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STAR FORMATION EFFICIENCY IN THE OUTER FILAMENTS OF CENTAURUS A

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Abstract. We present a multi-wavelength study of the northern filaments of Centaurus A (at a distance of ∼ 20 kpc from the galaxy center) based on FUV (GALEX), FIR (Herschel) and CO (SEST and ALMA) emission. We also searched for HCN and HCO^+ (ATCA) and observed optical emission lines (VLT/MUSE) in different places of the filament. An upper limit of the dense gas of $L'_{HCN} < 4.8 \times 10^3$ K.km.s^{-1}.pc^2 at 3σ leads to a dense-to-molecular gas fraction < 23% in this region.

We compared the CO masses with the SFR estimates and found very long depletion times (11 Gyr on 730 pc scales) and a large scatter in the KS-relation with a standard conversion factor. Applying a metallicity correction to the CO/H_2 conversion factor would lead to even more massive clouds with higher depletion times.

Using ALMA archive data, we found 3 unresolved CO(2-1) clumps of size < 37×21pc and masses around $10^4 M_\odot$. The 3 clumps show resolved line profiles ($\Delta v \sim 10$km.s^{-1}) and are all three dynamically clearly separated by $\sim 10-20$km.s^{-1}. We derived a virial parameter $\alpha_{vir} \sim 10 - 16$ which indicates that the clumps are not gravitationally bound and input of energy likely inhibits star formation.

Keywords: Methods:data analysis, Galaxies:evolution, interactions, 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 example of **jet-induced star formation**: 3C 285/09.6 (van Breugel & Dey 1993) and Minkowski's Object (van Breugel et al. 1985). Here we study another famous example: the outer filaments of Centaurus A (Mould et al. 2000; Oosterloo & Morganti 2005).

NGC 5128 (or Centaurus A) is a giant nearby early type galaxy that is surrounded by faint arc-like stellar shells (at several kpc around the galaxy). In the shells, HI emission has been detected (Schiminovich et al. 1994) and CO emission was observed at the intersection with the radio jet (Charmandaris et al. 2000). In addition, large amount of dust ($\sim 10^5 M_\odot$) lies around the northern shell region (Auld et al. 2012).

Along the radio-jet, optically bright filaments (so-called inner and outer filaments) have been observed (Morganti et al. 1991). These filaments located along the direction of the northern radio jet (at a distance of ∼ 7.7 kpc and ∼ 13.5 kpc, respectively) are the place of star formation (Auld et al. 2012).

We gathered archival data of the outer filaments in FUV (GALEX), FIR (Herschel) and CO (SEST and ALMA). We also searched for HCN/HCO^+ (ATCA) and observed optical emission lines (VLT/MUSE) in the filaments.

Our main goal was to determine whether star formation is more efficient in the shocked region along the jet. Throughout this work, we assume the cold dark matter concordance Universe, with $H_0 = 70$km.s^{-1}.Mpc^{-1}, $\Omega_m = 0.30$ and $\Omega_\Lambda = 0.70$.

2 Results

Star formation rate For all the CO positions, we derived a SFR from the FIR and FUV emission (Kennicutt 1998; Kennicutt & Evans 2012). The FIR emission also enabled us to estimate the molecular gas-to-dust ratios.

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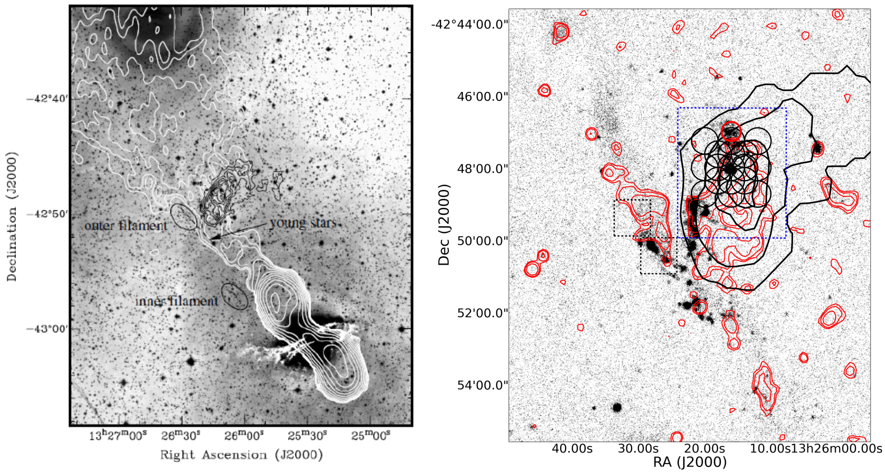

Fig. 1: *Left:* Optical image of Cen A in the range $\lambda = 3850 - 5400$ Å showing the diffuse emission and the location of the so-called inner and the outer filaments. The white contours denote the radio continuum emission of the inner lobes and the large-scale jet. The black contours refer to the north-east outer HI cloud. *Right:* FUV image of the outer filament from GALEX. The black and red contours correspond to the HI and the Herschel-SPIRE 250 μm emission, respectively. The circles show the positions observed (black; Charmandaris et al. 2000) and ATCA (red). The dashed boxes show the field of view of MUSE observations (Santoro et al. 2015).

Filaments oxygen abundance We computed oxygen abundance maps following the method of Pettini & Pagel (2004). The maps show that (i) there is no major metallicity difference between the inner and the outer filaments, (ii) there is no major metallicity gradient along each filament and (iii) both filament have relatively high abundances (roughly solar), but with local variations, even if as far as several kpc away from the center of NGC 5128.

Molecular gas mass CO emission was detected in almost all the positions of the 3×3 half beam central map. It has also been detected in the two positions 44″ upward and downward the central position. We found CO luminosities L'_{CO} of a few $10^5 - 10^6$ K.km.s^{-1}.pc^2 (with a standard conversion factor). Taking into account local low-metallicity corrections (Leroy et al. 2013) to the standard CO/H_2 conversion factor would lead to higher molecular masses and thus larger depletion times. **Dense gas tracers** HCN and HCO^+ were not detected with ATCA. We derived upper limits at 3σ assuming a line width of the order of the one detected in CO ($\sim$ 10km.s^{-1}): $L'_{HCN} < 4.8 \times 10^3$ K.km.s^{-1}.pc^2 and $L'_{HCO^+} < 4.8 \times 10^3$ K.km.s^{-1}.pc^2. This leads to a dense-to-molecular gas fraction < 23%. **Clumpy CO emission** CO(2-1) emission is detected by ALMA and reveals the presence of 3 distinct unresolved clumps. They show resolved line profiles (Δv $\sim$ 10 km.s^{-1}) and are dynamically separated by $\sim 10 - 20$ km.s^{-1}. The total integrated flux of the clumps is $S_{CO}\Delta v \sim 3.0$ Jy.km.s^{-1}, leading to $M_{H_2} \sim 8.7 \times 10^4$ $M_\odot$ with a standard CO/H_2 conversion factor. From FUV emission, we derived a SFR of $\sim 1.4 \times 10^{-5}$ $M_\odot$.yr^{-1} on scale of a few pc.

The **virial parameter** $\alpha_{vir} = 5\sigma_c^2 R_c/(GM_c)$ (Bertoldi & McKee 1992) measures the ratio of the kinetic to gravitational energy of the clouds. For the ALMA clumps, we found $\alpha_{vir} \sim 10 - 16$ (8 km.s^{-1}, 20 pc, 4×10^4 $M_\odot$), so an input of kinetic energy may have happened and could explain why these clouds appear inefficient (large depletion time) to form stars despite their surface density $N_{H_2} \geq 10^{20}$ cm^{-2}.

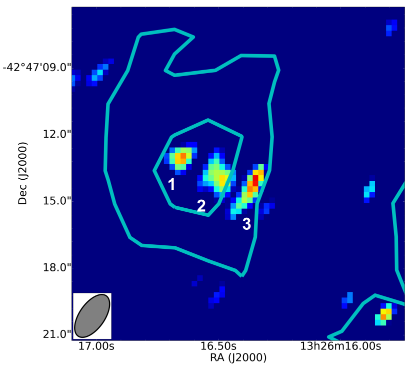

Fig. 2: ALMA CO(2-1) integrated emission line over Δv $\sim$ 30 km.s^{-1}. The contours show the FUV emission from GALEX.

Clump	offset	v_0 (km.s^{-1})	Δv (km.s^{-1})	M_{H_2} (10^4 $M_\odot$)
1	5.8″, −17.25″	∼ −231	12.5	4.0 ± 1.7
2	4.4″, −18.2″	∼ −222	8.0	2.6 ± 1.7
3	2.0″, −19.3″	∼ −214	7.5	2.1 ± 1.5

Table 1: CO(2-1) emission line properties for each clump (central velocity, FWHM and molecular gas mass estimated with a standard and fixed conversion factor with no metallicity correction). Offsets from the ALMA phase center: $\alpha = 13^h26^m16^s.1$, $\delta = -42{:}46{:}55.7$ are given in the first column.

3 Conclusion

The Σ_{SFR} vs Σ_{gas} diagram (see figure 3; Bigiel et al. 2008; Daddi et al. 2010) shows that, while the central galaxy is forming stars very efficiently (Espada et al. 2009), similar to ULIRG, the positions where CO has been detected in the filaments have large depletion times indicating very inefficient star formation. This trend would be even stronger if we take into account local metallicity correction. High spatial and spectral resolution of the CO line emission by ALMA hints for a large α_{vir}, in agreement with a kinetical energy injection in the molecular gas, preventing further collapse and thus star formation in the filaments aligned with the AGN jet direction.

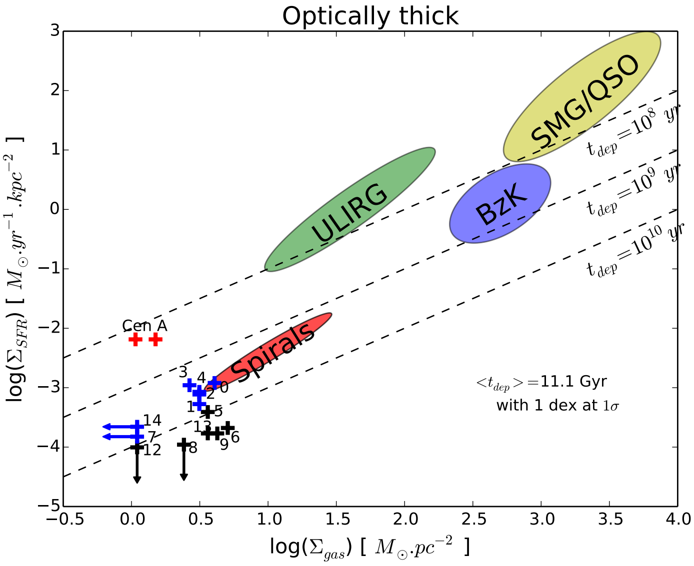

Fig. 3: Σ_{SFR} vs. Σ_{gas} for the different regions of CO emission. The diagonal dashed lines show lines of constant SFE, indicating the level of Σ_{SFR} needed to consume 1%, 10%, and 100% of the gas reservoir in 10^8 years. Thus, the lines also correspond to constant gas depletion times of, from top to bottom, 10^8, 10^9, and 10^{10} yr. The coloured regions come from Daddi et al. (2010). The blue and black colors separate the CO positions in two groups, depending on the depletion time. The red crosses correspond to the central galaxy.

References

Auld, R., Smith, M. W. L., Bendo, G., et al. 2012, MNRAS, 420, 1882
Bertoldi, F. & McKee, C. F. 1992, ApJ, 395, 140
Bigiel, F., Leroy, A., Walter, F., et al. 2008, AJ, 136, 2846
Charmandaris, V., Combes, F., & van der Hulst, J. M. 2000, A&A, 356, L1
Daddi, E., Elbaz, D., Walter, F., et al. 2010, ApJ, 714, L118
Espada, D., Matsushita, S., Peck, A., et al. 2009, ApJ, 695, 116
Kennicutt, R. C. & Evans, N. J. 2012, ARA&A, 50, 531
Kennicutt, Jr., R. C. 1998, ApJ, 498, 541
Leroy, A. K., Walter, F., Sandstrom, K., et al. 2013, AJ, 146, 19
Morganti, R., Robinson, A., Fosbury, R. A. E., et al. 1991, MNRAS, 249, 91
Mould, J. R., Ridgewell, A., Gallagher III, J. S., et al. 2000, ApJ, 536, 266
Oosterloo, T. A. & Morganti, R. 2005, A&A, 429, 469
Pettini, M. & Pagel, B. E. J. 2004, MNRAS, 348, L59
Salomé, Q., Salomé, P., & Combes, F. 2015, A&A, 574, A34
Santoro, F., Oonk, J. B. R., Morganti, R., Oosterloo, T. A., & Tremblay, G. 2015, A&A, 575, L4
Schiminovich, D., van Gorkom, J. H., van der Hulst, J. M., & Kasow, S. 1994, ApJ, 423, L101
van Breugel, W., Filippenko, A. V., Heckman, T., & Miley, G. 1985, ApJ, 293, 83
van Breugel, W. J. M. & Dey, A. 1993, ApJ, 414, 563