcsec (~4 kpc), but the signal outside the central aperture is too weak to fit accurately a 2-component model. There is no significant evidence of rotation in the data (although we note that our spectra were not chosen to be aligned with any kinematical axis).

The systemic velocity derived from the average central velocity of the narrow component of the [N II]+Hα lines in the central region is $v_{\rm sys} = 16\,502 \pm 24$ km s^{-1} or $z = 0.055046 \pm 0.000078$ (using the barycentric optical velocity definition). This redshift agrees with the estimate by Xu et al. (1994) and Rodriguez et al. (2006).

Figure 1 shows the width and central velocity of the narrow and broad emission-line components in relation to the H I absorption profile. Interestingly, the broad component has a width that is comparable to that of the absorption profile. Thus, as in many other radio galaxies similar to 4C37.11 (i.e. young,

Table 1. Ionised gas kinematics.

Spectral line	Narrow component		Broad component		Δv
	v_{center}	v_{width}	v_{center}	v_{width}	
[N II]	16505 ± 15	544 ± 26	16674 ± 83	1353 ± 126	169 ± 84
Hα	16500 ± 18	398 ± 36	16845 ± 303	1634 ± 779	345 ± 304
[S II]	16469 ± 18	513 ± 43	16725 ± 88	1384 ± 253	256 ± 90

Notes – All units are km s^{-1} and values have been corrected for instrumental resolution. Δv is the difference between the central velocity of the narrow and the broad component. Results for [S II] need to be taken with caution (because, due to the underlying stellar continuum, the intensity ratio of the broad component was constrained to be the same as that of the narrow component) and are merely included to show the reliability of our model for fitting [N II]+Hα.

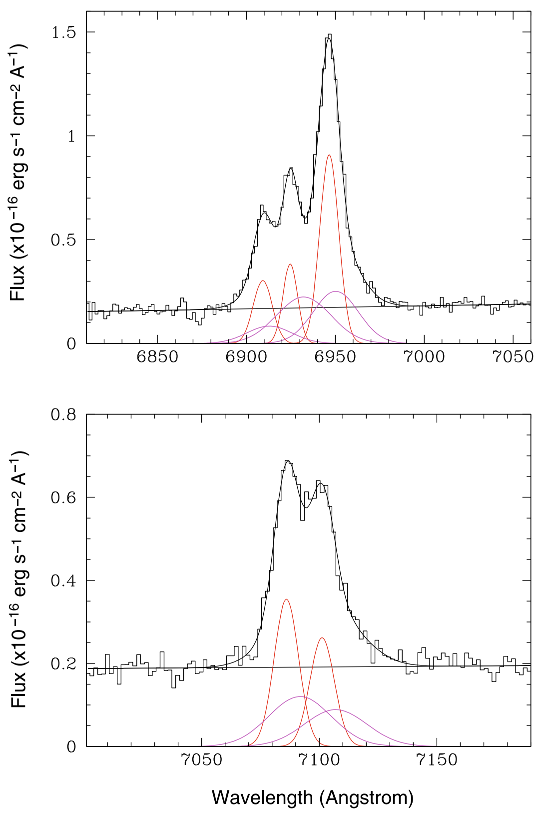

Fig. 2. Two-component fit to the [N II]+Hα triplet (*top*) and [S II] doublet (*bottom*). Details of the fit are given in Table 1.

compact radio sources), the ionised and neutral gas phases appear to have similar kinematical characteristics. This suggests that the absorbing H I gas is located in the central (i.e. inner kpc) region of the galaxy where the optical spectrum was taken.

4. Discussion: gas kinematics and binary black holes

4.1. The unusual nature of the gas kinematics in 4C37.11

The intriguing result presented above is the detection, in a radio source possibly hosting one of the rare examples of a binary black hole, of very broad H I absorption, whose main feature is two absorption components separated in velocity by ~1100 km s^{-1}. To be able to interpret this absorption, we first discuss how the properties of this absorption compare with what is seen in other radio sources.

Broad H I absorption profiles ($FWZI$ > 1000 km s^{-1}) have been detected in a handful of young or re-started powerful radio sources (see e.g., Morganti et al. 2005, and references therein). In this respect, it is unsurprising to find this broad absorption in 4C37.11, a CSO which are typically considered to be young radio sources where the radio jet could still be embedded in a relatively dense medium, perhaps left over from a merger event. The FWZI width of the absorption profile in 4C37.11 is as large as that of the broadest profiles observed by Morganti et al. (2005). However, the feature that makes 4C37.11 unusual is that the absorption profile is centred on the systemic velocity. The 4 radio galaxies observed by Morganti et al. (2005) with H I profile widths in excess of 1000 km s^{-1}, all have profiles that are quite asymmetric and blueshifted relative to the systemic velocity of the host galaxy. This difference means that the absorption in 4C37.11 may not be connected to gas outflows, or if it is, some key difference exists, e.g., in the geometry.

On the other hand, symmetric H I absorption profiles centred on the systemic velocity of the host galaxy have been found in many radio sources (e.g., Conway & Blanco 1995; Morganti et al. 2001; Vermeulen et al. 2003). However, the typical width of these absorption profiles is of the order of 200 km s^{-1}, much narrower than that of 4C37.11. Such relatively narrow symmetric absorption is often assumed to be caused by circumnuclear disks on the hundred-pc scale in which the rotational velocity reflects the galactic potential. The fact that the absorption in 4C37.11 is much broader most likely means that here it is not caused by such a large structure.

It is interesting to note that the ionised gas also has a broad component centred close to the velocity of the narrow component i.e., on the systemic velocity. This is also different from other compact (steep spectrum) radio sources (Holt et al. 2008, and refs therein). In these young radio sources, the broad components of the ionised gas are mainly found to be blueshifted and associated with outflows connected with the first phases of the nuclear activity.

4.2. Effects of binary BH on the gas kinematics?

The central question is, of course, what causes the broad, two-component absorption in 4C37.11. Maness et al. (2004) argued that the H I absorption detected by them (i.e., only the redshifted component) is gas expelled by the receding radio jet. Since the gas producing the H I absorption must be located in front of the continuum source, this can only occur if the outflowing gas is accelerated and dragged by the jet cocoon (so that it appears in front of the jet). Because the H I absorption is now found to be symmetric about the systemic velocity, this would then suggest that also on the side of the main jet an outflow of similar amplitude is present. The fact that the source is classified as a compact *symmetric* object could indeed suggest that the jets are orientated close to the plane of the sky, although this would require high flow velocities to explain the large observed (radial) component.

Moreover, Rodriguez et al. argued that the jets are orientated at <66° from the line-of-sight, not quite in the plane of the sky. A further complication is that the location of the blueshifted absorption is unknown and may not occur against the main jet. Nevertheless, given all uncertainties, a model explaining the two absorption components as approaching and receding outflows is probably not inconceivable.

However, the discussion in Sect. 4.1 illustrates that the properties of 4C37.11 are quite unusual, and perhaps this means that the absorption is caused by a different mechanism. Maness et al. (2004) and Rodriguez et al. (2006) inferred from their observations that the most likely explanation for the radio morphology of 4C37.11 is the presence of a binary system with two radio-loud, flat spectrum AGN separated by 7.3 pc. The unique characteristics of the very broad, two-component H I absorption are perhaps a further indication that extreme conditions are present in this object. It is conceivable that the absorbing gas is part of a structure in rapid rotation due to the two orbiting black holes. If so, one can use the H I velocity to estimate the combined mass of the two black holes. In this case, we would have to assume that the blueshifted part of the absorption is located against the (northern) lobe of 4C37.11 at ~20 pc from the nucleus, i.e. symmetrical to the redshifted part detected in VLBI by Manness et al. (2004). The velocity separation between the two peaks of the H I suggest that the orbital velocity is about ~500 km s^{-1}. Using these values, we find an estimated black holes mass of $\sim 10^9\ M_\odot$.

This mass compares well with the mass of the central compact object derived from the luminosity of the host galaxy, for example using the relations presented in Ferrarese & Ford (2005) and by Marconi & Hunt (2003). The observed *K*-band magnitude (2MASS) implies a black hole mass of just over $10^9\ M_\odot$, which is much higher than that estimated in a similar way by Rodriguez et al. (2006) using a *V*-band magnitude. However, the Galactic latitude of 4C37.11 is only 10°.5 and the correction for Galactic extinction is very uncertain. For example, the Galactic *V*-band extinction from Schlegel et al. (1998) is almost 3 mag larger than that used by Rodriguez et al. If this higher extinction value is used, a value for the combined BH mass is derived that is similar to the one found from the *K* mag. It appears, therefore, that if the broad absorption is interpreted as the kinematical signature of a binary black hole, it leads to a consistent mass estimate. The weakness of the argument is that the location of the blueshifted component in unknown and this makes a detailed interpretation of the data uncertain. It may indicate that the blueshifted part occurs on the scale of many tens of pc (i.e., resolved out by the observations of Maness et al. 2004). Even in this case the gas kinematics may be affected by the presence of the binary BH, although the kinematics would be more difficult to interpret and deriving the BH mass would not be straightforward.

5. Conclusions

We have presented the detection of surprisingly broad H I absorption, mainly consisting of two components separated in velocity by ~1100 km s^{-1}, against the compact symmetric object 4C37.11. Interestingly, this radio source hosts a candidate supermassive binary black-hole system. The characteristics of the H I absorption are unusual compared to H I absorption seen in other radio sources. The presence of a fast outflow that would explain the broad H I absorption cannot be ruled out, but an alternative interpretation is that there is a binary black hole in 4C37.11. If interpreted as the kinematic signature of a binary black hole, an estimate of the mass of the combined black holes is derived that is consistent with the value derived from the luminosity of the spheroid. However, the fact the location of the blueshifted absorption is unknown prevents an unambiguous interpretation. It is clear that further high-resolution H I observations of 4C37.11 are needed to determine what is really occuring in the central regions of 4C37.11. Indeed, after submission of this Letter, we have become aware of new, deeper VLBA observations of the H I absorption in 4C37.11 (Rodriguez et al. 2009, ApJ, submitted). These new data now also show the second absorption component at VLBA scales and lend further support to the binary black hole hypothesis.

Finally, our data do show that the nucleus of 4C37.11 is gas rich, and, if 4C37.11 indeed harbours a binary black hole, underline the importance of gas in the formation of these systems.

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