LETTER TO THE EDITOR

A circumnuclear disk of atomic hydrogen in Centaurus A

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May 12, 2008

ABSTRACT

We present new observations, performed with the Australia Telescope Compact Array, of the H₁ absorption in the central regions of Centaurus A. For the first time, absorption is detected against the radio core at velocities blueshifted with respect to the systemic velocity. Moreover, the data show that the nuclear redshifted absorption component is broader than reported before. With these new results, the kinematics of the H₁ in the inner regions of Cen A appears very similar to that observed in emission for the molecular circumnuclear disk. This suggests that the central H₁ absorption is not, as was previously claimed, evidence of gas infall into the AGN, but instead is due to a cold, circumnuclear disk.

Key words. galaxies: active – galaxies: individual: Centaurus A – galaxies: ISM

1. Introduction

In the central regions of galaxies with an Active Galactic Nucleus (AGN), gas can play different, sometimes competing roles. This gas is considered to be essential for fuelling the AGN and for turning a dormant black hole into an active one. On the other hand, the gas can also be expelled from these regions as a result of the release of energy from the active nucleus, so that fuelling and star formation are quenched. Moreover, some of the nuclear gas can be arranged in regular structures. Such circumnuclear disks, under certain geometries, can hide the active nucleus from our direct view and can play an important role in explaining the apparent differences between the various types of AGN. The conditions in these central regions are clearly harsh, but nevertheless they are such that not only very dense or highly ionised clouds, but also atomic and molecular gas can survive.

It has been suggested that neutral hydrogen falling onto the central black hole is a possible mechanism for fuelling an AGN. For many years, the available data seemed to indicate that if H₁ absorption is detected against the core of a radio-load AGN, it is seen at velocities redshifted with respect to the systemic (see e.g. van Gorkom et al. 1989). Although other factors, such as non-circular motions, can explain redshifted absorption in a single galaxy (see e.g. García-Burillo et al. 2005). Many cases of blueshifted H₁ absorption against the radio-core are now known (Vermeulen et al. 2003; Morganti, Tadhunter & Oosterloo 2005) and as a result, the evidence for nuclear H₁ absorption to be more often redshifted than blueshifted, and hence for gas infall fuelling the AGN, has disappeared in recent years. A particularly well-known example of possible H₁ infall is the detection of redshifted absorption against the nucleus of the closest radio galaxy, Centaurus A¹ (van der Hulst, Golish & Haschick 1983). This case is important because if it would indeed be due to gas falling into the AGN, the proximity of Cen A would allow a detailed study of the infall and related processes.

In this Letter we present new observations of the H₁ absorption in Cen A that suggest a different interpretation of what causes the H₁ absorption against the core of this galaxy. The broad observing band has allowed us to detect, for the first time, blueshifted H₁ absorption against the core of Cen A. This obviously complicates the interpretation of the H₁ absorption as infall. Below, we discuss the various possibilities and we conclude that it is evidence that the H₁ absorption is caused by a cold, circumnuclear disk and not by infall into the AGN.

2. The ATCA Data

Here, we only give a brief summary on the new observations of Cen A, a full description, including results on the large-scale gas disk, will be presented in a forthcoming paper (Struve et al., in prep). The observations were done using the Australia Telescope Compact Array (ATCA) in three standard 750-m, 1.5-km and 6-km configurations, and were carried out on 12, 14 and 20 April 2005 (12 h in each configuration). The choice of the configurations used was made to obtain good spatial resolution, but at the same time to avoid to include too many too short baselines. Given the very strong, very extended continuum emission of Cen A, bandpass calibration is very difficult for short baselines (see below). A 16-MHz band with 512 channels was used, equivalent to a velocity range of ~3000 km s⁻¹. This is much broader than used in earlier observations (van der Hulst, Golish & Haschick 1983; Sarma, Troland & Rupen 2002). The centre of the band was set to $v_{\text{pec}} = 304$ km s⁻¹ and the velocity resolution is 13.2 km s⁻¹, after Hanning smoothing. The broad band was chosen to

¹ At the assumed distance of Cen A of 3.5 Mpc, 1 arcsec corresponds to ~17 pc, or equivalently, 1 arcmin to 1 kpc
make sure that the full width of the central H\textsc{i} absorption would be sampled if broad signals would appear (as have been seen in other radio galaxies, see Morganti, Tadhunter & Oosterloo (2005)). PKS 1934–638 was used as bandpass calibrator. Short observations of about 10 minutes were done every hour on the phase calibrator PKS 1315–46. The data reduction was carried out using the MIRIAD package (Sault, Teuben & Wright 1995).

The extremely strong radio continuum of Cen A (> 100 Jy on the shortest baseline) makes the bandpass calibration the most delicate part of the calibration. We have used the same technique applied by Oosterloo & Morganti (2005) on earlier observations of Cen A. This involves smoothing the bandpass calibration obtained from PKS 1934–638 with a box-car filter 15 channels wide. This smoothing effectively increases the flux level of PKS 1934–638 to about 60 Jy which is higher than the detected flux on almost all baselines of Cen A. This procedure is allowed because the features in the instrumental bandpass are fairly broad in frequency. This smoothed bandpass correction is applied to the unsmoothed data of Cen A. The resulting spectral dynamic range is better than 1:10000 on the shortest baselines.

The subtraction of the continuum was done using the task UVLIN, making a second order fit to the line-free channels of each visibility record and subtract this fit from the spectrum. In order to improve on the phase calibration obtained from PKS 1315–46, frequency independent self-calibration was performed taking advantage of the strong nuclear H\textsc{i} absorption at some velocities. The final cube was made using the combined datasets. In this Letter we will use the high-resolution cube obtained with uniform weighting and including the 6-km antenna. The lower resolution cubes will be discussed in Struve et al. (in prep). The restoring beam is 8.1 × 6.8 arcsec with PA = −12.3°. The rms noise per channel is ∼ 1.3 mJy beam\(^{-1}\). The continuum image obtained from the line-free channels is shown in Fig. 1.

3. Broad nuclear H\textsc{i} absorption

As expected, we detect H\textsc{i} in emission and, against the strong continuum, in absorption. A full description of these data will be given in Struve et al. (in prep). In this letter we focus on the H\textsc{i} absorption detected against the very central regions.

Both deep H\textsc{i} absorption near the systemic velocity and fainter redshifted absorption against the radio core had been detected before by van der Hulst, Golish & Haschick (1983) and Sarma, Troland & Rupen (2002). Our data show, of course, the deep absorption component near the systemic velocity. However, the new and interesting result is that in our new data, the absorption against the nucleus covers a much larger velocity range compared to previous observations. This larger width of the fainter component is due to both the fact that the redshifted absorption extends to more extreme velocities and to a newly detected blueshifted component. The absorption spectrum is shown in Fig. 2. The total velocity width is about 400 km s\(^{-1}\). The band-width used by van der Hulst, Golish & Haschick (1983) was 300 km s\(^{-1}\) while that used by Sarma, Troland & Rupen (2002) only 150 km s\(^{-1}\). It is therefore clear that it is due to the limited band-width used that only part of the redshifted H\textsc{i} absorption was detected in those observations and that the blueshifted absorption was not detected at all.

The nuclear H\textsc{i} absorption appears asymmetric with respect to the systemic velocity (542 km s\(^{-1}\) van Gorkom et al. (1990), covering (heliocentric) velocities from −400 km s\(^{-1}\) (about −140 km s\(^{-1}\) blueshifted compared to systemic) up to ∼800 km s\(^{-1}\) (i.e. about +260 km s\(^{-1}\) redshifted relative to systemic). The peak absorption has an optical depth of \(\tau \approx 0.83\). The column density of the deeper absorption component is \(N_{\text{HI}} \approx 2.7 \times 10^{19} T_{\text{spin}} \text{ cm}^{-2}\). This column density is in good agreement with what derived by van der Hulst, Golish & Haschick (1983). One should note that the spin temperature \(T_{\text{spin}}\) for H\textsc{i} absorption occurring close to an AGN is a very uncertain parameter. Another uncertainty in \(N_{\text{HI}}\) is that above we have assumed that the absorption covers the entire underlying continuum source (see also below).

3.1. A circumnuclear H\textsc{i} disk?

One of the central questions is of course what structure in Cen A is causing the faint, broad nuclear H\textsc{i} absorption that we see. The detection of blueshifted absorption obviously complicates the interpretation that it is due to infall. We can exclude that the broad, fainter absorption is produced by gas located at large (kpc) distance from the nucleus. Figure 2 shows that the gas in the large-scale disk is on (almost) circular orbits and that absorption due to the large-scale disk against the radio core is near the systemic velocity. Projected on the centre, the large disk shows some spread in velocity (due to non-circular motions) but this spread is much smaller than required to explain the broad central absorption. If some of the absorption would instead occur against the inner continuum jet, the fact that the jet is more or less aligned with the minor axis of the large-scale gas disk means that we would still expect this absorption to be mainly at the systemic velocity. The deep absorption component near the systemic velocity is most likely due to the large-scale gas disk seen in front of the core and jet, but the fainter, broad absorption cannot be caused by it.

One possibility for explaining the nuclear absorption at velocities away from systemic is to assume that the large-scale gas disk is quite thick. In the models of Eckart (1990), the redshifted nuclear absorption components are explained by high-latitude clouds of the large-scale disk at radii of ~500 pc. However, such models fail to explain the simultaneous occurrence of blueshifted and redshifted absorption. This means that in order to reproduce the observed width of the broad, shallow absorption, large radial motions, both inward and outward, would be required to exist in the large-scale disk and such motions are not observed.
An entirely different possibility is that the broad, shallow absorption is caused by a circumnuclear \( \text{H}_1 \) disk. If so, one of the prime cases for cold gas falling into an AGN would disappear.

The presence of a cold circumnuclear disk with a size of roughly 100 parsec has been suggested by a number of studies (see e.g. Israel et al. 1990, and references therein). The central regions of Cen A are highly obscured in the optical, but they have been studied in detail using observations at longer wavelengths. Ionised and molecular gas was observed in the K-band using both long-slit (Marconi et al. 2001) and integral-field spectroscopy (Krajnović, Sharp, Thadde 2007; Neumayer et al. 2008). The most recent observations (Neumayer et al. 2008) show that in the central few arcseconds (i.e. tens of pc) very different morphologies are found between the high- and low-ionisation lines. The highly ionised gas shows a strong kinematical influence of the jet. On the other hand, the molecular gas (\( \text{H}_2 \)) appears to be in a regularly rotating disk, influenced only by gravity. The velocity channel maps (Fig. 8 in Neumayer et al. 2008) show the kinematics of this inner molecular disk, with velocities ranging from \(-230 \text{ km s}^{-1}\) to \(230 \text{ km s}^{-1}\) compared to systemic. Part of this velocity range is due to the velocity dispersion of the gas, whose origin is not known, the rest is due to rotation. The \( \text{H}_2 \) kinematics are best modelled by a tilted-ring model of a warped gas disk that, in the inner part, appears quite face on (34\(^\circ\)) and with position angle of the kinematic major axis of \(-155^\circ\).

Other evidence for a circumnuclear molecular disk comes from CO observations (Eckart 1990; Israel et al. 1990; Rydbeck et al. 1993). In particular, JCMT CO \( J=3-2 \) observations (Liszt 2001) have been explained by a disk of radius 168 pc seen nearly edge-on (in position angle 138.5\(^\circ\) on the sky, therefore perpendicular to the base of the radio jet). In these observations - that have a resolution of 14 arcsec - this disk is barely resolved. For both the CO and the \( \text{H}_2 \) data the kinematic modelling is somewhat uncertain. Nevertheless, the difference in the inclination derived for the inner \( \text{H}_2 \) disks and the somewhat larger CO structure suggests that it is heavily warped at all spatial scales.

In an attempt to see whether the broad \( \text{H}_1 \) absorption could be related to this circumnuclear disk, we have compared the CO \( J=3-2 \) data (kindly provided by H. Liszt) and the \( \text{H}_1 \) data cubes. Figure 2 shows the position-velocity plot obtained along a line (position angle 139\(^\circ\)) through the nucleus of Cen A. The gray-scale and the thin contours represent the \( \text{H}_1 \) data while the CO data is given by the thick contours. Note that the field of view of the CO observations was only 2\( \times \)2 arcmin so the CO information does not extend beyond 1 arcmin radius.

The CO data clearly show two kinematical components: a large component with a relatively shallow velocity gradient and a smaller, inner component with a steep velocity gradient. The large CO component corresponds to the large-scale gas disk associated with the dustlane, while the inner component is the circumnuclear disk modelled by Liszt (2001). The comparison with the \( \text{H}_1 \) clearly suggests that both the outer (in emission, and part in absorption) and the inner component (in absorption) are seen also in \( \text{H}_1 \). Figure 2 illustrates the point made earlier that the kinematics of the large disk is clearly such that it cannot explain the large velocity range seen in the very centre.

For the inner part, Fig. 2 shows that the broad, inner \( \text{H}_1 \) absorption corresponds very well with the fast rotating, inner CO disk. In particular, the redshifted \( \text{H}_1 \) absorption covers the same velocity range as the CO, suggesting that it is not associated with falling gas. It is also clear that the \( \text{H}_1 \) and CO show differences: the extent of the CO, both spatially and in the blueshifted velocities, is larger than of the inner \( \text{H}_1 \). Such differences can be expected given that the characteristics of the inner \( \text{H}_1 \) absorption is set by the size of the background continuum emission, not by the \( \text{H}_1 \) structure itself. With the spatial resolution of our \( \text{H}_1 \) data (8 arcsec), the inner \( \text{H}_1 \) absorption is unresolved while the total extent of the CO disk is about 20 arcsec. If the background continuum against which we see the \( \text{H}_1 \) absorption is smaller than the circumnuclear CO disk (see below), this would explain the apparent difference in size and velocity range.

3.2. The nature of the absorbed continuum

As already eluded to above, for the interpretation of the \( \text{H}_1 \) absorption, it is important to understand what the continuum background could be. It turns out that it is not quite obvious to unravel this. It is natural to assume that the strongest absorption is against the very inner radio core. However, this is unlikely to be the case. The radio continuum emission on the sub-kpc scale has been studied using high-frequency VLA (about 0.5 arcsec resolution at 8.4 GHz, Hardcastle et al. 2003) as well as VLBI observations at frequencies 2.3 GHz and higher, with very high spatial
resolution (a few millarcsec resolution at 2.3 GHz; Jones et al. 1996; Tingay et al. 1998). The highest frequency data show that, on parsec and sub-parsec scales, the radio continuum in the central region is dominated by a core-jet structure. However, the VLBI data also show that the core has a strongly inverted spectrum and that it is actually not visible at 2.3 GHz. This suggests that the very innermost part of the radio source (up to ∼ 0.4 – 0.8 pc) is seen through a disk or torus of ionised gas which is opaque at lower frequencies due to free-free absorption (Jones et al. 1998). The above means that the radio core is unlikely to be detected also at 1.4 GHz and it is not the core itself against which the 21-cm absorption can be occurring.

Given that, at 1.4 GHz, the radio core is not seen, the radio continuum on the milli-arcsec scale appears concentrated in the jet and counter-jet. Given the circumnuclear disk structure discussed above, with a PA close to perpendicular to the jet axis, the fact that the main jet is coming toward us means that it is likely to be in front of the circumnuclear disk and that it cannot cause the absorption. One possibility would be then that the H\textsc{i} absorption is against the counter-jet. However, given the small opening angle of the jet this can be excluded as most of the absorption would be seen at velocities close to systemic.

An interesting clue is that extra flux (at least 50 mJy) is clearly present on the short baselines in the 1.4-GHz VLBI experiments (Tingay priv. comm.), indicating the presence of large-scale structures that are not evident in the images. This structure would be still well inside the 1 arcsec (∼18 pc) imaged at the highest VLA resolution (for 21 cm). It is difficult to quantify the amount of flux on larger scales from a comparison of VLBI data with lower-resolution data due to the variability of the nuclear regions (Romero, Benaglia & Combi 1997; Abrahm et al. 2007) because simultaneous observations are needed. It is therefore unclear whether this extra component can cause the absorption.

If, however, this would be the case, we have a situation similar to that suggested for Cygnus A (Conway & Blanco 1995, Conway 1999). In this source, the H\textsc{i} opacity peaks off the jet, on the counter-jet side, with maximum opacities occurring north and south of the jet axis. The counter-jet of Cyg A alone is too narrow to explain the broad width of the absorption. Therefore, Conway (1999) suggested that a more diffuse component could be at the origin of the absorption. This component could be due to thermally emitting ionised gas evaporated from the inner edge of a torus or disk. Also in Mrk 231 evidence of H\textsc{i} absorption against a diffuse component has been found (Carilli et al. 1998). In this object, they identify the H\textsc{i} and the radio continuum disk as the inner part of the molecular disk seen on the larger scale.

If the scenario described above is correct, we can make some remarks about the conditions of the H\textsc{i} material and whether the location of the H\textsc{i} and of the molecular gas are what expected from the physical models of the circumnuclear disks/tori. In this case, the column density of the H\textsc{i} is going to be much larger than estimated above, because the absorption will likely cover only a small fraction of the sub-arcsec continuum. For example, if the absorption is only against the counterjet-side, and assuming the jet/counterjet ratio from Jones et al. (1996) of 4 - 8, the column density is at least a factor four higher. This factor would be even higher in the case of the absorption against the more diffuse component. In addition, in a circumnuclear structure, \( T_{\text{spin}} \) is likely to be a few \( \times 10^3 \) K, as the H\textsc{i} is affected by the central AGN (Maloney et al. 1996). Therefore the column density could easily be as high as \( 5 \times 10^{23} \) cm\(^{-2}\). Interestingly, this is a similar column density as derived from the hard X-ray spectrum of Cen A that is fitted with an heavily absorbed power-law model with a column density of \( \sim 10^{23} \) cm\(^{-2}\) (Evans et al. 2004).

Physical models of the circumnuclear disks/tori have been investigated by Maloney et al. (1994, 1996 and refs therein). They identify an effective ionisation parameter that determines whether, given the distance from the nucleus, the material is atomic or molecular. This effective ionisation parameter is \( \xi_{\text{eff}} = L_X N_{22}^{-1/2} r^{-2} \), where \( L_X \) is the luminosity of > 2 keV X-rays, \( n \) is the gas density, \( r \) is the distance to the nucleus, \( N_{22} \) is the total column density in units of \( 10^{22} \) cm\(^{-2}\). For \( \xi_{\text{eff}} > 10^{-3} \), the gas will be largely atomic, otherwise mainly molecular. For Cen A, the X-ray luminosity is \( L_X = 5 \times 10^{41} \) erg/s (Evans et al. 2004) and the X-ray column density is \( 10^{23} \) cm\(^{-2}\). A rough estimate of the density can be derived from the H\textsc{i} column density if we assume that the region of absorption is comparable to the region with free-free absorption (that covers the innermost ∼ 0.4 – 0.8 pc). This gives a density of \( 1 - 2 \times 10^6 \) cm\(^{-3}\). These values give a radius of 1-3 pc for \( \xi_{\text{eff}} = 10^{-3} \). Thus, we may hypothesise that the central region of Cen A hosts a gaseous disk composed of multiple phases where the inner part (but outside the fully ionised region) is mainly atomic and after that molecular.

4. Conclusions

Using new, broad-band, H\textsc{i} observations of Cen A we have shown that the nuclear absorption is broader than previously known and that it has a blueshifted component. Using various arguments, but in particular the comparison with the molecular gas data, we have shown that the H\textsc{i} absorption is likely to be caused by a cold, circumnuclear disk and that it does not constitute direct evidence of gas infall into the AGN.

Sensitive VLBI observations are now needed to further explore the characteristics of the nuclear H\textsc{i} as well as the picture proposed in this paper and, in general, to learn more about the central regions of this fascinating, nearby AGN.

Acknowledgements.

We are most grateful to Harvey Liszt for providing us the CO cube that has been crucial in this work. Based on observations with the Australia Telescope Compact Array (ATCA), which is operated by the CSIRO Australia Telescope National Facility. This research was supported by the EU Framework 6 Marie Curie Early Stage Training programme under contract number MEST-CT-2005-19669 ESTRELA.

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