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Anomalous H I kinematics in Centaurus A: Evidence for jet-induced star formation

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Abstract. We present new 21-cm H I observations performed with the ATCA of the large H I filament located about 15 kpc NE from the centre of Centaurus A and discovered by Schiminovich et al. (1994). This H I cloud is situated (in projection) near the radio jet of Centaurus A, as well as near a large filament of ionised gas of high excitation and turbulent velocities and near regions with young stars. The higher velocity and spatial resolution of the new data reveals that, apart from the smooth velocity gradient corresponding to the overall rotation of the cloud around Centaurus A, H I with anomalous velocities of about 100 km s^{-1} is present at the southern tip of this cloud. This is interpreted as evidence for an ongoing interaction between the radio jet and the H I cloud. Gas stripped from the H I cloud gives rise to the large filament of ionised gas and the star formation regions that are found downstream from the location of the interaction. The implied flow velocities are very similar to the observed anomalous H I velocities. Given the amount of H I with anomalous kinematics and the current star formation rate, the efficiency of jet-induced star formation is at most of the order of a percent.

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

1. Introduction

Interaction between the non-thermal plasma ejected from the active nucleus and the interstellar medium (ISM) of a galaxy is responsible for a variety of phenomena in radio galaxies such as ionisation of the gas and AGN driven outflows. Such interactions are considered to be particularly relevant in high redshift radio galaxies, as they are typically living in a gas-rich environments (see e.g. van Breugel 2000, and references therein). One aspect of jet-ISM interaction is that it can trigger star formation. Such jet-induced star formation is considered a possible mechanism to explain the UV continuum emission observed in the host galaxies of distant radio sources and the "alignment effect" between the radio emission and this continuum (Rees 1989).

Detecting and studying star formation produced by this mechanism in high-z radio galaxies is very challenging. The only case where this has been done is 4C 41.17 (Dey et al. 1997). Because of the observational problems for high-redshift sources, it is important to find nearby examples of star formation triggered by the radio jet that can be studied in more detail.

Moreover, recent numerical simulations have shown some interesting results. It is found that the interaction of a radio jet with a clumpy gaseous medium can produce fragmented clouds that cool and condense very quickly (Mellema et al. 2002; Fragile et al. 2004). Even for moderate jet velocities, the interaction and the consequent production of shocks by the radio jet has the potential to trigger large-scale star formation in a galaxy (Fragile et al. 2004; van Breugel et al. 2003). More data, in particular for nearby objects, are needed to better constrain these models.

Only a few cases are known of nearby radio galaxies where off-nucleus young stars are found and where a possible relation exists with the radio jet (Minkowsky's object and 3C285; van Breugel et al. 1985; van Breugel & Dey 1993). The best example is perhaps the nearby radio galaxy Centaurus A. About 15 kpc NE from the centre of the galaxy, well outside the main optical body, groups of young stars (with an estimated age of about 15 Myr) are found at the location where the large-scale radio jet passes large filaments of highly ionised gas with turbulent kinematics and where also a large cloud of neutral gas is found (Schiminovich et al. 1994; SGHK). The presence of these young stars has been explained by several authors as resulting from star formation triggered by gas shocked by the passage of the radio jet. Given the proximity of Centaurus A, many aspects of the jet-cloud interaction, the star formation and the spatial variation of the properties of the gas and the stars, can be studied much better than in any other source and it can serve as a prototype case. In this paper we investigate the jet-induced star formation hypothesis in more detail using the kinematics of the neutral hydrogen found in this location.

2. The north-east region of Centaurus A

The north-east region of Centaurus A, up to a few tens of kpc from its nucleus, is a particularly complex site where different

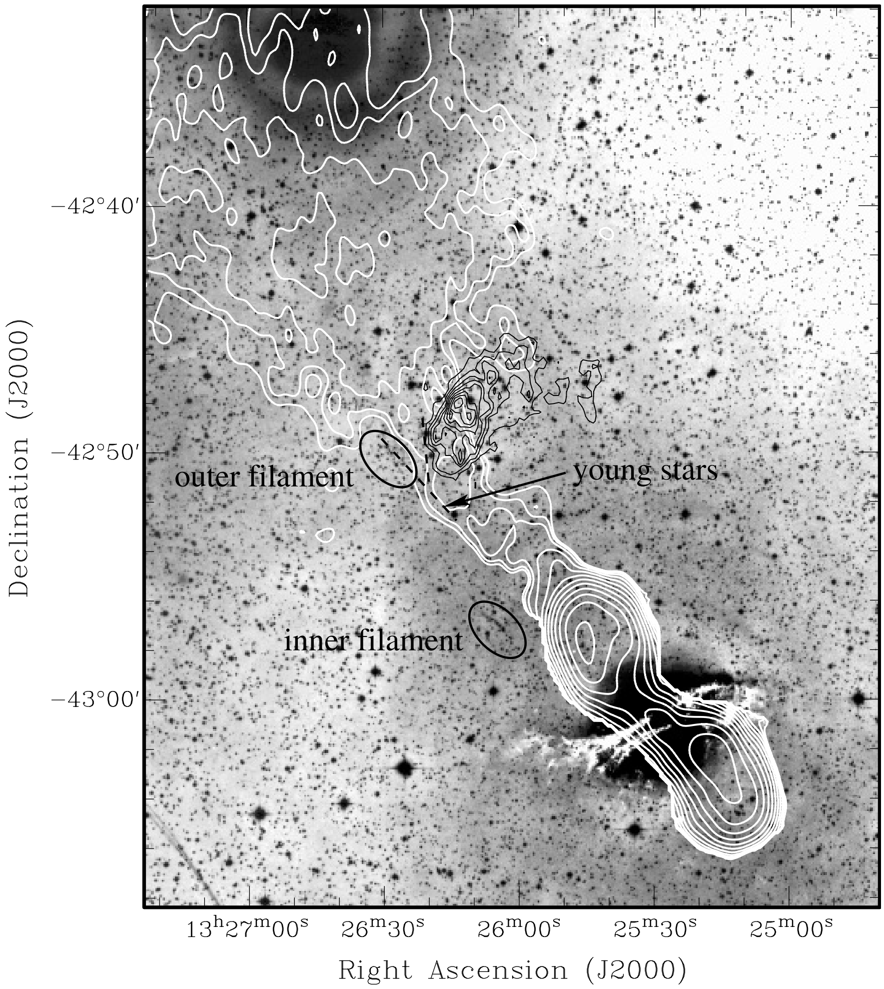

Fig. 1. Overlay showing the positions of the various components described in the text. The optical image (kindly provided by D. Malin) shows the well-known dust lane of Centaurus A and the faint diffuse optical emission that extends to very large radius. The white contours denote the radio continuum emission (after Morganti et al. 1999) showing the bright inner radio lobes and the large-scale jet that connects these lobes to the so-called Northern Middle Lobe (NML) in the top-left of the figure. The black contours denote the H I cloud discussed in this paper (see also Fig. 2). The locations of the inner and outer filaments of highly ionised gas are indicated, as well as the location of young stars (see also Fig. 4).

structures have been found and studied: 1) a complex system of filaments of ionised gas: the so-called *inner filament*, located ~8 kpc[1], and the *outer filament* ~ 15 kpc from the centre (Blanco et al. 1975; Morganti et al. 1991); 2) a large-scale radio jet that connects the bright inner radio lobes to the much larger Northern Middle Lobe (NML) and outer radio lobe (Morganti et al. 1999). This radio jet is either a classic jet driven by the AGN in Cen A, or it is part of a buoyant bubble of plasma deposited by an intermittently active jet (Saxton et al. 2001); 3) regions of recent star formation (Graham 1998; Fassett & Graham 2000; Mould et al. 2000; Rejkuba et al. 2002); and 4) large H I clouds that appear to form a partial ring rotating around the galaxy (SGHK). Near the location of the peak of the H I emission CO and cold dust are detected (Charmandaris et al. 2000; Stickel et al. 2004).

Although the inner and outer filaments are not ionised by star formation (Morganti et al. 1991; Sutherland et al. 1993), young stars (as young as 15 Myr) and a few small star forming regions have been detected in optical observations at the location of both the inner and the outer filaments of ionised gas (Mould et al. 2000; Rejkuba et al. 2002), while also recent GALEX data (Neff et al. 2003) indicate the presence of young stars. In the outer filament, the optical observations show that the stars are found in two groups, one aligned with the radio jet and one in a north-south alignment along the edge of the H I cloud (Rejkuba et al. 2002; see Fig. 3). This morphology is confirmed by the GALEX data.

The large-scale radio jet appears to pass (at least in projection) very close to the location of the H I cloud as well as close to the outer filament of ionised gas. This is illustrated in Fig. 1. The spatial coincidence of these structures, together with the fact that the ionised and neutral gas have the same overall velocity, has led to the suggestion (e.g. Graham 1998) that the radio jet is interacting with the H I cloud leading to the filaments of very turbulent and highly excited ionised gas and triggering the star formation in this region.

[1] We have assumed a distance of Centaurus A of 3.7 Mpc (Hui et al. 1993), 1 arcsec ~ 18 pc.

If the radio jet is indeed interacting with the H I cloud, one may expect to see direct evidence in the kinematics of the H I for this interaction in the form of deviations, driven by the radio plasma, from the overall rotation of the H I cloud about the galaxy. Due to the limited spatial and spectral resolution of the data of SGHK, only the overall coincidence in space and velocity of the neutral and ionised gas could be established. To investigate whether there is indeed direct kinematical evidence for a jet-cloud interaction, where this is occurring and how large the kinematical anomalies are, we have obtained new H I data with higher spatial and spectral resolution.

3. Observations and data reduction

The observations were done using the Australia Telescope Compact Array (ATCA) in two standard 750-m and 1.5-km configurations. The observations (12 h in each configuration) were carried out on the 12th and 20th April 2000. The choice of these two configurations was made to obtain good spatial resolution for the region of interest (as imaged by SGHK). Another important consideration was to use configurations that do not contain (many) short baselines. Given the very strong continuum emission of the radio source in Centaurus A, bandpass calibration is in practise impossible on short baselines. The shortest baseline in the combination of the two configurations is 30 m long, but the remaining ones are all longer than 100 m. The continuum flux on the 30-m baseline was too strong to allow proper bandpass calibration of the data on this baseline (see below) and the data from this baseline was not used in making the images. This implies that structures in a single channel that are larger than about 7 arcmin are not detected in our data. The extent of the H I cloud in a single channel is well below this size, therefore not using baselines shorter than 100 m does not influence the results.

One pointing was observed, centred on α(J2000) = $13^{h}26^{m}15^{s}$ and δ(J2000) = $-42°45'00''$. Using this pointing centre, the strong continuum emission from the central region of Centaurus A was located at the half-power point of the primary beam. This somewhat attenuates the strong continuum signal that otherwise would make the detection of the relatively weak H I emission more difficult. A band of 16 MHz with 512 channels was used and the central frequency was set at 1418 MHz, corresponding to the velocity of the previously detected H I emission ($\sim$300 km s^{-1}, SGHK). The final velocity resolution is 13.2 km s^{-1} after Hanning smoothing the data. This is about a factor three better than that of the data of SGHK.

The source PKS 1934−638 was used as bandpass calibrator and observed for about 1 h. Short observations of about 5 min were done every hour on the phase calibrator PKS 1315−46. The data reduction was carried out using the MIRIAD package (Sault et al. 1995).

As also described by SGHK, the extremely strong radio continuum of Centaurus A (>100 Jy on the shortest baseline) makes the bandpass calibration the most delicate part of the data reduction and it requires extra care to make sure that fairly flat spectral baselines are obtained. Even the strong bandpass calibrator PKS 1934−638 (14.9 Jy at the observed frequency) is not strong enough compared to Centaurus A. In order to minimise the contribution of extra-noise from the bandpass calibration, we have smoothed the bandpass calibration obtained from PKS 1934−638 with a box-car filter 15 channels wide. This 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 Centaurus A. This smoothed bandpass correction has been applied to the *unsmoothed* data of Centaurus A. This ensures that the velocity resolution is preserved without increasing too much the noise of the data. This procedure to calibrate the bandpass appears to work very well, mainly due to the relatively flat intrinsic bandpass-shape that is typical of the ATCA. Only for the data on shortest (i.e. 30-m) baseline it failed to produce usable spectra and for this reason the data of this baseline were not used in making the line-images of the H I cloud. Only residuals that are very broad in frequency remain in the data, but this does not have any effect on the conclusions of this paper. The noise level in the final datacube is 1.5 mJy beam^{-1} while the theoretical noise level for the instrumental setup used is 1.1 mJy beam^{-1}. Hence our method of calibrating the spectral response appears to have worked fairly well.

In order to improve on the phase calibration obtained from PKS 1315−46, frequency independent selfcalibration was also performed taking advantage of the strong unresolved nuclear H I absorption, still visible in a few channels despite the large offset from the nucleus of our pointing centre.

The subtraction of the continuum was done using the task UVLIN, which makes a linear fit to the continuum in the visibility data and subtracts it.

The final cube was made using the combined dataset using robust weighting (Briggs 1995) with the robustness set to 0. The restoring beam is 29.1 × 19.5 arcsec in PA = −4.7°. The spatial resolution of these observations is therefore slightly more than a factor two higher than what obtained by SGHK. The 3-σ detection limit over 13.2 km s^{-1} is 1.0×10^{20} cm^{-2} which is the same as the detection limit in the SGHK data.

In our data, we detect mainly the large H I cloud that peaks 15′ NE of the nucleus. The other H I detected by SGHK that is part of the outer H I ring, as well as the H I associated with the well-known dust lane of Centaurus A, is visible in our data, but the signal-to-noise of this emission is strongly affected by the primary beam. Therefore, we will not discuss this further as it is much better studied by the SGHK observations.

4. Results: Morphology and kinematics of the H I cloud

4.1. Morphology of the H I cloud

The total intensity image of the NE H I cloud is shown in Fig. 2, while in Figs. 1 and 4 the position of the H I cloud can be seen in relation to the large-scale radio jet, the optical filaments and the young stars.

Except for the higher spatial resolution, the morphology of the H I agrees well with that obtained by SGHK. The extent of the cloud is about 8′ × 3′, corresponding to about 8.6 × 3.2 kpc. The peak column density is 1.7×10^{21} cm^{-2}, which is perfectly consistent (considering the difference in spatial resolution) with

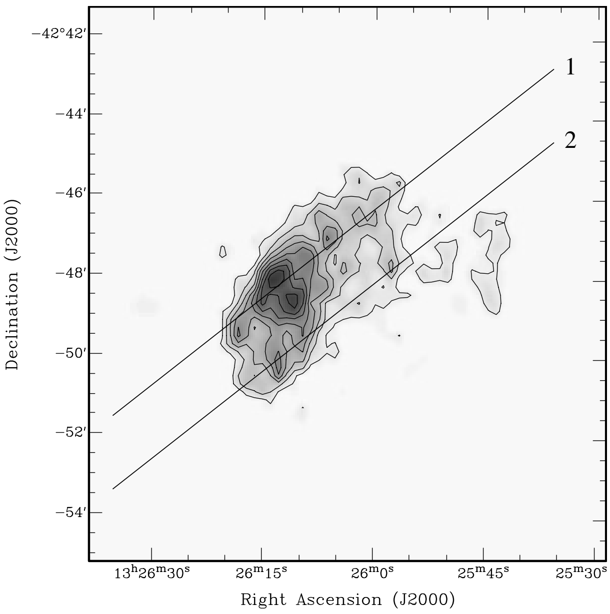

Fig. 2. Total HI intensity image of the NE H I cloud. The locations of the two position-velocity plots of Fig. 3 are indicated. Contour levels are 1, 3, 5, 7, 9, 11, 13, 15 × 10^{20} cm^{-2}.

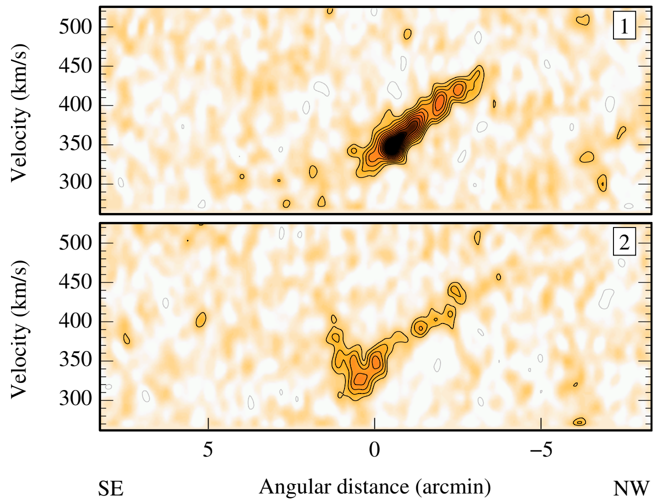

Fig. 3. Position-velocity plots taken along the lines indicated in Fig. 2. Contour levels are –6.75, –4.5, 4.5 (3σ), 6.75, 9.0... mJy $beam^{-1}$.

the value 1×10^{21} cm^{-2} of SGHK. The total H I mass of the cloud is 5.6×10^7 $M_\odot$. SGHK give a total mass of 1.5×10^8 $M_\odot$ for all H I clouds at large radius combined. Given the relative sizes of the clouds detected by SGHK, our mass estimate appears well consistent with their results. This underlines that the missing short baselines in our observations have not affected our images.

4.2. Kinematics of the H I

While the morphology of the H I emission agrees with the results presented by SGHK, it is the kinematics of the H I in the new observations that gives the interesting new result. Due to the higher velocity resolution of the new data we can investigate this in much more detail compared to what previously done by SGHK.

The main characteristic of the kinematics of the gas is illustrated by the two position-velocity slices presented in Fig. 3. They are taken along position angle −42° centred on two different positions of the cloud (as indicated in Fig. 2). The slices show, as the data of SGHK, that the overall kinematics of the cloud is characterised by a smooth velocity gradient of about 30 km s^{-1} kpc^{-1} corresponding to the rotation of the cloud around the galaxy. However, the slice taken along line 2 clearly shows that the most southernly region along this slice (corresponding to the southern tip of the cloud) does not conform to this regular gradient and that it shows a velocity anomaly. The southern tip of the cloud shows, when going to the SE, an abrupt reversal of the large-scale velocity gradient in the form of a sudden upturn in the velocities of about +100 km s^{-1} over 1 kpc. This upturn is not observed in the parallel slice centred on a slightly more northernly position. The anomalous velocities are therefore confined to a small region (Fig. 4).

5. Discussion

5.1. Is the velocity anomaly indicating a jet-cloud interaction?

The central question is whether the velocity anomaly observed at the S tip of the H I cloud is the result of an interaction with the radio jet. In principle, the reversal of the velocity gradient could simply be reflecting the overall kinematics (driven by gravity) of the cloud about the centre of Centaurus A. In our opinion, this possibility is unlikely. The overall morphology and kinematics of the outer H I clouds as observed by SGHK suggest that the outer H I forms one single, coherent structure of about 30 kpc in length, half encircling the galaxy from the NE to the SW. The data of SGHK show that the velocities of this outer H I ring vary smoothly over its entire length of 30 kpc. Hence, SGHK interprete these outer H I structures as forming a partial ring around Centaurus A that rotates with uniform velocity. A sudden velocity upturn occurring only at the southern tip is not consistent with a ring structure 30 kpc in size with regular kinematics.

Even if the outer H I clouds do not form a relatively settled structure, but instead form a less settled tidal tail-like feature, the anomalous velocities are not consistent. In general, the velocities along tidal arms vary fairly smoothly (e.g. Hibbard 2003). Velocity reversals are observed, but these are often due to projection effects and follow naturally from the overall spatial wrapping of the tidal feature. The reversal observed here in Centaurus A is different in character since the overall morphology and kinematics of the outer H I structure does not suggest that wrapping is occurring. In other cases, velocity reversals are observed near optically bright regions that could be small objects forming out of the tidal material (i.e. Tidal Dwarf Galaxies, Hibbard 2003; Weilbacher et al. 2003). However, these regions are always readily visible in the optical as bright star forming "knots" in the tidal arm. The H I cloud in Centaurus A discussed here completely lacks such an optical counterpart.

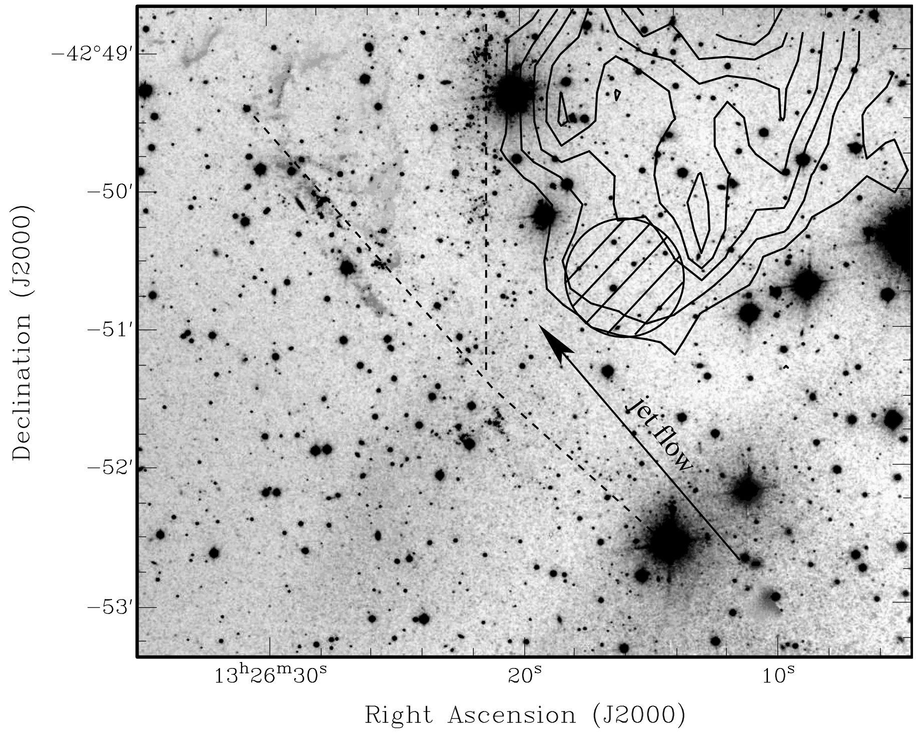

Fig. 4. H I contours of the southern region of the H I cloud, drawn on top of a broad band optical image (kindly provided by M. Rejkuba). The hatched area indicates the location where the anomalous H I velocities are detected while the arrow indicates the location and the flow direction of the radio jet. The filament of ionised gas is visible in the top left. The dashed lines roughly indicate the locations of young stars. Contour levels are as in Fig. 2.

The location and the kinematics of anomalous H I suggest a different interpretation, namely that a connection exists between this anomalous gas on the one hand and the young stars and ionised gas on the other hand. As is illustrated in Fig. 4, given the location and orientation of the radio jet, it would hit the H I cloud at the S edge of the H I cloud. The young stars and the ionised gas are found downstream from the location with the anomalous H I, as one would expect in a jet-cloud interaction scenario. An important additional observational fact is that the velocities of the anomalous H I range from 300 km s^{-1} to 430 km s^{-1}. This coincides quite closely with the velocity range of the bulk of the ionised gas just E of the H I cloud (Morganti et al. 1991; Graham 1998). The match between the H I and the other features observed therefore does not only exist in space (which could in principle be a projection effect), but also in velocity.

5.2. Jet-induced star formation

Assuming that the anomalous H I is related to the interaction of the H I cloud with the radio jet, the following may be occurring. The outer H I structure as detected by SGHK is rotating about the galaxy and at a particular point in time a small region of it is rotating into the relatively narrow cone defined by the radio plasma. It has often been assumed (e.g. SGHK; Graham 1998; Mould et al. 2000) that the interaction between the jet and the H I cloud would occur at the E edge of the H I cloud since this is where the ionised gas and the young stars are found. However, given the jet location and direction, the S tip is a more likely location where this occurs (see Fig. 4). The interaction causes some gas to be dragged along the jet and be displaced from the region where the jet interacts with the H I. This disturbed gas is ionised by the interaction (and likely also by the energetic photons coming from the nucleus of Centaurus A; Morganti et al. 1991) while the interaction also causes the kinematics of the ionised gas to be turbulent (as observed). Subsequently, a fraction of the ionised gas cools down quickly (see below) and star formation occurs in the cooled fragments. Given that the gas is dragged along the jet, the young stars are found displaced from the region where the jet is interacting with the H I cloud. The oldest young stars observed have an age of about 15 Myr, while the displacement of these young stars from the S tip of the H I cloud is about 2 kpc in projection. This implies an overall displacement velocity of the ionised gas of the order of 130 km s^{-1}. This appears consistent, considering differences in projection factors, with the anomalous velocities detected in the H I that are up to 100 km s^{-1}.

Observations of the kinematics of the ionised gas could provide confirmation of the above model. It is natural to assume that the H I follows a fractal-like distribution in size and density. Clouds with different sizes and densities will be accelerated differently and a segregation of clouds will result away from the location of the interaction. At a given time, smaller and/or less dense clouds will have been accelerated to larger velocities than larger and/or denser clouds. This means that starting from the S tip and following the jet direction, superposed on the very turbulent motions, the kinematics and the physical conditions of the ionised gas must show a systematic trend. Kinematical information is available only along a few slit positions and it is difficult to see whether the data confirms this. Two-dimensional spectroscopy in several emission lines and covering a large fraction of the outer filament is needed to study this in more detail.

If the above overall description is correct, the jet induced star formation is fairly inefficient. Mould et al. (2000) report a star formation rate for the region of the order of a few times 10^{-3} $M_{\odot}$ yr^{-1}. Assuming that the star formation rate has been constant, this implies a total mass for the stars formed over 15 Myr (the age of the young stars) to be of order of a few times 10^4 $M_{\odot}$. The amount of H I showing the anomalous velocities is about 1×10^6 $M_{\odot}$. Thus, unless the current rate by which the H I is stripped from the cloud is much higher than in the past, this appears to imply that the efficiency of converting the gas stripped of the cloud into stars is at most a few percent.

5.3. Comparison with models

The only detailed theoretical model of the interaction of the radio plasma with the environment available for Centaurus A is the model of the NML by Saxton et al. (2001). Instead of assuming that the NML is a standard radio lobe, they postulate that it is a buoyant bubble of plasma deposited by an intermittently active jet. In their model, the "large-scale jet" that may be interacting with the H I cloud is not a classic radio jet but is the trunk of material trailing the buoyant bubble. They explicitely discuss the interaction of the trunk with the H I cloud and postulate that the star formation is triggered by shocks due to the passage of the buoyant material. Many of the morphological and kinematical features of the ionised gas can be explained by this model, as well as the age of the young stars. The flow velocities in this model are very similar to the flow velocity derived from the displacement of the young stars from the location of the interaction, giving further support to this model. Although they do not predict their magnitude, the fact that the velocities of the anomalous H I are very similar to the flow velocity indicates that the interaction between the H I cloud and the buoyant trunk is indeed occurring at the velocities of their model.

A few other models have recently been published regarding the properties of jet-induced star formation, although they cover a part of parameter space, e.g. shock velocity, that is not directly applicable to Centaurus A. Mellema et al. (2002) model jet-cloud interactions where they postulate that the cocoon of a fast jet drives a fast shock (~3500 km s^{-1}) into ambient clouds of density 10 cm^{-3}. Fragile et al. (2004) give similar models with shock velocities above 1000 km s^{-1} and apply their models to Minkowsky's object. The interesting finding in these models is that despite the high velocities involved, most of the gas cools on a very short timescale (of order 10^2 yr) by radiative cooling and forms dense, cool fragments with temperatures below 100 K. Although the conditions are very different from the case of Centaurus A, where the shock velocities are most likely much smaller, it suggests that it is not surprising to see *neutral* gas with anomalous kinematics. When applying their model to Cygnus A and trying to reproduce the star formation rates observed, Mellema et al. have to assume an efficiency for the jet-induced star formation rate of 1%, while Fragile et al. have to assume a value of 0.1% for Minkowsky's object. Again, the conditions in these models are different from the situation in Centaurus A, but it is interesting to see that these values are not too different from our rough estimate of the star formation efficiency in Centaurus A.

A possible problem with models of the kind of Mellema et al. and Fragile et al. is that it is not clear whether the outflow velocities for the H I predicted by the models are large enough. The fact that the gas very quickly forms dense clumps means that it is difficult to accelerate them to high velocities. In the model of Mellema et al., the fast shock results in fragments that move with outflow velocities between 90 and 500 km s^{-1}, with the densest clumps having the lowest velocity. The dispersion between that star associations is about 80 km s^{-1}. In the model by Fragile et al., the cold, dense material are hardly accelerated at all. Given that it is likely that the shock velocities in Centaurus A are much smaller that assumed in the models by Mellema et al. and Fragile et al., it remains to be seen whether they can generate anomalous velocities of the magnitude observed in Centaurus A.

6. Summary

We have reported the discovery of anomalous velocities of about 100 km s^{-1} in the H I cloud situated about 15 kpc from the centre of Centaurus A. These anomalous velocities are very localised in the southern tip of the cloud and we suggest that they are related to the interaction between the radio jet and the neutral hydrogen. The cooling of the gas is then responsible for the formation of the young stars observed downstream. From the displacement of the young stars from the location of the anomalous velocities we derive a flow velocity of about 130 km s^{-1}. The jet induced star formation appears to be fairly inefficient, of the order of few percent.

The results presented here give further support to the idea that star formation can be produced via interaction of a radio jet with the ISM.

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References

Blanco, V. M., Graham, J. A., Lasker, B. M., & Osmer, P. 1975, ApJ, 198, L3
Briggs, D. 1995, Ph.D. Thesis, New Mexico Inst. Mining Tech.
Charmandaris, V., Combes, F., & van der Hulst, J. M. 2000, A&A, 356, L1
Dey, A., van Breugel, W., Vacca, W. D., & Antonucci, R. 1997, ApJ, 490, 698
Fassett, C. I., & Graham, J. A. 2000, ApJ, 538, 594
Fragile, P. C., Murray, S., Anninos, P., & van Breugel, W. 2004, ApJ, 604, 74
Graham, J. A. 1998, ApJ, 502, 245

Hibbard, J. E. 2003, in Recycling Intergalactic and Interstellar Matter, ed. P.-A. Duc, J. Braine, & E. Brinks, IAU Symp., 217, 82
Hui, X., Ford, H. C., Ciadullo, R., & Jacoby, G. H. 1993, ApJ, 414, 463
Mellema, G., Kurk, J. D., & Röttgering, H. J. A. 2002, A&A, 395, L13
Morganti, R., Robinson, A., Fosbury, R. A. E., et al. 1991, MNRAS, 249, 91
Morganti, R., Killeen, N. E. B., Ekers, R. D., & Oosterloo, T. A. 1999, MNRAS, 307, 750
Mould, J. R., Ridgewell, A., Gallagher, J. S., III, et al. 2000, ApJ, 536, 266
Neff, S. G., Schiminovich, D., Martin, C. D., & GALEX Science Team 2003, A&AS, 103, 9607
Rees, M. J. 1989, MNRAS, 239, 1
Rejkuba, M., Minniti, D., Courbin, F., & Silva, D. R. 2002, ApJ, 564, 688
Sault, R. J., Teuben, P. J., & Wright, M. C. H. 1995, in Astronomical Data Analysis Software and Systems IV, ed. R. Shaw, H. E. Payne, & J. J. E. Hayes, ASP Conf. Ser., 77, 433
Saxton, C. J., Sutherland, R. S., & Bicknell, G. V. 2001, ApJ, 563, 103
Schiminovich, D., van Gorkom, J. H., van der Hulst, J. M., & Kasow, S. 1994, ApJ, 423, L101 (SGHK)
Stickel, M., van der Hulst, J. M., van Gorkom, J. H., Schiminovich, D., & Carilli, C. L. 2004, A&A, 415, 95
Sutherland, R. S., Bicknell, G. V., & Dopita, M. A. 1993, ApJ, 414, 510
van Breugel, W., Filippenko, A. V., Heckman, T. M., & Miley, G. K. 1985, ApJ, 293, 83
van Breugel, W., & Dey, A. 1993, ApJ, 414, 563
van Breugel, W. 2000, Proc. SPIE, 4005, 83 [arXiv:astro-ph/0006238]
van Breugel, W., Fragile, P. C., Anninos, P., & Murray, S. 2003, in Recycling Intergalactic and Interstellar Matter, ed. P.-A. Duc, J. Braine, & E. Brinks, IAU Symp., 217, 29 [arXiv:astro-ph/0312282]
Weilbacher, P. M., Fritze-von Alvensleben, U., & Duc, P.-A. 2003, in Recycling Intergalactic and Interstellar Matter, ed. P.-A. Duc, J. Braine, & E. Brinks, IAU Symp., 217, 16