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A NEW INSIGHT OF THE NORTHERN FILAMENTS OF CENTAURUS A

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Abstract. We present new APEX observations of the CO(2-1) in the northern filaments of Centaurus A, at the intersection between the radio jet and the northern HI shell. The CO emission was compared with archival FUV (GALEX), FIR (Herschel) and VLT/MUSE data.

The molecular gas mass of the filaments is $(8.2 \pm 0.5) \times 10^7\,\mathrm{M}_\odot$, distributed in two filamentary structures. We found a surprisingly strong molecular filament that lies outside the HI gas. The filaments are mostly molecular, suggesting a scenario where the radio-jet triggers the atomic-to-molecular phase transition.

We then compared the CO masses with the SFR estimates and found very long depletion times ($\sim 75\,$Gyr over the whole filaments), in agreement with the results of Salomé et al. (2016). Analysis of optical excitation lines indicates that the filaments are mostly excited by the AGN or shocks.

Comparison with the Hα and HI emission suggests that the three gas phases are spatially and kinematically linked. In particular, the CO emission shows the same velocity gradient as the HI gas.

Keywords: Methods:data analysis, Galaxies:evolution, star formation, Radio lines:galaxies

1 Introduction

AGN are supposed to regulate gas accretion and thus slow down star formation (negative feedback). However, evidence of AGN **positive feedback** has also been observed in a few radio galaxies. In a previous work (Salomé et al. 2015), we studied two of the most famous examples of **jet-induced star formation**: 3C 285/09.6 (van Breugel & Dey 1993) and Minkowski's Object (van Breugel et al. 1985). Although CO emission was not detected by the IRAM 30m telescope, we found efficient star formation in both star-forming regions, with molecular depletion times ≤ 1 Gyr and ≤ 0.02 Gyr, respectively.

Here we study another famous example: the outer filaments of Centaurus A (Mould et al. 2000; Oosterloo & Morganti 2005). NGC 5128 is a giant nearby early type galaxy that is surrounded by faint arc-like stellar shells (at several kpc around the galaxy). The shells also present HI emission (Schiminovich et al. 1994), CO emission (Charmandaris et al. 2000), and dust continuum (Auld et al. 2012). Along the radio-jet, optically bright filaments (so-called inner and outer filaments) have been observed (Blanco et al. 1975; Graham & Price 1981). These filaments located along the direction of the northern radio jet (at a distance of $\sim 7.7\,$kpc and $\sim 13.5\,$kpc) are the place of star formation (Auld et al. 2012).

We conducted a multi-wavelength study of the outer filaments based on archival FUV (GALEX), FIR (Herschel) and new CO APEX data. We also looked at optical emission lines (VLT/MUSE) in the filaments.

2 Results

Molecular gas distribution We mapped the whole northern filaments in CO(2-1) with APEX. The observations cover three regions (figure 1): (1) one within the HI cloud, (2) one outside the HI and within the dust emission, (3) One outside the HI with FUV emission only. CO emission has been detected at almost all the positions observed with APEX, and follows the dust emission. The total molecular mass is $\mathrm{M}_{\mathrm{H}_2}^{\mathrm{tot}} = (8.2 \pm 0.5) \times 10^7\,\mathrm{M}_\odot$. Surprisingly, CO emission is stronger in the eastern part of the filaments, outside the HI shell (figure 1).

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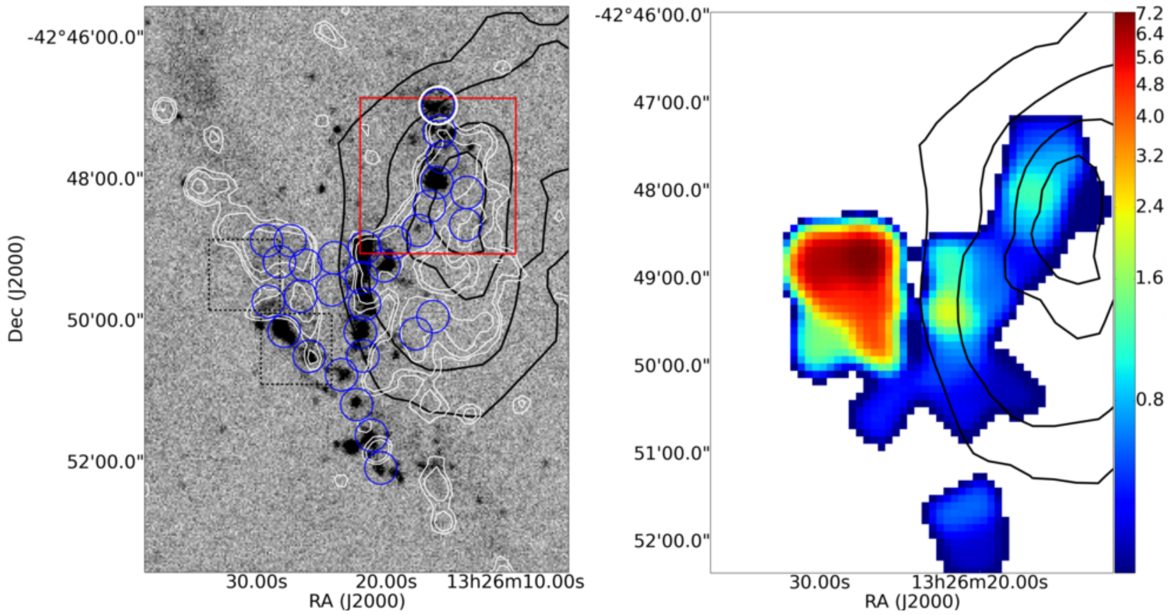

Fig. 1: *Left:* FUV image of the outer filament from GALEX. The black and white contours correspond to the HI and the Herschel-SPIRE 250 μm emission, respectively. The red box corresponds to the region observed by Charmandaris et al. (2000) with SEST, and the dashed boxes show the field of view of MUSE observations (Santoro et al. 2015). The circles show the positions observed with APEX (blue) and ALMA (white). *Right:* Intensity map of the CO(2-1) emission from APEX in K.km.s^{-1}, with the HI emission overlaid in black contours.

Molecular-to-atomic mass ratio We compared the APEX CO data with VLA HI data and derive H_2/HI mass ratios. However, the resolution of VLA is lower ($40'' \times 78''$), therefore we combined APEX pointings contained in a single VLA beam to simulate a lower resolution. The filaments are mostly molecular, with total masses $M_{H_2} = 7.7 \times 10^7$ $M_\odot$ and $M_{HI} = 2.1 \times 10^7$ $M_\odot$ (ratio of 3.66).

Star formation efficiency For each APEX position, we derived the molecular mass from CO, and the star formation rate (SFR) from the FUV and FIR emission. For the whole region, the SFR is $\sim 1.1 \times 10^{-3}$ $M_\odot$.yr^{-1}, leading to a molecular depletion time $t_{dep}^{mol} \sim 75$ Gyr. The Σ_{SFR} vs Σ_{gas} diagram (figure 2; Bigiel et al. 2008; Daddi et al. 2010) shows that the filaments are very inefficient to form stars, compared to disc-like star-forming galaxies.

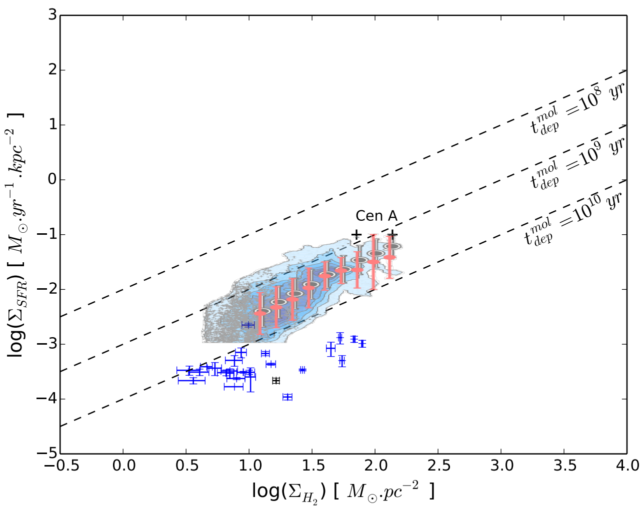

Fig. 2: Σ_{SFR} vs. Σ_{H_2} for the different regions of CO emission observed with APEX. The black crosses correspond to the central galaxy and the entire filaments ($\Sigma_{H_2} \sim 16.4$ $M_\odot$.pc^{-2}; $\Sigma_{SFR} \sim 2.17 \times 10^{-4}$ $M_\odot$.yr^{-1}.kpc^{-2}). The diagonal dashed lines show lines of constant molecular gas depletion times of, from top to bottom, 10^8, 10^9, and 10^{10}yr. We overlay the contours of Leroy et al. (2013) for nearby spiral galaxies.

Dynamics of the filaments The overall CO(2-1) emission of the filaments is blueshifted compared to the central galaxy, the eastern part being bluer than the west. MUSE observations suggest that the molecular and ionised components may be spatially and dynamically associated.

We computed a PV diagram along a slit oriented perpendicularly to the jet. The CO data (figure 3) show (1) a large scale velocity gradient similar to the HI gradient that extends further out to the east side. (2) The break in the slope of the HI velocity gradient (Oosterloo & Morganti 2005) is also seen in CO. Molecular and atomic gas thus seems to be dynamically associated.

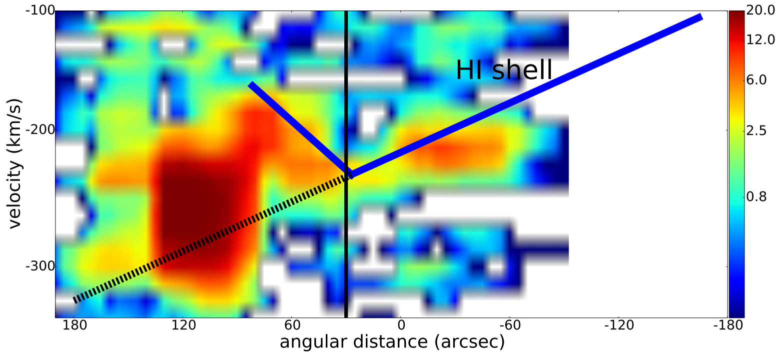

Fig. 3: PV diagram of the CO emission (in mK) centred in $\alpha = 13^{\mathrm{h}}26^{\mathrm{m}}15^{\mathrm{s}}$, $\delta = -42{:}49{:}00$ over the same slit orientation as Oosterloo & Morganti (2005) with a width of $4.2'$ (taking all the CO emission). The blue lines represent the HI cloud velocity gradient. The dashed line represents the continuity of this velocity gradient over the CO emission. The position of the radio jet is shown by the vertical black line.

Excitation of the filaments We re-reduce the MUSE data from Santoro et al. (2015) (Program 60.A-9341(A) during the Science Verification). We then computed pixel-by-pixel BPT diagrams (Baldwin et al. 1981; Kewley et al. 2006). Most of the filaments seem to be excited by the radio jet or shocks (figure 4). Those large regions contains smaller inclusions that are excited by star formation, similar to what has been claimed by Santoro et al. (2016).

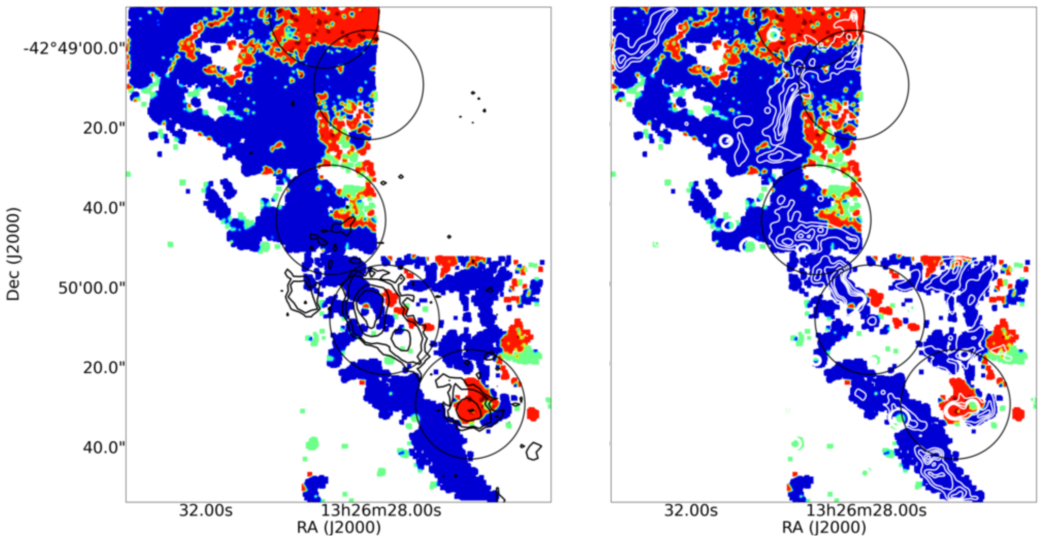

Fig. 4: Map of the excitation processes in the field of view of MUSE. RGB map with star formation in green, AGN/shocks in blue, composite in red. The contours show the UV emission from GALEX (black; *left*) and the Hα-[NII] emission from MUSE (white; *right*). The APEX beams are represented by the circles.

3 Conclusions

APEX was used to map the full region of Centaurus A's northern filaments ($5' \times 4'$). The molecular gas lies in two separated prominent structures: the eastern region (the brightest) and the western region. Those two structures follow the optically identified east and west arms of the northern filaments.

The CO emission in the north is also ~ 5 times more massive $\left((8.2 \pm 0.5) \times 10^7\ \mathrm{M_\odot}\right)$ than what was derived by Charmandaris et al. (2000) in the smaller region S1 only $\left(1.7 \times 10^7\ \mathrm{M_\odot}\right)$. The filaments are mostly molecular with a small atomic-to-molecular gas fraction and with the brightest emission being far outside the HI cloud itself.

The star formation efficiency (SFE) is very low in the northern filaments, even if traces of recent star formation are claimed in this region. This suggests that some processes may prevent the star formation to proceed in the cold gas. A possible process that may prevent the molecular gas to form stars is kinetic energy injection from the larger scale dynamics at play in this system.

However, we found that the radio jet could have compressed the gas and triggered the phase transition from atomic to molecular gas. This is certainly a way the AGN and its jets can have a positive feedback effect on the star formation in NGC 5128. Statistical studies with higher resolution CO data all along the filaments are underway (ALMA cycle 3 project) and will shed light on possibly local effects.

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