Infall, outflow, and rotation in the G19.61-0.23 hot molecular core

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ABSTRACT

Aims. The main goal of this study is to perform a sub-arcsecond resolution analysis of the high-mass star formation region G 19.61−0.23, both in the continuum and molecular line emission. While the centimeter continuum images will be discussed in detail in a forthcoming paper, here we focus on the (sub)mm emission, devoting special attention to the hot molecular core.

Methods. A set of multi-wavelength continuum and molecular line emission data between 6 cm and 890 μm were taken with the Very Large Array (VLA), Nobeyama Millimeter Array (NMA), Owens Valley Radio Observatory (OVRO), and Submillimeter Array (SMA). These data were analyzed in conjunction with previously published data.

Results. Our observations resolve the HMC into three cores whose masses are on the order of 10³−10⁴ M⊙. No submm core presents detectable free-free emission in the centimeter regime, but they appear to be associated with masers and thermal line emission from complex organic molecules. Towards the most massive core, SMA1, the CH₃CN (18−17) lines reveal hints of rotation about the axis of a jet/outflow traced by H₂O maser and H¹³CO⁺(1−0) line emission. Inverse P-Cygni profiles of the ¹²CO(3−2) and C¹⁸O(3−2) lines seen towards SMA1 indicate that the central high-mass (proto)star(s) is (are) still gaining mass with an accretion rate ≥ 3×10⁻⁵ M⊙ yr⁻¹. Due to the linear scales and the large values of the accretion rate, we hypothesize that we are observing an accretion flow towards a cluster in the making, rather than towards a single massive star.

Key words. ISM: evolution — HII regions — individual (G19.61-0.23) — jets and outflows — Stars: early-type — Submillimeter: ISM

1. Introduction

Understanding the formation of high-mass (M∗ ≥ 8M⊙) stars, as well as their evolution, is the key to investigate the origin of the diversity of stars and stellar clusters in the Galaxy. This is because high-mass stars not only affect the evolution of the interstellar medium in general, but are also preferentially born in clusters containing a large number of low-mass stars, like, e.g., in the Trapezium cluster in Orion (Muench et al. 2002). Despite their importance, the formation process and early evolution of OB stars is still far from being understood. In the past decade, observations have suggested the existence of flattened rotating disk-like structures around newly formed massive (proto)stars. In particular, Keplerian disks appear to exist around B-type stars, whereas only massive toroids have been found in association with O-type stars. These toroids are very different from circumstellar disks, as they appear to be transient, non-equilibrium entities (Cesaroni et al. 2007). In spite of the substantial difference between the two types of objects, their existence suggests that high-mass star formation may also proceed through accretion with angular momentum conservation, as well as in the case of low-mass stars.

This scenario implies the existence of infalling gas onto the newly formed stars. Detection of gas infall in the vicinity of high-mass stars is hampered by confusion with other processes such as outflow and rotation. Nonetheless, to date interferometric observations at centimeter and (sub)millimeter wave-lengths have succeeded in detecting infall in a handful of cases (e.g., Keto et al. 1988; Cesaroni et al. 1992; Beltrán et al. 2006; Zapata et al. 2008; Girart et al. 2009) lending support to the accretion scenario. All these findings, however, do not suffice to explain the clustered mode of OB-type star formation, which is another crucial issue in high-mass star formation theories. A way to shed light on this process is to perform detailed observational studies of selected star forming regions containing a large number of very young OB-type (proto)stars, possibly in different evolutionary phases. Excellent signposts of these are ultra compact (UC) HII regions and hot molecular cores (HMCs) (see e.g. Kurtz et al. 2000).

With all this in mind, we performed a detailed study of the G 19.61−0.23 high-mass star forming region (SFR) which is known to harbor several UC HII regions and a HMC (Garay et al. 1985, 1998; Wood & Churchwell 1989; Forster & Caswell 2000; Furuya et al. 2005a; hereafter paper I). The HMC was firstly identified by Garay et al. (1998) in the NH₃(2,2) inversion transition. A summary of molecular line observations towards the HMC up to 2004 is given in Remijan et al. (2004; see references therein). No unambiguous proof of the presence of OB-type (proto)stars inside the HMC, such as the detection of free-free emission, has been found yet. However, the detection of H₂O (Hofner & Churchwell 1996; Forster & Caswell 2000) and OH (Garay et al. 1985) maser emission is considered evidence of their existence. All these features make the G 19.61−0.23 star forming region an ideal target to study the early phase of the high-mass star formation process.
Based on lower quality images of the region, in paper I, we estimated the lifetime ratio between the UC H\(\text{II}\) and the HMC phases, concluding that the former should last \(\sim 3\) times longer than the latter. With the new observations presented here, we wish to set tighter constraints on the statistical study of paper I and improve our knowledge of the HMC. In this paper we will focus on the latter issue, while a forthcoming paper will be devoted to a more general analysis of the high-mass young stellar cluster in the region.

It is worth noting that the G 19.61–0.23 SFR was believed to be located at the near kinematical distance, based on H\(\alpha\) emission and H\(2\)CO absorption line observations towards the UC H\(\text{II}\) region. This is why in the literature one finds distance estimates of 3.8 kpc (Georgelin & Georgelin 1976), 4.5\(\pm\)1 kpc (Downes et al. 1980), and 3.5 kpc (Churchwell, Walmsley & Cesaroni 1990). However, interferometric observations of the HI line at 21 cm seen in absorption against the H\(\text{II}\) regions (Kolpak et al. 2003) have established that the region is located at the far kinematical distance of 12.6\(\pm\)0.3 kpc. A similar result has been obtained by other authors (Pandian, Momjian & Goldsmith 2008), who derive a value of 11.8\(\pm\)0.5 kpc or 12.0\(\pm\)0.4 kpc, depending on the adopted rotation curves. Note that the latter measurement was done towards the center of the nearby G 19.61-0.13 region, which is offset by 11\(\prime\) from the HMC position. For this reason, in this paper, we prefer to adopt \(d = 12.6\) kpc which comes from a measurement made towards the center of the region of interest for us (G 19.61–0.23).

Finally, we point out that recently, Wu et al. (2009) have reported on the detection of inverse P-Cygni profiles in \(^{13}\)CO \(J = 3 - 2\) and CN \(J = 3 - 2\) lines towards the G 19.61–0.23 HMC. This result was obtained using the Submillimeter Array (SMA) archive data originally taken by us. Wu et al. (2009) conclude that such profiles are due to infall motions inside the HMC. In this paper, we improve on this result presenting a larger study of the line emission from the HMC.

### 2. Observations and Data Reduction

Aperture synthesis observations of the continuum and molecular line emission towards the G19.61–0.23 star forming region, from centimeter (cm) to sub-millimeter (submm) wavelengths, were carried out using the Very Large Array (VLA) of the National Radio Astronomy Observatory (NRAO\(^4\)) (Sect. 2.1), the Nobeyama Millimeter Array (NMA) of the Nobeyama Radio Observatory\(^3\) (Sect. 2.2), the Owens Valley Radio Observatory (OVRO\(^2\)) millimeter array (Sect. 2.3), and the Submillimeter Array (SMA\(^2\)) (Sect. 2.5), in the period from 2002 to 2007. We summarize our continuum imaging and spectral line observations in Tables 1 and 2, respectively.

#### 2.1. VLA Observations

We performed VLA observations of the continuum emission at 6 cm, 1.3 cm, and 7 mm as summarized in Table 1. For all the observations described below, we used quasars J1832–105 as a phase-calibrator and J1331+305 and/or J0137+331 as flux- and bandpass-calibrator(s).

### 6 cm — The A- and C-array observations were done on November 1, 2004 (project code AF 415) and July 11, 2005 (AF 422), respectively, with the standard correlator configuration for continuum imaging providing a 172 MHz bandwidth with dual polarization.

### 1.3 cm — We performed the B-array observations on May 28 and 30, 2005 (AF 415), and the C-array observation on November 18, 2006 (AF 422). We observed the continuum emission in the “BD” intermediate-frequency (IF) pair, with 25 MHz bandwidth, and the \(\text{H}_2\)O maser emission in the “AC” pair with 3.125 MHz bandwidth and 64-channels, providing a velocity resolution of 0.66 km s\(^{-1}\). Because of hardware limitations during the EVLA transition phase, we manually supplied the sky-frequency of the maser line at the beginning of each switching.

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### Table 1. Summary of Interferometric Continuum Emission Imaging

| Frequency (GHz) | Array | Spatial Frequency Range (k.l) | \(\theta_{\text{LAB}}\) (arcsec) | Synthesized Beam Size (arcsec) | P.A. (deg) | Image Noise Level (mJy beam\(^{-1}\)) | Note |
|-----------------|-------|-------------------------------|-------------------------------|-----------------------------|----------|-----------------------------------|------|
| 4.860           | VLA-A, C | 0.242 – 596.7                 | 485                           | 0.630 \(\times\) 0.470       | 1.9      | 0.78                               | this work |
| 8.415           | VLA-A, B, C, D | 0.78 – 1027.8                 | 264                           | 0.329 \(\times\) 0.228       | 24.4     | 18.1                               | paper I |
| 14.940          | VLA-C, B, CuB | 7.72 – 554.0                  | 26.7                          | 0.550 \(\times\) 0.500       | -8.4     | 1.26                               | paper I |
| 22.722          | VLA-B, D | 1.96 – 826.8                  | 105                           | 0.357 \(\times\) 0.260       | -4.3     | 0.47                               | this work |
| 43.340          | VLA-D | 3.98 – 135.6                  | 51.8                          | 1.870 \(\times\) 1.300       | -16.1    | 2.57                               | this work |
| 90.700          | OVRO\(^2\)+NMA\(^3\) | 2.90 – 139.0                  | 69.7                          | 1.52 \(\times\) 1.51         | -9.6     | 2.72                               | paper I |
| 335.416         | SMA\(^2\) | 13.3 – 241.5                  | 15.5                          | 0.85 \(\times\) 0.78         | -32      | 34.9                               | this work |

\(\theta_{\text{LAB}}\) is the largest detectable size scale.

\(\theta_{\text{LAB}}\) L, E, H, and UH configurations.

\(\theta_{\text{LAB}}\) D, C, and AB configurations.

Extended and Compact configurations.
cycle (12 minutes) instead of using Doppler tracking. We excluded all the LHCP data taken at the B-array observations due to a 180° phase jump over the correlator band. Furthermore, all the data taken with five EVLA antennas during the D array observations were excluded due to error on the amplitude calibration. We have produced continuum images by merging the B- and D-array visibility data (Table 1). For the water maser emission, the two data sets were not merged due to variability between the B- and D-array observations. We thus prepared a 3D data cube of the maser line emission using only the B-array data, which allowed us to attain the best angular resolution.

7 mm — The 7 mm observations were performed on May 8, 2007 with the D array, employing the fast-switching technique. The adopted switching cycle consisted of a 2.0-minute integration on the target and a 50-second integration on the calibrator. Before making an image, we excluded all the data taken with the nine EVLA antennas due to an unknown error on the amplitude calibrations, leaving us with only 17 usable antennas.

2.2. NMA Observations

The NMA observations towards G 19.61−0.23 were carried out during December 2002 to May 2003 with 3 array configurations (D, C, and AB). We observed the SiO (2−1) ν = 0 line in the lower side band (LSB) using the FX correlator with 32 MHz bandwidth centered at the line frequency, giving a velocity resolution of 0.108 km s\(^{-1}\). For the continuum and line emission, we used the Ultra Wide Band Correlator (UWBC) with a narrow 512 MHz bandwidth in each sideband. Although this correlator configuration should allow us to observe a total bandwidth of 1 GHz with the dual side bands, after removing the channels affected by line emission, the effective bandwidth usable for continuum emission measurements was ∼450 MHz. We used 3C 273 as passband calibrator and J1743−038 as phase and gain calibrator. The flux densities of J1743−038 were bootstrapped from Uranus, and the uncertainty is estimated to be 10%. All the data were calibrated and edited using the UVPROC2 and MIRIAD packages.

2.3. OVRO Observations

The OVRO observations of G 19.61−0.23 were carried out in the period from September 2003 to May 2004 in the three array configurations E, H, and UH. We observed the H\(^{13}\)CO\(^+\) (1−0) and SiO (2−1) ν = 0 lines in the lower side-band (LSB). For the continuum emission, we simultaneously used the Continuum Correlator with an effective bandwidth of 4 GHz and the newly installed COBRA correlator with 8 GHz bandwidth. The line contamination could not be estimated as these correlators do not have spectroscopic capabilities. For molecular lines, we used the digital correlator with 15 MHz bandwidth and 60 channels for the SiO line, and 7.75 MHz and 62 channels for the H\(^{13}\)CO\(^+\) line. We used 3C 273 and 3C 454.3 as passband calibrators, and J1743−038 as phase and gain calibrators. The flux densities of NRAO 530 and J1743−038 were determined from observations of Uranus and Neptune. We estimate the uncertainty of the flux calibration to be 10%. The data were calibrated and edited using the MMA and MIRIAD packages.

2.4. Combining NMA and OVRO Data: The SiO (2−1) ν = 0 Line

We combined the interferometric SiO (2−1) ν = 0 data taken with the NMA (Sect. 2.2) and OVRO (Sect. 2.3) interferometers; the diameters of the element antennas are 10.0 m and 10.4 m, respectively. For this purpose, we adopted the observational setups adopted for both data sets were as similar as possible, with two important differences: the frequency resolution and the integration time for a single visibility. We therefore smoothed the NMA visibilities every 8 channels, and averaged them so to achieve a 3.35-seconds integration time per visibility. We verified that the visibilities taken with the two arrays have a fairly nice consistency in flux calibration when we compared them over the common range of the projected baseline length. Subsequently, we produced a 3D cube using task IMAGR of the AIPS package with a robust parameter of +1 to find a compromise between angular resolution and image-fidelity.

2.5. SMA Observations and Data Reduction

Aperture synthesis continuum and line emission observations of G 19.61−0.23 at 890\(\mu\)m were carried out with the SMA on May 12, 2005 in the compact array configuration and on July 8, 2005 in the extended configuration. The shortest projected baseline length, i.e. the shadowing limit, was about 11.9 m. This makes our SMA observations insensitive to structures more extended than 15".5, corresponding to 0.95 pc at a distance of 12.6 kpc. The SIS receivers were tuned at a frequency of 335.4158 GHz to observe the \(^{13}\)CO (3−2), \(^{13}\)CO (3−2), and CH\(_3\)CN (18−17) lines in the LSB, and the H\(^{18}\)O\(^+\) (4−3) and CN (3−2) lines in the USB. Each side-band covers a 2 GHz bandwidth. The at-

| Line | \(f_{\text{rest}}\) (MHz) | Array | \(\theta_{\text{maj}} \times \theta_{\text{min}}\) (arcsec) | P.A. (deg) | \(\Delta v_{\text{pp}}\) (km s\(^{-1}\)) | Noise Level (mJy beam\(^{-1}\)) |
|------|-----------------|-------|---------------------|-----------|-----------------|------------------|
| H\(_2\)O maser | 22235.080 | VLA-B | 0.32×0.23 | −9.6 | 0.66 | 90 |
| H\(^{13}\)CO\(^+\) (1−0) | 86754.328 | OVRO | 4.00×3.13 | −21 | 0.43 | 61 |
| SiO (2−1) ν = 0 | 86846.998 | OVRO+NMA | 3.67×2.40 | −3.0 | 0.90 | 38 |
| \(^{13}\)CO (3−2) | 33087.9601 | SMA | 0.94×0.83 | −27 | 0.40 | 340 |
| \(^{13}\)CO (3−2) | 329330.5453 | SMA | 0.94×0.85 | −22 | 0.80 | 338 |
| CH\(_3\)CN | | | | | | |

\(a\) Effective velocity resolution.

\(b\) Typical RMS noise level per velocity channel.

\(c\) CH\(_3\)CN 18\(K\) − 17\(K\) lines as well, see Fig. 11.

\(d\) For CH\(_3\)CN K = 0

Table 2. Summary of Interferometric Molecular Line Observations

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tained synthesized beam sizes, effective velocity resolution after smoothing, and image sensitivity are summarized in Tables 1 and 2. We used 3C 454.3 as bandpass calibrator, and J1743–038 and J1924–292 as phase and gain calibrators. Flux densities of the two calibrators were bootstrapped from observations of Uranus and Neptune (J1743–038: 1.64 Jy in May and 1.55 Jy in July; J1924–292: 3.16 Jy in May and 3.60 Jy in July), and were stable within 12% during the observing period. We estimate a final uncertainty on the flux calibration of ~ 20%. The data calibration was done using the MIR and MIRIAD packages. Following standard calibration procedures, we tentatively subtracted the continuum emission from the visibility data, then imaged the continuum in each side-band. After verifying that the continuum emission is confined within a compact region at (Δα, Δδ) = (~1″, 2″) with respect to the phase tracking center (PTC; R.A. = 18h 27m 38.15s, Dec. = -11°56′39″50 in J2000), we subtracted the continuum contribution from the visibility data by giving the position offset in task UVLIN in MIRIAD package. For the final continuum subtraction process, we identified, at least, 33 and 24 lines in the USB and LSB, respectively. Subsequently, we constructed continuum emission images with natural and uniform visibility weighting functions in conjunction with the multi-frequency synthesis technique. For the continuum imaging, we did not apply another visibility weighting based on the system temperature (Tsys) of each element antenna, because the Tsys information in the USB for the compact array observations were not recorded properly. In contrast, the Tsys-based visibility weighting was applied to the line data in the LSB, for which the Tsys was properly recorded. Note that the Tsys problem affecting the USB was not realized by Wu et al. (2009), who thus produced the incorrectly weighted, low-resolution continuum image shown in their Fig. 1.

Atmospheric seeing was estimated using the continuum emission maps of the (point-like) calibrators, because the apparent angular diameter of the calibrators is related to the size scale characterizing the atmospheric turbulence. The time-averaged size scale over each observing track should be comparable to the beam-deconvolved diameters of the calibrators. By this means, we estimate the average seeing for J1743–038 to be 0″15 and 0″95 for the extended and compact configuration observations, respectively. We found that the seeing towards J1924–292 was twice worse than that towards J1743–038 in the extended array observations. In addition, given the fact that the angular distance between J1924–292 and the PTC is rather large (21.8″) we decided not to use this quasar as phase calibrator. Finally, we reconstructed all the images of the continuum and line emission data.

3. Results and Analysis

3.1. Continuum Emission

3.1.1. Overview of the G 19.61–0.23 Star Forming Region

Fig. 1 presents the continuum emission maps, including already published 3.8 cm and 3 mm images. As discussed in paper I, the cm maps, representing free-free emission, show that the region contains a cluster of UC Hii regions, i.e., young massive stars. One can see that the overall morphology of the cm emission does not change much with wavelength. Most of the apparent differences are due to different angular resolution and sensitivity to extended structures (see Table 1). The 7 mm and 3 mm maps, which have comparable angular resolutions, also show similar structures. Such a similarity implies that these two images contain both thermal dust emission and optically thin free-free emission, as discussed for the 3 mm map in paper I. Note that the compact 7 mm emission to the east of UC Hii region A (see paper I for labeling of the UC Hii regions) is very likely an artifact due to inadequate sampling of the visibility plane (Sect. 2.1). The SMA 890 μm image looks significantly different from the cm- and mm maps, as it shows a bright compact source towards the HMC position previously reported. No other 890 μm sources than the HMC are detected over the SMA FoV, above a 3σ upper limit of 105 mJy beam⁻¹ corresponding to a brightness temperature in the synthesized beam of Tbb(3σ) = 0.22 K. In the following, we describe the continuum results obtained at 890 μm.

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**Fig. 1.** Continuum emission maps toward the G 19.61–0.23 high-mass star forming region. All the contour levels are drawn with ±7σ · 2σ where σ is the RMS noise level of the image (Table 1) and n = 0, 1, 2, . . . . The wavelength and FWHM of the synthesized beam are indicated in the bottom right corner of each panel. See Table 1 for the values of the synthesized beams.
believe that this is due to the fact that visibilities have not been weighted taking into account the system temperature of each antenna weighting. The solid contours start at the \(3\sigma\) level and increase in steps of \(+2\sigma\) up to the 50\% level for a clarity of the maps. The dashed contours start at the \(-3\sigma\) level and decrease in steps of \(-2\sigma\). The image noise levels are 54.1 and 34.9 \text{mJy beam}^{-1} for panels (a) and (b), respectively. The sensitivity of the uniformly weighted map is better than that of the naturally weighted map. We believe that this is due to the fact that visibilities have not been weighted taking into account the system temperature of each antenna (see Sect. 2.5). The synthesized beams are shown in the bottom right corners (1\′′38×1′′22 with P.A. = −44° for natural weighting; 0′′85×0′′78 with P.A. = −32° for uniform weighting).

**Table 3.** Results of Submm Continuum Emission Observations

| Name  | Peak Position (J2000) | \(I_{890}\mu m\) (Jy beam\(^{-1}\)) | \(S_{890}\mu m\) (Jy) | \(D_{\beta}\) (arcsec) | \(R_{\alpha}\) (pc) | \(M_{\alpha}\) (\(M_\odot\)) |
|-------|-----------------------|----------------|-----------------|----------------|----------------|----------------|
| SMA1  | R.A. (hh:mm:ss): Dec. (dd:mm:ss) | 18:27:38.069: −11:56:37.30 | 1.89 | 3.2 | 2.4 | 0.072 | 1300 |
| SMA2  | 18:27:38.021: −11:56:38.75 | 0.29 | 0.52 | 1.5 | 0.045 | 220 |
| SMA3  | 18:27:37.955: −11:56:35.08 | 0.25 | 0.15 | 0.81 | 0.025 | 60 |

\(a\) Peak intensity. The uncertainty may be given by the 3\(\sigma\) level of the image noise level, i.e., 0.1 Jy beam\(^{-1}\).

\(b\) Flux density, see Sect. 3.1.2.

\(c\) Effective diameter of the submm emission, which is given by \(2\sqrt{\pi}/A\) where \(A\) is the area enclosed by the 5\(\sigma\) level contour enclosing each source. Notice that, at SMA2 and SMA3, the 5\(\sigma\) level corresponds to the 61\% and 71\% levels with respect to their peak intensities, respectively.

\(d\) Effective radius of the submm emission.

\(e\) Mass of the core estimated from the flux \(S_{890}\mu m\) in Col. 5, assuming \(\beta = 1\) and a dust temperature of 80 K.

(See Fig. 2c in paper I and Fig. 3 of this work). This means that the 890\(\mu m\) and 3 mm continuum peaks coincide within the errors. Therefore, in this study we will identify SMA1 with the HMC, whose position is obtained from the 890\(\mu m\) image (Table 3). The peak intensity \(I_{\nu}\) of the 890\(\mu m\) continuum emission is 1.89 Jy beam\(^{-1}\), corresponding to \(T_{\text{dust}} = 310\ \text{K}\). The spectral index \(\alpha\) between 3 mm and 890\(\mu m\) is \(\alpha_{3\text{mm}}-890\mu m \gtrsim 2.7\), implying a power-law exponent for the dust emissivity, \(\beta\), of \(\geq 0.7\), assuming optically thin dust emission and the Rayleigh-Jeans approximation. For this estimate, we integrated the 890\(\mu m\) flux over the three sources SMA1, SMA2, and SMA3 and used the continuum flux at 3 mm (147 \text{mJy}) obtained from the data of paper I, where the free-free continuum contribution from the nearby UC H\(\alpha\) region was subtracted by extrapolating the 1.3 \text{cm} continuum map to 3 mm under the assumption of optically thin emission. We stress that the latter flux is affected by significant uncertainties due to the method adopted to subtract the free-free contribution (see paper I). Therefore, in the following we prefer to adopt \(\beta = 1\), which is consistent with the value derived above, within the uncertainty, and falls in the range \(\beta = 1\pm2\) found in the literature.

The 890\(\mu m\) flux densities \(S_{\nu}\) in Table 3 allow us to estimate the gas-plus-dust mass traced by thermal emission \(M_{\text{dust}}\). For this purpose we have assumed a dust temperature \(T_{\text{dust}}\) of

3.1.2. 890 \(\mu m\) Continuum Emission

In paper I, we have demonstrated that the 3 mm continuum emission towards the HMC is mostly due to thermal dust emission with a small contribution from free-free emission. The latter is instead insignificant in the newly obtained SMA image at 890\(\mu m\), which is dominated by the dust continuum emission. Fig. 2 shows a close-up view of the SMA 890\(\mu m\) images produced with natural and uniform visibility weighting functions. It is noteworthy that the continuum emission in the natural weighted map (Fig. 2a) is elongated to both the south and northwest. The uniformly weighted map (Fig. 2b) clearly resolves the emission and shows that the elongation is attributed to two additional weak sources, whose peak intensities are slightly above the 7\(\sigma\) level. These results indicate that there are (at least) three submm sources in the region. Hereafter, we will name these SMA1 (the HMC), SMA2 (the core to the south), and SMA3 (the core to the north-west), as indicated in Fig. 2.

The most intense 890\(\mu m\) source, SMA1, is located 0′′.32 northeast of the peak of the 3 mm “dust” continuum emission (Sect. 3.1.2) and the high-resolution images at cm wavelengths (Sect. 3.1.3).
Fig. 3. Comparison of the 6 cm (greyscale plus white contour), 3.8 cm (magenta contour), and 1.3 cm (yellow contour) continuum emission maps generated with the common minimum UV distance of 13.3 $\lambda$ (see Sect. 3.1.3). Contour intervals for the cm maps and the submm map are the same as those in Figs. 1 and 2, respectively, where the 1$\sigma$ noise levels are 0.23, 0.18, and 0.36 mJy beam$^{-1}$ and the beams $0'.433 \times 0'.321$, $0'.262 \times 0'.195$, and $0'.344 \times 0'.251$, for the 6.0, 3.8, and 1.3 cm maps, respectively. The largest of the three beams is shown in the bottom right. The filled red rectangular and the double red circles indicate the peak positions of the 3 mm (paper I) and 890 $\mu$m (Sect. 3.1.2) continuum emission, respectively. The filled green circles and light-blue triangles show the positions of the OH (Garay et al. 1985) and H$_2$O (Hofner & Churchwell 1996) masers, respectively. Labels A and C refer to the UC H II regions (notation as in paper I and references therein). The filled yellow circle associated with the UC H II region C indicates the peak position of the isolated 7 mm emission seen in Fig. 1e close to the HMC.

80 K (paper I) and have calculated the values of $S_\nu$ by integrating the emission in Fig. 2 over the regions inside the 5$\sigma$ contour levels of the sources. The value $T_{\text{dust}} \approx 80$ K was obtained from the fit to the continuum spectrum (see paper I), from the cm to the mid-infrared regime, including the newly obtained 7 mm and 890 $\mu$m fluxes. We estimate that the ambiguity in defining the boundary between SMA1 and SMA2 causes a $\sim 5\%$ error on the value of $S_\nu$. The resulting masses are given in Table 3. Note that these values are approximately inversely proportional to the dust temperature and are thus affected by the uncertainty on this latter parameter accordingly. Since the assumed temperature is likely to be correct within a factor 2, we believe that the estimated masses are also affected by a similar uncertainty.

3.1.3. Centimeter Continuum Emission towards the HMC

To assess the presence of cm emission towards the HMC, we reconstructed the VLA 6 cm, 3.8 cm, and 1.3 cm continuum images in Fig. 3 by making use of visibilities whose minimum spatial frequency range is set to be the same for the 3 bands. We chose the shortest baseline equal to 13.3 k$\lambda$, namely that of the 890 $\mu$m maps (see Table 1). This allows one to resolve out the extended emission. Fig. 3 clearly shows that no free-free emission is detected towards the peak positions of the three 890 $\mu$m sources. Note that SMA1 is located at the center of the H$_2$O and OH masers’ distributions, whereas no H$_2$O and OH maser spot appears to be associated with SMA2 and SMA3. The upper limits (3$\sigma$) obtained from the cm images correspond to brightness temperatures over the synthesized beam ($T_{\text{syn}}$) of 199, 230, and 30.9 K, respectively at 4.86, 8.42, and 22.27 GHz (see the caption of Fig. 3 for the corresponding noise levels and beam sizes).

We point out that the 7 mm emission seen to the north of the HMC (see Fig. 1e) coincides with the cometary UC H II region C (Fig. 3). We thus argue that free-free emission from this UC H II region would significantly contribute to the corresponding 7 mm continuum emission, whose peak intensity is 25.3 mJy beam$^{-1}$ ($\sim 10\sigma$). It is also interesting to note that SMA3 lies right in front of the vertex of the cometary shaped UC H II region C, suggesting a physical connection between the two. This could explain the cometary shape, with the existence of dense material preventing expansion of the ionized gas towards north-west.

3.2. H$_2$O masers

3.2.1. Overall Results

Fig. 4 shows the H$_2$O maser distribution with respect to the UC H II regions. The color image is a map of the first-order moment of the maser lines. We detected two out of the six “maser features” previously reported by HC96, i.e. features N. 1 and 2 in their notation. Here, we use the term “maser feature” for a well-defined, spatially isolated group of maser spots (see, e.g., HC96 and Furuya et al. 2005b). With an angular resolution of $0'.3$, one cannot distinguish the maser spots associated with all the different lines seen in the spectrum (Fig. 5). The fact that no maser...
emission was detected towards the other four features identified by HC96, must be due to the high-variability of H$_2$O masers, because the intensities measured by HC96 are all well above our 3σ sensitivity of 135 mJy beam$^{-1}$.

Figs. 4 and 5 clearly show that feature 1 presents only blueshifted emission, whereas feature 2 is mostly redshifted, despite the presence of a few blueshifted lines. Notwithstanding the well known high variability of water masers, we note that these two features have persisted with approximately the same spectral shape since December 1991, when the VLA observations of HC96 were made. The terminal velocities ($V_t$) at which blue- and red-shifted maser emissions are seen towards features 1 and 2 differ by $\sim$15–20 km s$^{-1}$ with respect to the systemic velocity ($V_{sys}$) of 41.6 km s$^{-1}$. All this suggests that the maser emission may be originating in a bipolar jet driven by a putative young stellar object (YSO) inside the HMC. We will come back to this issue in Sect. 3.3.4.

3.2.2. Origin of the H$_2$O Maser Features 1 and 2

Features 1 and 2 (see Figs. 4 and 5) seem to have persisted more than a decade. From their distribution (see Fig. 3 of HC96), one can argue that only these two features out of the six reported by HC96 are associated with SMA1.

Interferometric observations of H$_2$O masers at 22 GHz indicate that they are likely excited in shocked regions at the interface between (proto)stellar jets and the ambient gas (e.g., Furuya et al. 2000), although in some objects these masers have been suggested to be tracing rotating disks (e.g., Torrelles et al. 1996). If the latter were the case of the masers in SMA1, from the separation between the blue- and red-shifted features (1.′70) and their relative velocities ($\sim$35 km s$^{-1}$) one could estimate the mass needed to ensure centrifugal equilibrium: this is $\sim$3700 $M_\odot$, which is $\sim$3 times greater than that obtained from the submm continuum emission (see Table 3). This suggests that rotation is not a viable explanation for the kinematics of the masers in the HMC. Moreover, as we will see in Sect. 3.3.4, the H$^{13}$CO$^+$ (1–0) line appears to trace a bipolar outflow oriented SE–NW. In this scenario the two H$_2$O maser fea-
Fig. 6. Total integrated intensity maps of the $^{13}\text{CO}$ (3–2) (left panels) and C$^{18}\text{O}$ (3–2) (right panels) lines produced with natural (upper panels) and uniform (lower panels) visibility weighting functions. Note that the upper panels show the whole area of the G 19.61−0.23 star forming region, while the lower panels magnify the region centered on the HMC (greyscale plus thin contour; see Table 2). For a comparison purpose, the $7\sigma$ level contour of the 6 cm continuum (i.e., free-free) emission as in Fig. 1a is shown by thin green contours. The magenta stars in the lower-panels indicate the peak positions of the three 890 $\mu$m continuum sources (Table 3). The contours of the CO isotopomer maps start from the $5\sigma$ level in steps of $3\sigma$, where the $1\sigma$ noise levels are 1.9 and 1.8 Jy beam$^{-1}$ km s$^{-1}$ for the natural and uniform weighted $^{13}\text{CO}$ maps, and 0.8 Jy and 1.7 beam$^{-1}$ km s$^{-1}$ for the natural and uniform weighted C$^{18}\text{O}$ maps, respectively. We have integrated the emission over the LSR-velocity ranges $30.2 \leq V_{\text{LSR}}$ km s$^{-1} \leq 42.2$ for $^{13}\text{CO}$, and $34.7 \leq V_{\text{LSR}}$ km s$^{-1} \leq 44.5$ for C$^{18}\text{O}$. All the other symbols are the same as those in Fig. 1. The emission seen in the top of the upper-panels is an artifact due to cleaning problems.

tures can be associated with a bipolar jet feeding the outflow. We thus conclude that the jet interpretation is more likely.

3.3. $^{13}\text{CO}$ (3–2), C$^{18}\text{O}$ (3–2), $\text{H}^{13}\text{CO}^+$ (1–0) and SiO (2–1) Line Emission

3.3.1. Maps of $^{13}\text{CO}$ (3–2) and C$^{18}\text{O}$ (3–2) Line Emission

Fig. 5 presents total integrated intensity maps of the $^{13}\text{CO}$ and C$^{18}\text{O}$ J =3–2 lines made with natural and uniform weightings. For the sake of comparison, we plot the $7\sigma$ contour level of the 6 cm continuum emission map, i.e. the lowest level from Fig. 1. The natural weighted maps show that the $^{13}\text{CO}$ and C$^{18}\text{O}$ (3–2) emitting regions are compact and centered on the HMC, while these lines are not detected towards SMA3. Since single-dish observations of similar objects indicate that these CO isotopomers trace extended regions, it is reasonable to argue that in G19.61−0.23 the extended emission is filtered out by the interferometer. We also note that the $^{13}\text{CO}$ and C$^{18}\text{O}$ (3–2) lines are not seen towards SMA1 in the uniform weighted maps.

3.3.2. Spectra at the Peak Position of the HMC

Fig. 7 shows the molecular line spectra obtained from the interferometric observations towards the peak position of SMA1. The H$^{13}\text{CO}^+$ line peaks at $V_{\text{sys}}$, but its line profile is not a single Gaussian. The SiO line shows prominent high velocity wing emission. Noticeably, the $^{13}\text{CO}$ (3–2) and C$^{18}\text{O}$ (3–2) lines do not show prominent wing emission, but present deep absorption features. In both CO isotopomers redshifted absorption (i.e. an inverse P-Cygni profile) is seen, albeit fainter in the C$^{18}\text{O}$ line.
Fig. 7. Spectra of four molecular lines in $T_{\text{mb}}$ scale towards the peak of the 890 $\mu$m continuum emission, i.e., SMA1. The SiO and $^{13}$CO$^+$ intensities are scaled by a factor 2.0 in the $T_{\text{mb}}$ scale. The vertical dashed line indicates the systemic velocity ($V_{\text{sys}}$) of the cloud, $V_{\text{LSR}}=41.6\,\text{km}\,\text{s}^{-1}$. In the CO isotopomers spectra, we mark the positions of all possible (molecular) lines, calculated assuming that they are emitted with velocity equal to $V_{\text{sys}}$ (see Sect. 3.3.4). The thick horizontal blue and red bars denote the velocity intervals over which the line emission has been integrated to produce the maps in Figs. 9, 10, and 16. The emission seen around $V_{\text{LSR}} \approx 70\,\text{km}\,\text{s}^{-1}$ of the C$^{18}$O spectrum is likely due only to the HNCO line.

The straightforward interpretation of these findings is that the HMC is undergoing infall. The LSR-velocity of the deepest absorption channel is $V_{\text{LSR}} = 44.5\,\text{km}\,\text{s}^{-1}$ for $^{13}$CO, and $46.0\,\text{km}\,\text{s}^{-1}$ for C$^{18}$O, the latter being redshifted by $4.4\,\text{km}\,\text{s}^{-1}$ with respect to $V_{\text{sys}}$. The deepest absorption channels of the $^{13}$CO and C$^{18}$O lines have $-29.3\,\text{K}$ and $-15.0\,\text{K}$ in $T_{\text{mb}}$, respectively. Note that the brightness temperature of the $^{13}$CO line (and even more so for the C$^{18}$O line) is, in absolute value, less than that of the continuum peak (see Sect. 3.1.2); this indicates that the absorption line is real and not an artifact due to resolving out the extended emission.

Finally, we note that we cannot exclude that part of the blueshifted wing emission of the $^{13}$CO (3–2) line might be due to the CH$^{13}$CN $K = 7$ line, as we will argue in Sect. 3.4. After considering all the other molecular lines that could overlap with the two CO isotopomer lines, we conclude that line-contamination of the $^{13}$CO line over the velocity range between $V_{\text{LSR}} \sim 34\,\text{km}\,\text{s}^{-1}$ and $50\,\text{km}\,\text{s}^{-1}$, and of the C$^{18}$O line over the range from $\sim 0\,\text{km}\,\text{s}^{-1}$ to $65\,\text{km}\,\text{s}^{-1}$, is unlikely.

3.3.3. Comparisons of the Absorption Features Seen in the $^{13}$CO (3–2) and HCO$^+$ (1–0) Lines

To assess the origin of the redshifted absorption seen in the $^{13}$CO and C$^{18}$O (3–2) spectra, we made Fig. 8 where we compare the $^{13}$CO(3–2) spectrum with an HCO$^+$ (1–0) spectrum taken with the IRAM 30 m telescope (R. Cesaroni, unpublished data). The HCO$^+$ spectrum shows a number of prominent absorption features. To make the comparison as consistent as possible, we reconstructed the $^{13}$CO image from the visibility data adopting the same beam as the HCO$^+$ line ($\theta_{\text{HPBW}} = 29\,\text{arcsec}$). We then took the $^{13}$CO spectrum towards the same position observed in the HCO$^+$ line. Notice that all the absorption features seen in the two lines are redshifted with respect to $V_{\text{sys}}$. However, absorption is detected at different velocities in the two tracers: the absorption dips are seen at $V_{\text{LSR}} - V_{\text{sys}} = +3.5\,\text{km}\,\text{s}^{-1}$ for $^{13}$CO, and at $V_{\text{LSR}} - V_{\text{sys}} = +10, +29, +57\,\text{km}\,\text{s}^{-1}$ for HCO$^+$. As for the two features seen at the highest velocities in HCO$^+$, we believe that these are due to clouds along the line-of-sight, because their velocities correspond to those of the 21 cm HI lines observed by Kolpak et al. (2003) – see their Fig. 4. This suggests that all the HCO$^+$ absorption likely occurs against the UC HII regions in G19.61−0.23. In contrast, no HCO$^+$ absorption is detected in the velocity range where $^{13}$CO and C$^{18}$O absorption is seen. These facts suggest that the latter is due to the HMC, i.e. has a local origin, and is thus indicating that the core is undergoing infall. The nature of the absorption will be further discussed in Sect. 4.2.1 where we study the gas infall in the core.

3.3.4. $^{13}$CO$^+$ (1–0) Emission

Here, we present the results of the $^{13}$CO$^+$ (1–0) line observations made with the OVRO array (Table 2). Fig. 9 presents maps of both the bulk and line wing emission. One can see that, while the former outlines a structure elongated approximately NE–SW,
the latter can be interpreted as a bipolar outflow oriented SE–NW.

Comparison with the positions of the three submm continuum sources shows that SMA1 is the closest to the geometrical center of the outflow and is hence the most likely candidate for powering it. Here the geometrical center is defined as the middle point on the line connecting the peaks of the blue- and redshifted lobes. We obtain (projected) angular distances to the center of $3\arcsec/2$, for SMA1, and $3\arcsec/8$, for SMA2. That SMA1 is at the origin of the flow is also supported by comparison with the H$_2$O maser jet associated with SMA1, discussed in Sect. 3.2. This jet is also oriented parallel to the H$^{13}$CO$^+$ outflow and has the same red–blue symmetry, which strongly suggests a common origin for the two.

Using the bulk emission map, we have estimated the H$^{13}$CO$^+$ abundance relative to H$_2$ ($X_{H^{13}CO^+}$) from the ratio between the mean H$^{13}$CO$^+$ column density over the $3\sigma$ contour level of the 890 $\mu$m continuum emission (see Fig. 5) and the corresponding H$_2$ column density obtained from the submm continuum emission. Such an estimate is very sensitive to the temperature of the gas and dust. In our calculation, we have assumed that the gas and dust are well-coupled, thus having identical excitation and dust temperatures. For a fiducial value of 80 K (Sect. 3.1.2), we obtain an abundance of $\sim 10^{-10}$, but one should keep in mind that $X_{H^{13}CO^+}$ spans a range from $3 \times 10^{-11}$ to $6 \times 10^{-10}$ for $T$ varying by a factor 2 with respect to the fiducial value.

Assuming $X_{H^{13}CO^+} = 10^{-10}$ and $T = 80$ K (Sect. 3.1.2), we have computed the outflow parameters by integrating the line emission for the blue and red wings (see caption of Fig. 9 for their velocity ranges). With these assumptions, we obtain a total outflow mass ($M_{\text{outflow}}$) of 3700 $M_\odot$ and a momentum of 14000 $M_\odot$ km s$^{-1}$. Note that, even ignoring the error on $X_{H^{13}CO^+}$, a factor 2 uncertainty on the gas temperature affects by an additional factor ~2 the outflow parameters. The dynamical timescale ($t_d$) is estimated from the ratio between the diameter of the lobes and the difference (in absolute value) between the systemic velocity and the terminal wing velocity. We obtain $\sim 8 \times 10^4$ yr, without correcting for the (unknown) outflow inclination. The mass loss rate ($M_{\text{flow}}$) and a momentum rate ($F_{\text{flow}}$) are thus 0.05 $M_\odot$ yr$^{-1}$ and 0.17 $M_\odot$ km s$^{-1}$ yr$^{-1}$, respectively. Values that large are very likely overestimated due to the various assumptions made. Nevertheless, they indicate that the powering source should be as luminous as $\sim 10^5 L_\odot$, according to the empirical relationship derived by Beuther et al. (2002). Here, we have implicitly assumed that one is dealing with a single star. If this is correct, then such a star must be in a pre-HII region phase, as no free-free continuum emission has been detected towards the HMC. We will further discuss this in Sect. 4.1 and Sect. 4.3.

3.3.5. SiO (2–1) $v = 0$ Emission

Maps of the SiO Emission — From Fig. 7 one sees that the $V_t$ of the SiO emission is blueshifted by $\sim 11$ km s$^{-1}$ and redshifted by $\sim 15$ km s$^{-1}$ with respect to $V_{\text{sys}}$. The presence of HV wing emission strongly suggests the existence of a molecular outflow driven by a YSO in one of the cores. In order to analyze the structure of the SiO emitting gas, we produced maps of the bulk emission and HV wing emission in Fig. 10. In panel (b), one sees that the HV wing emission is elongated along the east-west direction, with the blue lobe lying to east and the red lobe to the west. Such a bipolarity indicates that the SiO HV gas very likely traces a bipolar outflow, although the lobes do not appear very collimated. The fact that the two lobes are largely

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**Fig. 9.** (a) Integrated intensity map of the H$^{13}$CO$^+$ (1–0) bulk emission. The velocity range used for the integration is $35.5 \leq V_{\text{LSR}}$ km s$^{-1} \leq 48.9$. The interval between the thin-black contours is $2\sigma$ with the lowest contour corresponding to the $3\sigma$ level, where the $1\sigma$ RMS noise is 0.53 Jy beam$^{-1}$ km s$^{-1}$. The thin–white contours are the 95% and 90% levels of the corresponding peak intensities, where the 90% levels correspond to the $7.5\sigma$ level. All the other symbols are the same as those in Fig. 6 and the numbers associated with the three maser spots to the west are the same used by Hofner & Churchwell (1996). The dashed box indicates the area shown in the right-hand panel. (b) Overlay of the blue- and redshifted wing emission maps of the H$^{13}$CO$^+$ (1–0) emission. The contours are $2\sigma$ steps starting from the $3\sigma$ level. The blue- and redshifted wing emission maps were obtained by averaging the wing emission over the intervals $35.3 < V_{\text{LSR}}$ km s$^{-1} < 37.9$ and $43.1 < V_{\text{LSR}}$ km s$^{-1} < 49.2$, and their RMS noise levels are 43.8 and 30.2 mJy beam$^{-1}$, respectively.
overlapping each other suggests that the outflow is seen close to pole-on. Interestingly, the velocity structure of the SiO outflow is very different from that of the larger scale (~20") ^13CO (2−1) outflow mapped by López-Sepulcre et al. (2009) with the IRAM 30-m telescope. The latter has the redshifted lobe to the NE and the blueshifted to the SW. We stress that this is not due to the different velocity intervals used to produce the outflow maps, because the orientation of the SiO outflow does not change using the same velocity ranges adopted by López-Sepulcre et al. (narrower than those used by us). We conclude that in all likelihood the larger scale flow is originating from another YSO in the region.

What is the source powering the SiO outflow? We believe that it is SMA2, despite the small offset between this and the geometrical center of the outflow (see Fig. 10b), because Fig. 10a shows that the peak of the SiO bulk emission is clearly coincident with SMA2 (see Fig. 10a).

Note that this implies that (at least) three bipolar outflows are present in the region. Beside the large-scale flow mapped by López-Sepulcre et al., we have detected two compact outflows: one traced by H13CO+ (see Sect. 3.3.3) and powered by a YSO in SMA1, and another traced by SiO and powered by a YSO embedded in SMA2. Is the latter as massive as the former? Next, we attempt to estimate luminosity of the YSO from the SiO outflow parameters.

Properties of the SiO Outflow driven by SMA2 — To derive the mass and kinematical parameters of the outflow, we assume that the SiO line is optically thin and the SiO molecule is in LTE. We adopt an excitation temperature ($T_{\text{ex}}$) of 20 K (Appendix A) and an SiO/H$_2$ abundance ratio of 3×10$^{-9}$. The latter is estimated from the ratio between the SiO column density (obtained from the bulk emission − Fig. 10a) and the H$_2$ column density (calculated from the 890 $\mu$m continuum emission towards SMA 2− Table 1). We note that the outflow masses are likely underestimated because of missing-flux filtered out by our interferometric observations and the uncertainty in defining a boundary velocity ($V_\text{b}$) between the outflowing gas and the quiescent ambient gas.

We find an outflow mass of 90 $M_\odot$ and a momentum of 2100 $M_\odot$ km s$^{-1}$. We also obtain $\dot{M}_\text{flow} \approx 5 \times 10^{-3}$ $M_\odot$ yr$^{-1}$ and a momentum rate $F_{\text{flow}} \approx 0.06 M_\odot$ km s$^{-1}$ yr$^{-1}$. Since outflows are believed to be momentum driven (Cabrit & Bertout 1992), the latter value may be taken as an indicator of the outflow strength and hence of the mass and luminosity of the YSO powering it. Using the relationship between $F_{\text{flow}}$ and YSO luminosity obtained by Beuther et al. (2002), we estimate that the YSO powering the SiO outflow should be as luminous as $\sim 3 \times 10^4 L_\odot$. This indicates that the powering source is a high-mass star.

When deriving the outflow parameters as done here with SiO and in Sect. 3.3.4 with H13CO+, a word of caution is in order. The difference between the masses of the H13CO+ outflow driven by SMA1 and the SiO outflow from SMA2 amounts to a factor ~40. Such a large number may be due to multiple outflows unresolved in our observations as well as to the uncertainties on the fractional abundances of the two molecules, which are difficult to predict. These caveats cast some doubt on the values derived in our calculations. Therefore, although the basic conclusion that the two outflows are associated with high-mass YSOs is likely to be correct, the outflow parameters reported here must be considered with caution.

Fig. 10. (a) Integrated intensity map of the bulk emission of the SiO (2−1) $v = 0$ line (greyscale plus thin contours) observed with the OVRO and NMA interferometers. The green contours have the same meaning as in Fig. 5. The bulk emission has been integrated over the LSR-velocity range of 31.9 ≤ $V_{\text{LSR}}$/km s$^{-1}$ ≤ 48.4, and the RMS noise level is 0.28 Jy beam$^{-1}$ km s$^{-1}$. The yellow stars represent the positions of SMA1, SMA2, and SMA3 (see Table 1). (b) Overlay of the blue- and redshifted wing emission maps of the SiO (2−1) $v = 0$ emission. The contours are spaced by 2σ and start at the 3σ level. The blue- and redshifted wing emission maps have been obtained by averaging the wing emission over the intervals 21.1 < $V_{\text{LSR}}$/km s$^{-1}$ < 31.9 and 48.4 < $V_{\text{LSR}}$/km s$^{-1}$ < 58.0, and their RMS noise levels are 11.6 and 13.9 mJy beam$^{-1}$, respectively. The hatched ellipses in the bottom right indicates the FWHM of the synthesized beam (Table 2).
Fig. 11. Interferometric spectrum of the CH$_3$CN and CH$_{13}$CN (18–17) lines towards the peak position of the 890 µm continuum source, SMA1. The vertical bars above and below the spectrum indicate the rest-frequencies of the $K$ components of the CH$_3$CN and CH$_{13}$CN $J = 18 – 17$ transitions. We also indicate other lines that may be blended with the methyl cyanide lines.

Fig. 12. Integrated intensity maps of the CH$_3$CN (green contour) and CH$_{13}$CN (magenta contour) lines. The black dashed contour corresponds to the absorption region seen in the $^{13}$CO (3–2) line. The thin black contour represents the 7σ level of the uniform weighting 890 µm continuum emission map (Fig. 2b). All the transitions, except the CH$_3$CN $K = 0, 1,$ and $2$ components, are not blended with other lines (see Fig. 11 for the spectrum). The contour intervals are spaced by 2σ and start from the 3σ level. In the CH$_3$CN maps, we do not plot contours above the 17σ level to prevent saturation of the maps. The 1σ RMS noise levels are 6.3, 1.4, 1.3, 0.33, and 0.17 mJy beam$^{-1}$ km s$^{-1}$ for the CH$_3$CN (18–17) $K = 0$ to 2 emission, $K = 3$, $K = 4$, and CH$_{13}$CN (18–17) $K = 2$, and $K = 6$, respectively.

3.4. CH$_3$CN $18_K – 17_K$ Emission

3.4.1. Spectrum

Fig. 11 shows the spectrum of the CH$_3$CN and CH$_{13}$CN $J_K = 18_K – 17_K$ lines observed with the SMA towards the 890 µm continuum peak, SMA1 (Sect. 5.1.2). High-excitation $K$ components can be seen in this spectrum. In particular, one can recognize all lines up to $K = 10$ for CH$_3$CN, and up to $K = 6$ for CH$_{13}$CN, although overlap with transitions from other species (some of which are marked in the figure) cannot be excluded. Only the CH$_3$CN (18–17) $K = 3$ and $K = 4$ and the CH$_{13}$CN (18–17) $K = 2$ and 6 components do not appear to be affected by blending.

The peak intensities of the $K = 0$ to 4 lines of the CH$_3$CN are comparable each other, suggesting that these CH$_3$CN lines are optically thick. One can calculate the optical depth of the corresponding CH$_{13}$CN lines from the ratio between the two isotopomers. The values of $\tau$ for the $^{13}$C substituted species range from 0.1 to 0.5 for $K \leq 5$. These imply optical depths of 5 to 29 for CH$_3$CN, assuming a $^{12}$C/$^{13}$C abundance ratio of 55 at a galactocentric distance of 5.3 kpc (Wilson & Rood 1994). As we will discuss in Sect. 3.4.3, opacities that large hinder the usage of rotation diagrams to estimate the gas temperature and column density.

3.4.2. Maps: Comparison with the Other Lines

Fig. 12 shows maps of some CH$_3$CN and CH$_{13}$CN (18–17) lines that are not blended with transitions of other molecules. For the sake of comparison, in the same figure we also outline
the uniform weighted 890 μm continuum map (Fig. 2b) and map of the redshifted absorption seen in the $^{13}$CO (3–2) emission, described in Sect. 3.3.2. The $^{13}$CO (3–2) map corresponds to the velocity channel where the maximum absorption is attained, i.e., at $V_{LSR} = 44.0$ km s$^{-1}$. We remind that no emission is seen towards SMA1 in the integrated intensity maps of the $^{12}$CO and C$^{18}$O (3–2) lines (Fig. 6). From all this, one obtains the following results: (i) CH$_{3}$CN and CH$_{3}^{15}$CN line emission is detected towards SMA1 and SMA2, but not towards SMA3; (ii) the peak of the methyl cyanide emission coincides with the peak of SMA1; (iii) the redshifted $^{13}$CO absorption is seen towards the center of the HMC (i.e., SMA1), but is not detected towards SMA2 and SMA3; (iv) the emitting region of the low $K$-transition, e.g., $K = 0, 1$, and 2, has a size similar to that of the higher $K$-lines, while in similar objects (e.g., Beltrán et al. 2004) the emitting region is smaller for higher excitation transitions.

### 3.4.3. Excitation Conditions of CH$_{3}$CN

Methyl cyanide is known to be an excellent temperature tracer and rotation diagrams obtained from the different $K$ components are commonly used to estimate the gas temperature and column density. However, as argued in Sect. 3.4.1 most CH$_{3}$CN(18–17) transitions are optically thick thus making the column density in the corresponding level a lower limit. To circumvent this problem, we have used the optically thin ($\tau < 0.5$ – see Sect 3.4.1) lines of CH$_{3}$CN. Despite heavy blending with other transitions, we managed to obtain an estimate of the line parameters by fitting groups of $K$ components simultaneously, by fixing their separation in frequency to the laboratory values and forcing the line widths to be the same. In this way we could successfully fit the $K = 0, 1, 2, 4, 5$, and 6 components and produce the rotation diagram shown in Fig. 13. In our calculation, we have assumed a source angular diameter of 2"4 from Table 3 and a $^{12}$C/$^{13}$C abundance ratio of 55. The best fit gives a temperature of $208 \pm 41$ K and a source averaged CH$_{3}$CN column density of $2.7 \times 10^{16}$ cm$^{-2}$. While the latter is consistent with the values quoted by Wu et al. (2009) and Qin et al. (2010), the former is significantly less than their estimates of 552±29 K (Wu et al. 2009) and 609±77 K (Qin et al. 2010). Such a discrepancy is due to these authors using the optically thick CH$_{3}$CN lines in their calculations, which leads to a severe overestimate of the true rotation temperature.

Since the source angular diameter is comparable to the SMA beam and the CH$_{3}$CN line are optically thick, the line brightness temperature should be similar to the gas kinetic temperature of ~200 K. Indeed, only ~20 K are measured with the SMA (see Fig. 11), implying a beam filling factor of 0.1. Although the existence of sub-structures due to clumpiness on angular scales smaller than the interferometer beam is very likely, such a filling factor appears too small, as we do not reveal important fragmentation of the HMC in our maps. We thus believe that beam dilution may explain only in part the low value of $T_{mb}$ and conclude that the optically thick CH$_{3}$CN lines must be tracing the outer regions of the core, where the gas temperature is significantly less than the temperature measured in the thinner CH$_{3}^{15}$CN transitions, originating from the innermost regions.

### 3.4.4. Velocity Structure of the HMC Traced by CH$_{3}$CN Emission

To investigate the velocity field of the innermost part of the SMA1 core, in Fig. 14, we plot maps of the CH$_{3}$CN line centroid velocity over the HMC. This velocity field was obtained by fitting simultaneously multiple $K$-components with Gaussian pro-

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**Fig. 13.** Rotation diagram obtained from the $K = 0, 1, 2, 4, 5$, and 6 components of the CH$_{3}^{15}$CN (18–17) lines shown in Fig. 11.

**Fig. 14.** Maps of the line peak velocity (color) obtained from simultaneous Gaussian fits to the CH$_{3}$CN and/or CH$_{3}^{15}$CN $J_K = 18 - 17$ lines (see Sect 3.4.2 for details). The names of the lines above each panel show the transitions that have been analyzed. The thin contours are a map of the integrated emission of the corresponding lines. The contours are in 2$\sigma$ steps, starting from the $3\sigma$ level. The thick contours corresponds to the $5\sigma$ level of the 890 μm continuum emission shown in Fig. 2b. The two stars mark the peak positions of SMA1 and SMA2 (Sect. 3.1.2).
files with separations in frequency fixed to the laboratory values (see Pearson & Mueller 1996) and line widths forced to be equal. The method employed here is described in e.g., Beltrán et al. (2005) and Furuya et al. (2008). Considering the line-blending and high opacity at low-K lines of CH$_3$CN (Sect. 3.3.1), we decided to fit the CH$_3$CN $K = 7$ and CH$_3$CN $K = 5$ lines simultaneously, to obtain the map in Fig. [14]h, and the CH$_3$CN $K = 8$ and CH$_3$CN $K = 6$ lines, for the map in Fig. [13]. The values of the velocity are displayed only inside the area encompassed by the 9σ contour level of the corresponding integrated emission map.

Unlike other cases (Beuther et al. 2005), in our study the CH$_3$CN lines appear to trace a clear velocity gradient, increasing from SW to NE, as observed in similar sources (e.g. Beltrán et al. 2004). In the G 19.61−0.23 HMC, the inferred velocity field maps show a coherent pattern, suggestive of the presence of systematic motions of the gas. In addition, the two maps show a fairly nice consistency. To further confirm these findings, we made velocity-field maps by fitting a single-Gaussian profile to the weak, optically thin CH$_3$CN emission. The map confirms the existence of a velocity gradient and demonstrates that this is not due to opacity effects.

Note that the velocity gradient is almost perpendicular to the axis of the H$_2$O maser jet in Fig. 4 and that of the H$^13$CO$^+$ outflow in Fig. 9. Therefore, our interpretation of the velocity gradient is that the HMC is rotating about the jet/outflow axis oriented SE–NW, alike the “toroids” imaged by Beltrán et al. (2006).

4. Discussion

4.1. Evolutionary Stage of the Massive YSOs in the 3 Submm Sources

Previous studies (e.g., Codella et al. 1997) have shown that H$_2$O masers are preferentially coincident with dense molecular cores that do not show continuum emission from ionizing gas, implying that such cores may harbor massive YSOs prior to the formation of an H II region. This is also consistent with the case of low- and intermediate mass stars, where H$_2$O masers are known to be associated with the youngest evolutionary phases (Furuya et al. 2001; 2006). Given the large masses of the three submm cores in G 19.61−0.23 – on the order of $10^3$–$10^4$ M$_\odot$ – one can hypothesize that each of them could develop an H II region; the fact that, instead, no free-free emission is detected inside the cores (Sect. 3.1.3), as well as the presence of a H$_2$O masers jet in SMA1 (Sect. 3.2), suggest that the YSOs harbored in the cores are massive but in an early evolutionary stage.

It is possible to constrain the properties of the putative H II regions and corresponding ionizing stars embedded in the cores using the upper limits obtained from our observations of the continuum emission. For this purpose, we use the method illustrated by CT97 (see also Molinari et al. 2000).

For the sake of simplicity, we arbitrarily assume that each submm source develops a single massive YSO, instead of a cluster. As explained in CT97, the peak brightness temperature, $T_{\text{sb}}$, of a Strömgren H II region at a given frequency can be expressed as a function of the radius, $R_*$, and Lyman continuum photon rate, $N_{\text{Ly}}$, of the star. In the calculation, we also adopted a source distance of 12.6 kpc, and an electron temperature ($T_e$) of 7200 K, corresponding to the mean for the UC H II regions in G 19.61−0.23 (Garay et al. 1998). For a given $T_{\text{sb}}$, one obtains a curve like those plotted in Fig. 15. Note that we have not considered the 7 mm image (Sect. 3.3.3), because this has resolution and sensitivity about 3–5 times worse than the cm images. The three curves correspond to $3\sigma$ upper limits obtained from the VLA continuum maps at 1.3, 3.8, and 6 cm. The permitted values of $T_{\text{sb}}$ are those lying under each curve. An additional constraint is set by the maximum radius of the H ii region, which cannot be larger than the core radius, namely 0.025–0.072 pc, depending on the core (Table 3).

If the putative embedded stars are massive, i.e. earlier than approximately B0.5, they must be also very young, as the corresponding H ii regions cannot be larger than $6 \times 10^3$ pc = 130 AU, which means that they are basically quenched. On the other hand, we cannot rule out the possibility that the stars are later than B0.5, and in this case the H ii regions could be larger and optically thin. We believe, though, that the latter possibility is less likely given the above mentioned large masses of the cores and the signposts of high-mass star formation associated especially with SMA1 (i.e. water masers, high temperature, and high-excitation lines), and thus conclude that in all likelihood the HMC hides OB type stars in a pre-UC H ii region phase.

4.2. Velocity Structure of the SMA1 Core: Infall plus Rotation

The velocity structure seen in CH$_3$CN, a high-density, high-temperature tracer, is very different from that obtained from the $^{13}$CO and C$^{18}$O (3–2) lines (see Fig. 16). A comparison between the blue- and red-shifted emission in these lines and the velocity field of the CH$_3$CN transition is shown in Fig. 16. The most interesting result is that both the deepest absorption and the 890 µm continuum peak roughly coincide with the center of symmetry (both in space and velocity) of the CH$_3$CN distribution. This configuration is strongly suggestive of the HMC to be both rotating about a SE–NW axis and collapsing. The fact that no hint of infall, i.e. no redshifted (self)absorption is detected in Fig. 15.
The problem is thus complicated by the fact that gas and dust are mixed, so that both line and continuum photons are emitted from any point inside the core. However, in the outer region of the core (where absorption occurs) the density is probably low enough to decouple the line radiative transfer from that in the continuum, whereas in the innermost region (where the bright continuum emission comes from) the dust optical depth is large enough to absorb all line photons. With this in mind, we can simplify the problem assuming a spherical core made out of two regions: an outer molecular shell enshrouding an inner, optically thick dusty nucleus. The temperature increases outside-in, so that the nucleus is hotter than the shell. In this configuration, the line brightness temperature measured along the line of sight through the center of the core can be written as

$$T_B = \left[ J_v(T_{\text{ex}}) - J_v(T_{\text{cont}}) \right] (1 - e^{-\tau})$$  \hspace{1cm} (1)

where $T_{\text{ex}} \simeq 31$ K (Sect. 3.1.2) is the measured continuum brightness temperature, $\tau$ is the line optical depth, and $J_v$ is defined as $J_v(T) = h\nu/[k(\exp(h\nu/kT) - 1)]$, with $h$ and $k$ Planck and Boltzmann constants, respectively. We have neglected the contribution of the cosmological background temperature ($T_{\text{BG}} = 2.7$ K), as this is very small at the $^{13}$CO and C$^{18}$O (3–2) line frequencies ($h\nu/k \simeq 15.9$ K, hence $J_v(T_{\text{BG}}) \simeq 0.045$ K).

Equation (1) can be written for both the $^{13}$CO and the C$^{18}$O (3–2) lines, taking into account that the values of $T_B$ are respectively $-29$ K and $-15$ K and $\tau(13CO) = 6.4 \tau(C^{18}O)$. From the two equations one obtains $\tau(13CO) \approx 4.5$ and $T_{\text{ex}} \approx 7$ K. For a line width of $-6$ km s$^{-1}$, these imply a $^{13}$CO column density of $\sim 1.8 \times 10^{17}$ cm$^{-2}$ and an H$_2$ column density $N_{H_2} \approx 10^{21}$ cm$^{-2}$, assuming a $^{13}$CO abundance of $1.5 \times 10^{-6}$.

Such a low value of $T_{\text{ex}}$ is not consistent with the absorbing gas being associated with the HMC and suggests that absorption could be due to a cold layer of molecular gas located in the outer regions of the cloud. Alternatively, the absorbing gas could cover only a fraction of the continuum. In this case, one must introduce a filling factor $< 1$ multiplying $J_v(T_{\text{ex}})$ in Eq. (1) and the value of 7 K becomes a lower limit.

Assuming that the absorbing gas is indeed associated with the HMC, one can roughly estimate the mass accretion rate for a constant density distribution:

$$M = 4\pi m_\odot R N_{H_2} V_{\text{inf}}$$  \hspace{1cm} (2)

where we take the infall speed $(V_{\text{inf}} \approx 4$ km s$^{-1}$) equal to the difference between the velocity of the absorption dip and the systemic velocity (Sect. 3.3.2). The radius, $R$, at which absorption occurs is difficult to estimate, but it seems clear that only the outermost layers of the core can contribute, because the excitation temperature derived above (7 K) is much less than the HMC temperature obtained from CH$^3$CN (208 K; Sect. 3.4.3). Since $^{13}$CO is likely thermalized, $T_{\text{ex}}$ must be very close to the gas kinetic temperature and this implies that the radius corresponding to 7 K must be much greater than that of the CH$^3$CN emitting core. Therefore, we can only estimate a lower limit on the mass accretion rate assuming a (minimum) value of $R$ equal to the radius of the HMC, 0.072 pc (Table 3).

We obtained $M > 3 \times 10^{-3} M_\odot$ yr$^{-1}$, consistent with the findings of Wu et al. (2009). Note, however, that this is a very conservative lower limit as in all likelihood a temperature of 7 K pertains to gas layers located much further than 0.072 pc from the HMC center. Indeed, comparison with the large outflow mass loss rate (Sect. 3.3.3) suggests that the actual infall rate could be much larger than the lower limit quoted above.

Finally, we note that such a large accretion rate is sufficient to quench an H$\alpha$ region even from a star as luminous as suggested...
Fig. 17. Position-velocity diagram of the CH$_3$CN 18–17 component toward the SMA1 core. The cut is made along a direction with P.A. =37$^\circ$, i.e. along the velocity gradient identified in Fig. 14. The contour levels range from 0.61 to 4.1 in steps of 0.6 Jy beam$^{-1}$. The horizontal and vertical bars in the bottom left indicate the spatial and velocity resolutions, respectively. The solid green curves encompass the region of the plot inside which emission is expected if the gas undergoes Keplerian rotation about and free-fall infall onto a massive star with mass $83 \, M_{\odot}$.

by the outflow momentum rate, i.e. $10^5 \, L_{\odot}$ (see Sect. 3.3.4). This corresponds to a zero-age main-sequence O7 star, which requires an infall rate $\geq 2 \times 10^{-5} \, M_{\odot} \, yr^{-1}$ to quench the corresponding H$_2$ region (see Walmsley 1995), much less than the lower limit derived by us. It must be noted, though, that the system we are considering is not spherically symmetric, so that one cannot exclude that a hypercompact H$_2$ region would form even under such extreme conditions.

4.2.2. Rotation

As discussed in Sect. 3.4.3, we believe that the SMA1 core is undergoing rotation about the SE–NW axis of the water maser jet and H$^{13}$CO$^+$ outflow. Is this rotation sufficient to stabilize the HMC? We know that infall is occurring on a larger scale than the HMC, but it is to be understood if gravitational collapse continues inside the HMC or, instead, the infalling material attains centrifugal equilibrium. The mass that can be supported by rotation is $M_{\text{dyn}} = RV_{\text{rot}}^2/G \geq 83 \, M_{\odot}$, with $G$ gravitational constant and $V_{\text{rot}}$ rotational velocity at the outer radius of the HMC, $R$. The fact that the HMC core mass obtained from the sub-mm continuum emission ($\sim 1300 \, M_{\odot}$) is much greater than $M_{\text{dyn}}$ argues in favor of the core to be undergoing gravitational collapse.

To check if the idea of a an infalling and rotating HMC is consistent with our results, we have made a position–velocity diagram of the CH$_3$CN (18–17) $K$-3 line emission, along the direction of the velocity gradient (i.e. approximately NE–SW). This is shown in Fig. 17, where we have also overlayed a pattern representing the maximum and minimum velocities expected at a given position from a rotating and collapsing core. We have arbitrarily assumed Keplerian rotation and infall with zero velocity at infinite distance from the HMC center. The pattern in the figure corresponds to a central mass of $83 \, M_{\odot}$ and an outer radius of 10100 AU.

Although the simple scenario depicted here is far from being unique, the pattern is consistent with the line emission, once the limited angular resolution is taken into account. This shows that one cannot rule out the possibility that the infalling material is settling onto a centrifugally supported disk in the innermost regions of the HMC.

4.3. Nature of the SMA1 Core

What is the stellar content of the HMC? Does this consist of one (or a few) massive stars, or is the core hosting a cluster of lower mass stars? Our findings do not allow to draw any firm conclusion, as the molecular gas cannot be investigated with sufficient resolution and only a loose upper limit can be set on the HMC luminosity. With the advent of the next generation of large telescopes, it will be possible to overcome these problems, but at present we can only make speculations.

We have seen in Sect. 4.1 that no free-free emission is detected towards the HMC and that this may imply that no star earlier than B0.5 is present in the core or that the star is still in a pre-UCHi region phase. If the scenario proposed in Sect. 4.2 is correct, we are dealing with a well defined system, consisting of a massive core undergoing infall and rotating about a water maser jet/H$^{13}$CO$^+$ outflow. Such a symmetric structure and the large mass accretion rate derived suggest that only few high-mass YSOs might be located at the center of this system, rather than a cluster with a significant contribution from low-mass stars. This hypothesis is supported by the comparison between the fragmentation time scale, $t_{\text{frag}}$, and the free-fall time, $t_{\text{ff}}$, of the HMC. The former can be estimated as the ratio between the core diameter and the line width of a typical HMC tracer, e.g. CH$_3$CN: $t_{\text{frag}} = 0.14 \, pc/10 \, km \, s^{-1}$ $\approx 1.4 \times 10^5 \, yr$. The latter is calculated for a mean $H_2$ density of $\sim 4 \times 10^7 \, cm^{-3}$, and is $t_{\text{ff}} \approx 6 \times 10^5 \, yr$. Because of $t_{\text{frag}} \sim 2t_{\text{ff}}$, we argue that fragmentation could be partially inhibited during the collapse.

It is worth pointing out that the previous discussion has limited validity, as it is mostly based on qualitative arguments and neglects the effect of the magnetic field, which might contribute significantly to stabilize the core against gravitational collapse. Nonetheless, we believe that our findings lend support to the idea that the stellar content of the core could be biased towards very young, OB-type stars.

5. Conclusions and Future Perspectives

We have performed deep continuum imaging from the centimeter to the sub-millimeter regime of the G 19.61−0.23 high-mass star forming region. Our observations have confirmed the existence of a large number of UC H$_2$ regions, as well as that of a HMC. The latter is resolved into three cores, with one of these (here called “the HMC”) being $\sim 10$ times more massive than the others. We have also mapped the region in a number of molecular lines at 3 mm and 890 $\mu$m, most of which appear to trace the three cores. Star formation is likely to occur not only in the HMC (SMA1), but also in the other two (SMA2, SMA3), as witnessed by the existence of a bipolar outflow seen in the SiO (2−1) line towards SMA2.

The CH$_3$CN (18–17) line emission reveals a velocity gradient across SMA1, roughly perpendicular to a water maser jet and bipolar H$^{13}$CO$^+$ outflow directed in the SE–NW direction. We interpret this velocity gradient as due to rotation about the jet/outflow axis. We also confirm the existence of an inverse P-Cygni profile in the $^{13}$CO (3−2) line, already detected by Wu et al. (2009) and reveal a similar profile also in the C$^{18}$O (3−2) line. This redshifted absorption strongly suggests that the SMA1 core is infalling – beside being rotating – with a mass accretion rate
> 3 \times 10^{-3} \, M_\odot \, yr^{-1}. \text{ We conclude that very young OB-type stars are likely forming inside the HMC.}

The study presented here is an excellent benchmark of what will be feasible, with much better resolution and sensitivity, with new generation instruments. Deep unbiased surveys of selected high-mass star forming regions will permit to improve our knowledge of the OB star formation process, identifying newly formed stars by means of their free-free continuum emission and investigating at the same time the structure and velocity field of the molecular cores associated with them.

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Appendix A: Rotation Diagram Analysis of the SiO Lines

We estimated the excitation temperature of the SiO molecule from the (2–1), (3–2), and (5–4) transitions (Fig. 4). J. M. Acord, personal communication) that have been observed simultaneously with IRAM 30 m telescope. In this way, problems due to relative gain calibration and pointing errors are minimized. Following Acord et al. (1997), we have applied the “rotation diagram” method, whose advantages and limitations are discussed in detail in (Goldsmith & Langer 1999). For this purpose, in Fig. 4 we plot the logarithm of the column density in the lower level of each transition, divided by the corresponding statistical weight, against the energy of the upper level, E_u. The column densities were obtained from the line intensities under the assumption of optically thin emission. The column densities were also corrected for the different beam filling factors of the three lines, assuming the source to be point-like and referring all measurements to the 28 beam at the frequency of the (2–1) line. The slope of the linear fit to the data, 1/T, gives the “rotational temperature” (T_rot) of the SiO molecules, which is likely an underestimate of the kinetic temperature of the H_2 gas (see e.g. Acord et al. 1997). The data are well fitted by a straight line, which indicates that the method used is likely correct, although the SiO molecule is known to be subthermally excited as noted above. We obtain T_rot=20 K and a total SiO beam averaged column density of 4.6 x 10^{13} cm^{-2}.
Fig. A.1. Spectra of thermal ($v = 0$) emission of the SiO molecule towards G19.61–0.23 taken with the IRAM 30 m telescope (J.M. Acord personal communication) in main-beam brightness temperature ($T_{mb}$) scale. The vertical dashed-line indicates systemic velocity ($V_{sys}$) of $V_{LSR} = 41.6$ km s$^{-1}$.

Fig. A.2. Rotation diagram of the SiO thermal emission shown in Fig. A.1. The dashed line is the best-fit to the data. The values of the rotation temperature and column density thus obtained are given in the bottom left of the figure.