Physical conditions in the warped accretion disk of a massive star

349 GHz ALMA observations of G023.01–00.41

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ABSTRACT

Young massive stars warm up the large amount of gas and dust that condenses in their vicinity, exciting a forest of lines from different molecular species. Their line brightness is a diagnostic tool of the gas’s physical conditions locally, which we use to set constraints on the environment where massive stars form. We made use of the Atacama Large Millimeter/submillimeter Array at frequencies near 349 GHz, with an angular resolution of (′1, to observe the methyl cyanide (CH3CN) emission which arises from the accretion disk of a young massive star. We sample the disk midplane with twelve distinct beams, where we get an independent measure of the gas’s (and dust’s) physical conditions. The accretion disk extends above the midplane, showing a double-armed spiral morphology projected onto the plane of the sky, which we sample with ten additional beams: Along these apparent spiral features, gas undergoes velocity gradients of about 1 km s−1 per 2000 au. The gas temperature (T) rises symmetrically along each side of the disk, from about 98 K at 3000 au to 289 K at 250 au, following a power law with radius R−1.8. The CH3CN column density (N) increases from 9.2×1013 cm−2 at a distance of 250 au from the star. We study the disk stability against fragmentation following the methodology by Kratter et al. (2010, ApJ, 708, 1585), which is appropriate under rapid accretion, and we show that the disk is marginally prone to fragmentation along its whole extent.

Key words. stars: formation – ISM: individual objects: G023.01-00.41 – ISM: molecules – techniques: high angular resolution

1. Introduction

The circumstellar regions within a few 1000 au from early-type young stars, where the (average) kinetic temperature of the interstellar medium exceeds 100 K, are rich in methyl cyanide gas (CH3CN), whose relative abundance with respect to H2 is typically larger than 10−9 (e.g. Hernández-Hernández et al. 2014). We note that CH3CN is a symmetric top molecule whose millimetre spectrum is divided into groups of rotational transitions, with the following favourable properties (e.g. Boucher et al. 1980; Loren & Mundy 1984): (i) each group corresponds to a single J → (J − 1) transition with varying K, where J and K are the two quantum numbers of total angular momentum and its projection on the axis of molecular symmetry, respectively; (ii) each group of transitions covers a ‘narrow’ bandwidth, within a gigahertz, and is separated by a few tens of gigahertz from the lower and higher J transitions; (iii) the energy levels within a group are only populated through collisions, and their excitation temperatures span several 100 K; and (iv) rotational transitions of the isotopologue CH313CN emit within the same narrow bandwidth of the CH3CN transitions with same quantum numbers. These spectral properties make CH3CN emission a sensitive thermometer for the interstellar gas, where the H2 density exceeds a critical value of approximately 105 cm−3 (e.g. Shirley 2015); this critical density would be reached, for instance, inside a spherical core of 0.1 pc radius (R), a gas mass of 50 Msol, and a density proportional to R−1.5.

Since the first CH3CN interferometric observations by Cesaroni et al. (1994), which were performed with the Plateau de Bure Interferometer at 110 GHz, CH3CN emission and its isotopologue CH313CN have been observed at (sub-)arcsecond resolution towards tens of early-type young stars, in order to estimate the linewidth, temperature, and H2 number density of a gigahertz. This approach, however, can only probe temperatures of order 100 K, whereas the CH3CN emission reflects the much higher excitation temperature of the gas at the vicinity of the young star. In this work we present the first radio interferometric measurements of CH3CN emission towards a young star at mm wavelengths, where the CH3CN emission arises from the accretion disk, at higher excitation temperatures. A sample of protostars will be presented in a forthcoming paper.

We used the Atacama Large Millimeter/submillimeter Array (ALMA), which is an interferometer with antennas distributed over a 16 km baseline, thus able to provide unprecedented angular resolution at mm wavelengths. The investigation of the emission at mm wavelengths allows us to study the physical conditions in the accretion disk, where the mean temperature is expected to be higher than in the interstellar medium, where CH3CN is typically observed. The CH3CN transitions with J = 15−14, 14−13, and 13−12, with Kmax = 4, 5, and 6, respectively, are currently observable at mm wavelengths, mostly with ALMA, thus allowing us to probe the disk environment at a wavelength of 349 GHz. The CH3CN transition with J = 15−14, K = 4 (the CH3CN 1514 transition) is a good diagnostic with respect to other CH3CN transitions, since it is a sensitive thermometer of the gas, and its intensity is more likely to be affected by the high gas temperature in the accretion disk, while it is not affected by the abundance of the (rare) CH313CN isotopologue.

We present the first high angular resolution observations of the CH3CN J = 15−14, K = 4 transition, which we detect towards G023.01–00.41, an ONeMg star forming region in the CGale-2 sampling region of the G023.01-00.41 protostar. This protostar is a massive star, with a mass of approximately 6.5 Msol, and is located at a distance of 330 pc from the Sun. The protostar is surrounded by a circumstellar environment, which is composed of a large amount of gas and dust, which are excited by the energy from the protostar. The CH3CN emission is a sensitive thermometer of the gas, and it is expected to be excited by the high mean temperature of the gas in the accretion disk. The CH3CN emission is also a diagnostic of the gas's physical conditions locally, which we use to set constraints on the environment where massive stars form.
local gas (e.g. Zhang et al. 1998; Beltrán et al. 2005; Beuther et al. 2005; Chen et al. 2006; Qiu et al. 2011; Hernández-Hernández et al. 2014; Hunter et al. 2014; Sánchez-Monge et al. 2014; Zinchenko et al. 2015; Bonfand et al. 2017; Ilee et al. 2018; Ahmadi et al. 2018; Johnston et al. 2020). For instance, CH$_3$CN ($12K$–$11K$) observations at 220 GHz, whose lower excitation energy ($E_l/K$) exceeds 58 K, indicate average rotational (and kinetic) temperatures of 200 K approximately, and CH$_3$CN column densities of the order of 10$^{16}$ cm$^{-2}$. These conditions are met at radii of 1000 au from the brightness peak of the dust continuum emission at the same frequency, whose position is assumed to pinpoint a young star. Alternatively, temperature and density gradients measured through CH$_3$CN transitions are proxies for the radiative feedback of luminous stars in the making (>10$^3 L_\odot$).

In this paper, we report on spectroscopic CH$_3$CN, CH$_3$OH (methanol), and dust continuum observations with the Atacama Large Millimeter/submillimeter Array (ALMA) at 349 GHz with an angular resolution of $0\farcs1$. We exploit the CH$_3$CN ($19K$–$18K$) K-ladder, with excitation energies ranging from 168 K (for $K = 0$) to 881 K (for $K = 10$), to probe, at different radii, the physical conditions in the accretion disk of an early-type young star. We targeted the star-forming region G023.01$-$0.41, at a trigonometric distance of 4.59$^{+0.38}_{-0.33}$ kpc from the Sun (Brunthaler et al. 2009), where we recently revealed the accretion disk around a young star of 10$^{6.6}$ $L_\odot$, corresponding to a ZAMS star of 20 $M_\odot$ (Sanna et al. 2019, their Fig. 1); the disk was imaged by means of spectroscopic ALMA observations of both CH$_3$CN and CH$_3$OH lines at $0\farcs2$ resolution in the 230 GHz band. The disk extends up to radii of 3000 au from the central star where it warps above the midplane; here, we resolve the outer disk regions in two apparent spirals projected onto the plane of the sky. We showed that molecular gas is falling in and slowly rotating with sub-Keplerian velocities down to radii of 500 au from the central star, where we measured a mass infall rate of $6 \times 10^{-4} M_\odot$ yr$^{-1}$ (Sanna et al. 2019, their Fig. 5). The disk and star system drives a radio continuum jet and a molecular outflow aligned along a position angle of 57$^\circ$, measured east of north (Sanna et al. 2016, their Fig. 2); their projected axis is oriented perpendicular to the disk midplane whose inclination with respect to the line-of-sight was estimated to be less than 30$^\circ$ (namely, the disk is seen approximately edge-on; Sanna et al. 2014, 2019). Previously, we also measured the average gas conditions over the same extent of the whole disk, by means of Submillimeter Array (SMA) observations of the CH$_3$CN ($12K$–$11K$) emission, and we estimated a kinetic temperature of 195 K and CH$_3$CN column density of $5.1 \times 10^{16}$ cm$^{-2}$ (Sanna et al. 2014, their Fig. 2 and Table 4).

### 2. Observations and calibration

We observed the star-forming region G023.01$-$0.41 with the 12-m-array of ALMA in band 7 (275–373 GHz). Observations were conducted under program 2016.1.01200.S on 2017 July 10 (Cycle 4) during a 3 hour run, with precipitable water vapour of 0.35–0.38 mm. The 12-m-array observed with 40 antennas covered a baseline range between 16 m and 2647 m and achieved an angular resolution and maximum recoverable scale of approximately 0$\rlap{\scriptstyle .}''08$ and 1$\rlap{\scriptstyle .}''4$, respectively. Observation information is summarised in Table 1.

We made use of a mixed correlator setup consisting of four baselines (BB1–4), three operated in time division mode (TDM) and one in frequency division mode (FDM). Each TDM window had 64 spectral channels spaced over a bandwidth of 1875 MHz. These bands were used for continuum (full) polarisation observations and tuned at the central frequencies of 336.57 (BB1), 338.57 (BB2), and 348.57 GHz (BB3) for optimal polarisation performance (cf. ALMA Cycle 4 Proposer’s Guide, Doc 4.2, ver. 1.0, March 2016). The FDM window had 1920 spectral channels spaced over a bandwidth of 938 MHz to achieve a velocity resolution of 0.84 km s$^{-1}$ after spectral averaging by a factor of 2. This band was used for spectral line observations and tuned at the central frequency of 349.15 GHz (BB4), and it overlaps with the higher half of BB3. BB4 was placed to cover the K-ladder of the CH$_3$CN ($19K$–$18K$) transition, with K ranging from 0 to 10, and its isotopologue CH$_3^{13}$CN.

In the following, we report on the analysis of the high spectral-resolution band (BB4); the targeted molecular lines are listed in Table A.1, and they include a bright CH$_3$OH line previously identified in a preparatory SMA experiment (project code 2014B-S006). The visibility data were calibrated with the Common Astronomy Software Applications (CASA) package, version 4.7.2 (r39762), making use of the calibration scripts provided with the quality assessment process (QA2). To determine the continuum level, we made use of the spectral image cube and selected the line-free channels from a spectrum integrated over a circular area of 0$\rlap{\scriptstyle .}''5$ in size, which was centred on the target source. The task uvcontsub of CASA was used to subtract a constant continuum level across the spectral window ($fitorder = 0$). We imaged the line and continuum emission with the task clean of CASA, setting a circular restoring beam size of 0$\rlap{\scriptstyle .}''114$ equal to the geometrical average of the major and minor axes of the beam obtained with a Briggs’s robustness parameter of 0.5. We achieved a sensitivity of approximately 1 mJy beam$^{-1}$ per resolution unit, which corresponds to a brightness temperature of about 1 K over a beam of 0$\rlap{\scriptstyle .}''1$. The continuum emission was integrated over

### Table 1. Summary of ALMA observations at Cycle 4 (project code 2016.1.01200.S).

| Array Conf. | RA (J2000) (h m s) | Dec (J2000) (°’’’) | V$_{LSR}$ (km s$^{-1}$) | Freq. cove. (GHz) | $\Delta v$ (kHz) | BP cal. | Phase cal. | Pol. cal. | HPBW (°) |
|-------------|-------------------|------------------|----------------------|-----------------|----------------|---------|-----------|-----------|---------|
|             |                   |                  |                      |                 |                |         |           |           |         |
| C40–6       | 18:34:40.290      | –09:00:38.30     | 77.4                 | 335.6, 349.6    | 976.5          | J1751+0939 | J1825–0737 | J1733–1304 | 0.10    |

Notes. Column 1: 12 m-array configuration. Columns 2 and 3: target phase centre (ICRS system). Column 4: source radial velocity. Column 5: minimum and maximum rest frequencies covered with four baselines (BB1–4) and the LO frequency set at 343.5 GHz. Column 6: spectral resolution on BB4. Columns 7, 8, and 9: bandpass, phase, and polarisation (and absolute flux) calibrators employed. Calibration sources were set by the ALMA operators at the time of the observations. Column 10: beam size at a representative frequency of 338.57 GHz.
a line free\(^1\) bandwidth of 52 MHz, achieving a sensitivity of 0.2 mJy beam\(^{-1}\).

3. Results

In Fig. 1, we present the brightness map of a CH\(_3\)OH line at 349.107 GHz with an excitation energy of 260 K, which is the brightest line emission in our band. The emission was integrated in velocity around (±2 km s\(^{-1}\)) the line peak to emphasise the gas spatial distribution; this emission extends within a radius of approximately 3000 au from the young massive star in the region (star symbol) at the current sensitivity. For comparison with our cycle-3 ALMA observations, we drew the disk midplane at three radii as marked in Fig. 1 of Sanna et al. (2019), from the central star position to 1000 au (yellow), from 1000 to 2000 au (black), and up to 3000 au (magenta). In Fig. 2, we plotted the same image rotated clockwise by 57° in order to align the (projected) outflow direction with the vertical axis of the plot. The CH\(_3\)OH emission is centrally peaked near (but offset from) the star, and it outlines two apparent spiral features which extend on each side of the disk midplane. In Fig. A.1, we also show that the CH\(_3\)CN gas has a similar spatial distribution at a similar excitation temperature (for \(K = 4\)). In Fig. A.2, we present a continuum map of the dust emission at the centre frequency of 349.150 GHz, where the contours of Fig. 1 have been superposed for comparison.

We have extracted the integrated spectra at 22 distinct positions in the frequency range 348.7 to 349.5 GHz; this range includes the K-ladder of the 19 → 18 rotational transition of the CH\(_3\)CN molecule and its isotopologue CH\(_{13}\)CN (Table A.1). Each position covers a circular area with a radius of 250 au and they are plotted and labelled with white numbers in Fig. 1; these positions were used to sample the disk midplane and its apparent spiral features and, hereafter, they are referred to as P1, P2, ..., P22. Examples of the CH\(_3\)CN spectra are shown and analysed in Fig. 2, while the complete set of 22 spectra is reported in Figs. A.3 and A.4. We analysed these spectra in two steps.

In step 1, we made use of the Weeds package of GILDAS (Maret et al. 2011) to reproduce the CH\(_3\)CN and CH\(_{13}\)CN spectra and estimate the physical conditions of the emitting gas. Under the assumption of local thermodynamic equilibrium (LTE), and accounting for the continuum level, Weeds produces a synthetic spectrum of an interstellar molecular species, depending on the following five parameters: (i) the intrinsic full width at half maximum (FWHM) of the spectral lines; (ii) the line offset with respect to the rest velocity in the region; (iii) the spatial extent (FWHM) of the emitting region, assumed to have a Gaussian brightness profile; (iv) the rotational temperature of the emitting gas; and (v) the column density of the emitting gas. We fixed parameters (i) and (ii) by fitting a Gaussian profile to five K-components simultaneously, which are forced to have the same linewidth and whose separation in frequency was set to the laboratory values (command MINIMIZE of CLASS). This procedure assumes that each spectral component is excited within the same parcel of gas. This ‘observed’ linewidth was used to derive the ‘intrinsic’ linewidth by correcting iteratively for the opacity broadening, with the opacity computed by Weeds (e.g. Eq. (4) of Hacar et al. 2016). Parameter (iii) was varied about the beam size at discrete steps of 5 mas; emission at the same distance from the star was forced to have the same size (only within the midplane). This assumption was verified a posteriori based on the fit convergence (step 2). The same set of parameters was used to compute the spectra of CH\(_3\)CN and CH\(_{13}\)CN species, whose relative abundance was set to 30 (Wilson & Rood 1994; Sanna et al. 2014).

In step 2, we input the initial parameters estimated with Weeds into MCWeeds (Giammatti et al. 2017), which implements a Bayesian statistical analysis for an automated fit of the spectral lines. We made use of a Monte Carlo Markov chains method to minimise the difference between the observed and computed spectra and derived the rotational temperature (iv) and column density (v) of the emitting gas with their statistical errors. Parameters (i), (ii), and (iii) were fixed from step 1. The following additional criteria apply: we simultaneously fitted optically thin and partially opaque spectral lines with an opacity lower than 5; the CH\(_3\)CN K = 0–3 components were excluded from the fit, except for P6 and P12, because their profiles show signs of either filtering or an excess of warm envelope emission (e.g. side panels in Fig. 2; cf. Appendix B of Ahmadi et al. 2018); and the number of lines processed by MCWeeds is ≥7 for each pointing.

Notably, in more than half of the 22 spectra of Figs. A.3 and A.4, the methanol line at the centre of the band stands brighter than the CH\(_3\)CN lines at low excitation energies. Their emission is optically thick and sets an upper limit to the expected maximum brightness from gas in LTE. Assuming that

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\(^1\) The line free channels in the high spectral-resolution dataset were selected based on an accurate eye inspection of the band, with the line frequencies of abundant molecular species marked in the spectrum to avoid them, and eventually comparing maps produced with different selections of channels to exclude the effect of line contamination.
the CH$_3$OH and CH$_3$CN molecular species are fully coupled and emit cospatially, this is evidence that the CH$_3$OH ($^{13}$CH$_3$+1$_{13}$$^0_1$) A$^+$ transition is emitting by maser excitation, which adds to a plateau of thermal emission. In this context, we remind readers that G023.01$-$00.41 is among the brightest Galactic CH$_3$OH maser sources at 6.7 GHz, and, for comparison, in Fig. A.5 we overplotted the positions of the 6.7 GHz maser cloudlets, derived at milliarcsecond accuracy by Sanna et al. (2010, 2015), to the emission from Fig. 1. The distributions of the emission in different CH$_3$OH maser lines usually resemble each other closely, and this evidence is confirmed in Fig. A.5 where, for instance, the brightest emission in both transitions clusters on the western side of the disk. Also, we note that the same 349.1 GHz CH$_3$OH transition was found to emit by maser excitation around the early-type young star, S255 NIRS3 (Zinchenko et al. 2018). In Table 2, we summarise the properties of the line and continuum emission associated with each of the 22 spectra: Col. 1 identifies each position as labelled in Fig. 1; Cols. 2 and 3 list the offset positions with respect to the phase centre of the observations (Table 1); Col. 4 quantifies the (projected) linear distance of the centre of each pointing from the star position, as defined in Sanna et al. (2019); Col. 5 lists the integrated continuum flux at 860 $\mu$m associated with each pointing, as measured from Fig. A.2; Cols. 6 to 10 list the best fit parameters of the gas emission output by MCWeeds with their statistical errors, with Col. 11 specifying the opacity of the CH$_3$CN $K=4$ line; and Cols. 12 and 13 list the gas mass and H$_2$ column density estimated from the dust continuum emission within an area with a 500 au diameter. This calculation assumes that the dust emission is optically thin at an equilibrium temperature equal to that listed in Col. 8, with a standard gas-to-dust mass ratio of 100, for a source of given distance ($d$) and dust continuum flux ($S_{dust}$), the gas mass is evaluated from the following formula (Hildebrand 1983): 
\[ M = \frac{d^2 \cdot S_{dust} \cdot R}{\kappa_v \cdot B_v(T_{dust})} \]
where $R$ is the gas-to-dust mass ratio, $B_v$ is the Planck function at a dust temperature of $T_{dust}$, and $\kappa_v$ is the dust absorption coefficient.

Fig. 2. Physical conditions in the accretion disk of G023.01$-$00.41. Main panel: same image (and symbols) as in Fig. 1, with the equatorial reference system (top right) rotated clockwise by 57$^\circ$, in order to align the (projected) outflow direction with the vertical axis of the plot. For three selected pointings indicated in white, we plotted the local integrated spectra at 349 GHz in the side panels (grey histograms), as an example of the molecular line profiles and fitting. The cluster source ‘mm2’ is marked; this source might alter the accretion disk around the primary (star symbol). Side panels: examples of different CH$_3$CN ($19K$$-$$18K$) spectra extracted in the inner (P8), outer (P6), and apparent spiral regions (P13) of the accretion disk (identifier on the top left). Positions of CH$_3$CN and CH$_{13}$CN components are labelled in red and blue, respectively, with $K$ ranging from 0 up to 10. The brightest line at a rest frequency of 349.107 GHz corresponds to the CH$_3$OH emission imaged in the main panel; this line shows a bright maser contribution in the inner-region spectra (e.g. P8). Red profiles draw the synthetic spectra fitted with MCWeeds by a Monte Carlo Markov chains method, assuming LTE; the best fit parameters of intrinsic FWHM, excitation temperature, and column density of CH$_3$CN are listed on the top right (cf. Table 2). We note that the excess of emission visible in the higher $K$ lines of the observed spectrum at position P8, with respect to the synthetic spectrum, is likely due to contamination from different molecular species.
Table 2. Physical parameters of the CH$_3$CN gas and dust observed near 349 GHz towards the accretion disk in G023.01−00.41.

| ID  | X-offset (") | Y-offset (") | $R_p$ (au) | $S_{dust}$ (mJy) | $v_{off}$ (km s$^{-1}$) | FWHM$_{int}$ (km s$^{-1}$) | $T_{rot}$ (K) | $N_{CH_3CN}$ (10$^{16}$ cm$^{-2}$) | Size (mas) | $\tau_4$ | $M_{dust}$ (M$_{\odot}$) | $N_{H_2}$ (10$^{22}$ cm$^{-2}$) |
|-----|--------------|--------------|--------|-----------------|----------------|----------------------|---------|----------------------|--------|------|----------------------|----------------------|
|     | (1)          | (2)          | (3)    | (4)             | (5)            | (6)                   | (7)     | (8)                   | (9)    | (10) | (11)                 | (12)                 |
| P1  | 0.074        | 0.056        | 250    | 29.7            | +0.78 ±0.03    | 7.37 ±0.20           | 267$^{+2}_{-2}$ | 56.75$^{+0.53}_{-0.58}$ | 70     | 6.94       | 0.16                  | 10.0                 |
| P2  | 0.015        | 0.147        | 750    | 13.6            | +3.25 ±0.03    | 5.17 ±0.56           | 197$^{+2}_{-2}$ | 35.80$^{+0.80}_{-0.30}$ | 95     | 15.00       | 0.10                  | 6.2                  |
| P3  | +0.045       | 0.238        | 1250   | 4.6             | +2.69 ±0.03    | 4.79 ±0.16           | 140$^{+2}_{-2}$ | 9.33$^{+0.11}_{-0.30}$ | 95     | 6.31        | 0.05                  | 2.9                  |
| P4  | +0.104       | 0.330        | 1750   | 3.8             | +2.83 ±0.03    | 3.09 ±0.09           | 118$^{+2}_{-2}$ | 6.17$^{+0.27}_{-0.30}$ | 90     | 7.01        | 0.05                  | 2.9                  |
| P5  | +0.163       | 0.421        | 2250   | 2.8             | +1.86 ±0.07    | 3.94 ±0.06           | 110$^{+2}_{-2}$ | 1.41$^{+0.17}_{-0.12}$ | 100    | 1.27        | 0.04                  | 2.3                  |
| P6  | +0.223       | 0.512        | 2750   | 2.9             | +1.70 ±0.04    | 3.82 ±0.07           | 90$^{+5}_{-5}$  | 0.83$^{+0.07}_{-0.02}$ | 100    | 0.75        | 0.05                  | 2.9                  |

Notes. Column 1: position label with reference to Fig. 1. Columns 2 and 3: offset positions of each pointing with respect to the phase centre. Column 4: projected distance from the star position. Column 5: integrated continuum flux at 860 μm. The following parameters inCols. 6 to 11 were estimated by modelling the 19K → 18K emission of CH$_3$CN and CH$_3$CN with Weeds and MCWeeds, assuming LTE conditions, and they are shown with their statistical errors. Columns 6 and 7: line velocity offset, with respect to 77.4 km s$^{-1}$. Columns 8 to 11: rotational temperature and column density of molecular gas and source size. Column 11: open parenthesis of the CH$_3$CN (19K−18K) line. Columns 12 and 13: gas mass and H$_2$ column density estimated from $S_{dust}$ within a circular area with a 500 au diameter each. $^a$Upper limit set at 3σ. $^b$The north-eastern and south-western directions are named here with respect to the disk midplane in Fig. 2.

and a uniform dust absorption coefficient of 1.98 cm$^2$ g$^{-1}$ at the observing frequency, obtained for thick ice mantles, densities of 10$^3$ cm$^{-3}$, and linearly interpolated from the values tabulated by Ossenkopf & Henning (1994). The validity of this assumption is commented on in Sect. 4.1. Although the synthetic spectra reproduce the bulk of the emission very well (red profiles in Figs. A.3, A.4), discrepancies between the observed and expected emission of the higher K lines exist at the inner disk radii, where molecular chemistry is rich and contamination from different molecular species is expected (e.g. CH$_3$OCHO, cf. Liu et al. 2020). Also, towards these regions, the line-of-sight crosses large portions of gas at different distances from the star, and one can expect that the integrated emission will be the combination of different gas’s physical conditions. Then, the working hypothesis we have provided, that only a single temperature and density component exists, may not be fully satisfied, and local gradients of both temperature and density might affect the observed line profiles. This second order effect is neglected in the following analysis and will contribute to the uncertainty in the assumptions.

4. Discussion

4.1. Physical conditions

Having on hand the information about the gas’s physical conditions across the extent of the disk, in the following we want to study the dependence of the gas temperature, column, and volume densities with distance from the central star. In Fig. 3, we present a diagram for each of these three quantities plotted against the projected distance (listed in Col. 4 of Table 2), where disk loci are marked with different symbols: Filled and empty black circles are used for the eastern and western disk sides, respectively, and red and blue diamonds for the north-eastern and south-western apparent spirals, respectively. We explicitly note that the uncertainties reported in Table 2 quantify statistical errors only, meaning that they hold under the assumptions used for the analysis. While the statistical errors convey information on the quality of the assumptions, they do not consider the uncertainties inherent in the assumptions themselves, which can be of the order of 10% on average. Error bars plotted in Fig. 3 account for a nominal uncertainty of 10% summed in quadrature to the statistical errors.
from the star. The dotted bold line traces the distribution along the disk midplane as a function of the projected distance.

midplane measurements are drawn, which account for an additional western apparent spirals, respectively (Table 2). Error bars of (only)

and blue diamonds mark measurements in the north-eastern ad south-

Dependence of the gas physical conditions with the projected distance from the star, as determined from the relative intensities of the CH$_3$CN lines near 349 GHz. Filled and empty black circles mark measurements in the north-eastern and south-western apparent spirals, respectively (Table 2). Error bars of (only) midplane measurements are drawn, which account for an additional western apparent spirals. The dotted bold line draws the best fit to the sample distribution, similar to the upper panel, and the best fit parameters are reported in the plot with their uncertainties. In comparison with the upper panel, the data points are still strongly correlated (0.90), but show a steeper slope with a relative dispersion three times larger. Column densities along the apparent spiral arms are also consistent with the power law measured along the midplane.

At variance, the dashed blue line shows a shallower increase scaling with $R^{-0.5}$, as it would be expected for a spherical distribution of gas (e.g. an envelope/core) with a density profile proportional to $R^{-1.5}$; this curve starts with the same column density ($9.2 \times 10^{15}$ cm$^{-2}$) of the best fit at 3000 au.

In the middle panel of Fig. 3, we plotted the CH$_3$CN column density in units of $10^{16}$ cm$^{-2}$, with respect to the same distance scale. The dotted bold line draws the best fit to the sample distribution, similar to the upper panel, and the best fit parameters are reported in the plot with their uncertainties. In comparison with the upper panel, the data points are still strongly correlated (0.90), but show a steeper slope with a relative dispersion three times larger. Column densities along the apparent spiral arms are also consistent with the power law measured along the midplane.

At variance, the dashed blue line shows a shallower increase scaling with $R^{-0.5}$, as it would be expected for a spherical distribution of gas (e.g. an envelope/core) with a density profile proportional to $R^{-1.5}$; this curve starts with the same column density ($9.2 \times 10^{15}$ cm$^{-2}$) of the best fit at 3000 au.

In the lower panel of Fig. 3, we can evaluate the average volume density of H$_2$ gas along the line-of-sight, $\langle n_H \rangle$, under the assumption that the central star is surrounded by a circular gaseous disk observed approximately edge-on, that has a sharp cut-off at radii of 3000 au ($R_{\text{max}}$). At each of the 12 pointings in the midplane, we divided the CH$_3$CN column density value by the local disk length intercepted by the observer, $2 \times (R_{\text{max}} - R_p)^{0.5}$, where $R_p$ is the projected distance of each pointing from the star position (as listed in Table 2). In the calculation, we assumed a constant relative abundance of $10^{-8}$ between CH$_3$CN and H$_2$ species for temperatures above 100 K, for consistency with previous work (e.g. Johnston et al. 2020; Ahmadi et al. 2019). The best fit parameters are reported in the plot with their uncertainties, with the volume density in units of $10^8$ cm$^{-3}$. The volume density fit implies an average of $1.8 \times 10^8$ cm$^{-3}$ at a radius of 3000 au, which increases to $8.2 \times 10^8$ cm$^{-3}$ at a ten times smaller (projected) distance from the star.

The average volume density evaluated at the projected radius ($R_p$) of 250 au is a robust underestimate for the gas density in the inner disk regions. At the corresponding positions (P1 and P7 in Fig. 1), the line-of-sight crosses a large range of disk radii, from the outer disk regions down to 250 au. We can still exploit this average volume density to obtain a better approximation for the peak density at 250 au from the star. The average integral of the best fit power-law, $\frac{1}{4\pi} \int_0^{R_{\text{max}}} 10^{4.6} \times R^{-1.5} \, dR$, would equal a volume density of $8.2 \times 10^8$ cm$^{-3}$ by definition, when evaluated from 3000 au to 250 au ($b$). By solving this equation at the inner radius, one derives a peak density of $4.8 \times 10^9$ cm$^{-3}$ (or $1.6 \times 10^{14}$ g cm$^{-3}$), which is approximately a factor of 6 higher than the average.

In Cols. 12 and 13 of Table 2, we have estimated the mass and column density of H$_2$ gas from the dust continuum fluxes at 860 μm, assuming the dust emission is optically thin. However, the dust emission is optically thick at these wavelengths (with a dust opacity of the order of unity and higher), as it can be inferred by comparing the low brightness temperature of the continuum data points, obtained by minimising a linear relation between the logarithms of the gas temperature and radius, $\log_{10}(T_{\text{gas}}) = k \cdot \log_{10}(R_p) + h$. The grey shadow marks the dispersion about the best fit (1σ). Values of $k$ and $h$ are reported in the plot with their uncertainties, together with the linear correlation coefficient ($r = 0.98$). Only for the sake of comparison did we draw a ‘classical’ temperature dependence with the radius $R^{-3/4}$, which is expected for geometrically thin disks heated externally by the star or internally by viscosity (e.g. Kenyon & Hartmann 1987); this curve starts with the same temperature (98.4 K) of the best fit at 3000 au (the estimated outer disk radius).
Fig. 4. Variation of the temperature slope with time, as determined at the disk midplane of a massive star with the simulations by Kuiper & Hosokawa (2018, their Fig. 6), with the corresponding stellar mass indicated on top. The \( k_{\text{sim}} \) is the mean linear variation determined over the range of radii, 100–2000 au. The red dashed line marks the observed value fitted in the upper panel of Fig. 3, and the grey shadow denotes the dispersion about the best fit (1σ).

In Fig. 4, we present a plot of the temperature slope at the disk midplane \( k_{\text{sim}} = \frac{\partial \log T}{\partial \log R} \) as a function of time, as derived from the simulations by Kuiper & Hosokawa (2018, their Fig. 6). The slope is defined by a linear fitting of the change in temperature with radius in the distance range 100–2000 au, and it varies (almost) monotonically over a small range between −0.55 and −0.37. The axis on top indicates the corresponding stellar mass at a given time. The steeper slope at early times describes the settling of a very young (with lower mass) accreting star and the formation of its circumstellar disk. The observed slope is fully consistent with the model expectation and is drawn with a dashed line in Fig. 4 for comparison. The magnitude of the modelled temperature at a given radius depends on the stellar mass. In Fig. 6 of Kuiper & Hosokawa (2018), the temperature at a radius of 250 au increases with time from 300 K to 500 K, when the stellar mass approximately increases from 20 \( M_\odot \) to 100 \( M_\odot \). The lower end of this range is consistent with the combination of stellar mass (20 \( M_\odot \)) and disk temperature (289 K) of our observations within the uncertainties, suggesting that the stellar system is still in a very early stage of evolution (<40 kyr). The comparison above shows that those basic quantities, obtained for the model and with our observations independently, are consistent with each other and this validates these conditions for future model developments.

4.2. Disk stability

In the following, we want to study whether opposite forces are in equilibrium inside the accretion disk, or whether self-gravity might dominate locally, causing the disk to fragment. For this purpose, we applied the analysis by Kratter et al. (2010) who describe the stability of a disk where gas is falling in rapidly, as it is observed in the target source. In Sanna et al. (2019), we quantified a mass infall rate of \( 6 \times 10^{-4} \) \( M_\odot \) yr\(^{-1} \) by comparing position-velocity diagrams observed along the disk midplane with synthetic diagrams simulated through a dedicated disk model.

Following Kratter et al. (2010), we calculated two dimensionless accretion rates describing the state of the system. The first ‘rotational’ parameter, \( \Gamma = \frac{M_{\text{inf}} \cdot (M_{\text{sys}} \cdot \Omega)}{\dot{M}} \), relates the accretion timescale to the orbital timescale of infalling gas, where \( M_{\text{inf}}, M_{\text{sys}}, \) and \( \Omega \) are the mass accretion rate, the system mass of the star plus disk at a given radius, and the angular velocity at the same radius, respectively. The second ‘thermal’ parameter, \( \xi = \frac{M_{\text{inf}} \cdot G \cdot c_s^3}{\dot{M}} \), relates the mass accretion rate to the local sound speed of disk material. The \( M_{\text{inf}} \) and \( M_{\text{sys}} \) were quantified in Sanna et al. (2019); \( \Omega(R) \) was evaluated based on the enclosed mass at a given radius and considering an orbital motion which is either Keplerian or 70% of its value; and \( c_s \) was evaluated from the excitation temperatures in Table 2.

These parameters were calculated for each of the 223 points marked in Fig. 1, and they are plotted in Fig. 5 for a direct comparison with Fig. 2 of Kratter et al. (2010).

In Fig. 5, the upper and lower panels describe the state of the system for a sub-Keplerian and Keplerian rotation curve, respectively. We have demonstrated that the system is sub-Keplerian outside of 500 au from the central star and that it might approach centrifugal equilibrium inside this radius (Sanna et al. 2019). For this reason, we expect the system to behave in between these two extremes. The diagram is divided in two regions where the system is either stable (white) or prone to fragmentation (grey); this empirical boundary condition is defined at \( \Gamma = x^2 \cdot 850^{-1} \) (Kratter et al. 2010). We note that \( \Gamma \) – \( \xi \) couples characterising the disk midplane are labelled according to the numbers in Fig. 1; \( \Gamma \) – \( \xi \) couples characterising the apparent spiral features are grouped over a small range of values in the plot and are indicated with red and blue diamonds for clarity (same symbols as in Fig. 3).

This analysis outlines that \( \Gamma \) – \( \xi \) couples are distributed near the boundary between a stable and unstable disk, and the

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3 The sound speed was calculated from the formula, \( c_s = \sqrt{\gamma k_B T / \mu m_H} \), where \( \gamma = 7/5 \) is the adiabatic index for a diatomic gas (H\(_2\)), \( k_B \) is the Boltzmann constant, \( \mu = 2.8 \) is the mean molecular weight per hydrogen molecule, and \( m_H \) is the mass of a hydrogen atom.
From a theoretical point of view, and in agreement with our snapshot taken in Fig. 5, unstable accretion disks are a robust product of distinct models simulating the formation of massive stars (e.g. Kratter et al. 2010; Klassen et al. 2016; Rosen et al. 2016, 2019; Harries et al. 2017; Meyer et al. 2017, 2018; Ahmadi et al. 2019; Oliva & Kuiper 2020). Unstable disks can fragment, leading to hierarchical star systems that consist of (several) low-mass stellar companions surrounding a massive primary. These simulations also predict that unstable accretion disks will develop substructures and density-enhanced spiral features, which wrap along the equatorial plane. In the following section, we comment on the apparent spiral morphology imaged in Fig. 1.

**Spiral arms or accretion streams?**

Spiral arms can be produced by gravitational instabilities, being the manifestation of underlying density waves in a self-gravitating disk (e.g. Lodato & Rice 2005), and by tidal interactions between the disk and a cluster companion, either internal or external to the disk itself (e.g. Zhu et al. 2015). From an observational point of view, evidence for disk substructures have been recently reported towards a couple of massive young stars (Maud et al. 2019; Johnston et al. 2020). In particular, Johnston et al. (2020) have outlined the existence of a spiral arm branching off the disk of a massive star at a varying pitch angle (20°–47°). Arguably, the asymmetric spiral morphology they found could be triggered by tidal interactions with cluster companions (e.g. Forgan et al. 2018).

In order to interpret the apparent spiral morphology imaged towards G023.01–00.41, we have to take into account the viewing angle to the observer. In Fig. 2, the horizontal axis of the plot approximately coincides with the equatorial plane of the disk, whose inclination was inferred to be nearly edge-on. Consequently, the vertical axis of the plot provides approximate altitudes above the disk midplane, implying that the apparent spiral features extend up to 2500-3000 au off the plane (up to 3500 au in the limit of 30° inclination). This evidence suggests that the apparent spiral features might be rather streams of gas, producing a warp in the outer disk regions and, hereafter, we refer to the north-eastern and south-western apparent spirals as the north-eastern and south-western streams, respectively. Whether these streams of gas are due to inward or outward motions can be tested based on the line fitting presented in Sect. 3.

The combined fitting over a group of spectral lines, emitting from the same spatial region, allowed us to determine the offset velocity ($v_{\text{off}}$) of local gas with an accuracy better than 0.1 km s$^{-1}$ (Col. 6 of Table 2). This analysis reveals two velocity gradients of the order of 1 km s$^{-1}$ per 2000 au along the north-eastern (positions 13 to 16) and south-western (positions 19–22) streams. Gas accelerates from the ambient velocity in the outer stream regions, at about 79 km s$^{-1}$, to blueshifted velocities close to the disk plane. If disk material were moving outward, due to a disk wind, one would expect the gas velocity to be very different from the ambient velocity at the stream tip. On the contrary, these velocity gradients are consistent with a scenario where gas accelerates towards the disk moving from the outer envelope at the ambient velocity, thus supporting the existence of an accretion flow. This scenario naturally explains the infall profile previously detected in the position-velocity diagrams along the disk midplane (Sanna et al. 2019, their Fig. 5).

At positions P17 and P18, the measured velocity differs from that expected for a regular gradient along the entire streams. This
discrepancy can be interpreted as an effect of contamination from the outer disk gas at position P17, and the local gas dynamics at position P18 (see further discussion below). For completeness, we also mention a third scenario where the apparent spiral features might just be overdensities within the larger envelope around the disk, although we consider this hypothesis very unlikely given the spatial morphology and physical conditions observed.

Explaining the three-dimensional morphology of the accretion streams prompts a dedicated theoretical study which goes beyond the scope of the current paper. Therefore, in the following we highlight a number of observational features which should be taken into account in future dedicated simulations. First, the north-eastern and south-western streams appear approximately symmetric in gas emission, but not in dust, with the south-western stream being deficient in continuum emission with respect to the north-eastern stream (Fig. A.2). Whether this difference is related to the origin of the streams themselves should be clarified. Second, to the east of the accretion disk, at a (projected) distance of approximately 3500 au from the star, the continuum map shows a dust overdensity which also coincides with a local peak of molecular emission, labelled as ‘mm2’ in Fig. 2. Whether and how this source could perturb the stream morphology and affect the local warp of the disk should be clarified. Finally, we note that the outer tips of both streams are the regions with the higher combination of column density and temperature along the streams (P13 and P18 of Table 2). Simulations of in-plane spiral arms show that their overdensities can fragment, leading to companion stars that, in turn, can influence the morphology of disks and spirals (e.g. Figs. 1 and 12 of Oliva & Kuiper 2020). By analogy, we pose the question of whether or not the stream tips could host newly formed stars, and, if yes, how they could interact with the stream morphology.

5. Conclusions

We report on spectroscopic ALMA observations near 349 GHz with a spectral and angular resolutions of 0.8 km s$^{-1}$ and 0′′1, respectively. We targeted the star-forming region G023.01−00.41 and imaged the accretion disk around a luminous young star of 10$^4.6 L_\odot$ in both methyl cyanide and methanol emission. We fitted the K-ladder of the CH$_3$CN (19$_K$−18$_K$) transitions, and that of the isotopologue CH$_{3}^{13}$CN, to derive the physical conditions of dense and hot gas within 3000 au from the young massive star. Our results can be summarised as follows:

1. We resolved the spatial morphology of the accretion disk which shows two apparent spiral arms in the disk outskirts at opposite sides (Fig. 2, main). These apparent spirals likely represent streams of accretion from the outer envelope onto the disk. They appear almost symmetric in molecular gas, but not in dust, with one stream being deficient in continuum emission with respect to the other (Fig. A.2). The disk is remarkably bright in CH$_3$OH (14$_{13}$−14$_{13}$) A$^+$ emission, showing a maser contribution up to (at least) 2000 au from the young star.

2. We derived the temperature, column, and volume densities of molecular gas along the disk midplane and accretion streams, and studied their dependence with distance from the central star (Fig. 3). The gas temperature varies as a power law of exponent $R^{-0.45}$, which is significantly shallower than that expected around Solar-mass stars ($R^{-0.75}$). The volume density averaged along the line-of-sight through the disk varies as a power law of exponent $R^{-1.25}$; this slope implies a peak density of $1.6 \times 10^{-14}$ g cm$^{-3}$ at 250 au from the star.

3. Our findings are in excellent agreement with the results of recent hydrodynamics simulations of massive star formation (Kuiper & Hosokawa 2018), and this comparison supports the idea that we are tracing disk conditions as opposed to envelope conditions. In turn, this comparison provides evidence that the high excitation-energy transitions of CH$_3$CN allow us to peer into the inner disk regions.

4. We have studied whether the disk is stable against local gravitational collapse, following the analysis by Kratter et al. (2010), who describe the stability of a disk undergoing rapid accretion. This analysis outlines that the accretion disk marginally meets the condition for fragmentation along its whole extent, and regions beyond radii of 1000 au are progressively more unstable and have the higher likelihood to produce stellar companions (Fig. 5). Notably, the tips of the accretion streams are the loci of higher temperature and column density, and they could host young stars in the making. The fact that the disk is gravitationally unstable, together with the effect of tidal interactions with cluster member(s), might be the origin of disk substructures to be probed by observations of optically thin dust emission. These observations provide direct constraints for models trying to reproduce the formation of stars of tens of Solar masses, with a particular focus on the disk properties, the spatial morphology of gas accreting onto the disk, and the perspective of forming a tight cluster of stellar companions.

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### Table A.1. Observed lines

| $\nu$ (GHz) | Species / Line | $E_{up}$ (K) |
|-------------|----------------|--------------|
| **CH$_3$CN** |                |              |
| 348.784     | CH$_3$CN (19$_{10}$ – 18$_{10}$) | 880.6        |
| 348.911     | CH$_3$CN (19$_{9}$ – 18$_{9}$)  | 745.4        |
| 349.024     | CH$_3$CN (19$_{8}$ – 18$_{8}$)  | 624.3        |
| 349.125     | CH$_3$CN (19$_{7}$ – 18$_{7}$)  | 517.4        |
| 349.212     | CH$_3$CN (19$_{6}$ – 18$_{6}$)  | 424.7        |
| 349.286     | CH$_3$CN (19$_{5}$ – 18$_{5}$)  | 346.2        |
| 349.346     | CH$_3$CN (19$_{4}$ – 18$_{4}$)  | 281.9        |
| 349.393     | CH$_3$CN (19$_{3}$ – 18$_{3}$)  | 232.0        |
| 349.426     | CH$_3$CN (19$_{2}$ – 18$_{2}$)  | 196.3        |
| 349.446     | CH$_3$CN (19$_{1}$ – 18$_{1}$)  | 174.8        |
| 349.453     | CH$_3$CN (19$_{0}$ – 18$_{0}$)  | 167.7        |
| **CH$_3^{13}$CN** |             |              |
| 348.853     | CH$_3^{13}$CN (19$_{8}$ – 18$_{8}$) | 624.3       |
| 348.953     | CH$_3^{13}$CN (19$_{7}$ – 18$_{7}$) | 517.3       |
| 349.040     | CH$_3^{13}$CN (19$_{6}$ – 18$_{6}$) | 424.6       |
| 349.113     | CH$_3^{13}$CN (19$_{5}$ – 18$_{5}$) | 346.1       |
| 349.173     | CH$_3^{13}$CN (19$_{4}$ – 18$_{4}$) | 281.9       |
| 349.220     | CH$_3^{13}$CN (19$_{3}$ – 18$_{3}$) | 231.9       |
| 349.254     | CH$_3^{13}$CN (19$_{2}$ – 18$_{2}$) | 196.2       |
| 349.274     | CH$_3^{13}$CN (19$_{1}$ – 18$_{1}$) | 174.8       |
| 349.280     | CH$_3^{13}$CN (19$_{0}$ – 18$_{0}$) | 167.7       |
| **CH$_3$OH** |                |              |
| 349.107     | CH$_3$OH (14$_{13}$,13 – 14$_{0}$,14) A$^+$  | 260.2       |

**Notes.** Frequencies and upper energy levels for each molecular transition are obtained from the CDMS (Endres et al. 2016) and JPL (Pearson et al. 2010) catalogues.
Fig. A.1. Moment-zero map of the CH$_3$CN (19$_4$−18$_4$) emission (colours and black contours) for a direct comparison with the CH$_3$OH (14$_{13}$–14$_{12}$) A$^+$ emission of Fig. 1 (white contours). These CH$_3$CN and CH$_3$OH transitions have similar excitation energies ($E_{\text{up}}$) of 281.9 K and 260.2 K, respectively, and the line emission has been integrated over the same velocity range. The upper wedge quantifies the line intensity from its peak to the maximum negative in the map; black contours are drawn at levels of 10, 50, and 100 times the 1$\sigma$ rms of 2.5 mJy beam$^{-1}$ km s$^{-1}$. We note that the white and black contours should be used for a direct comparison between the spatial morphology of the CH$_3$OH and CH$_3$CN emissions, respectively, because they correspond to relative levels of comparable rms (at variance with the colour map which depends on the maximum in the map). The synthesized ALMA beam is shown in the bottom left corner.
Fig. A.2. Dust continuum emission at 860 µm (colours and white contours) imaged with ALMA towards G023.01–00.41 and derived from 52 MHz of emission-free band in the spectra. The upper wedge quantifies the continuum brightness from its peak to the maximum negative in the map; white contours are drawn at levels of 3, 10, and 20 times the 1σ rms of 0.2 mJy beam⁻¹. The moment-zero map of the CH₃OH (14₁₃–1₄₀₁₄) A⁺ mission is overlaid with the same black contours of Figs. 1 and 2 for comparison. The synthesized ALMA beam is shown in the bottom left corner.
Fig. A.3. Spectra of the CH$_3$CN (19$_K$–18$_K$) transitions along the eastern (left column) and western (right column) sides of the disk plane. Spectra are integrated at radial steps of 500 au as indicated in Fig. 1, and each pointing is labelled on the top left accordingly. The CH$_3$CN components, with K ranging from 0 to 10, are marked in red in each spectrum. The brightest line at a rest frequency of 349.107 GHz corresponds to the CH$_3$OH (14$_{13}$–14$_{12}$) A$^+$ emission imaged in Fig. 2. Modelled spectra are overplotted in red; we note that the first four K components were not fitted, except at positions P6 and P12 (cf. Sect. 3).
Fig. A.4. Same as Fig. A.3, but for spectra of the CH$_3$CN (19K–18K) transitions along the north-eastern (left column) and south-western (right column) spirals.
Fig. A.5. Same as Fig. 1, but, for comparison, the positions of the 6.7 GHz CH$_3$OH maser cloudlets are overplotted with cyan dots (from Sanna et al. 2010, 2015).