The excitation of the molecular gas in jet-driven winds

and its implications for the creation and detection of winds

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ABSTRACT

Winds that could be important for the evolution of their host galaxies are frequently seen in molecular gas lines. Their importance is largely attributed to their high mass load and to their direct connection with star formation. Excitation studies of the CO molecules now provide a refined view of the ISM conditions in winds versus in ambient interstellar media (ISM) of galaxies: measurable heating characterizes the gas out of dynamical equilibrium. A typical example is that of the galaxy IC5063. It is a nearby elliptical with a disk in its center and a radio jet nearly aligned with the disk. ALMA CO data of IC5063 reveal that the accelerated gas reaches temperatures of order 100K near jet-ISM impact points. Besides heated and excited, part of the accelerated gas is optically thin. This result can translate in an easier detection of molecular winds in CO lines of moderate rotational number J, and in a much lower than Galactic CO-intensity-to-H_2-mass factor. Lower wind mass loads are, thus, plausible. A spatially-resolved fitting of the CO spectral line energy distribution (SLED) with the radiative transfer code RADEX provides maps of the volume density n_{H2}, column density N_{CO}, and kinetic temperature T_{kin} of the gas. We used them to create the first pressure maps for jet-impacted regions with winds. Pressure gradients exceeding an order of magnitude are seen between jet-impacted clouds and quiescent parts of the disk. Gas dispersal and a potential delay in the associated star formation are, thus, plausible. Still, the detection of HCO^+ (4-3), with a critical density of 10^7 cm^{-3}, at the centers of the overpressurized regions indicates that ongoing star formation can continue or even get enhanced at the densest parts of the jet-impacted cores.

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INTRODUCTION

Molecular gas winds are intensively being studied as they affect massive reservoirs of galaxies that are directly related to star formation. Studies of the CO excitation are needed to provide robust estimates of the gas mass in these winds. We present such a study for the galaxy IC5063, which can be thought of as a prototype for jet-driven winds. IC5063 is a nearby elliptical galaxy with a gas disk and a radio jet propagating nearly parallel to this disk for several hundred parsec. IC5063 has two radio lobes, which are regions where the jet impacts dense clouds, prior to bifurcating and leaving the disk. Atomic (ionized, neutral) and molecular winds form at the radio lobes (Oosterloo et al. 2000; Morganti et al. 2007, 2013; Tadhunter et al. 2014), as well as at other regions near the jet trail (Dasyra et al. 2015). Excitation differences were indicated for the few thousand Kelvin H_2 between the disk and the wind (Dasyra et al. 2015). However, the H_2 emission differences could reflect fluorescence instead of heating. Changes in the CO excitation are needed to reliably indicate an increase in the molecular gas temperature due to energy deposition by the jet. Using Atacama Large Millimeter Array (ALMA) observations of various molecular gas lines and CO spectral line energy distribution (SLED) modeling, we prove that the accelerated gas is heated and partly optically thin. We also investigate for pressure gradients along the disk that are capable of altering star formation: the interplay between pressure gradients and gravity can affect the expansion or the contraction rate of clouds.

DATA

We used ALMA data of ^{12}CO (1-0), (2-1), (3-2), (4-3), and ^{13}CO(2-1), creating the deepest possible cubes from own (2015.1.00420.S) and archival data (2012.1.00435.S, 2015.1.00467.S, 2016.1.01279.S). All cubes had a pixel scale of 0.12'', a spectral resolution of 20 km/s, and a beam of 0.73''x0.65''. They reached sensitivities between 0.23-1.8 mJy/beam. SiO(5-4), HCN(1-0), HCO^+ (1-0), HCO^+(4-3) were also available, which provided extra constraints for our modelling.

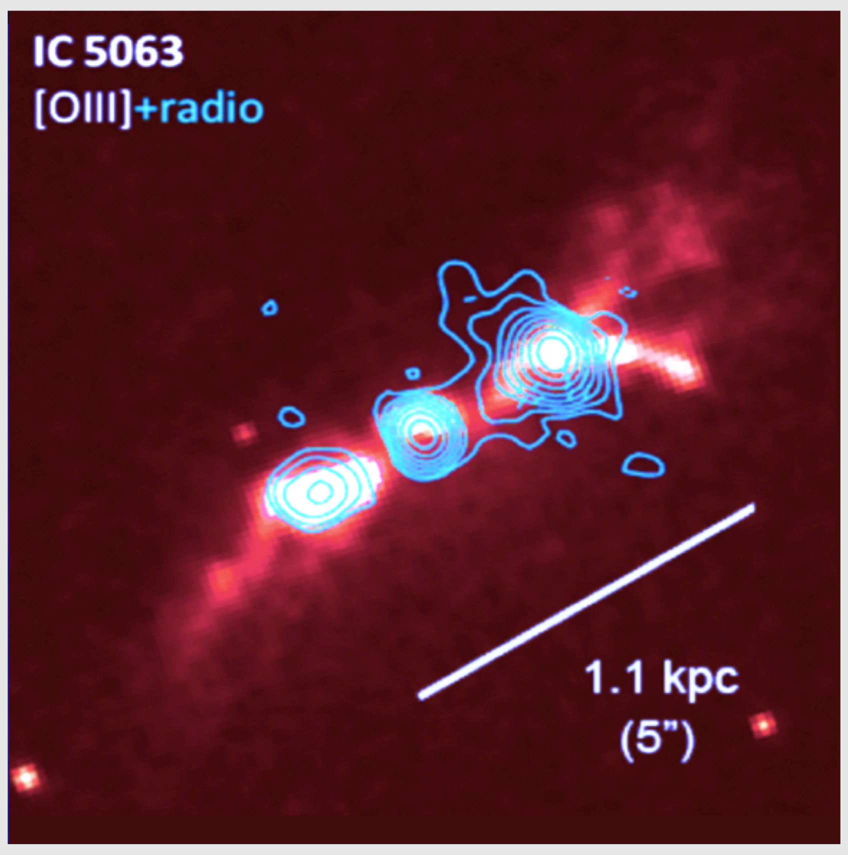

Fig. 1 - HST FOC F502 M data of the gas disk of IC5063 comprising [OIII] + Hβ emission that follows the jet trail. Radio contours at 17.8 GHz are overplotted (Morgant et al. 2007). Adapted from Dasyra et al. (2015).

RESULTS

A first, analytical examination of the CO(4-3)/CO(2-1) ratio indicated a significant temperature increase as well as a drop of optical depth between the ambient and the outflowing gas (Dasyra et al., 2016; Oosterloo et al., 2017). For the disk, the typical value of the CO(4−3)/CO(2−1) ratio was 1. When subtracting the disk from the overall emission, the flux ratio of the wind-associated residuals, significantly exceeded the upper limit of 4 for optically thick gas and obtained values in the optically thin gas regime, e.g., 5-12. Excitation temperatures of 30-150 K were found for the molecules in the wind. If all of the outflowing molecular gas was optically thin, then its mass would be 2 × 106 $M_{\odot}$. This lower mass limit is an order of magnitude below the mass in case of optically thick emission. The analytical examination thus indicated that molecular winds can be less massive, but more easily detectable at high z than previously thought (Dasyra et al. 2016).

To compare wind and disk properties, we performed our CO SLED modelling for the -200<V<200 km/s range, which comprises low-V and perpendicular-to-our-line-of-sight wind components. We find that, even at low velocities, the gas T_{ex} exceeds 50K along most of the jet trail. It reaches 100K at the jet lobes (Fig. 4). This is a clear sign of energy deposition by the jet into the disk, as the ambient gas has T_{ex} of order 10K. In the NE radio lobe, the gas is even in LTE, with all CO lines having equal T_{ex} and T_{kin}. Besides the best-fit T_{kin} map, our code also provides the best-fit n_{H2} map, which also displays spatial variations. From them, we obtain a pressure P map shown in Fig. 5.

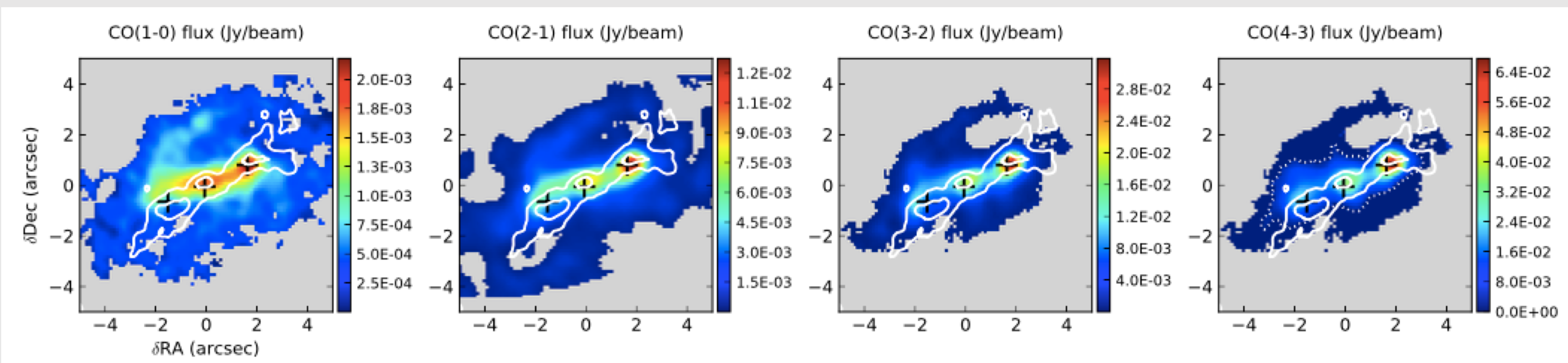

Fig. 2 – ALMA observations of the first four CO rotational transition lines in IC5063. The emission in the velocity range -200<V<200 km/s is used in the spatially-resolved CO SLED modeling, as it comprises emission from the disk and from the winds (Fig. 3), enabling comparisons between the accelerated and the ambient ISM (Dasyra et al. 2019, in prep). Regions with S/N<3 are masked, in all images except that of CO(4-3). For CO(4-3), the dotted contours mark the region where S/N=3. Outside the dotted region, upper limits for the flux were used, computed from the noise. Solid contours in all panels mark the jet trail as indicated from the HST data (Fig. 1)

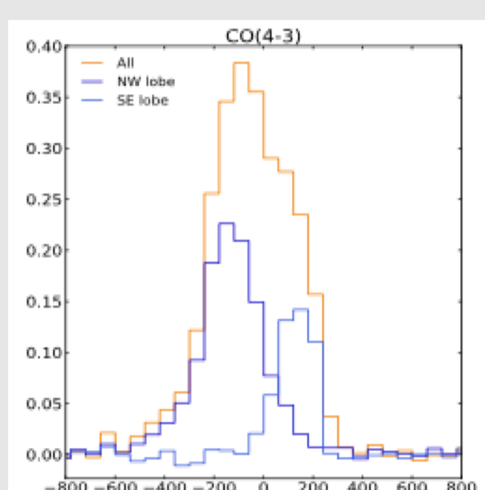

Fig. 3 – CO(4-3) spectrum of IC5063 in the area shown in Fig. 2. The total emission (including the disk) is plotted in orange. The emission of the NE and SW radio lobes are shown in purple and blue, respectively. High fraction of the flux is attributed to the jet-impacted gas even at low velocities.

MAPS OF CO SLED MODELS

We modeled the SLED of all CO lines (including the ^{12}CO and ^{13}CO isotopologues) on a pixel-by-pixel basis with the widely-used code RADEX (van der Tak et al., 2007), which solves the radiative transfer equation for molecular lines in non-LTE, assuming molecules excited by collisions and embedded in a background radiation field. It takes as input the kinetic temperature (T_{kin}), the column density N of the molecule, and the volume density of the H2 (n_{H2}), which is the main collision partner. It returns as output the excitation (T_{ex}) and the radiation (T_R) temperature of the gas in the requested transitions. To find the optimal set of radiation temperatures for the CO line maps, we ran RADEX for a very broad grid of parameters in the following ranges: 3<T_{kin}<200K, 10^{15}<$N_{CO}/\Delta V$<10^{18} cm^{-2} /km s^{-1}, 10^2<n_{H2}<10^7 cm^{-3}. An abundance of 70 was assumed for the column densities of the ^{13}CO grid. To select the optimal solution per pixel, we performed an error-weighed χ^2 minimization between the modelled fluxes and the observed fluxes, corrected for the beam filling factor. We iterated this procedure for all cube pixels. A unique beam filling factor of 0.01, providing a solution for all pixels, was used for the map. While the N_{CO} map normalization was a free parameter of the fit, the spatial distribution of it followed that of the CO(1-0) flux.

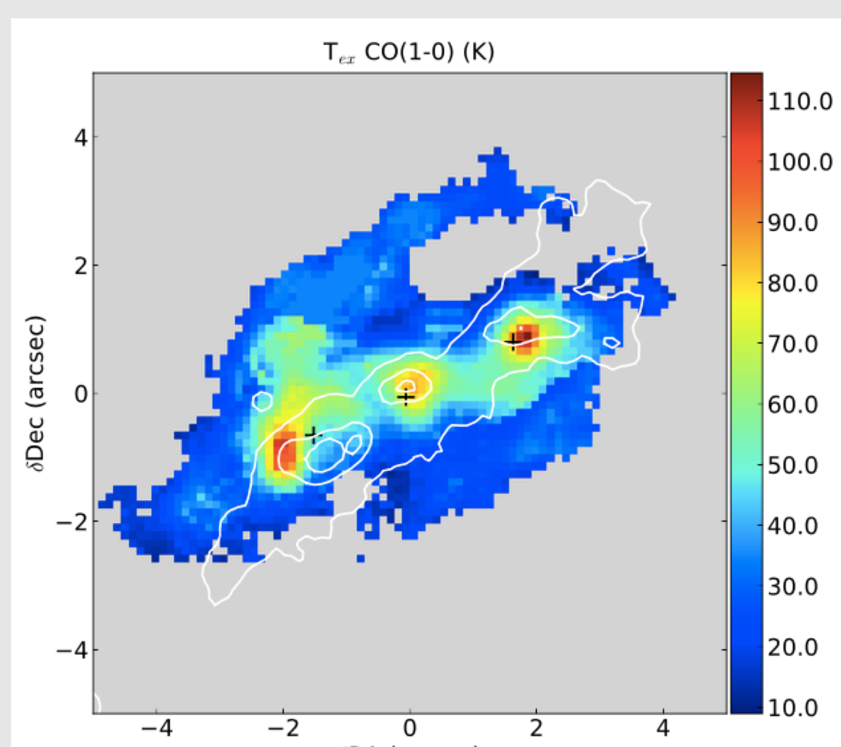

Fig. 4 – Kinetic temperature map constructed from the best-fit RADEX model per pixel. Crosses mark the positions of the nucleus and the two radio lobes. High temperatures are seen all along the jet trail. The highest values, of order 100K, are seen at the jet-cloud impact points.

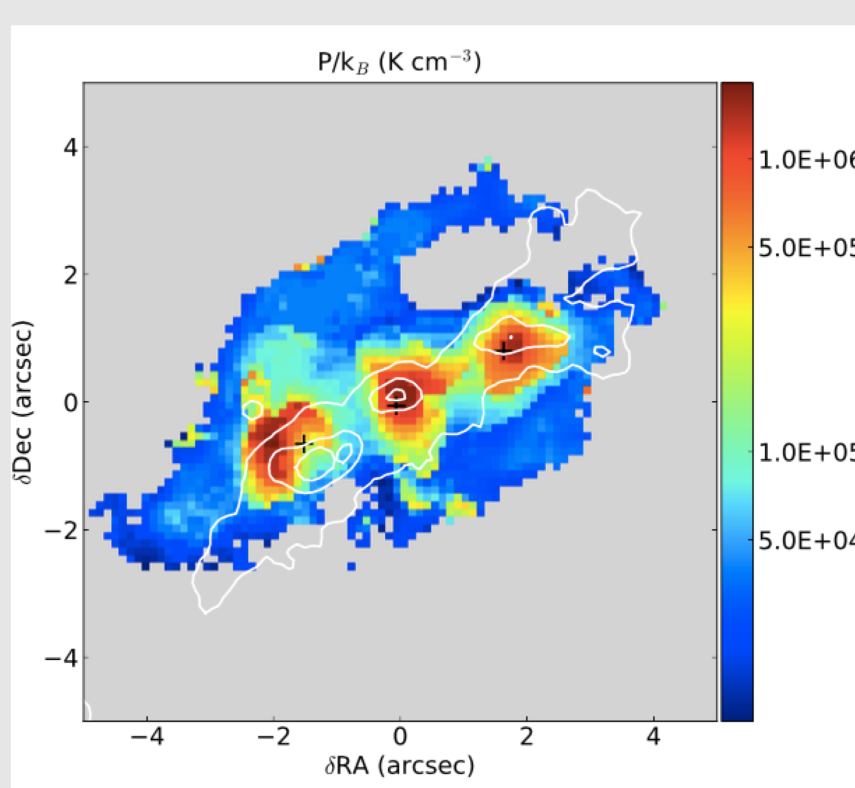

Fig. 5 – Pressure map, constructed from the combination of the T_{kin} and n_{H2} maps of the best-fit RADEX models. Very high pressure gradients of more than an order of magnitude, are seen between the jet-cloud impact points at the radio lobes and the ambient gas at the disk/spiral arms of the galaxy.

JET-DRIVEN PRESSURE GRADIENTS

The quiescent ISM pressure that we measure (Fig. 5) is comparable to GMC values in the literature, e.g., 10^4-10^5 K cm^{-3} (Blitz & Rosolowsky, 2006).

The pressure of the jet-impacted regions exceeds that of the quiescent ISM by more than an order of magnitude (Dasyra et al. 2019, in prep).

Pressure gradients of the molecular gas in regions associated with jet-driven winds are seen for the first time. Given the spatial coincidence between the over-pressurized regions and the radio lobes, we deduce that the over-pressurization occurs because of the energy deposition by the jet. In general, over-pressurization also occurs during cloud collapse. The detection of HCO^+(4-3), with critical density ~10^7 cm^{-3}, indicates that collapse is likely ongoing in the cloud cores. But the fate of the more tenuous cloud layers is linked with cloud dissipation and wind formation.

CONCLUSIONS

By performing a spatially-resolved fitting of the CO SLED of the inner ~2kpc galaxy IC5063, which comprise several winds at jet-cloud impact points near the radio lobes/core we find that :

- Heated molecular gas is seen all along the jet trail. At the radio lobes, the molecular gas T_{ex} exceeds 100K, i.e., exceeds the T_{ex} of the disk by an order of magnitude.
- Optically thin emission is seen for the high-V gas in the wind, and for some low-V gas at the radio lobes. This implies higher emission and easier wind detection in intermediate-J lines.
- X_{CO} may need downward revision in jet-driven winds compared to its Galactic/ULIRG value. It implies a decrease in measured wind masses.
- Pressure gradients capable of destabilizing clouds are seen between the radio lobes and the disk. While gas dispersal is occurring, core compression and collapse can also occur at the jet-cloud impact points.

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