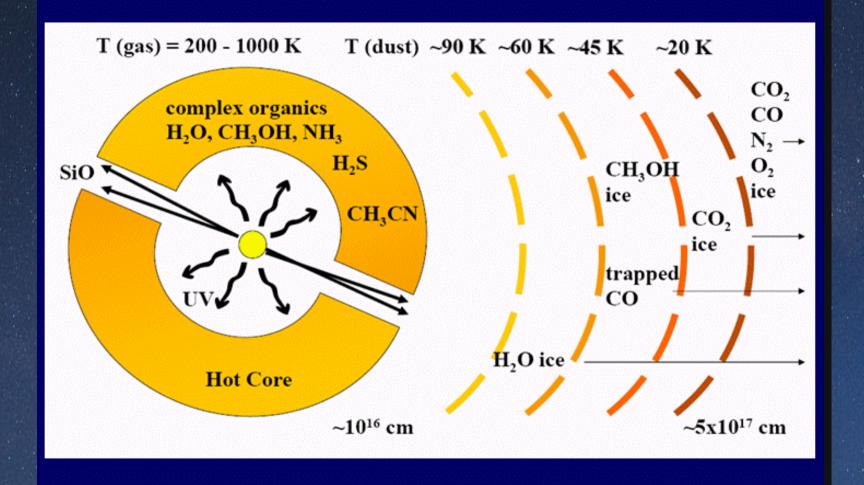
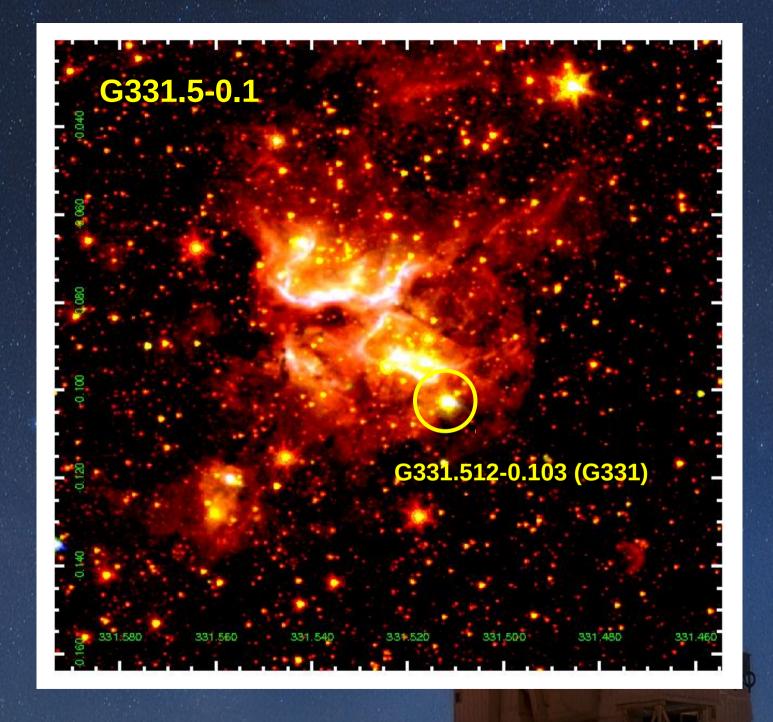
Cyanoacetylene in the outflow/hot molecular core G331.512-0.103

Duronea N.U.
Bronfman L.
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Nyman L-A.

Schematic of a Hot Core





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DISCOVERY OF AN EXTREMELY HIGH VELOCITY MASSIVE AND COMPACT MOLECULAR OUTFLOW IN NORMA

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ABSTRACT

G331.5—0.1 in the Norma spiral arm is one of the most luminous and extended cores of a giant molecular cloud (GMC), centaining at least six massive and dense data condensations. Here we report the discover, from observations of the continuous and the continuous and continuous continuou

Online material: color figure

1. INTRODUCTION

The G331.5−0.1 radio source corresponds to a diffuse region of ionized gas of ~d in size (Shaver & Goss 1970), with hydrogen recombination line velocity of ~82 km s⁻¹ (Caswell & Haynes 1987). This extended If irregion is spatially projected near the peak position of a giant molecular cloud (EMC) Located in the tangent region of the Norms spiral arm in the southern Galaxy, at distance of ~7.5 kp from the Sum (Bronfinan et al. 1985, 1989). a distance of σ^2 kpc from the Sunt Bronfman et al. 1985, 1989. Observations at several wavelengths show that the central core of this GMC harbors one of the most extended, massive, and luminous regions of massive and formation in the Calaste the GM, From 1997. On the Calaste the GMC and th lelescope (a.I.MIPS: survey data, which show that there are set-eral sites of massive star formation spread over a region of ~6' in diameter. Observations of the dust continuum emission at 12 mm, made with SIMBA at the Swedish-ESO submillimeter. Telescope (SEST), further show that the core contains six massive dust concentrations with a total mass of ~1.4 v 10³ M, (Wyman et al. 2001), in addition, made critical survey and content of the content of t transitions of OH and CH₃OH (Goss et al. 1970; Caswei et al. 1980; Caswei 1997, 1998). The presence of hydroxyl and meth-anol maser emission suggests that G331.5-0.1 is an active mas-sive star-forming region, and it is therefore an ideal case in which to study the process of the formation of protoclusters.

We have recently mapped the line emission toward the whole G331.5-0.1 core, using ASTE and APEX, in several molecular

transitions (CS(7 \rightarrow 6) and 12 CO(3 \rightarrow 2) with ASTE. CO(3 \rightarrow 2), CO(4 \rightarrow 3), and CO(7 \rightarrow 6) with AFEX, M. Merello et al. 2008, in perparation, line his pure we report on some of these observations, which have revoked the presence of a compact, respectively. The compact of the property of the

2 ORSEDVATIONS

The molecular line observations were made using the 12 m Atacams Pathfinder Experiment Telescope (APEX*), located at Llano declarigantor, and the 10 m Atacams Submillameter Telescope (ASTE), located at Pampa La Bola, both near the Atacams desert of Chile. The observed transitions and basic observational parameters are summarized in Table 1. Columns (1) and (2) give, especitively, the observed transition and the line frequency, Colrespectively, the observed transition and the line frequency. Colresponding the control of the control of the collection of the control of the collection umn (3) gives the telescope used, and columns (4) and (5) give the half-power beamwidth and the main beam efficiency at the

PHYSICAL CHARACTERISTICS OF G331.5-0.1: THE LUMINOUS CENTRAL REGION OF A GIANT MOLECULAR CLOUD

Marrier Menera of 2 Troyanno Brownia v Carro Canari Lang Ave Nyuavi MERELLO ¹², LEONARDO BROWHAN², GUIDO GARAY¹, LARS-AKE I. NEAL J. EVANS II², AND C. MALCOLM WALMASLEY² is persumento de Astroamin, Universidad de Chile, Casilla 3-fd, Sarrigao, Chile ²-University of Tens as Austin, I University Satzon, Austin, TX 78712. USA ³-Joset ALM Observatory (J.O., Alonso de Codoro 3 107, Vincura, Sartigao, Chile ³-Oservatoro Astrofisico di Accesti. Large I. Eveni S. 3-902. Fibrerae, Indy

We report molecular line and dust continuum observations beaust the high mass star-forming region G331, 5-0.1, one of the most luminous regions of massive star formation in the Milky Way, located at the tangent region of the Norma spiral arm, at a distance of 7.5 by, Moderular emission was namped toward the G331, 5-0.1 (Au in the COJ.) = $1 \rightarrow 0$) and $C^{2}OJ = 1 \rightarrow 0$ and $C^{2}OJ = 1$ an \sim 89 km s⁻¹, see 10 water of time clumps, as power lower of the molecular clump, with spectral index often two changes see 10 water of the molecular clumps, with spectral index estimated for two of them of 54 ± 0.2 and 1.2 ± 0.2. A high-velocity index clump, with spectral index estimated for two of them of 54 ± 0.2 and 1.2 ± 0.2. A high-velocity index clump with a factor for the estimated for two of them of 1.2 ± 0.2. A high-velocity index clump with a factor for the other of 1.2 ± 0.2 and 1.2 ± 0.2. A high-velocity index of SO(I = 12 - 6 and I = 12 - 6

Key words: ISM: clouds - ISM: molecules - stars: formation

1. INTRODUCTION

Massive stars play a key role in the evolution of the Galaxy, hence they are important objects of study in astrophysics. Although their number is much smaller than the low mass stars, though their number is much smaller than the low mass stars, and the stars of the star of the star

et al. 1995. Ceasion et al. 1991; Phume et al. 1992; Bondmun et al. 1996; M. Formalion process of high-mass stars is, how-ever, still under debate (Garay & Lizana 1999). Observationally, recently formed massies stars cannot be detected at optical swavelengths because they are embedded within regions with high dust etitation. Another proberts are from theoretical considerations: as are with a mass larger than eight solar masses stars briming hydrogen duffing the accretion phase and the radiation processe (e.g., Lazano a, Charrifold 1971; Edmi 1974; Yorke & Kruegel 1977. Larson & Starrifield 1971; Kinh 1974; Votrke 2004; Kunjer et al., Wupper et al., Wupper et al., Wupper et al., 2010). Due to three directives, a paradigm that explains the formation of massive stars does not extra (Zinnecker & Yorke 2007). Me & & Ottoriker 2007). Me & & Ottoriker 2007). Me & & Ottoriker 2007). Contrary to they successful model accepted for low mass starts. Understanding the physical process that we man stars to Understanding the physical process that we man stars for the stars of the formation of massive stars and the siltmence back on its furnerouting massive stars and the siltmence back on its furnerouting massive stars and the siltmence back on its furnerouting massive stars and the siltmence back on its furnerouting massive stars and the siltmence back on its furnerouting massive stars and the siltmence back on its furnerouting massive stars and the siltmence back on its furnerouting massive stars and the siltmence back on its furnerouting massive stars and the siltmence back on its furnerouting massive stars and the siltmence back on its furnerouting massive stars and the siltmence back on its furnerouting massive stars and the siltmence back on its furnerouting massive stars and the siltmence back on its furnerouting massive stars and the siltmence back on its furnerouting massive stars and the siltmence back on its furnerouting massive stars and the siltmence back on its furnerouting massive stars and the siltment of the s

outflow; the compact emission (not resolved at 8"0 re lution with APEX, Bronfman et al. 2008), which we

require a study of the physical contains of the environment represent when the first fements on at every step types. The object of our study is used in most massive CMCs in the Southern Galaxy, at l = 3315 and b = -0.71, in the angent region of the Norma spiral and Homothama et al. 1983. The study is the study of the CMC and the Southern Galaxy, at l = 3015 and b = -0.71, in the angent region of massive at formatton in the Goldaric disk. Single dish radio continuum observations show the presence of an attack of 3-d inputs of the study o

THE ASTROPHYSICAL JOURNAL LETTERS, 7741.7 (6pp), 2013 September 1

ALMA OBSERVATIONS OF THE MASSIVE MOLECULAR OUTFLOW G331.512-0.103

MANUEL MERELLO^{1,2}, LEONARDO BRONFMAN¹, GUIDO GARAY¹, NADIA LO¹, NEAL J. EVANS II², STANCEL MERCHO[®], LEONARD BROWNSON, VOLHO CALCH, VOLHO LEO, VALLE LE, VALLE

ABSTRACT

The object of this study is one of the most energetic and luminous molecular outflows known in the Galaxy. Key words: ISM: jets and outflows - ISM: molecules - stars: formation Online only material: color flavors

The formation of massive stars has a major impact on the surrounding interstellar medium, and regions of massive star formation dominate the star formation appearance of galaxies. While during the last couple of decades significant progress (both observational and theoretical) has been made in the study of massive stars and their parental molecular clouds, we are still far away from a complete picture of their formation process (for a recent discussion about this subject, see Kennicutt & Evans

Massive stars rapidly affect their surroundings, so catch-Massive stars rapidly affect their surroundings, so calcining one early in the formation process can provide valuable insights. Since they form rarely compared with their
low-mass counterparts, most are at large distances, making
high-resolution observations challenging. The Alacama Large
Millimeter/submillimeter Array (ALMA) provides the capability of studying distant objects in the Galaxy with good spatial resolution and sensitivity.

The G331.5=0.1 molecular cloud is a giant, elongated (178 The G331.5—0.1 molecular cloud is a giant, elongated (178 by 41 pc) cloud in the Norms spiral arm, at a distance of 7.5 kpc, with a total CO mass of $8.7 \times 10^9 M_{\odot} \, (M_{127} = 3.5 \times 10^9 M_{\odot} \, rm \, Cl^{10} \, cm)$ signon and a total infrared luminosity of $3.6 \times 10^9 \, L_{\odot} \, (Bronfman et al. 2008; Merello et al. 2013), making it one of the most active and extreme high-mass star-forming environments in our Galaxy. The central region$ hosts an extended H II region/infrared source and a number of ultracompact H II (UCHII) regions. Maps at submillimeter of ultracompact H II (CVHII) regions. Maps at submillimeter wavelengths show six continuum sources, with masses above 10 M_S and average gas surface densities of 0.4 g cm⁻². Single dish spectral line observations with the Alacama Shrimllimeter Telescope Experiment and the Alacama Pathfinder Experiment (APEX) of one of these sources, MASI, revealed extremely broad (420 Km s⁻¹) wings on lines of CO, CS (Broufman et al., 2008), SO, and SO (Otherdio et al., 2013). This highly massive and energetic outflow, GSI3 (12) –0.103, is unresolved spatially in 27 beam.

Here we present observations with ALMA that resolve the G331.512-0.103 molecular outflow, allowing derivation of the outflow properties including age. In forthcoming papers, we will describe the full set of molecular lines observed with ALMA

2 ORSERVATIONS AND RESULTS

The observations were performed on 2012 January 12 at frequencies around 350 GHz (0.86 mm) with ALMA Band 7 frequencies around 350 GHz 0.86 mm1 with ΔLMA Band 7 in Cycle 0 with 71 C2 m diametery amemus in the compact configuration, with baselines ranging from 18.5 m to 250 m. We observed a single field of view centered at $25_{500} = 10^{12}$ 219 (1909, $5_{2000} = -51^{12}$ 28384. The primary beam was 178 as of the synthesized beam was 1788 at 0.86 m with position angle (PA.) of -37.6. The integration time was 34 minutes on source, with an additional 24 minutes on calibrators. The nearby minutes of calibrations are distributed as 0.00 m for 0.00 315 (2) 0.00 10 (3) source, we will be 0.00 10 (3) 0.00 10 (4) 0.00 10 using the Common Astronomy Software Application (CASA, MeMbilli et al. 2007), and the resulting maps have cells with sizes of 0'14, with 224 cells in each spatial dimension. Our images were detained considering a "briggs" weighting mode on the data with robust =0.5. The four spectral windows have bandwidth of 1875 MHz containing 5840 channels. The abandwidth of 1875 MHz containing 5840 channels. The abandwidth of 1875 MHz containing 5840 channels. The abandwidth of 1875 MHz containing 5840 channels. The 1875 MHz containing 5840 channels. The abandwidth of 1875 MHz containing 5840 channels. The 2875 MHz containing 5840 channels of 1875 MHz containing 5840 channels. The 2875 347.2 GHz, 357.3 GHz, and 358.60587 GHz.

341.2 GHz, 357.3 GHz, and 358.60387 GHz.

Wille a rich spectrum of lines was observed, this Letter focuses on the lines of \$i0(8-7) (347.33058 GHz), H¹³CO*(4-3) (346.99835 GHz), HCO*(4-3) (356.73424 GHz), and CO(3-2) (346.998.0 GHZ), HCO'(4-3) (350.5.4342 4(HZ), and CO(3-2) (345.7999 GHZ), mostly diagnosing the outflow and is inter-action with the surrounding cloud. Table 1 presents the four lines reported in the present work, the noise for each, the peak flux density, and the velocity at the peak. The rms noise was assessed over a reglon of 35° x 35° centered on the source, avoiding a square area of 11° in size centered on the source, avoiding a channels, the noise was ~0.014 Jy beam-1. However, for strong emission lines, the noise is larger, presumably because of in-complete uv coverage. On the channels of maximum intensity,

ALMA OBSERVATIONS OF THE MASSIVE MOLECULAR OUTFLOW G331.512-0.103 II: PHYSICAL PROPERTIES, KINEMATICS, AND GEOMETRY MODELING

Carlos Hervías-Caimapo^{1,2s}, Manuel Merello³, Leonardo Bronfman¹, Lars Åke-Nyman⁴, Guido Garay¹, Nadia Lo¹, Neal J. Evans II^{6,6}, Cristian López-Calderón⁴, and Edgar Mendoza³

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ADSTRACT

We present observations and analysis of the massive molecular outflow G331.512.0.103, obtained with ALMA band 7, continuing the work from [Merello et al] (2013a). Several lines were identified in the observed bandwidth, consisting of two groups: lines with narrow profiles, tracing the emission for the contraction of the contraction o Subject headings: ISM: clouds — ISM: molecules — ISM: jets and outflows — stars: formation

1 INTRODUCTION

The formation of massive stars is an important tonic in The formation of massive stars is an important topic in stellar astrophysics that is open for debate. Despite the wealth of knowledge that has been obtained on young massive stellar sources, still there is no universal agree-ment on how massive stars are formed and evolve (Caray) (E. Lizano [1998] Zinnecker & Yorke [2007], [Kennicutt & University of the Committee of the Caragon of the Caragon

(K. Ilfanie) [1988] Zhimeckie e. Konsepper P. Fixans [2012].

There is an accepted paradigm on how low-mass stars form and worlve (Shu et al. [1987]. However, problems such as scarcity of young sources, large heliocentric distances (several kpc in some cases) and the lack of appropriate spatial resolution (that has been addressed and the lack of appropriate spatial resolution (that has been addressed and LAMA intel in recent years). with interferometers such as ALMA just in recent years)
make the subject of formation of massive stars an open
question. Two main theories compete on trying to explain this mechanism: the monolithic gravitational collarges (urbulent core accretion model (McKee & Tan)
2003), which is basically the extension of the model of
formation of low-mass stars to the massive ones, but with higher accretion rates and energetics; and the competi-tive accretion model (Bonnell et al. [2001], 2004), which states that low-mass seeds that will eventually form massive stars compete for the available gas in the gravita-tional potential of their native cluster.

Since massive stars have very short lifetimes, sources that are currently in the process of formation are very valuable. Molecular outflows are commonly detected to-

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G331.512-0.103: An Interstellar Laboratory for Molecular Synthesis, I. The Ortho-topara Ratios for CH₃OH and CH₃CN

Edear Mendoza D. Leonardo Bronfman D. Nicolas II. Duronea Jacques R. D. Lénine D. Ricardo Finger Manuel Merello D

Mendoua' © Leouardo Bronfama' © Nicolas U Duroneci Jacques R. D. Lépine ® Ricardo Finger, 'Manuel Mere Carlos Hervis-Canapos' Diana R. G. Gamia ® Noolas Reys, 'and Lass Ake Synam 'Useswinde de San Fash, Ind Fas de Maño. 125: Culat Universities, 105:100-03, to Pash, India, Sanshoofen-pole Sanshooden-pole Sanshooden-po

Spectral line surveys reveal rich molecular neservoirs in G331.512-0.103, a compact radio source in the center of an energetic molecular outflow. In this first work, we analyze the physical conditions of the source by means of CLF(H) and CLF(A). The observations were performed with the AFEX Telescope. Six different system configurations were defined to over most of the band within G22-2369 GHz; as a consequence, we detected a forest of lines toward the central core. A cloud TO lines on AFECT-HGFH and AfE-CHFGN were analyzed. forest of lines toward the central core. A total of 70 lines of A/E-CH,OH and A/E-CH,CN were analyzed, including breatoning located instantions of CH/QH/H₂ = 11, no actuar for all this topologous, we lederalized transitions of 'CH₂OH. The physical conditions were derived considering collisional and nadaritee processes. We included the control of the con

Key words: ISM: molecules - molecular processes - radio lines: ISM

G331.512-0.103 is one of the most luminous and energetic molecular outflows known in the Galaxy. All of the system is molecular outflows known in the Galaxy. All of the system is embedded in a staff-softening region known as G313-G31, located in the Norma spiral arm at a distance of e^{-7} pc. This source chibbs typical III region propriets and interac measure emission of OH and GH,OH (Caswell 1998; Nyman et al. 2018). An the cutter of the system, a young and massive stellar object drives a bipolar flow of around $5M_{\odot}$ with a momentum of $-2.4 \times 10^{4} M_{\odot}$ km s $^{-1}$. Radio continuum otherwalton known excellad a compact and the Radio continuum otherwalton known excelled a compact and the staff of the control of the cont central structure associated with a dust core. The central region has been also mapped with ALMA observations with transitions of SiO (8–7), H³³CO+ (4–3), HCO+ (4–3) and CO (3-2). The observations revealed a ring-like structure, consistent with a cavity, and the existence of a high-velocity outflow emission confined in a region lower than 5" in size (Merello et al. 2013a, 2013b; Hervías et al. 2015). In this work we present new results on the emission of CH₃OH and CH₃CN detected toward the central core, denominated hereafter

As an interstellar laboratory, G331 exhibits active chemistry As an interelletar lateropts, (3.51) ethnibs, calive chemistry in prebotic and complex organic molecules likely stimulated by physical processes in the molecular cont 4PMC Telescope, we detected a vast number of molecular lines potentially linked to service a servicin teach (9 (4.01) ethnical teleprocesses are serviced as a candidates to the control of the definent physical components that O and Service and the control of the definent physical components that O and Service are serviced as the control of the definence of the control of the definence of the defin

molecular cores (Sandell et al. 1994; Wyrowski et al. 1999; Jørgensen et al. 2004; Beuther et al. 2005; Fontani et al. 2007; Fuente et al. 2014; Giannetti et al. 2017). In addition, from a chemical point of view, CH₂OH and CH₂CN are considered as chemical point of view, CH₂OH and CH₂CN are considered as pirent and daughter moleculae, respectively, in the route of interstellar molecular formation (e.g., Nomura & Millar 2004). With that motivation, we started a systematic study of G331 beginning with spectral analyses of A/E-CH₂OH and A/E-CH₂CN.

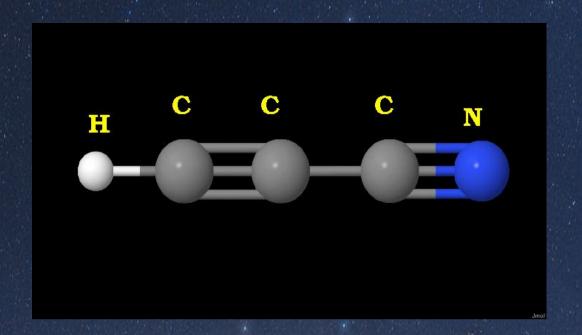
1.1. The Tracers CH₂CN and CH₂OH

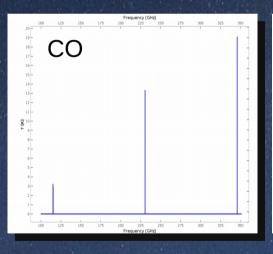
CH₃CN (methyl cyanide) is a symmetric top molecule. The nuclear spin state of the hydrogen atoms defines whether the molecule has an ortho (E) or para (A) symmetry. Rotational levels of CH-CN are characterized by two quantum numbers:

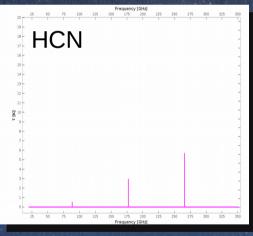
levels of CH,CN are characterized by two quantum numbers; the total angular momentum (*I*) and its projection on the axis of symmetry (*S*). Spectral signatures are associated to *K*-balder sunctures whose nutation for the *A* and *B* configurations and a constraint on the *A* and *B* configuration and a constraint on the *B* and *B* configuration and *B* modes. Methanol also exists in two species denoted as A and E depending on the nuclear spin alignment of the three H-atoms of the methyl group (CH₀). The energy levels of methanol can be assigned with the total angular momentum J and its component K along the symmetry axis (Lees & Baker 1968, Lovas et al. 1982).

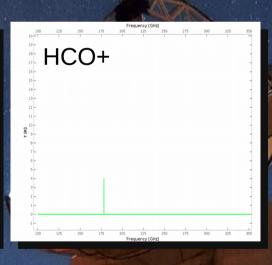
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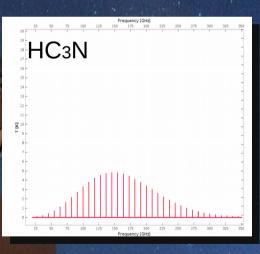


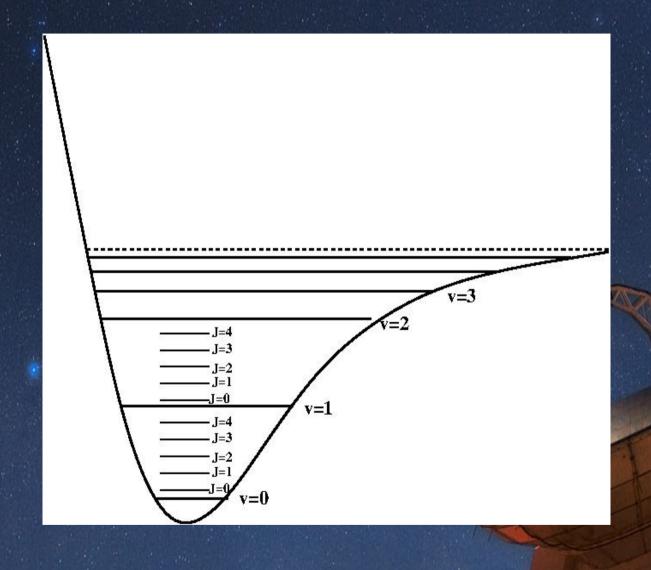


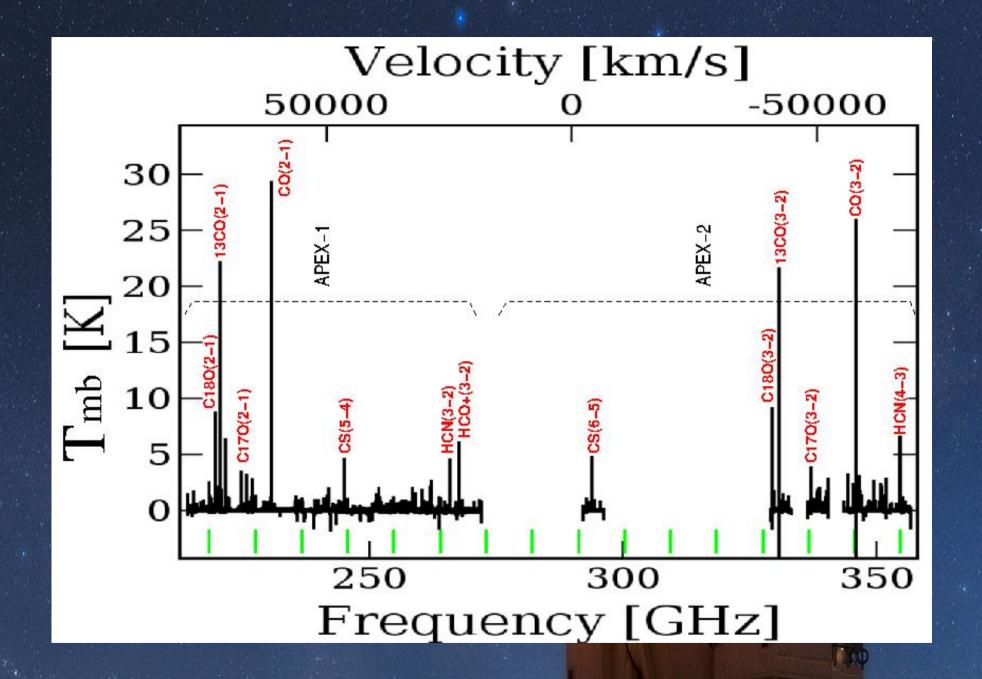












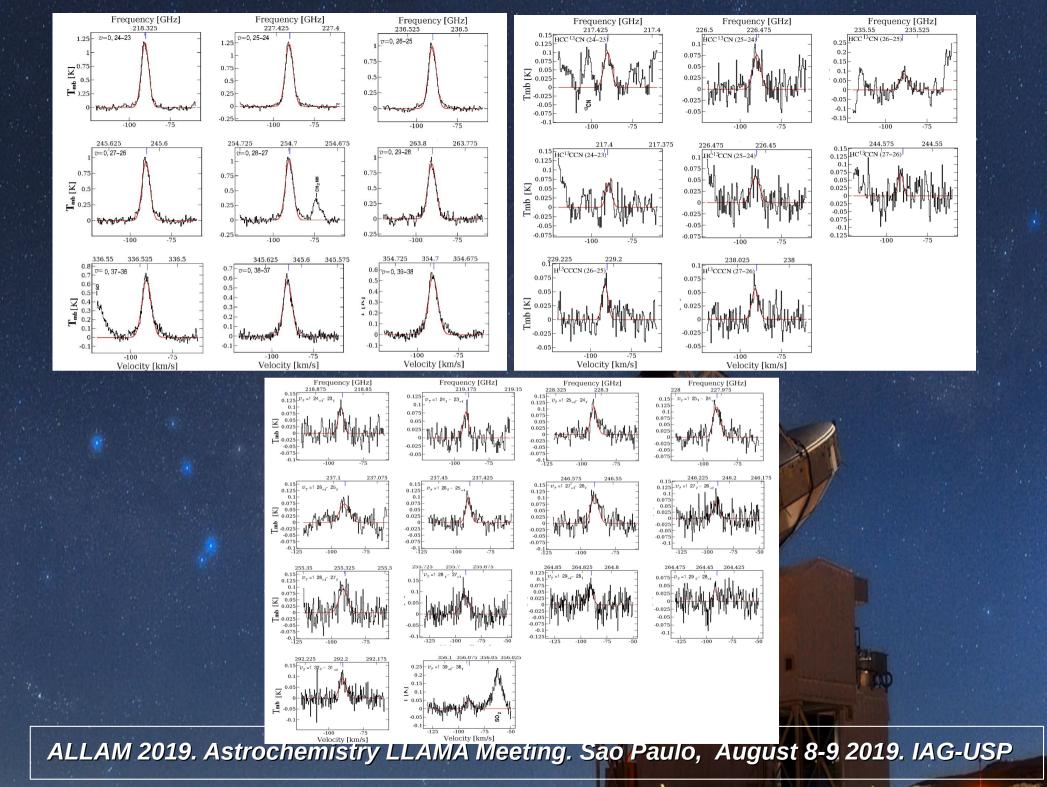


Table 1. HC₃N lines detected in G331 and their parameters obtained from Gaussian fits.

Transition	Frequency (MHz)	E_u (K)	$^{A_{ul}}_{(\times \ 10^{-5} \rm s^{-1})}$	$\int T_{\rm mb} dv$ (K km s ⁻¹)	$\frac{V_{lsr}}{(km s^{-1})}$	T_{peak} (K)	FWHM (km s ⁻¹)	τ	Remark§
v = 0					101 1		111		
24-23	218324.72	130.98	82.6	6.94 ± 0.72	-90.35 ± 0.05	1.17 ± 0.05	5.39 ± 0.11	0.298*	cl
25-24	227418.91	141.89	93.5	7.49 ± 0.75	-90.37 ± 0.05	1.23 ± 0.05	5.57 ± 0.11	0.278*	cl
26-25	236512.78	153.24	105.2	6.20 ± 0.62	-90.35 ± 0.05	0.99 ± 0.04	5.55 ± 0.12	0.260*	cl
27-26	245606.31	165.03	117.9	6.02 ± 0.61	-90.37 ± 0.07	0.94 ± 0.06	5.63 ± 0.17	0.248*	cl
28-27	254699.51	177.25	131.6	6.47 ± 0.66	-90.37 ± 0.07	1.02 ± 0.06	5.58 ± 0.15	0.235*	pbw ³³ SO nl CH ₂ NH
29-28	263792.31	189.91	146.3	5.85 ± 0.59	-90.49 ± 0.07	0.89 ± 0.06	5.93 ± 0.16	0.206*	pbw CH ₃ O
37-36	336520.08	306.91	304.8	4.86 ± 0.50	-90.50 ± 0.08	0.65 ± 0.05	6.67 ± 0.19	0.082*	nl SO
38-37	345609.01	323.49	330.2	3.87 ± 0.39	-90.57 ± 0.06	0.58 ± 0.04	6.16 ± 0.14	0.077*	pbw CH ₃ O
39-38	354697.46	340.51	357.1	4.14 ± 0.43	-90.54 ± 0.08	0.53 ± 0.04	6.92 ± 0.18	0.060*	cl
³ C Isotopologues									
H ¹³ CCCN									
26-25	229203.09	148.51	95.7	0.28 ± 0.04	-91.1 ± 0.2	0.06 ± 0.02	4.1 ± 0.4	0.024^{\dagger}	cl
27-26	238015.68	159.93	197.3	0.30 ± 0.04	-90.9 ± 0.2	0.06 ± 0.02	4.8 ± 0.5	0.022^{\dagger}	cl
HC ¹³ CCN									
24-23	217398.56	130.42	81.5	0.28 ± 0.05	-89.4 ± 0.4	0.07 ± 0.02	4.2 ± 0.8	0.025^{\dagger}	cl
25-24	226454.18	141.29	92.3	0.32 ± 0.05	-90.7 ± 0.4	0.06 ± 0.02	5.9 ± 1.0	0.024^{\dagger}	cl
27-26	244564.44	164.33	116.4	0.32 ± 0.06	$\textbf{-91.5}\pm0.4$	0.07 ± 0.03	3.6 ± 0.8	0.027^{\dagger}	pbw CH ₃ O
HCC ¹³ CN									
24-23	217419.57	130.44	81.6	0.51 ± 0.06	-90.2 ± 0.2	0.10 ± 0.02	5.4 ± 0.4	0.035^{\dagger}	pbw CH ₃ O nl ¹³ CN
25-24	226476.04	141.31	92.3	0.43 ± 0.06	-89.9 ± 0.4	0.08 ± 0.03	5.4 ± 0.7	0.031†	cl
26-25	235532.20	152.61	103.9	0.50 ± 0.07	-88.9 ± 0.3	0.09 ± 0.02	5.6 ± 0.6	0.037†	cl
$v_7 = 1$									
24_1-231	218860.81	452.15	82.7	0.58 ± 0.07	-91.3 ± 0.3	0.10 ± 0.03	4.9 ± 0.5	0.015*	cl
24_{1} - 23_{-1}	219173.75	452.34	83.0	0.34 ± 0.05	-91.6 ± 0.3	0.08 ± 0.02	4.1 ± 0.6	0.018*	cl
251 - 24 - 1	227977.27	463.09	93.5	0.69 ± 0.08	-90.2 ± 0.2	0.12 ± 0.02	6.0 ± 0.5	0.013*	cl
25_{-1} - 24_{1}	228303.17	463.29	93.4	0.70 ± 0.09	-90.8 ± 0.3	0.10 ± 0.02	6.8 ± 0.6	0.011*	cl
26_{-1} - 25_{1}	237093.38	474.47	105.2	0.53 ± 0.07	-90.5 ± 0.4	0.07 ± 0.02	8.4 ± 1.2	0.009*	cl
$26_{1}-25_{-1}$	237432.26	474.69	105.7	0.57 ± 0.07	-91.0 ± 0.2	0.10 ± 0.03	5.3 ± 0.5	0.014*	cl
$27_{1}-26_{-1}$	246209.14	486.29	118.0	0.45 ± 0.08	-91.4 ± 0.5	0.07 ± 0.03	9.0 ± 1.9	0.011*	cl
27_{-1} -26_{1}	246560.95	486.52	118.5	0.78 ± 0.10	-89.3 ± 0.4	0.10 ± 0.03	8.1 ± 0.9	0.009*	cl
28_{-1} - 27_{1}	255324.55	498.54	131.7	0.58 ± 0.10	-91.5 ± 0.5	0.09 ± 0.03	6.7 ± 1.1	0.011*	cl
281-27-1	255689.29	498.79	132.2	0.72 ± 0.11	-91.3 ± 0.6	0.08 ± 0.02	8.9 ± 1.6	0.008*	cl
29_{1} -28_{-1}	264439.58	511.23	146.4	0.20 ± 0.04	-91.6 ± 0.3	0.05 ± 0.02	2.6 ± 0.7	0.029*	cl
29-1-281	264817.24	511.50	147.1	0.40 ± 0.07	-91.0 ± 0.5	0.07 ± 0.03	6.2 ± 1.1	0.012*	cl
32_{1} - 31_{-1}	292198.64	552.26	197.9	0.50 ± 0.08	-90.2 ± 0.3	0.09 ± 0.02	4.9 ± 0.6	0.014	cl
39_{-1} -38_{1}	356072.44	662.68	359.2	0.30 ± 0.08 0.31 ± 0.06	-90.2 ± 0.3 -90.3 ± 0.4	0.05 ± 0.02 0.05 ± 0.02	6.6 ± 1.0	0.008*	nlo SO ₂

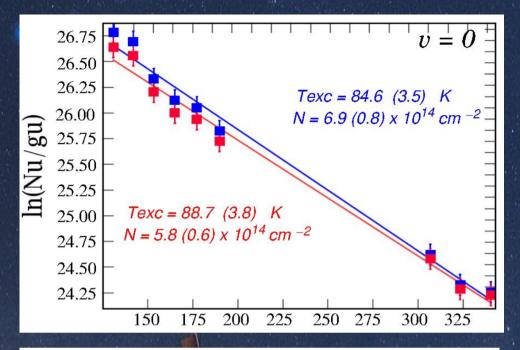
^{*}Obtained iteratively from the opacity correction (Sect 4.2.1) †Obtained from Eq.8 (Sect. 4.2.3)

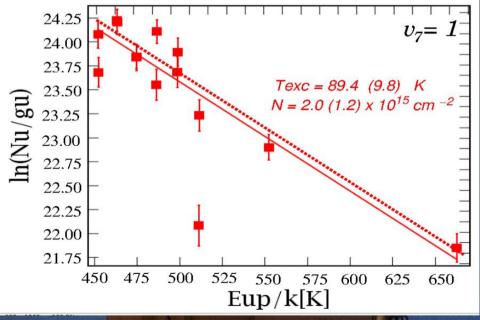
LTE analysis

$$N_u = \frac{8\pi k \nu^2}{hc^3 A_{ul}} \times \int T_{\rm mb} \ d\mathbf{v}$$

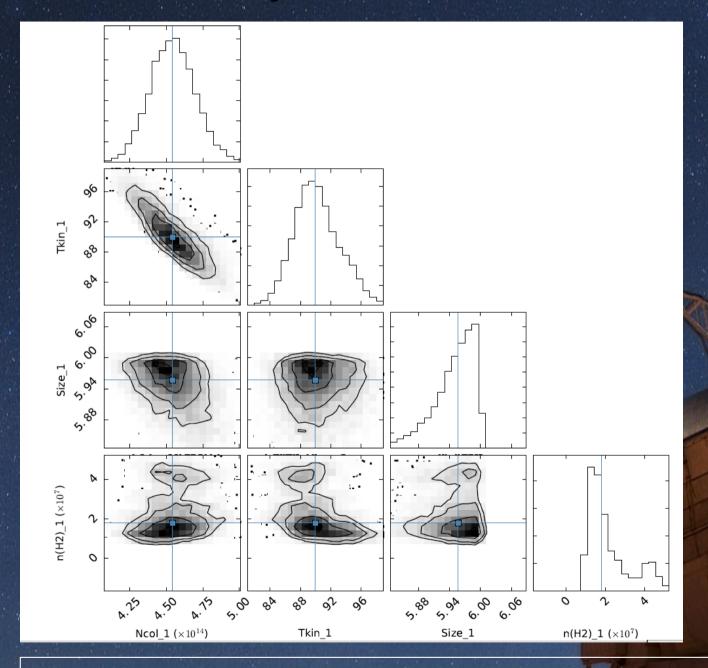
$$\ln\left(\frac{N_u}{g_u}\right) = \ln\left(\frac{N_{\text{tot}}}{Q(T_{\text{exc}})}\right) - \frac{E_u}{kT_{\text{exc}}},$$

$$y = B + Ax$$





Non-LTE analysis



N(HC3N)=4.5x10¹⁴ cm⁻² Tkin= 90 K n(H2)=2x10⁷ cm⁻³

(size <= 6")

¹³C Isotopologues

$$\tau = -\ln\left[1 - \frac{T_{\rm mb}}{f\left[J(T_{\rm exc}) - J(T_{\rm bg})\right]}\right] \tag{8}$$

being

$$J(T) = \frac{h\nu}{k} \left[e^{\left(\frac{h\nu}{kT}\right)} - 1 \right]^{-1},\tag{9}$$

and

$$N = \tau \frac{3h\Delta v}{8\pi^3} \sqrt{\frac{\pi}{4 \ln 2}} \frac{Q}{\mu^2 (J_l + 1)} e^{\left(\frac{E_l}{kT_{\text{exc}}}\right)} \left[1 - e^{\left(-\frac{h\nu}{kT_{\text{exc}}}\right)}\right]^{-1}$$

$$\tag{10}$$

Isotopologue	$N \ [\times 10^{13} \text{ cm}^{-2}]$	$\begin{array}{c} X \\ [\times \ 10^{-11}] \end{array}$	$^{12}C/^{13}C$
HC_3N	$69 \pm 8^{\dagger}$	79 - 62	
$\mathrm{HCC^{13}CN}$	6.7 ± 0.9	7.8 - 5.9	~ 10
$\mathrm{HC^{13}CCN}$	3.8 ± 0.8	4.7 - 3.1	~ 18
$\mathrm{H}^{13}\mathrm{CCCN}$	3.7 ± 0.6	4.4 - 3.2	~ 19
$^{13}\mathrm{C}\;\mathrm{HC_3N}$	$3.3 \pm 0.2^{\ddagger}$	3.6 - 3.2	~ 21

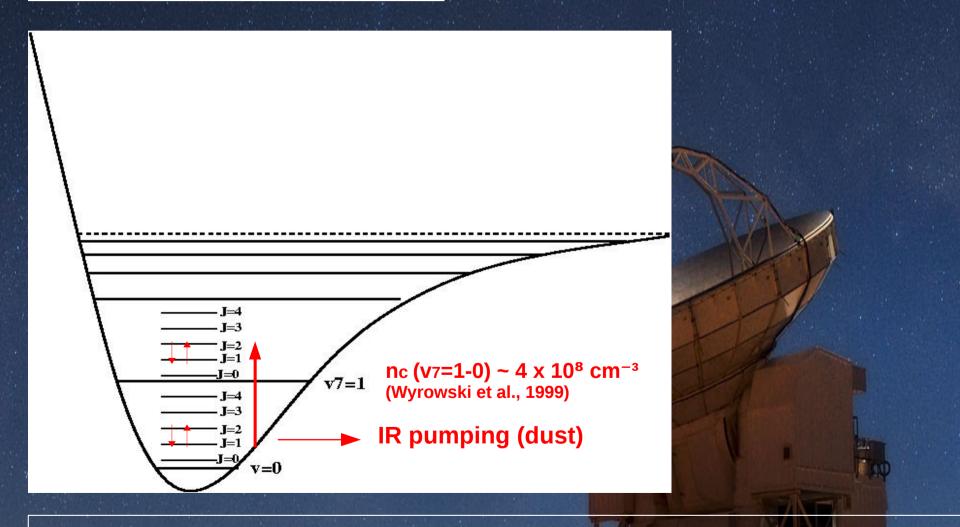
Excitation of the v=0 and $v_7=1$ lines

$$n_{\rm c}^{J,J-1} \approx \frac{A_{(J,J-1)}}{\gamma(J,J-1)}$$

J=38-37 nc (80-100 K) ~ 1.5 x 10⁷ cm⁻³

n(RADEX)~2 x 10⁷ cm⁻³

→ rotational transitions in LTE



Excitation of the v=0 and $v_7=1$ lines

Tdust ~ Tvib

$$\frac{W_{(v_7=1)}}{W_{(v=0)}} = \exp\left(\frac{-\Delta E_{70}}{kT_{\text{vib}}}\right)$$

 $T_{Vib} = 140 K$

$$\frac{L_{\rm hc}}{L_{\odot}} = 1.8625 \times 10^{-5} \left(\frac{r}{10^{16} \text{ cm}}\right)^2 T_{\rm dust}^4$$

< 04 (ZAMS)

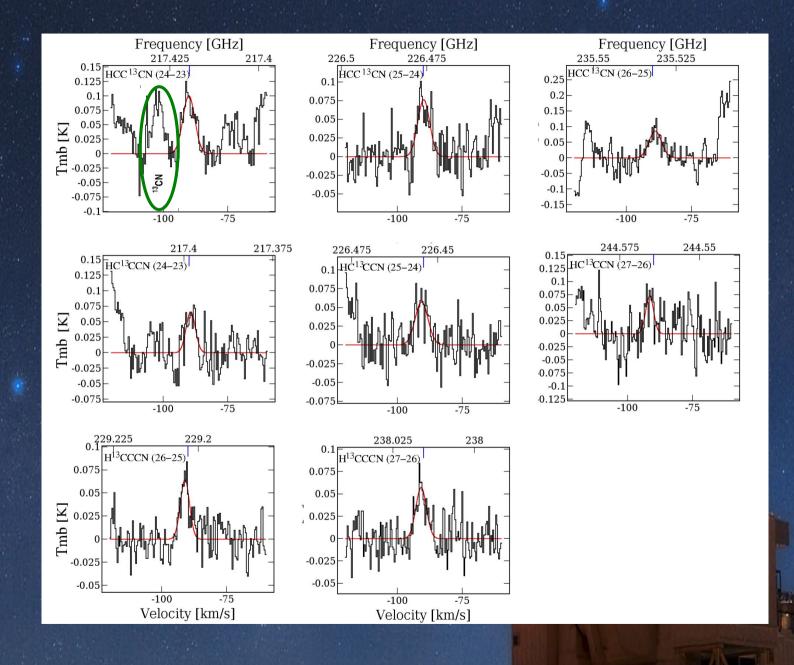
Isotopologue abundances

Isotopologue	$N \times 10^{13} \text{ cm}^{-2}$	$\begin{array}{c} X \\ [\times \ 10^{-11}] \end{array}$	$^{12}C/^{13}C$
HC_3N	$69 \pm 8^{\dagger}$	79 - 62	
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$^{13}\mathrm{C}\;\mathrm{HC_3N}$	$3.3 \pm 0.2^{\ddagger}$	3.6 - 3.2	~ 21

$$[HCC^{13}CN]:[HC^{13}CCN]:[H^{13}CCCN] = 1.8(\pm 0.5):1.0:1.0(\pm 0.4)$$

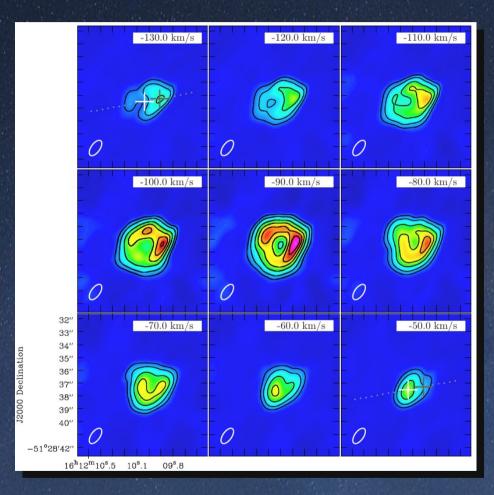
 $[HCC^{13}CN]$: $[HC^{13}CCN]$: $[H^{13}CCCN] = a:b:c, with a>b\approx c$

Isotopologue abundances



Emission of HC₃N

Merello et al. 2013



Hervias-Caimapo et al. 2019

SiO S¹⁸O "Broad" lines (~ 160-200 K) HCO+ (Shocked gas and outflow) H¹³CN HC₃N CH₃OH "Narrow" lines (~ 70 K) CH₃CCH (colder ambient core) H¹³CO

