Structure of the hot molecular core G10.47+0.03

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ABSTRACT

Context. The physical structure of hot molecular cores, where forming massive stars have heated up dense dust and gas, but have not yet ionized the molecules, poses a prominent challenge in the research of high-mass star formation and astrochemistry.

Aims: We aim at constraining the spatial distribution of density, temperature, velocity field, and chemical abundances in the hot molecular core G10.47+0.03.

Methods. With the Submillimeter Array (SMA), we obtained high spatial and spectral resolution of a multitude of molecular lines at different frequencies, including at 690 GHz. At 345 GHz, our beam size is 0.3′′, corresponding to 3000 AU. We analyze the data using the three-dimensional dust and line radiative transfer code RADMC-3D for vibrationally excited HCN, and myXCLASS for line identification.

Results. We find hundreds of molecular lines from complex molecules and high excitations. Even vibrationally excited HC15N at 690 GHz is detected. The HCN abundance at high temperatures is very high, on the order of 10−7 relative to H2. Absorption against the dust continuum occurs in twelve transitions, whose shape implies an outflow along the line-of-sight. Outside the continuum peak, the line shapes are indicative of infall. Dust continuum and molecular line emission are resolved at 345/355 GHz, revealing central flattening and rapid radial falloff of the density outwards of 104 AU, best reproduced by a Plummer radial profile of the density. No fragmentation is detected, but modeling of the line shapes of vibrationally excited HCN suggests the density to be clumpy.

Conclusions. We conclude that G10.47+0.03 is characterized by beginning of feedback from massive stars, while infall is ongoing. Large gas masses (hundreds of M⊙) are heated to high temperatures above 300 K, aided by diffusion of radiation in a high-column-density environment. The increased thermal, radiative, turbulent, and wind-driven pressure drives expansion in the central region and is likely responsible for the central flattening of the density.

Key words. ISM: molecules – ISM: structure – ISM: clouds – Stars: formation

1. Introduction

Massive stars and star clusters are born deeply embedded in molecular clouds (for a review, see Zinnecker & Yorke 2007). When cores have sufficiently contracted to form massive stars, the dense dust and gas is heated by these stars. The ice mantles around dust grains evaporate, and a rich plethora of molecular lines can be observed, along with strong dust emission (Kurtz et al. 2000; Cesaroni 2005). Often, these hot molecular cores are associated with ultracompact or hypercompact HII regions, which are ionized by newly formed massive stars (Hoare et al. 2007). The physical and chemical structure of hot molecular cores is of great importance for the study of high-mass star formation and of astrochemistry. Investigations of the structure are hampered, though, by the compactness of the sources, by their scarcity and large distance, and by the large foreground column density, which only long-wavelength radiation can pass.

What is needed, hence, is high angular resolution at (sub)millimeter wavelengths, combined with high spectral resolution of many molecular lines, which contain all the information about chemistry, velocity field, and temperature. With the Submillimeter Array (SMA) in Hawaii, we observed the massive hot molecular core G10.47+0.03 at around 200, 345, and 690 GHz, yielding a best resolution of 0.3′′ and 350 identified molecular lines. Due to its large dust mass and high temperatures, this hot core is among the strongest sources at submillimeter wavelengths, although it is located at a distance of 10.6 kpc (Pandian et al. 2008). It has an estimated luminosity of 7 × 105 L⊙ (Cesaroni et al. 2010) and displays exceptionally many lines from highly excited molecules (e.g. HC3N, Wyrowski et al. 1999).

2. Observations and data reduction

The high-mass star-forming region G10.47+0.03 was observed with the Submillimeter Array (SMA) during five nights in different array and receiver configurations, yielding six two-GHz-wide bands centered at around 201, 211, 345, 355, 681, and 691 GHz. Table summarizes the observations. We note that Jupiter was close (~ 10′′) to the target source in 2008, so its moon Callisto could be used as gain calibrator at 690 GHz, where it is otherwise very difficult to find a suitable calibrator source. It was observed repeatedly for 2 minutes after spending 10 minutes on the target source. For the 345 GHz observations in 2007 and 2009, after each 15 minutes we switched to 1733-130 (NRAO 1)

1 The Submillimeter Array is a joint project between the Smithsonian Astrophysical Observatory and the Academia Sinica Institute of Astronomy and Astrophysics and is funded by the Smithsonian Institution and the Academia Sinica (Ho et al. 2004).
Calibration and editing of the data were done in the IDL MIR package, involving correction and application of the system temperature, phase-only bandpass calibration, continuum regeneration (spectral averaging), phase-and-amplitude bandpass calibration, flagging, gain calibration (phase and amplitude), and flux calibration. The data were converted to MIRIAD (Sault et al. 1995), where the edge channels of each chunk were flagged and the channels were rebinned to a width of 1 km s$^{-1}$.

Observational summary

| Date             | frequency (GHz) | array configuration | baseline (m) | no. antennas | integration time (min) | gain calibrator |
|------------------|-----------------|---------------------|--------------|--------------|------------------------|----------------|
| 12 Aug 2007      | 345/355         | extended            | 205          | 7            | 281                    | 1733-130       |
| 10 May 2008      | 681/691 + 201/211 | compact north       | 125          | 5            | 270                    | Callisto       |
| 6 Sep 2008       | 681/691 + 345/355 | subcompact          | 70           | 6            | 82                     | Callisto       |
| 7 Sep 2008       | 681/691 + 345/355 | subcompact          | 70           | 7            | 93                     | Callisto, Ganymede |
| 4 July 2009      | 345/355         | very extended       | 516          | 8            | 330                    | 1733-130       |

Notes. (a) Maximum projected baseline

| Frequency (GHz) | beam$^a$ (arcsec) | rms$^a$ (mJy/Beam) | (K) |
|-----------------|-------------------|-------------------|-----|
| 199.9–201.8     | 4.27 $\times$ 1.84; 57  | 38                | 0.15 |
| 200.9–211.8     | 4.14 $\times$ 1.95; 55  | 37                | 0.13 |
| 201/211 cont.   | 4.14 $\times$ 1.48; 60 | 2.9               | 0.014|
| 344.1–355.9     | 0.45 $\times$ 0.29; 18  | 55                | 4.3  |
| 354.1–355.9     | 0.42 $\times$ 0.29; 22  | 55                | 4.4  |
| 345/355 cont.   | 0.42 $\times$ 0.28; 20  | 12                | 1.0  |
| 680.3–682.2     | 2.12 $\times$ 0.63; 37  | 840               | 1.6  |
| 690.3–692.2     | 2.08 $\times$ 0.60; 38  | 820               | 1.7  |
| 681/691 cont.   | 1.77 $\times$ 0.50; 42  | 227               | 0.67 |

Notes. (a) Different weighting schemes were used for continuum and line images. Major and minor axis and position angle (from north to east) are given. (b) rms noise is given for a frequency width of 1 km s$^{-1}$ in the line maps. It is evaluated from -10 to -5$^a$ in both RA and Dec relative to the phase center.

Fig. 1. Continuum maps of G10.47+0.03 observed with the SMA at 201/211 GHz (top panel), 345/355 GHz (central), and 681/691 GHz (bottom). The map size is either 5 or 10$^a$. Contours mark 20 and 50% of the peak flux, which is given in the lower right (in K). The beam is depicted in the lower left. The white crosses denote the H$n$ regions B1, B2, and A (Cesaroni et al. 2010, from left to right).

Table 1. Observational summary

Table 2. Beam sizes and noise levels

530), which lies 10.9$^a$ away from the target source. In addition, strong sources (Uranus, Ceres, 3c454.3, 3c273) were observed before and after these loops to allow bandpass and flux calibration.

2 http://www.cfa.harvard.edu/cgi/mircook.html
3 http://bima.astro.umd.edu/miriad
3. Observational results

3.1. Continuum

Figure 1 shows the obtained continuum maps. The total flux is 6 Jy at 201/211 GHz, 27 Jy at 345/355 GHz, and 95 Jy at 681/691 GHz, corresponding to a spectral index of 2.8 between the lower two and 1.8 between the upper two frequencies. While the beam sizes are not sufficient to resolve the continuum emission at 201/211 and 681/691 GHz, the extension can be clearly seen at 345/355 GHz. At this frequency, the peak intensity is 158 K (1.84 Jy/Beam), and the 3σ contour extends over 3″.

3.2. Line identification

The data cubes were convolved to a common resolution of 5″. \( \text{CH}_3\text{NH}_2 \) decreases the noise and the effects of a strong continuum, as well as to facilitate a comparison between the different frequencies; it gives the total (source-integrated) flux for most lines.

To identify the spectral features, a simple homogeneous model was computed in Local Thermodynamic Equilibrium (LTE), using the myXCLASS program, which takes the different optical depths of the transitions into account. Synthetic spectra are compared to the data. A source size of 1.5″ (half-maximum diameter of a Gaussian source), a temperature of 200 K and a line width of 5 km s\(^{-1}\) were fixed, while the column density of each molecule was varied to obtain a good fit to the data (see Table 3). The continuum was neglected in the radiative transfer, only a foreground absorbing column density of \( n = 5 \times 10^{24} \text{ cm}^{-2} \) was taken into account to approximate the higher absorption at the higher frequencies (corresponding to \( \tau = 0.3 \) at 345 GHz and \( \tau = 1.3 \) at 690 GHz). Although this is only foreground absorption, it serves to account for both absorption and continuum emission, as the latter weakens the lines as well. Continuum levels of 6, 8, and 7 K were added to the spectra at 201/211, 345/355, and 681/691 GHz, respectively. Figures A.1, A.2, and A.3 show the spectra and the model, and Table 3 gives the derived column densities. We note that the model is not supposed to give an optimum fit to the data, but is just for identification purposes.

3.3. Line maps

From many maps of interesting lines (see appendix, Figs. B.1–B.5), we show here only a selection, which are relevant for the expansion motion (Fig. 2) and the high excitation (Fig. 3). They chose common velocity ranges for the four lines, which are 30–50 km s\(^{-1}\), representing the high-velocity part of the (front-side) outflow, 51–64 km s\(^{-1}\), the low-velocity part, 65–70 km s\(^{-1}\), the systemic velocity, and 71–84 km s\(^{-1}\), the low-velocity part of the back-side outflow. Higher velocities are not detected, probably due to dust absorption. In case of contamination by a neighboring line, the velocity range was chosen to avoid this line. Still, blending is likely for SO at 344.3 GHz by methanol (frequency corresponds to a 1.5 km s\(^{-1}\) lower velocity), H\(^3\)CN at 345.3 GHz by SO\(_2\) (1 km s\(^{-1}\) higher velocity), H\(^2\)CN at 345.4 GHz by CH\(_3\)CH\(_2\)OH (3.3 km s\(^{-1}\) lower velocity), and CH\(_3\)NH\(_2\) at 354.8 GHz by CH\(_3\)OCHO (3.8 km s\(^{-1}\) higher velocity).

3.4. Spectra

Figure 4 shows central spectra of the 12 transitions with absorption. Most of the absorption is blue-shifted relative to the systemic velocity of 68 km s\(^{-1}\).

3.5. Comparison to APEX data

To estimate calibration and filtering of extended emission, we compare the SMA data to data from the APEX (Atacama Pathfinder Experiment) 12-m telescope (Güsten et al. 2006, Schuller et al. 2009, Rolffs et al. 2011b). The 345 GHz flux from the LABOCA bolometer array is 34 Jy/Beam, the 850 GHz flux from SABOCA is 450 Jy/Beam. At both frequencies, the source is unresolved with the beams of 18.2 and 7.4″, respectively. The spectral index is 2.86, so the 690 GHz flux would be 250 Jy. The SMA fluxes at 210 and 345 GHz fit very well to the APEX data, but at 690 GHz the continuum is much lower. This might be partly explained by decorrelation due to fast phase fluctuations.

### Table 3. List of identified molecules

| Molecule | no. lines | column density \( \text{cm}^{-2} \) |
|----------|-----------|-------------------------------|
| SO       | 5         | (17)                          |
| SO\(_2\) | 3         | (17)                          |
| OCS      | 2         | (18)                          |
| CN       | 1         |                               |
| HCN      | 8         | 1(18); 3(18)                  |
| HNC      | 1         | (17)                          |
| CH\(_3\)NH\(_2\) | 2 | (17)                  |
| CH\(_3\)NC | 4 | (17)                  |
| NH\(_2\)CN | 7 | 2(16)                  |
| NH\(_2\)CHO | 15 | 2(17)                  |
| HC\(_3\)N | 76        | 5(16); 1(18)                 |
| CH\(_2\)CN | 33        | 7(17)                          |
| CH\(_2\)CN | 55        | 9(17)                          |
| H\(_2\)O | 1         | 1(20)                          |
| CO       | 2         |                               |
| H\(_2\)CO | 6         | 3(18)                          |
| CH\(_3\)OH | 23        | 9(18)                          |
| H\(_2\)C\(_2\)O | 4 | 4(17)                  |
| C\(_2\)H\(_2\)OH | 23 | 6(17)                  |
| CH\(_3\)OCH\(_3\) | 14 | 1.5(18)                |
| CH\(_2\)OCHO | 38 | 7(17)                  |
| CH\(_3\)CH\(_2\)CO | 26 | 5(17)                  |

Notes. The molecules are ordered by S-, N-, and O-bearing and by complexity. (a) Number of identified lines (labeled in Figs. A.1–A.3). (b) Column density used in the myXCLASS model, with a source size of 1.5″ and a temperature of 200 K. The parentheses are powers of 10. (c) The lines are in absorption, which is not modeled here. (d) For HCN and HC\(_3\)N, an additional component of 0.5″ and 500 K was used to more closely match the vibrational lines.
Fig. 2. Line maps (selected to trace expansion motions) integrated over the velocity range indicated in each panel (which can be considered, from left to right, as high-velocity part of the outflow, low-velocity part, systemic velocity, and low-velocity part of the outflow at the far side). The first velocity range of HC$_3$N is blended by other lines, in the second velocity range of CO the emission is so extended to cause imaging artifacts. The map size is 5′′ (tick spaces are 1′′, centered on R.A. 18:08:38.236, Dec. -19:51:50.25). Beams are shown in the lower left, and the number in the lower right of each panel is the maximum flux in K km s$^{-1}$ (contours are ±20 and 50% of that value). The color scale is from -1000 to 1000 K km s$^{-1}$. The energy of the lower level is given in the upper left.

and partly by missing short baselines filtering out extended emission.

Figure 5 shows APEX spectra overlaid with SMA spectra which were convolved to the APEX beam (18.2′′ at 345 GHz, 17.7′′ at 355 GHz, and 9.1′′ at 690 GHz). The lines match very well. The most notable exception is CO 6–5, which is purely in absorption with the SMA, but has strong emission as seen with APEX (>1000 Jy). Extended emission of CO 6–5 is filtered out due to missing short spacings, leaving an apparant absorption towards the continuum, which is more compact and hence not affected as much as CO by the filtering.

4. Modeling

In this section, we compare a few models to continuum and vibrationally excited HCN in order to constrain the structure of this complex region, mainly density distribution and velocity field. Testing different models of the source structure allows to exclude certain structures and to approach the real structure by adapting the models. The models are inevitably simplified, and we used a trial-and-error technique with parameter variations and comparison of model and data by eye to approach a good fit if possible for a tested structure, but no global optimization of fit parameters was performed.
Fig. 3. Selected high-excitation line maps. Above each panel, the molecule, the frequency of the transition (in GHz), and the velocity range (in km s\(^{-1}\)) are given. The color scale ranges from 0 to 1000 K km s\(^{-1}\) at 345/355 GHz, where the map size is 5\(''\), and from 0 to 100 K km s\(^{-1}\) at 690 GHz, where the map size is 10\(''\). Beams are shown in the lower left, and the number in the lower right of each panel is the maximum flux in K km s\(^{-1}\) (contours are \(\pm\)20 and 50% of that value). The energy of the lower level is given in the upper left.

The three-dimensional radiative-transfer code RADMC-3D\(^8\), developed by C. Dullemond, was employed to compute the dust temperature from stellar heating and the continuum and line emission of a model. The basic setup is the same as described in Rolffs et al. (2011a), but here we also test clumpiness and velocity structure in the models. The line transfer assumes LTE, which is a good approximation for vibrationally excited HCN, but prevents the modeling of the ground-state lines.

4.1. The Models

While no perfect fit was found, we selected five of the tested models for presentation and comparison to the data. Models A and B have been previously used to fit APEX and VLA data of this source, respectively (Rolffs et al. 2011b). Model C has a radial density profile that best matches the observed continuum (if heated by the stars in the H\textsc{ii} regions). Models D and E have density fluctuations on small scales, which are expected from self-gravity and which improve the line fitting. Model E is an attempt to include the outflow (which is seen by the blue-shifted absorption features) and is presented in more detail.

The models are described explicitly in the following. Table 4 summarizes the main properties of the models.

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Fig. 4. Lines with absorption features toward the continuum peak. The systemic velocity of 68 km s\(^{-1}\) and a blue-shifted velocity of 50 km s\(^{-1}\) are marked. There are absorption components centered at both velocities, indicating expansion. The dashed horizontal line denotes the continuum level.

Table 4. Summary of the models described in Sect. 4.1

| Model      | density     | heating     | velocity field | displayed in Figs. |
|------------|-------------|-------------|----------------|-------------------|
| A          | power-law   | 1 star      | infall         |                   |
| B          | Gaussian    | 3 stars     | none           |                   |
| C          | Plummer     | 3 stars     | none           |                   |
| D          | clumpy      | 3 stars     | dispersion     |                   |
| E          | clumpy, outflow cone | 3 stars dispersion, outflow |                   |

is radially infalling with 1 km s\(^{-1}\) to the center at B1. The total mass (in a cube of 3 pc diameter) is \(2.4 \times 10^4\) \(M_\odot\), of which 70 \(M_\odot\) are at temperatures above 300 K.

Model B This is the model that was presented in Rolffs et al. (2011a) to fit the VLA data of vibrationally excited HCN. The density follows a Gaussian, centered at B1, with \(7 \times 10^7\) \(H_2\) cm\(^{-3}\) at the half-maximum radius of 7000 AU. As in all following models, heating sources are the stars in the H\(_\text{ii}\) regions B1 with \(10^5\) \(L_\odot\), B2 with \(8.3 \times 10^4\) \(L_\odot\), and A with \(4.6 \times 10^4\) \(L_\odot\), which are placed in the plane of the sky. The dust opacity is from Ossenkopf & Henning (1994) without grain mantles or coagulation, as in all following models. The HCN abundance is \(10^{-5}\) at temperatures above 300 K and \(10^{-6}\) below, as in the following models. The intrinsic line width (FWHM) is 8.3 km s\(^{-1}\), and there is no macroscopic velocity field. The total mass is \(6.8 \times 10^3\) \(M_\odot\), of which 350 \(M_\odot\) are at temperatures above 300 K.

Model C The density in this model follows a Plummer profile, \(n = 1.4 \times 10^8 \times \left(1 + \left(\frac{r}{1500 \text{ AU}}\right)^2\right)^{-2.5}\) \(H_2\) cm\(^{-3}\) (half-maximum radius 6500 AU). It is centered 2000 AU south and 1000 AU west of B1. The Plummer model is very similar to a Gaussian inside the half-maximum radius, but has higher density outside (still falling off steeply as \(r^{-5}\)). The HCN abundance is \(10^{-5}\) at temperatures above 300 K and \(10^{-6}\) below, as in the following models. The intrinsic line width (FWHM) is 8.3 km s\(^{-1}\), and there is no macroscopic velocity field. The total mass is \(6.8 \times 10^3\) \(M_\odot\), of which 350 \(M_\odot\) are at temperatures above 300 K.

Model D This model consists of 100 clumps, which have a Plummer half-maximum radius of 1000 AU and central densities ranging from \(4 \times 10^6\) to \(2 \times 10^6\) \(H_2\) cm\(^{-3}\). The distribution of clump masses follows the same slope as the stellar Initial Mass Function. They are randomly placed in the model according to a Plummer distribution with half-maximum radius 4000 AU. The density in each model cell is the maximum of all contributions from the clumps. So with a lot of overlap, this structure consists rather of density fluctuations than of separate cores. The intrinsic line width (FWHM) is 5 km s\(^{-1}\). Each clump has a random line-of-sight velocity with Gaussian half-maximum value of \(\pm 5\) km s\(^{-1}\). The line-of-sight velocity of each cell is an average of all clumps, weighted with their density contribution. The total mass
is 9.4 × 10^3 \text{M}_\odot, of which 470 \text{M}_\odot are at temperatures above 300 K.

Model E This model has the same structure as model D, but a half-maximum radius of the distribution of the clumps of only 3000 AU. In addition, a bipolar outflow is present, with an opening angle of 100° and a length of 2 × 10^4 AU. Its center lies 1000 AU south and 500 AU west of B1. The axis is tilted from the line of sight by 20°, and the foreground part directed towards B2. Inside the outflow cone, the density is reduced to 20% of the original value (preserving the clumpy structure) and the velocity is 10 km s\(^{-1}\) outwards. This is only a toy model of the outflow. The total mass is 4.6 × 10^3 \text{M}_\odot, of which 400 \text{M}_\odot are at temperatures above 300 K. The clumpy structure is visualized in Fig. 6.

4.2. Continuum

The continuum radiation that the models emit is compared to the data. Models D and E have randomly placed core centers; therefore their radiation (continuum and lines) have a random component, which cannot be exactly reproduced in different runs with the same parameters.

The radial profile of the 345/355 GHz continuum map is extracted with central position R.A. 18:08:38.237, Dec. −19:51:50.421, which is the center of a two-dimensional Gaussian fit (1.4" × 1.17", elongated along the B1-B2 axis). The model maps were Fourier-transformed, folded with the uv-coverage of the observations, and imaged in the same way as the data. The radial profile of the model was extracted from the same central coordinates. Figure 7 shows a comparison of the radial profiles, Fig. 8 a comparison of the continuum map of model E to the data. Model A (power-law) fits worse to the radial profile, model C (Plummer) fits best.

The flux from APEX/LABOCA (345 GHz) is 34 Jy/Beam (18.2" beam size) and from APEX/SABOCA (850 GHz) 450 Jy/Beam (7.4" beam size). The models emit 31 (A), 20 (B), 26 (C), 20 (D), and 18 (E) Jy/Beam for LABOCA and 266 (A), 231 (B), 311 (C), 146 (D), and 162 (E) Jy/Beam for SABOCA. In models B-E an extended component similar to A could be added without affecting the results of the interferometer modeling.
4.3. Vibrationally excited HCN

The models are compared to lines from vibrationally excited HCN, including the \(J=13\) direct \(\ell\)-type transition at 40.7669 GHz observed with the VLA (Rolffs et al. 2011a). Figures 9 and 10 show this line and three rotational transitions of vibrationally excited HCN observed with the SMA, overlaid with models A–D. To reproduce the direct \(\ell\)-type line, the rotational lines must be very optically thick, leading to self-absorption in the models. This is inevitable for optically thick lines from centrally heated spheres; the data however do not show self-absorption. The self-absorption decreases from model A to E. Model E is shown in more detail in comparison to the \(J=13\) direct \(\ell\)-type line of vibrationally excited HCN (Fig. 11), the 4–3 line of vibrationally excited HCN (Fig. 12) and H\(^{13}\)CN (Fig. 13), and the 8–7 transition of vibrationally excited H\(^{13}\)CN (Fig. 14). The outflow is imprinted in the line shapes. The levels of all these transitions lie between 1050 and 1400 K above ground.
Fig. 12. Model E (right) compared to the $J=4–3$ line of vibrationally excited HCN at 354.5 GHz (SMA), shown as integrated line map and spectra at two locations (left, model spectra are overlaid in red). The white contours denote the 355 GHz continuum in steps of 25 K.

Fig. 13. Model E (right) compared to the $J=4–3$ line of vibrationally excited $^{13}$CN at 345.2 GHz (SMA), shown as integrated line map and spectra at two locations (left, model spectra are overlaid in red). The white contours denote the 345 GHz continuum in steps of 25 K.
5. Discussion

5.1. Chemistry

In addition to about 350 identified lines, there are around 90 unidentified (U-) lines. 75 of these 90 U-lines are in the 201/211 GHz range, which covers a similar velocity range as the higher-frequency bands combined (almost 6000 km s$^{-1}$). This is probably due to the lower noise at these frequencies. The line density is mainly determined by the width of single lines (5–10 km s$^{-1}$), i.e. a forest of overlapping lines covers most of the bands. The identified molecules (3 S-bearing, 10 N-bearing, and 9 other,
Fig. 9. Models A (red) and B (green) compared to lines from vibrationally excited HCN at the position of B1 and 0.3″ (VLA) or 0.8″ (SMA) south of B1.

Fig. 10. Models C (red) and D (green) compared to lines from vibrationally excited HCN at the position of B1 and 0.3″ (VLA) or 0.8″ (SMA) south of B1.

O-bearing, molecules) represent only the strongest lines, while more complex molecules have many weak lines which probably add up to the continuum and are undetectable due to line confusion. No spatial separation of different molecules could be seen. The differences in the maps can probably be explained by excitation and optical depth.

In the detailed models (Sect. 4), the abundance of HCN in the hot gas is very high, on the order of $10^{-5}$ relative to H$_2$. This is needed to reproduce the direct $\ell$-type line and the vibrationally excited H$_{13}$CN. Around 5% of the nitrogen and 1.4% of the carbon is in HCN (for solar N/H of $1.1 \times 10^{-4}$ and C/H of $3.6 \times 10^{-4}$, Anders & Grevesse 1989), and HCN/CO is on the order of 0.1 in the hot central region. We note that such a high HCN abundance needs an explanation by future chemical models, incorporating high-temperature reaction networks. The abundance of HC$_3$N seems to follow a similar increase at high temperatures, as the strong emission from vibrational states suggests (Figs. A.1-A.3). Notable line detections are HC$_{15}$N$_{v_2=1}$ at 691.6 GHz (lower level is 1139 K above ground), HC$_3$N$_{v=1}$ at 355.1 GHz (1908 K), and the $^{12}$C substituted HC$_3$N$_{v_7=2}$ (970 K). The H$_2^{18}$O line at 692.1 GHz (694 K) implies a high abundance of water in the dense, warm gas. These abundance enhancements could be connected, e.g. through a reduced abundance of OH, which at high temperatures reacts to form water instead of destroying N-bearing molecules (Rodgers & Charnley 2001).

5.2. Density Distribution

As the high-resolution continuum map at 345/355 GHz shows, a power-law radial density is not consistent with the data. A Gaussian fits well in the inner part, but falls off too steeply in the outer parts. What fits best to the data is a Plummer model (Fig. 7, blue). This profile is very similar to a Gaussian inside the half-maximum radius, but is denser outside, where it falls off as $r^{-3}$. It is also used to describe the stellar density of star clusters. Although that might reveal a connection of this forming star cluster to later stages, it could also have completely different physical reasons. The stellar density distribution is determined by stellar dynamics, while the gas density distribution is determined by the interplay of different sources of pressure (gravitational versus turbulent, rotational, magnetic, radiative, and thermal pressure). The observed central flattening of the density can be explained by centrally increased pressure, which is expected from feedback by the newly formed massive stars. This pressure stalls the infall and piles up the mass where the infall stops, resulting in a less centrally peaked mass distribution.
The SMA continuum at 690 GHz is rather weak compared to the 345 GHz flux and the high-frequency single-dish flux. As interferometer observations at these frequencies are challenging and only very few have been conducted yet (e.g. Beuther et al. 2006), this could be due to decorrelation caused by rapid phase noise. On the other hand, the line strengths are similar to the APEX data (Fig. 5), supporting the data quality and the calibration, so if the low continuum is real, it can be due to optical depth effects in very dense, small condensations, while extended emission is filtered out. The continuum at 690 GHz must be much more extended than at 345 GHz because the larger dust opacity makes it stronger only in the optically thin regions, while it can be weaker in the optically thick case - instead of the whole hot interior, one sees only up to the colder foreground. In addition, the image fidelity at 690 GHz is not as good as at 345 GHz, in particular the shortest baselines are twice as large. As the flux rises with shorter baselines, this means much more filtering out of extended emission at 690 GHz.

There is no fragmentation observed in neither the continuum nor the lines. The reason may be that we do not resolve structures smaller than the beam size of about 3000 AU. We note that the continuum source extends over about 10 beams (3′′), so no large-scale fragmentation is present. Models of the line emission reveal that a spherical density distribution leads to strong self-absorption features, which are not observed. Clumpiness better reproduces the line shapes, but without sufficient spatial resolution we cannot derive the properties of fragmentation.

This missing fragmentation is similar to the continuum data recently obtained by Qin et al. (2011) for SgrB2-N, which follows a very similar radial profile and also displays a similar spectral line content. Maybe the two sources are at the same evolutionary stage, where the first hypercompact H\textsc{ii} regions have developed and heated the gas, but large-scale fragmentation has not set in.

The rotational transition of vibrationally excited HCN (4–3 at 354.46 GHz) has a very high optical depth. The Einstein A coefficient is 50,000 times larger than for the direct $\ell$-type line ($J=13$ at 40.7669 GHz, observed with the VLA), which has an optical depth of $\lessapprox 1$. Also the comparison to the $^{13}$CN line (Fig. 3) shows its high optical depth. In models which are homogeneous on small scales (smooth density gradient, such as models A–C), this optically thick line is self-absorbed due to the temperature gradients caused by internal heating. Such large temperature gradients are inevitable as the stars must be deeply embedded, shown by the high efficiency of heating and the compactness of the H\textsc{ii} regions. The observed single-peaked profile can only be explained by an inhomogeneous density and velocity field (such as models D–E), where the self-absorption is smeared out. Such small-scale clumpiness might persist in later stages of evolution, when the gas is ionized (Ignace & Churchwell 2004).

The observed continuum depends on density, temperature, and dust opacity. The density can vary by many orders of magnitude, and therefore dominates the resulting continuum. It is clear that the temperature is high in the inner region and falls off outwards; this is included in the models as the stars in the hypercompact H\textsc{ii} regions heat the dust. It is entirely possible, however, that more heating sources are present, although they are not needed for heating the central region. The extension of high-excitation lines is generally a bit smaller in the models than in the data, especially highly excited HCN is somewhat extended to the east (Fig. 3).

5.3. Velocity Field

While most lines do not show any velocity structure in their maps, there seems to be a component of highly excited CH$_3$OH at lower velocity close to the UCH\textsc{ii} region A (Fig. 9). Alternatively, this could arise from blending by a different line.

On large scales, the asymmetries of self-absorbed lines clearly indicate infall motions (Rolffs et al. 2011b and Fig. 5), and also the absorption of the $^{12}$CO line is a bit red-shifted (Fig. 4). On smaller scales, we see expansion motions, as very nicely traced by the absorption features (Fig. 5). The blue-shifted absorption is stronger in the western part of the continuum.

In addition, the SO line at 344.3 GHz, the HCN line at 354.5 GHz, and the CO line at 345.8 GHz have red-shifted emission in the north-eastern part. A red-shifted clump 5′′ north of the hot core, which is only seen in HCN and CO, seems to be too far away to be related to the outflow (Fig. 2).

Olmi et al. (1996) detected a north-south velocity gradient in $^{13}$CO, and Holter & Churchwell (1996) see blue-shifted water masers 0.2′′ north and 0.4′′ south of B1, and a red-shifted water maser (at 70 km s$^{-1}$) 1.2′′ north of B1. Absorption against the hypercompact H\textsc{ii} regions B1 and B2 is found to be blue-shifted in NH$_3$(4,4) (Cesaroni et al. 2010) 53 km s$^{-1}$ toward B1 and 61 km s$^{-1}$ toward B2, and also partly in vibrationally excited HCN (Rolffs et al. 2011a and Fig. 11).

One can conclude that there is likely a bipolar outflow, whose foreground part is tilted to the south-west, and whose background part is tilted to the north-east. A sketch of the outflow scenario is presented in Fig. 15. This scenario explains qualitatively all observed velocity features. The different NH$_3$(4,4) velocities, for instance, can be understood as an effect of the projection of the outflow to the line-of-sight. An embedded source, which has not yet developed a detectable H\textsc{ii} region, is driving the outflow in this scenario. A nearly spherical infall with lower velocity, but higher rate than the expansion surrounds the outflow and produces the blue asymmetric line profiles seen on larger scales. This accretion probably continues well into the central region along certain paths, driven by gravitational attraction and the momentum of the large-scale accretion flow.

An alternative scenario might arise if the hypercompact H\textsc{ii} regions B1 and B2 are not spherical, but in the form of bipolar expanding bubbles from a photoevaporating disk (Hollenbach et al. 1994). In this case, the stars in the HCH\textsc{ii} regions would drive two outflows, which are both roughly aligned with the line-of-sight.

In addition, it is possible that the source is a large pseudodisk accreting from a massive envelope, rotating roughly in the plane of the sky, driving an outflow perpendicular to it, and having formed B1 and B2 as binaries (and maybe more stars). This would correspond to the transition between phase II and III of Zapata et al. (2010). A quantitative radiative transfer model, which reproduces all observed lines, is possible, but beyond the scope of this paper. That the outflow is important for reproducing the line shapes has been demonstrated in our modeling, as only model E could reproduce the shapes (Sect. 4).

6. Conclusions

With the SMA, we have obtained high-resolution, spectrally resolved maps of the massive hot molecular core G10.47+0.03 at different frequencies, covering a bandwidth of 12 GHz in total and including observations at 690 GHz. Our main results are
Fig. 15. Qualitative scenario for the outflow in G10.47+0.03. The observer is above the plot. Infalling molecular gas is shown in green, expanding molecular gas in blue, and ionized gas in white. The circles denote half-maximum and Plummer radius in Model C (the gas must be clumpy, though) and the boundaries of the H\textsuperscript{ii} regions, which have density gradients (Cesaroni et al. 2010). If the H\textsuperscript{ii} regions are not spherical, the outflow could also originate from the ionizing stars.

- Hundreds of molecular lines reveal a rich chemistry, with molecules such as HCN and HC\textsubscript{3}N especially abundant at high temperatures. This high abundance demands explanations from chemical models. Vibrationally excited HCN, whose levels lie more than 1000 K above ground, is very optically thick, and even vibrationally excited HC\textsubscript{15}N shows up at 690 GHz.

- Blue-shifted absorption in a dozen lines indicates an outflow oriented roughly along the line-of-sight. It is embedded as there is also absorption at the systemic velocity of cold foreground gas in CO and HCN.

- The averaged radial profile of the submm continuum displays a central flattening and rapid falloff, and is best fitted by a Plummer profile of the density. The mass of the source is on the order of several thousand \(M_\odot\), of which a few hundred are at high (>300 K) temperatures.

- No fragmentation is observed over the ~10 beam sizes (30,000 AU) of the continuum emission. High-excitation lines which are very optically thick do not show self-absorption. The line modeling suggests that this must be due to density fluctuations in combination with the velocity field. If the rather low continuum at 690 GHz is real, it points to small, very dense condensations.

From these findings, a picture emerges of a very young forming star cluster, characterized by beginning of feedback from massive stars, while infall is ongoing. This feedback includes heating of the dust and gas, ionization that is still confined to small regions, and increased pressure in the inner part that leads to expansion motions and central flattening of the density.

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Appendix A: Full Spectral Range

In Figs. A.1, A.2, and A.3 we show the full observed spectral range, convolved to a resolution of 5″, and label the identified lines with the molecule (see also Sect. 3.2).

Appendix B: Line maps

In Figs. B.1, B.2, B.3, B.4 and B.5 we show 100 integrated line maps, ordered by molecule as in Table 3 and by frequency of the transition (see also Sect. 3.3).
Fig. A.1. Full spectral range towards G10.47+0.03 convolved to 5\arcsec resolution. The green overlay is the myXLASS model for all molecules except HC$_3$N, whose emission is overlaid in red. The displayed panels cover 199.85–201.85 GHz (upper three) and 209.85–210.55 GHz (bottom); the rest is shown in Figs. A.2 and A.3.
Fig. A.2. As Fig. A.1 displaying 210.5–211.85 GHz (upper two) and 344.05–345.95 GHz (lower two).
Fig. A.3. As Fig. A.1 displaying 354.1–355.95 GHz (upper two), 680.2–682.3 GHz (third panel from top), and 690.2–692.3 GHz (bottom).
Fig. B.1. Integrated line maps. Above each panel, the molecule, the frequency of the transition (in GHz), and the velocity range (in km s$^{-1}$) are given. The map size is either 5, 10, or 15”, as written in the map (tick spaces are 1”, centered on R.A. 18:08:38.236, Dec. -19:51:50.25). Beams are shown in the lower left, and the number in the lower right of each panel is the maximum flux in K km s$^{-1}$ (the contours are ±20 and 50% of that value). The color scale ranges from the minimum to the maximum value. The energy of the lower level is given in the upper left.
Fig. B.2. As Fig. B.1 contd.
Fig. B.3. As Fig. B.1 contd.
Fig. B.4. As Fig. B.1 contd.
Fig. B.5. As Fig. B.1 contd.