Dense gas without star formation: The kpc-sized turbulent molecular disk in 3C326 N

N. P. H. Nesvadba1, F. Boulanger1, M. D. Lehner2, P. Guillard3, P. Salome4

1 Institut d’Astrophysique Spatiale, CNRS, Université Paris-Sud, 91405 Orsay, France
2 GEPI, Observatoire de Paris, CNRS, Université Denis Diderot 5, Place Jules Janssen, 92195 Meudon, France
3 Spitzer Science Center, IPAC, California Institute of Technology, Pasadena, CA 92215, USA
4 LERMA Observatoire de Paris, CNRS, 61, rue de l’Observatoire, 75014 Paris, France

Received / Accepted

ABSTRACT

We report the discovery of a 3 kpc disk of few 109 M⊙ of dense, warm H2 in the nearby radio galaxy 3C326 N, which shows no signs of on-going or recent star formation and falls a factor 60 below the Schmidt-Kennicutt law. VLT/SINFONI imaging spectroscopy shows broad (FWHM~500 km s⁻¹) ro-vibrational H2 lines across all of the disk, with irregular profiles and line ratios consistent with shocks. The ratio of turbulent and gravitational energy suggests that the gas is highly turbulent and not gravitationally bound. In absence of the driving by the jet, short turbulent dissipation times suggest the gas should collapse rapidly and form stars, at odds with the recent star-formation history. Motivated by hydrodynamic models of rapid H2 formation boosted by turbulent compression, we propose that the molecules formed from diffuse atomic gas in the turbulent jet cocoon. Since the gas is not self-gravitating, it cannot form molecular clouds or stars while the jet is active, and is likely to disperse and become atomic again after the nuclear activity ceases. We speculate that this low star-formation rate is a consequence of the gas motions controlled by the jet, indicating a close symbiosis between jet and molecular gas, but also suggesting that boosting the formation of molecular gas in turbulent jet cocoon is not sufficient to trigger star formation.

Key words. Galaxies – ... – ...

1. Introduction

The radio galaxy 3C326 N at z=0.1 is an excellent target to investigate how the mechanical energy output of radio-loud AGN affects the surrounding gas and star formation. In spite of a few 10⁹ M⊙ of dense H2, akin to LIRGs, the star-formation rate (SFR≤0.07 M⊙ yr⁻¹ Ogle et al. 2007) is orders of magnitude lower than expected from the Schmidt-Kennicutt law (Nesvadba et al. 2010, N10 hereafter). With the low SFR, an X-ray faint AGN (log L_X = 40.6 erg s⁻¹ Ogle et al. 2010), and a strong radio source (kinetic power log L_kin ≥ 44.6 erg s⁻¹, N10) 3C326 N provides a rare opportunity to clearly disentangle the effects of the jet from those of star formation and AGN radiation. It is one of the largest and oldest radio galaxies on the sky, with 2 Mpc size, dynamical and spectral ages of 6-20 × 10⁹ yrs (Willis & Strom 1978) and a radio core at 3 mm (N10). 3C326 N is not an obvious member of a group or cluster, but has a similarly old (≥ 10 Gyr), massive (M_dwarf ≈ few × 10¹¹ M⊙) companion at a projected distance of ~ 20 kpc.

3C326 N is amongst the 30% of nearby 3CR radio galaxies which have bright line emission from warm molecular hydrogen observed with Spitzer/IRS and line ratios consistent with shocks (Ogle et al. 2010). The gas kinetic energy and line luminosities exceed the energy injection rates from star formation and AGN radiation, making the deposition of mechanical energy by the radio source the only plausible culprit (N10). This energy injection does not only trigger an outflow, but also heats the ambient gas through shocks, where the turbulent kinetic energy roughly equals the bulk kinetic energy of the outflowing gas. About half the molecular gas in 3C326 N is warm (T>100 K), a fraction 100× greater than in star-forming galaxies, and suggesting that mechanical heating by the jet could be an important mode of suppressing the overall star formation in this galaxy. We present deep imaging spectroscopy of the ro-vibrational H2 emission lines at R=3000 and 0.7′′ spatial resolution, probing the spatially resolved gas properties and kinematics, which significantly enhances and complements the analysis of N10 which relied on unresolved Spitzer/IRS spectroscopy at R=120 (2500 km s⁻¹) with 5′′ spatial resolution. We find a kpc-sized rotating, turbulent disk with broad complex line profiles, suggesting that the mechanical energy deposition of the jet is not restricted to a small part of the disk. We argue that finding such a disk is difficult to reconcile with the recent star-formation history of 3C326 N unless the molecular gas formed in response to the turbulence created by the radio jet, indicating a close symbiosis between jet and molecular gas, but also suggesting that boosting the formation of molecular gas in turbulent jet cocoons is not sufficient to trigger star formation as often assumed in models of positive AGN feedback. Throughout the paper we adopt a H₀ = 70 km s⁻¹, Ω_M =0.3, Ω_Λ =0.7 cosmology.

2. The molecular gas in 3C326 N

Data were obtained with the near-infrared imaging spectrograph SINFONI (Bonnet et al. 2004) at the Very Large Telescope of ESO with a total of 15,000 seconds of on-source observing time in the K-band at a seeing-limited resolution of
therefore measure the width, cannot be fit with single Gaussians. To map the kinematics, we of our spatial resolution. They have irregular profiles (Fig. 2) that jet as the only plausible culprit.

Several arguments suggest this gas is heated by shocks, similar to the pure-rotational H2 and optical lines (N10). First, S(3)/Paτ and S(1)/Brγ ratios are factors 10 greater than the typical S(1)/Brγ ∼ 0.1–1.5 in star-forming galaxies dominated by UV heating (Puxley et al. 1990). Since we do not detect Brγ, we estimate S(1)/Brγ=18–22 from the Paτ flux and a line decrement Paτ/Brγ=12–14, which exceeds ratios in star-forming galaxies by a factor 10. Second, for star formation we expect ratios of the H2 2–1/ H2 1–0 S(3) lines factors of a few greater than the 3σ upper limit of 0.12 for S(1) and S(3) (Le Petit et al. 2006; see Herrera et al. 2011 for a similar analysis). A third diagnostics is the [OII]6300/Brγ ratio as a function of S(1)/Brγ (Mouri et al. 1989). For the [OII]6300/Brγ ratio of N10 the S(1)/Brγ ratio in 3C326 N exceeds that expected from star formation by a factor 10. Forth, the H2 line luminosity of S(1)-S(3), 1×1041 erg s−1, exceeds the X-ray luminosity of the AGN and the mechanical luminosity of star formation (N10), leaving shock heating by the jet as the only plausible culprit.

Paτ and H2 morphologies are disk-like and extend over 2.0′×1.1′ (3.2 kpc × 1.8 kpc) at PAcorr=80±20°. All H2 lines and Paτ are broad, FWHM=400–700 km s−1, down to the limit of our spatial resolution. They have irregular profiles (Fig. 2) that cannot be fit with single Gaussians. To map the kinematics, we therefore measure the width, Wp, and central wavelength, Cp, of each line at p = 0.2, 0.5, 0.7, and 0.9× the line core extracted from small apertures of 0.4″×0.4″ (Heckman et al. 1981). W50 corresponds to the FWHM, and C50 approximates the line core. For S(3) we also measure the asymmetry parameter A20, i.e., the shift of C20 compared to C50 (Fig. 2 of Heckman et al. 1981). S(1) and Paτ have telluric absorption features along their wings which makes measuring A20 difficult, but their C50 and W50 give results consistent with S(3).

Velocities increase monotonically from SSW to NNE along PA=345°±15° (Fig. 3) common to all percentiles and all lines. Lines are broadest NE of the nucleus (W50,PA≤1600 km s−1, W50,PA≤750 km s−1), and more narrow in the south (300–400 km s−1 for all lines). A Fourier analysis of non-circularities in the velocity map with Kinemetry (Krajnović et al. 2006) suggests the velocity gradient is indistinguishable from rotation with PAkin = 340°, inclination i = 35° and a deprojected circular velocity of vc = 1/2 Δvproj csc i = 290 km s−1. This would imply a dynamical mass Mdyn = v2 c 2R/G = 3×1010 M⊙, somewhat larger than the enclosed stellar mass of Mstellar = 2×1010 M⊙. (The enclosed stellar mass is derived from the total stellar mass of 3×1011 M⊙ (N10) for a mass profile consistent with a Hubble law.) The non-Gaussian line profiles suggest non-circular velocity components which are probably smoothed out by the low spatial resolution. This could affect the velocity gradient.

The FWHMs are larger than the velocity gradient, hence the broad lines cannot be artifacts of the velocity gradient and beam smearing, in which case most of the broadening should be near the nucleus, contrary to Fig. 3. The analysis of a toy data cube with constant FWHM=400 km s−1 and γ =15% of the FWHM (similar to our 1σ observational errors). We also used a toy data cube to quantify the contribution of rotation to the CO(1–0) line measured by N10 which has FWHM=350 km s−1. We find a minimal intrinsic line width of 250 km s−1 assuming that the CO has the same velocity gradient as H2 and Paτ and uniform surface brightness.

The small ratios of vrot/σ = 1.7–0.9 (with velocity dispersion σ=FWHM/2.355 = 170 – 270 km s−1, Fig. 3) imply an ellipsoidal configuration rather than a thin disk. Broad lines across all of the disk show that the mechanical energy of the AGN affects the gas globally. This differs strongly from the scenario of jet-cloud interactions which are confined to gas in small areas along the jet axis and is more akin to recent hydrodynamic models of jet cocoons where radio-emitting plasma permeates inhomogeneous gas disks along relatively low-density channels (Sutherland & Bicknell 2007; Wagner & Bicknell 2011).

The H2 emission lines in 3C326 N have blue asymmetries which are strongest in the north (A20 = 150 km s−1, where turbulent velocities are also largest). H2 emission has velocities of up to to 1000 km s−1 from C90, well above the local escape velocity, vesc = √2vrot ~ 400 km s−1 at the largest H2 radii. vesc is also very similar to the lowest FWHMs in the South. Fig. 2 suggests that of order 10% of the emission is from gas at v > vesc. Since the V(1–0) H2 lines only probe the warmest, but not the bulk of the gas, this is difficult to turn into a mass outflow rate M. If we assume that the pure-rotational lines, which trace most of the mass, have a similar profile (as recently reported for AGN with high-resolution Spitzer spectroscopy, Dasyra & Combes 2011; Guillard et al. 2011 ApJ submitted), we find ~1 × 106 M⊙ of entrained dense, warm H2 in the wind. For an outflow timescale of 107–8 yrs, this is consistent with or less than M estimated from Na D, 30–40 M⊙ yr−1 (N10), which traces neutral (atomic and/or molecular) gas down to lower column densities.
3. Jet-disk symbiosis

The gas in 3C326 N is in a kpc-sized, dense, thick disk. The broad line widths and complex profiles are not consistent with pure rotation, but require an additional source of turbulence which, following the energy arguments of N10, can only be the radio source. A fraction of the line emission is from gas at velocities above the local escape velocity. The rotational time of this disk, $\tau_{rot} = 2\pi R / v_c = 3 \times 10^7$ yrs, is shorter than the 6-20 $\times 10^7$ yrs age of the radio source, and comparable to the depletion time of the gas through the wind, $\tau_{diss} = M / M_{\text{gas}} \sim 5 \times 10^5$ yrs. It is also very similar to the dissipation time of turbulent energy $\tau_{diss} = R / c_S = 1.5 \times 10^7$ yrs. The similar time scales raise two major questions.

First, why do we find a fairly organized (albeit thick) disk, if the depletion time through the wind is short? The mass outflow rate of N10 may be uncertain to about an order of magnitude, but even if it was a factor 10 lower, much of the gas should have been removed in the 2 $\times 10^7$ yrs time span suggested by the oldest radio emission. Finding a disk associated with an old radio source like 3C326 requires that energy losses are roughly balanced by the injection of energy, and the entrained by cooling gas. This would imply that a fraction of the outflowing gas does not escape from the galaxy, but dissipates its kinetic energy, stalls and rains back onto the disk in a cycle that may be akin to 'cold feedback' models of galaxy clusters (Ciotti et al. 1991; Pizzolato & Soker 2005; Brighenti & Mathews 2006).

Second, with $\tau_{diss} \sim \tau_{rot}$ the H$_2$ disk cannot be stable in the absence of the jet. The absence of a gas-rich merger suggests the material accumulated gradually from mass return and accretion over $\gtrsim$few $\times 10^7$ yrs (N10), longer than the age of the radio jet. Collisions between clouds would rapidly dissipate the turbulent kinetic energy and the angular momentum of the disk in about one to a few rotational times (Verdoes Kleijn et al. 2006; Pizzolato & Soker 2010), consistent with our estimates. For the measured gas surface density $\Sigma_{gas} = 250 \, M_\odot \, pc^{-2}$, the Schmidt-Kennicutt law implies SFR=4.5 $M_\odot$ yr$^{-1}$. This is $\sim$60$\times$ greater than the upper limit of SFR=0.07 $M_\odot$ yr$^{-1}$ (Ogle et al. 2007) from Spitzer 70 $\mu$m imaging, and at odds with the recent star-formation history of 3C326 N. To quantify recent star formation we repeated the population synthesis analysis of the inner 3$'$ of 3C326 N from N10, this time adding small fractions of light from young (3-30 $\times 10^5$ yrs) stellar populations (YSPs) to the data. We find that the XTR SFR=4.5 $M_\odot$ yr$^{-1}$ stars must form for a few $\times 10^5$ yrs to produce detectable signatures. This is very short, hence, the absence of recent star formation suggests that the gas cannot have lost turbulent support for much longer than a free-fall time (10$^6$ yrs for $N=10^3$ cm$^{-3}$) in the last 300 Myr. Unless the jet has been nearly continuously active during this time (longer than the oldest estimate of the jet age and unlike many other giant radio galaxies with signs of repeated, shorter jet outbreaks, Schoenmakers et al. 2000), then why has this gas not been forming stars?

Resolving this paradox is possible if the molecules formed after the onset of AGN activity, boosted by the turbulence in the jet cocoon. Hydrodynamic simulations suggest that turbulent compression can turn a diffuse inhomogeneous, largely atomic medium within few $10^6$ yrs into a warm, largely molecular medium (Glover & Mac Low 2007). Molecules form in rather dense regions ($n \geq 1000$ cm$^{-3}$) and are transported to regions of lower density. The total amount of H$_2$ on macro-scales is set by the dynamic equilibrium of the rapid molecule formation and destruction on micro-scales. This gas would not be gravitation-

---

1 for $R=1.6$ kpc. N10 found a smaller offset with a fiducial $R=2.5$ kpc.
\( \alpha \) of Heyer et al. (2009). These points fall near the range implied by Larson’s scaling law and the range of velocities at kpc scales. Black circles show the molecular clouds of [Heyer et al. (2009)]. These points fall near the \( \alpha_{\text{vir}} \) relation for gas surface densities \( \sim 5 \) smaller than that of 3C326 N. The horizontal dot-dashed line shows the maximal clump size of \( \sim 100 \) pc. See Fig. 4 for details.

\( \alpha_{\text{vir}} = 1 \) (red line in Fig. 4), suggesting that the turbulent kinetic energy strongly exceeds the gravitational energy on all relevant scales. This includes for example the \( \sim 100 \) pc scale at which disks akin to that of 3C326 N, but without additional turbulence from the jet, would fragment ([Escala & Larson 2008], dot-dashed vertical line in Fig. 4), and also the cloud sizes of few 10s pc typical adopted in simulations of turbulent jet cocoons ([Wagner & Bicknell 2011], [Antonacci-Delogu & Silk 2008]).

Fig. 4 shows also that turbulent velocities in 3C326 N are likely much greater than those in typical molecular clouds in the Milky Way ([Heyer et al. 2009] grey circles in Fig. 3). This may hold the key to the low star-formation rates. Local density enhancements owing to turbulent compression may enable star formation in clouds with \( \alpha_{\text{vir}} \gtrsim 1 \), but the star formation efficiency decreases rapidly with increasing \( \alpha_{\text{vir}} \) (e.g., [Krumholz & McKee 2005], [Padoan & Nordlund 2011]).

These arguments rely on the assumption that Larson’s scaling relationship approximately holds for 3C326 N. Resolving scales of \( \sim 100 \) pc will only become possible once ALMA reaches its full capabilities, however, we already see in Fig. 4 that Larson’s scaling law (green hatched area) normalized to the range of velocities at kpc scales falls within the range of turbulence required to account for the observed H\(_2\) luminosity.

5. Concluding remarks

Our results suggest that AGN can create large reservoirs of dense, rapidly cooling molecular gas, as is suggested by models of AGN-triggered star formation (e.g., [Mellema et al. 2002], [Fragile et al. 2004], [Silk & Norman 2009]), but this does not per se seem sufficient to form stars. The turbulent energy injected by the jet seems capable to keep significant fractions of the gas warm (T > 150 K) and gravitationally unbound, making star formation very inefficient.

3C326 N is certainly an extreme example of a gas-rich radio galaxy with a very low star-formation efficiency, however, it is not unique. 30% of nearby 3CR radio galaxies have bright line emission from warm H\(_2\) ([Ogle et al. 2010]), and emission-line diagnostics suggest that much of this gas could be heated mechanically through shocks (N10). This includes galaxies like 3C293, which have on-going star formation, albeit not at the level expected from their H\(_2\) reservoirs ([Papadopoulos et al. 2010]). It will be interesting to investigate in more depth how star formation and molecular gas kinematics are related in these cases.

Acknowledgements. We are very grateful to the staff at Paranal Observatory for carrying out the observations. Without the continuous, excellent work of the ESO staff and fellows, our analysis would not have been possible. We thank the referee for comments that helped improve the manuscript.

References

Antonacci-Delogu, V. & Silk, J. 2008, MNRAS, 389, 1750
Bertoldi, F. & McKee, C. F. 1992, ApJ, 393, 140
Bonnet, H., Abuter, R., Baker, A., et al. 2004, The Messenger, 117, 17
Brightenti, F. & Mathews, W. G. 2006, ApJ, 643, 120
Ciotti, L., D’Ecreole, A., Pellegrini, S., & Renzini, A. 1991, ApJ, 376, 380
Dasyra, K. M. & Combes, F. 2011, ArXiv e-prints
de Koff, S., Best, P., Baan, S. A., et al. 2000, ApJS, 129, 33
de Ruiter, H. R. et al. 2002, A&A, 396, 857
Escala, A. & Larson, R. B. 2008, ApJ, 685, L31
Fragile, P. C., Murray, S. D., Anninos, P., & van Breugel, W. 2004, ApJ, 604, 74
Gloaver, S. C. O. & Mac Low, M. 2007, ApJ, 659, 1317
Guillard, P., Boulanger, F., Pineau Des Forets, G., & Appleton, P. N. 2009, A&A, 502, 515
Heckman, T. M. et al. 1981, ApJ, 247, 403
Herrera, C. N., Boulanger, F., & Nesvadba, N. P. H. 2011, ArXiv e-prints
Heyer, M., Krawczyk, C., Duval, J., & Jackson, J. M. 2009, ApJ, 699, 1092
Krajnoviè, D. et al. 2006, MNRAS, 366, 787
Krause, M. & Alexander, P. 2007, MNRAS, 376, 465
Krumholz, M. R. & McKee, C. F. 2005, ApJ, 630, 250
Larson, R. B. 1981, MNRAS, 194, 809
Le Petit, F., Nehmê, C., Le Bourlot, J., & Roueff, E. 2006, ApJS, 164, 506
McKee, C. F. & Ostriker, E. C. 2007, ARA&A, 45, 565
Mellema, G., Kulkj, D. J., & Rottgering, H. J. A. 2002, A&A, 395, L13
Mouri, H., Taniguchi, Y., Kawara, K., & Nishida, M. 1989, ApJ, 346, L73
Nesvadba, N., De Breuck, C., Lehndt, M., & Best, 2011a, A&A, 525, A43
Nesvadba, N. P. H., Boulanger, F., Salomé, P., et al. 2010, A&A, 521, A65
Nesvadba, N. P. H., Lehndt, M. D., Davies, R. I., Verma, A., & Eisenhauer, F. 2008, A&A, 479, 67
Nesvadba, N. P. H., Polletta, M., Lehndt, M. D., et al. 2011b, ArXiv e-prints
Ogle, P., Antonucci, R., Appleton, P. N., & Whysong, D. 2007, ApJ, 668, 699
Ogle, P., Boulanger, F., Guillard, P., et al. 2010, ApJ, 724, 1193
Oosterloo, T. A., Morganti, R., Sadler, E. M., van der Hulst, T., & Serra, P. 2007, A&A, 465, 787
Ostriker, E. C., Stone, J. M., & Gammie, C. F. 2001, ApJ, 546, 980
Padoan, P. & Nordlund, A. 2011, ApJ, 730, 740
Papadopoulos, P. P., van der Werf, P., Isaak, K., & Xilouris, E. M. 2010, ApJ, 715, 775
Pizzolato, F. & Soker, N. 2005, ApJ, 632, 821
Pizzolato, F. & Soker, N. 2010, MNRAS, 408, 961
Paxley, P. J., Hawarden, T. G., & Mountain, C. M. 1999, ApJ, 364, 77
Schoenmakers, A. P., de Bruyn, A. G., Röttgering, H. J. A., van der Laan, H., & Kaiser, C. R. 2000, MNRAS, 315, 371
Silk, J. & Norman, C. F. 2001, ApJ, 546, 980
Padoan, P. & Nordlund, A. 2011, ApJ, 730, 40
Oosterloo, T. A., Morganti, R., Sadler, E. M., van der Hulst, T., & Serra, P. 2007, A&A, 465, 787
Ostriker, E. C., Stone, J. M., & Gammie, C. F. 2001, ApJ, 546, 980
Padoan, P. & Nordlund, A. 2011, ApJ, 730, 740
Papadopoulos, P. P., van der Werf, P., Isaak, K., & Xilouris, E. M. 2010, ApJ, 715, 775
Pizzolato, F. & Soker, N. 2005, ApJ, 632, 821
Pizzolato, F. & Soker, N. 2010, MNRAS, 408, 961
Paxley, P. J., Hawarden, T. G., & Mountain, C. M. 1999, ApJ, 364, 77
Schoenmakers, A. P., de Bruyn, A. G., Röttgering, H. J. A., van der Laan, H., & Kaiser, C. R. 2000, MNRAS, 315, 371
Silk, J. & Norman, C. F. 2009, ApJ, 700, 262
Sutherland, R. S. & Bicknell, G. V. 2007, ApJS, 173, 37
Verdoes Kleijn, G. A., van der Marel, R. P., & Noël-Storr, J. 2006, ApJ, 131, 1961
Wagner, A. Y. & Bicknell, G. V. 2011, ApJ, 728, 29
Willis, A. G. & Strom, R. G. 1978, A&A, 62, 375
| Line             | $\lambda_0$ | $\lambda_{obs}$ | FWHM  | flux  |
|------------------|-------------|-----------------|-------|-------|
|                  | [\mu m]     | [\mu m]         | [km s$^{-1}$] | [10$^{-15}$ erg s$^{-1}$ cm$^{-2}$] |
| Pa$\alpha$       | 1.875       | 2.0443±0.0004   | 516±44 | 1.2±0.14 |
| H$\text{$_2$}$ 1-0 S(1) | 2.122       | 2.3132±0.0005   | 534±32 | 1.8±0.13 |
| H$\text{$_2$}$ 1-0 S(2) | 2.034       | 2.2170±0.0003   | 563±45 | 0.7±0.05 |
| H$\text{$_2$}$ 1-0 S(3) | 1.958       | 2.1339±0.0004   | 594±41 | 2.2±0.2 |
| H$\text{$_2$}$ 1-0 S(4) | 1.892       | 2.0624±0.0004   | 475±45 | 0.8±0.05 |
| Br$\gamma$      | 2.166       | <0.26 (3\sigma) |       |       |
| H$\text{$_2$}$ 2-1 S(3) | 2.074       | <0.24 (3\sigma) |       |       |

**Table 1.** Line properties derived from the “stacked” spectrum, i.e., the integrated spectrum with the large-scale velocity gradient removed. We also list the 3\sigma upper limit for Br$\gamma$ and H$\text{$_2$}$ 2-1 S(3), which are not detected.