A spectral line survey of IRC +10216 between 13.3 and 18.5 GHz

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ABSTRACT

A spectral line survey of IRC +10216 between 13.3 and 18.5 GHz is carried out using the Shanghai Tian Ma 65 m Radio Telescope (TMRT-65m) with a sensitivity of < 7 mK. Thirty-five spectral lines of 12 different molecules and radicals are detected in total. Except for SiS, the detected molecules are all carbon-chain molecules, including HC3N, HC5N, HC9N, HC5N, C2H, C2H, SiC2, SiC4, c-C3H2 and 1-C3H. The presence of rich carbon-bearing molecules is consistent with the identity of IRC +10216 as a carbon-rich AGB star. The excitation temperatures and column densities of the observed species are derived by assuming a local thermodynamic equilibrium and homogeneous conditions.

Key words. Stars: individual: IRC +10216 – Radio lines: stars – Line: identification

1. Introduction

IRC+10216 (CW Leo) is a well-known carbon-rich Asymptotic Giant Branch (AGB) star with a high mass-loss rate of about 1 × 10^{-5} M_☉ yr^{-1} (e.g., Crosas & Menten 1997; De Beck et al. 2012; Cernicharo et al. 2015a) at a distance of 123 ± 14 pc (Groenewegen et al. 2012). The effective stellar temperature is between 2500 K and 2800 K (Men'shchikov et al. 2001). The radial velocity (LSR) and terminal expansion velocity of IRC +10216 have been estimated in −26.5 ± 0.3 km s^{-1} and 14.5 ± 0.2 km s^{-1}, respectively (Cernicharo et al. 2000). IRC+10216 is surrounded by an extended circumstellar envelope (CSE) owing to its extensive mass loss. The CSE is a physically and chemically rich environment to form molecules and condense dust grains (e.g., Fonfría et al. 2008; Agúndez et al. 2012; Cabezas et al. 2013; Agúndez et al. 2014), and even metal halides such as NaCl, KCl, AlCl and AlF (Cernicharo & Guélin 1987; Ziurys et al. 1995; Quintana-Lacaci et al. 2016).

Observations at centimeter (cm) and millimeter (mm) wavelengths probe the cool, outer part of AGB winds and bring wealthy evidence of molecular species, from simple radicals such as OH to more complex species like cyanopolyynes. In previous works, linear carbon-chain molecules like C2N are observed to be abundant in the circumstellar envelopes of carbon-rich AGB stars (Winnewisser & Walmsley 1978; Cernicharo & Guélin 1996; Guélin et al. 1997; Agúndez et al. 2014; Gong et al. 2015; Agúndez et al. 2017). These molecules are proposed to be related to the formation and destruction of polycyclic aromatic hydrocarbons (PAH) (Henning & Salama 1998; Tielens 2008). The full characterization of carbon-chain molecules is regarded to be an important issue in astrochemistry (Sakai et al. 2010).

Molecular line survey is a powerful tool for analyzing both physical and chemical parameters of astronomical objects. Several systematical spectral line surveys of IRC+10216 have been reported in the literature. From Table 1, we find that existing surveys cover the frequency range from 4 GHz to 636.5 GHz for IRC +10216. Over 80 species (Agúndez et al. 2014) have been discovered toward IRC +10216, including unusual carbon-chain and silicon-carbon molecules such as SiC2, MgCCH, NCCP and SiCSi (Thaddeus et al. 1984; Cernicharo et al. 2010; Agúndez et al. 2014; Cernicharo et al. 2015b), metal cyanides/isocyanide such as MgNC, MgCN, AlNC, KCN, FeCN, NaCN, HgNC and SiH,N (Ziurys et al. 1995; 2002; Pulliam et al. 2010; Zack et al. 2011; Agúndez et al. 2012; Cabezas et al. 2013; Agúndez et al. 2014), and even metal halides such as NaCl, KCl, AlCl and AlF (Cernicharo & Guélin 1987; Ziurys et al. 1995; Quintana-Lacaci et al. 2016).

Complex molecules have small rotational constants so that their lowest-energy transitions arise at cm wavelengths. From Table 1, we find that there are several systematic and high sensitivity surveys at cm wavelengths toward IRC +10216. However, no systematic survey has been reported in the frequency range between 6 and 17.8 GHz.

In this paper, the results of a spectral line survey of IRC +10216 between 13.3 and 18.5 GHz are presented. The observations are introduced in Section 2. The observational results derived from the analysis of the molecular emission are shown in Section 3. Section 4 contains the analysis of the lines, the comparison of the results with those of previous works. Finally, the conclusions are presented in Section 5.
Table 1. Existing line surveys of IRC +10216.

| Frequencies (GHz) | Telescope | Reference | Sensitivity (1σ) (mJy) | FWHM beam or Angular Resolution (″) |
|-------------------|-----------|-----------|-------------------------|-------------------------------------|
| 4–6               | Arecibo-305m | Araya et al. (2003) | 0.3                     | 46–68                               |
| 13.3–18.5         | TMRT-65m   | This work          | 12                      | 52–73                               |
| 17.8–26.3         | Effelsberg-100m | Gong et al. (2015) | 1.0                     | 35–50                               |
| 28–50             | Nobeyama-45m | Kawaguchi et al. (1995) | 35                     | 35–62                               |
| 72–91             | Onsala-20m  | Johansson et al. (1984, 1985) | 665                   | 41–52                               |
| 80–116            | IRAM-30m   | Agúndez et al. (2014) | 23                     | 21–31                               |
| 129.0–172.5       | JCMT-15m   | Cernicharo et al. (2000) | 78                     | 14–19                               |
| 197–357.5         |              | Agúndez et al. (2008a) | 39                     | 7–13                                |
| 840–1155          | ALMA       | Agúndez et al. (2011) | 1.3                    | 1.0                                 |
| 131.2–160.3       | ARO-12m    | He et al. (2008)    | 1400                   | 39–47                               |
| 219.5–267.5       | SMT-10m    | Cernicharo et al. (2010) | 140                   | 28–34                               |
| 214.5–285.5       | SMT-10m    | Tenenbaum et al. (2014) | 20                   | 26–35                               |
| 253–261           | CARMA      | Veillet Prieto et al. (2015) | 5                     | 0.6                                 |
| 255.3–274.8       | ALMA       | Cernicharo et al. (2013) | 1.7                    | 1.0                                 |
| 293.9–354.8       | SMA        | Patel et al. (2011) | 35                     | 3                                  |
| 330.2–358.1       | CSO-10.4m  | Groesbeck et al. (1994) | 6000                   | 20–22                               |
| 222.4–267.9       | JCMT-15m   | Avery et al. (1992) | 3100                   | 18–22                               |
| 339.6–364.6       | Herschel/HIFI | Cernicharo et al. (2010) | 3400                   | 33–38                               |
| 554.5–636.5       |            | Veillet Prieto et al. (2015) | 5                     | 0.6                                 |

Notes. (†) The frequency range from 219.5 GHz to 267.5 GHz was discontinuously covered.
(2) The frequency range from 222.4 GHz to 267.9 GHz was discontinuously covered.
(3) The FWHM beam sizes are listed for single-dish, the angular resolutions are listed for interferometers.
(4) There are some other surveys using of IRC +10216 IRAM 30m, although only partially published, e.g., Cernicharo & Guélin (1987, 1996); Guélin et al. (1997, 2000); Ziurys et al. (2002); Guélin et al. (2004); Cernicharo et al. (2007); Agúndez et al. (2007, 2008); Cernicharo et al. (2008, 2009a, 2009b).

2. Observations and data reduction

The Tian Ma Radio Telescope (TMRT) is a 65 m diameter fully-steerable radio telescope located in the western suburbs of Shanghai, China (Li et al. 2016; Yan et al. 2015). The Digital Backend System (DIBAS) of TMRT is a Field Programmable Gate Array (FPGA) based spectrometer based upon the design of Versatile GBT Astronomical Spectrometer (VEGAS).

The observations were performed in a position-switching mode at Ku band (11.5–18.5 GHz) towards IRC +10216 in 2016 March and April with the TMRT. On-source and off-source integration times were two minutes per scan. In this work, the DIBAS sub-band mode 2 with a single spectral window was adopted for Ku band observation. The window has 16384 channels and a bandwidth of 1500 MHz, supplying a velocity resolution of about 2 km s⁻¹.

The data were reduced using GILDAS software package including CLASS and GREG. Linear baseline subtractions were used for all the spectra. Because of the contamination due to time variable radio frequency interference (RFI), the channels from 11.5 GHz to 13.3 GHz were discarded from further analysis. Since some unknown defects occurred at the edges of the spectra, the channels with a bandwidth of 150 MHz at each edge were excluded. All the spectra including two polarizations were averaged to reduce rms noise levels.

3. Results

Based on the molecular database “Splatalogue”², which is a compilation of the Jet Propulsion Laboratory (JPL, Pickett et al. 1998), Cologne Database for Molecular Spectroscopy catalogues (CDMS, Müller et al. 2005), and Lovas/NIST catalogues (Lovas 2004), the line identifications are performed. The local standard of rest (LSR) radial velocity of −26.5 km s⁻¹ is adopted to derive the rest frequency of the observed lines. A line is considered real if it has a signal-to-noise ratio (S/N) of at least five (Gong et al. 2015), although, a line is already significant if it is characterized by a S/N above three (Fonfría et al. 2014). Lines with a S/N of at least three are discussed in this paper. Figure 1 presents an overview of the spectral line survey of IRC +10216 between 13.3 and 18.5 GHz with strong lines marked.

1 http://www.iram.fr/IRAMFR/GILDAS.
2 www.splatalogue.net.
All detected transitions are shown in Figure 2 and Table 2. There are 41 transitions assigned to 12 different molecules and radicals found in this survey. Except for SiS, all other molecules are C-bearing molecules. The detected transitions include one transition of HC$_3$N, three transitions of the $^{13}$C-bearing isotopologues of HC$_3$N, two transitions of HC$_5$N, five transitions of HC$_7$N, and nine transitions of HC$_9$N, which are shown in Figure 2(a) and Figure 2(b). In Figure 2(a), HC$_{13}$CCN ($\nu = 0, J = 2 - 1$) is blended with HCC$^{13}$CN ($\nu = 0, J = 2 - 1$). Additionally, eight transitions of C$_6$H are detected. In Figure 2(c), C$_6$H ($^2\Pi_{3/2}, J = 11/2 - 9/2, l = f$) is blended with C$_6$H ($^2\Pi_{3/2}, J = 11/2 - 9/2, l = e$), and C$_6$H ($^2\Pi_{3/2}, J = 13/2 - 11/2, l = f$) is blended with C$_6$H ($^2\Pi_{3/2}, J = 13/2 - 11/2, l = e$). There is a transition of c-C$_3$H$_2$, five transitions of l-C$_3$H$_2$ from the $^4\Pi_{1/2}$ ladder and one transition of C$_6$H$^*$ in Figure 2(c). Spectra line profiles of three transitions of C$_6$H from the $^2\Pi_{3/2}$ ladder, SiS ($\nu = 0, J = 1 - 0$), SiC$_2$ ($\nu = 0, J = 1 - 0$), SiC$_3$ ($\nu = 0, J = 1 - 0$), and SiC$_4$ ($\nu = 0, J = 1 - 0$) are shown in Figure 2(d). There are five transitions of SiC$_2$ and two transitions of SiC$_3$ in this band. But other transitions of SiC$_2$ and SiC$_3$ are too weak to be detected. The peak intensities of the blended lines of HC$^{13}$CCN, HCC$^{13}$CN, l-C$_3$H, C$_6$H$^*$, C$_6$H$^*$, and C$_6$H$^*$ are smaller than 20 mK. These smoothed lines are weak and tentatively detected. The rest frequencies and the upper energy levels of these lines are obtained from the molecular database “Splatalogue”.

The SHELL fitting routine in Continuum and Line Analysis Single-dish Software (CLASS) is used to derive line parameters including peak intensity, integrated intensity, and expansion velocity which is defined as the half-width at zero power. Except for the blended lines, the observed lines are either double peaked or flat-topped. The fitting profiles are shown in Figure 2 when possible. For the line of HC$_3$N with hyperfine structure, only the main component is fitted to obtain the expansion velocity. For the lines that are blended and weak, the parameters are estimated directly by integrating the line profiles. Firstly, estimate the maximum velocities $v_1$ and $v_2$ of blueshift and redshift. Then, return the integrated area ($K$ km s$^{-1}$) of the current spectrum between velocities $v_1$ and $v_2$ by using the function TDV($v_1$, $v_2$) in CLASS. The observed properties of the lines are displayed in Table 2.

The spectrum is dominated by the strong transitions from five species: SiS, HC$_3$N, HC$_5$N, HC$_7$N and c-C$_3$H$_2$. The peak intensities of SiS, HC$_3$N and HC$_5$N lines are larger than 120 mK. The peak intensities of HC$_7$N and c-C$_3$H$_2$ lines are larger than 50 mK. The peak intensities of other lines are about 20 mK. Weak lines with the peak intensities smaller than 20 mK have been smoothed to have a channel width of 3.0 – 3.6 km s$^{-1}$ to improve signal to noise ratios. The smoothed lines are marked with red “smoothed” in the upper left of the corresponding panels in Figure 2 and marked with “S” in Table 2. The rms noise of peak intensity, which is estimated by fitting the baseline to a line or polynomial from frequency ranges around each particular transition where the spectrum is apparently free of lines, is about 3 – 7 mK in 1.5 – 3.6 km s$^{-1}$ wide channel. Since the terminal expansion velocity of IRC$+10216$ have been estimated in ~ 14.5 km s$^{-1}$ in previous studies. The error of integrated intensity given in this work, which is the product of the rms noise of peak intensity and the width of the line for about 29 km s$^{-1}$, is about 100 – 200 mK km s$^{-1}$. The lines in this work reveal an average LSR velocity of about $-26.7 \pm 2.0$ km s$^{-1}$ and an average terminal expansion velocity of about $13.9 \pm 2.0$ km s$^{-1}$, which are consistent with previous studies (e.g., $-26.5 \pm 0.3$ km s$^{-1}$ and $14.5 \pm 0.2$ km s$^{-1}$, respectively (Cernicharo et al. 2000), $-26.404 \pm 0.004$ km s$^{-1}$ and $13.61 \pm 0.05$ km s$^{-1}$, respectively (He et al. 2008)).

4. Discussion

It was suggested that single-peaked lines arise from optically thick transitions, while flat-topped and double-peaked lines arise from optically thin spatially unresolved and resolved transitions, respectively (Olofsson et al. 1982, Kahane et al. 1988). There are 11 double peaked lines and 19 flat-topped lines among the 30 unbinned lines detected in this work. Therefore, we can assume optically thin for the lines detected in this work. By assuming LTE, rotational temperatures and column densities can be estimated from the
Fig. 2. (a) Zoom in of all detected and tentatively detected lines for HC$_3$N, H$^{13}$CCCN, HC$^{13}$CCN, HCC$^{13}$CN, HC$_5$H and HC$_7$H. The corresponding rest frequency in MHz are shown in the upper right of each panel. Weak lines have been smoothed to have a channel width of 3.0–3.6 km s$^{-1}$, and are marked with “smoothed” in the upper left of the corresponding panels. Otherwise, the channel width is 1.5–2.1 km s$^{-1}$. The blue dashed lines of the blended transitions trace the systematic LSR velocity ($\sim$26.5 km s$^{-1}$) of IRC +10216.

rotational diagrams. The equation (Cummins et al. 1986):

$$N = \frac{3kW}{8\pi^3vS\mu^2} \frac{T_{rot}}{T_{rot} - T_{bg}} \exp \left(\frac{E_U}{kT_{rot}}\right)$$  

(1)
Fig. 2. (b) Same as Fig.2.(a) for HCN.

gives the relation between the column density and the line intensity, where \( k \) is the Boltzmann constant, \( W \left( \int T_R \, d\nu, \text{K km s}^{-1} \right) \) is the observed line integrated intensity, \( \nu \) (Hz) is the frequency of the transition, \( S\mu^2 \) is the product of the total torsion-rotational line strength and the square of the electric dipole moment. \( T_{rot} \) and \( T_{bg} \) (2.73 K) are the rotational temperature and background brightness temperature, respectively. \( E_u \) is the upper level energy, and \( Q(T_{rot}) \) is the partition function. Values of \( E_u/k \) and \( S\mu^2 \) are taken from the “Splatalogue” spectral line catalogs.
From equation (1), the formula for rotational diagrams is:

$$\ln \frac{3kW}{8\pi^3\nu^5\mu^2} = \ln \frac{N}{Q(T_{rot})} - \frac{E_U}{kT_{rot}}$$

(2)

where \(Q(T_{rot}) = Q(T_{rot})_\text{rot} \frac{T_{rot}}{T_{rot} - T_{bg}}\). To determine rotational temperatures with this method, there must be at least two transitions of the same molecule with significant rotational temperature differences.

Fig. 2. (c) Same as Fig.2.(a) for C\(_6\)H
SiS (1 − 0) is a maser in IRC +10216 [Henkel et al. 1983] and its populations must deviate from LTE, therefore this transition is excluded from the fitting. The lines of HC ≡ CCN (v = 0, J = 2 − 1) and HCC ≡ CN (v = 0, J = 2 − 1) are blended owing to large uncertainties of intensities, so are also excluded. Since only one line is detected in this work for each of HC ≡ N, H13 ≡ CCN, c-C ≡ H2, SiC2, SiC4 and C6H−, these lines can not be used to determine rotational temperatures directly. For molecules of HC5N, HC7N, HC9N, C6H, C8H and l-C5H, although at least two lines are detected, they do not have a wide dynamic range in upper level energies. The 17.8 GHz to 26.3 GHz data from Gong et al. (2015), the 28 GHz to 50 GHz data from Kawaguchi et al. (1995), the C8H data from Remijan et al. (2007) and the H13 ≡ CCN data from He et al. (2008) are adapted as the complementary to data in the current survey to derive rotational temperatures more precisely.

The integrated intensity (∫ Tmb dν, mK km s−1) of Gong et al. (2015) is obtained from the integrated flux density (∫ Sν dν, mJy km s−1), which is taken from Table 3 in Gong et al. (2015). And the conversion factor from the flux density (Sν, Jy) to the main beam brightness temperature (Tmb, K) is Tmb/Sν ∼ 1.5 K/Jy at 22 GHz. In Gong et al. (2015), across the whole frequency range, the beam size is 35″−50″ (~40″ at 23 GHz). The rms noise of intensity is estimated in the same way as in this work using online-data of the observed spectrum. In Kawaguchi et al. (1995), the main beam efficiency (η) was measured to be 0.78 ± 0.06 at 30 GHz, 0.79 ± 0.05 at 43 GHz and 0.71 ± 0.07 at 49 GHz. The main beam efficiency at the other frequencies was assumed to be 0.78 in the region between 28 and 35 GHz, and was interpolated form the measured values in the region between 35 and 50 GHz. The measured beam size (FWHM) was 34.9″ ± 1.1″ at 49 GHz and 41.5″ ± 1.1″ at 43 GHz. The brightness temperature (TR) of the molecular transition in the source is related to the antenna temperature (TA) as TR = TA/(η ηBD). The integrated intensity (∫ TA dν) and the rms noise of antenna temperature are taken from Table 1 in Kawaguchi et al. (1995). In Remijan et al. (2007), the beam size (FWHM) is approximated by θbeam = 740″/ν(GHz). The main beam efficiency (η), the integrated intensity (∫ TA dν) and the error to the integrated intensity are taken from Table 1 in Remijan et al. (2007). In He et al. (2008), the FWHM beam size of the KP12M is 43″ at 145 GHz. The integrated intensity (∫ TMB dν) and the rms noise of main beam temperature are taken from Table 10 in He et al. (2008). The errors to the integrated intensities of Gong et al. (2015), He et al. (2008) and Kawaguchi et al. (1995) are computed in the same way with this work.
Fig. 3. Rotational diagrams for the observed molecules in IRC +10216. The variable \( L \) denotes the left-hand side of equation (2). Black dashed lines represent linear least-squares fit to the rotational diagram. The blue circles are from our TMRT-65 m observations. The green triangles are obtained from Gong et al. (2015). The red diamonds are obtained from Kawaguchi et al. (1995). The magenta cross are obtained from Remijan et al. (2007). The cyan asterisks are obtained from He et al. (2008). Their values have been corrected for beam dilution. The molecules and their corresponding rotational temperatures are given in each panel.

The intensities of the detected lines should be divided by \( \theta_s^2/(\theta_s^2 + \theta_{\text{beam}}^2) \) for beam dilution to derive the physical parameters, where \( \theta_s \) is the source size, and \( \theta_{\text{beam}} \) is the beam size (Bell 1993). So, the brightness temperature \( T_R \) of the molecular transition in the source is related to the main beam temperature \( T_{MB} \) as

\[
T_R = T_{MB}/\eta_{BD} = T_{MB} \frac{\theta_{\text{beam}}^2 + \theta_s^2}{\theta_s^2}
\]

The source sizes are taken based on previous high resolution mapping of different molecules toward IRC +10216 by interferometer. For species without high resolution mapping, their sizes are taken to be the same as chemically related species. Therefore,
source sizes of HC$_3$N and HC$_5$N are 30″ that determined by new JVLA observations. Source size of H$^{13}$CCCN is taken to be the same as that of HC$_3$N. Source sizes of HC$_7$N and HC$_9$N are taken to be the same as that of HC$_5$N. The sizes of l-C$_5$H, c-C$_3$H$_2$, C$_6$H, C$_6$H$^+$ and C$_8$H are taken to be the same as that of C$_4$H (Guélin et al. 1993), which is 30″. The size of SiC$_2$ is 27″, and the source size of SiC$_4$ is assumed to be the same as it (Lucas et al. 1995). The size of SiS is 18″ by IRAM Plateau de Bure interferometer (Lucas et al. 1995). We carried out linear least-square fits to the rotational diagrams of 12 species. The results are shown in Figure 3 and Table 3. The results of Gong et al. (2015) and Kawaguchi et al. (1995) in Table 3 are obtained from the methods of rotational diagrams as well.

This work assumes the same source sizes as Gong et al. (2015), and the H$_2$ average column density ($N_{H_2}$) of 2.1 × 10$^{21}$ cm$^{-2}$ within a typical radius of 15″ taken from Gong et al. (2015) is used to calculate molecular fractional abundances relative to H$_2$. The derived rotational temperatures ($T_{rot}$), column densities ($N$) and molecular fractional abundances relative to H$_2$ ($X(N/N_{H_2})$) together with results from the literature, are listed in Table 3. The column densities of the molecules range from 10$^{12}$ to 10$^{15}$ cm$^{-2}$, and the fractional abundances relative to H$_2$ of the species detected in Ku band range from 2.91 × 10$^{-9}$ to 9.24 × 10$^{-7}$ in IRC +10216.
The blue-shifted component of the SiS (ν = 0, J = 1 − 0) line shown in Figure 2(d) is stronger than the red-shifted one due to maser amplification (18154.9 MHz, Henkel et al. 1983). The peak intensity ratio of the blue-shifted component to the red-shifted component is estimated to be 1.97 ± 0.02 in Gong et al. (2015). In this work, the peak intensity ratio is about 1.20 ± 0.02, which is smaller than the ratio observed in Gong et al. (2015). The reason for the difference of the peak intensity ratio of SiS may be that the velocity resolution at 18154.888 MHz of 1.5 km s⁻¹ in the work is bigger than that of 1.008 km s⁻¹ in Gong et al. (2015). Lines of HC₃N (ν = 0, J = 16 − 15), SiS (ν = 0, J = 1 − 0), and c-C₃H₂ (ν = 0, J = 1(1, 0) − 1(0, 1)) have also been detected in Gong et al. (2015). The parameters of HC₃N (ν = 0, J = 16 − 15), SiS (ν = 0, J = 1 − 0), HC₃N (ν = 0, J = 2 − 1) and c-C₃H₂ (ν = 0, J = 1(1, 0) − 1(0, 1)) in this work are shown in Table 2. The observed properties of these lines are displayed in Table 4.

The integrated intensities (∫ f T_dv) are shown in Table 5. The integrated intensities of HC₃N (ν = 0, J = 16 − 15), SiS (ν = 0, J = 1 − 0) and HC₃N (ν = 0, J = 2 − 1) in this work are consistent with the results derived from Gong et al. (2015). But the integrated intensity of c-C₃H₂ (ν = 0, J = 1(1, 0) − 1(0, 1)) in this work is much smaller than that in Gong et al. (2015). Since the c-C₃H₂ (ν = 0, J = 1(1, 0) − 1(0, 1)) line is at the edge of frequency range covered by the receiver, the flux calibration is less reliable there.

Light variability may also affect the accuracy of the integrated intensities. Intensity comparisons are more difficult for weaker lines. And for abundant species and their isotopologues toward the archetypical circumstellar envelope of IRC+10216, based on the existed observations (Cernicharo et al. 2000, 2014), some line intensities of the high rotational lines may follow the infrared flux variations, and some line intensities of the low-J transitions may not. But there is no direct evidence indicating line intensities of the emission lines detected in this work, Gong et al. (2015) and Kawaguchi et al. (1995) correlate with the continuum intensity. Since most of the detected lines in this work are weak, and the data for the strong transitions in this work is not enough to study the

| Species     | T_{rot}(K) | N cm⁻²  | X(N/N_{H_2}) | Ref. |
|-------------|-----------|---------|--------------|-----|
| HC₃N        | 27.2 ± 19.4 | (1.94 ± 0.21) × 10^{15} | 9.24 × 10^{-7} | 0   |
|             | 24.7 ± 18.5 | (1.4 ± 0.2) × 10^{15}   | 6.7 × 10^{-7}  | 1   |
|             | 26         | 1.7 × 10^{15}            |              | 2   |
| H^{13}CCCN  | 18.7 ± 3.3  | (3.25 ± 1.46) × 10^{13}  | 1.55 × 10^{-8} | 0   |
| HC₅N        | 13.6 ± 2.1  | (5.47 ± 0.77) × 10^{14}  | 2.61 × 10^{-7} | 0   |
|             | 18.8 ± 1.3  | (4.6 ± 0.2) × 10^{14}    | 2.2 × 10^{-7}  | 0   |
|             | 27 ± 5      | (2.7 ± 0.2) × 10^{14}    |              | 2   |
| HC₇N        | 21.5 ± 1.7  | (6.21 ± 0.67) × 10^{14}  | 2.96 × 10^{-7} | 0   |
|             | 12.1 ± 1.3  | (3.7 ± 0.4) × 10^{14}    | 1.8 × 10^{-7}  | 0   |
|             | 26 ± 2      | (1.52 ± 0.07) × 10^{14}  |              | 2   |
| HC₉N        | 19.8 ± 2.4  | (5.88 ± 1.28) × 10^{13}  | 2.80 × 10^{-8} | 0   |
|             | 20.9 ± 10.7 | (2.5 ± 1.4) × 10^{13}    | 1.2 × 10^{-8}  | 1   |
|             | 23 ± 8      | (2.7 ± 0.9) × 10^{13}    |              | 2   |
| c-C₃H₂      | 6.1 ± 2.8   | (1.39 ± 1.07) × 10^{14}  | 6.60 × 10^{-8} | 0   |
|             | 5.5 ± 0.6   | (2.1 ± 0.4) × 10^{14}    | 9.9 × 10^{-8}  | 1   |
| 1-C₅H       | 4.7 ± 2.0   | (2.96 ± 1.21) × 10^{14}  | 1.41 × 10^{-7} | 0   |
| 2Π₁/₂       | 8.3 ± 2.0   | (2.9 ± 0.6) × 10^{13}    | 1.4 × 10^{-8}  | 1   |
|             | 27 ± 5      | (2.9 ± 0.3) × 10^{14}    |              | 2   |
| C₆H⁻        | 8.9 ± 3.4   | (6.11 ± 2.99) × 10^{14}  | 2.91 × 10^{-9} | 0   |
|             | 26.9 ± 4.0  | (5.8 ± 0.5) × 10^{12}    | 2.8 × 10^{-9}  | 1   |
| C₆H²        | 13.7 ± 2.7  | (1.85 ± 0.90) × 10^{14}  | 8.82 × 10^{-8} | 0   |
| 2Π₁/₂       | 20.7 ± 2.4  | (1.0 ± 0.2) × 10^{14}    | 4.8 × 10^{-8}  | 1   |
|             | 46 ± 4      | (1.13 ± 0.6) × 10^{14}   |              | 2   |
| C₆H²        | 18.1 ± 5.8  | (5.38 ± 1.18) × 10^{14}  | 2.56 × 10^{-8} | 0   |
| 2Π₃/₂       | 47.2 ± 10.3 | (1.0 ± 0.1) × 10^{14}    | 4.8 × 10^{-8}  | 1   |
|             | 35 ± 2      | (1.65 ± 0.07) × 10^{14}  |              | 2   |
| C₆H²        | 12.3 ± 1.6  | (5.00 ± 1.08) × 10^{14}  | 2.38 × 10^{-8} | 0   |
| 2Π₃/₂       | 13.9 ± 1.3  | (8.4 ± 1.4) × 10^{12}    | 4.0 × 10^{-9}  | 1   |
| SiC₂        | 40.1 ± 36.2 | (1.87 ± 1.34) × 10^{13}  | 8.90 × 10^{-7} | 0   |
|             | 31.8 ± 0.9  | (1.2 ± 0.0) × 10^{15}    | 5.7 × 10^{-7}  | 1   |
| 16          | 2.2 ± 10^{14} |              |              | 2   |
| SiC₄        | 7.6 ± 3.0   | (1.46 ± 0.92) × 10^{13}  | 6.98 × 10^{-9} | 0   |
|             | 22.3 ± 17.5 | (1.1 ± 0.4) × 10^{13}    | 5.2 × 10^{-9}  | 1   |

Notes. References for rotational temperatures and column densities from: (0) This work; (1) Gong et al. (2015); (2) Kawaguchi et al. (1995). The results of Gong et al. (2015) and Kawaguchi et al. (1995) are also used the method of rotational diagrams.

Table 3. Column densities and rotational temperatures of the molecules in IRC+10216.


Table 4. Line Parameters of HC$_3$N ($\nu = 0$, $J = 16 - 15$), SiS ($\nu = 0$, $J = 1 - 0$), HC$_3$N ($\nu = 0$, $J = 2 - 1$) and c-C$_3$H$_2$ ($\nu = 0$, $J = 1(1, 0) - 1(0, 1)$) detected by this work and Gong et al. (2015).

| Species | Transitions | Rest Freq. (MHz) | $T_{MB} dv$ (mK km s$^{-1}$) | $\theta_v$ ($''$) | $\theta_{beam}$ ($''$) |
|---------|-------------|-----------------|-----------------|-----------------|-----------------|
| HC$_3$N | $\nu = 0$, $J = 16 - 15$ | 18047.970 | 1629(194) | 1577(116) | 30 | 54 | 50 |
| SiS     | $\nu = 0$, $J = 1 - 0$ | 18154.888 | 6692(186) | 7140(110) | 18 | 53 | 49 |
| HC$_3$N | $\nu = 0$, $J = 2 - 1$ | 18196.226 | 10337(197) | 10445(125) | 30 | 53 | 49 |
| c-C$_3$H$_2$ | $\nu = 0$, $J = 1(1, 0) - 1(0, 1)$ | 18343.143 | 1161(157) | 2973(116) | 30 | 53 | 49 |

Table 5. The integrated intensity ratios (This Work: Gong et al. (2015)) of HC$_3$N ($\nu = 0$, $J = 16 - 15$), SiS ($\nu = 0$, $J = 1 - 0$), HC$_3$N ($\nu = 0$, $J = 2 - 1$) and c-C$_3$H$_2$ ($\nu = 0$, $J = 1(1, 0) - 1(0, 1)$).

| Species | Rest Freq. (MHz) | $T_R dv$ (mK km s$^{-1}$) | Ratios |
|---------|-----------------|-----------------|--------|
| HC$_3$N | 18047.9697 | 6907(823) | 5958(438) | 1 | (0.863 ± 0.121) |
| SiS     | 18154.8880 | 6471(1799) | 6005(925) | 1 | (0.928 ± 0.029) |
| HC$_3$N | 18196.2260 | 42600(812) | 38309(458) | 1 | (0.899 ± 0.020) |
| c-C$_3$H$_2$ | 18343.1430 | 4784(647) | 10904(425) | 1 | (2.279 ± 0.321) |

Table 6. The abundance ratios (HC$_3$N: HC$_3$N: HC$_3$N: HC$_3$N) of this work, Gong et al. (2015) and Kawaguchi et al. (1995).

| Species | HC$_3$N | HC$_3$N | HC$_3$N | HC$_3$N |
|---------|--------|--------|--------|--------|
| This work | 100 | (28.2±5.0) | (32.0±4.9) | (3.0±0.8) |
| Gong et al. (2015) | 100 | (32.9±4.9) | (26.4±4.7) | (1.8±1.0) |
| Kawaguchi et al. (1995) | 100 | (15.9±1.2) | (8.9±0.4) | (1.6±0.5) |

The transitions of HC$_3$N and its $^{13}$C substitutions are optically thin. Thus, the isotopic ratio can be directly obtained from their integrated intensity ratio. The derived $^{12}$C/$^{13}$C ratios are $32 ± 16$ from [HCCCN]/[H$^{13}$CCCN] ($\nu = 0$, $J = 2 - 1$). This is much smaller than 71 obtained from $^{12}$CO/$^{13}$CO by Ramstedt & Olofsson (2014) and also is smaller than 49 ± 9 derived from HC$_3$N and its $^{13}$C isotopologues by Gong et al. (2015). This value agrees with 34.7 ± 4.3 derived from [SiC]/[Si$^{13}$CC] by He et al. (2008).

5. Summary

A spectral line survey of IRC +10216 between 13.3 and 18.5 GHz is carried out using the TMRT. Forty-one spectral lines of 12 different molecules and radicals are detected in total. Several carbon-chain molecules are detected, including HC$_3$N, HC$_5$N, HC$_7$N, HC$_9$N, C$_4$H, C$_5$H, C$_6$H$^-$, l-C$_7$H, SiC$_2$, SiC$_4$ and c-C$_3$H$_2$.

The rotational temperatures and column densities of the detected molecules are derived by assuming LTE. Their rotational temperatures range from 4.7 to 40.1 K, and molecular column densities range from $10^{12}$ to $10^{15}$ cm$^{-2}$. Molecular abundances relative...
Comparison of the column densities. The circles with error bars are from our TMRT-65 m observations. The triangles with error bars are obtained from (Gong et al. 2015). The asterisks without error bars are obtained from (Kawaguchi et al. 1995).

The H₂ range between 2.91 × 10⁻⁹ and 9.24 × 10⁻⁷. From the comparison with previous works, it is clear that the higher-J transitions of the HC₅N, HC₇N and HC₉N molecules in the circumstellar envelope of IRC +10216 traces the warmer molecular regions. And there are obvious differences in the abundance ratios derived from different transitions.

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Fig. 5. The red circles are from our TMRT-65 m observations. The green triangles are obtained from Gong et al. (2015). The blue asterisks are obtained from Kawagnchi et al. (1995). The dashed lines of different colors represent linear least-squares fit to the rotational diagram accounting for data obtained from corresponding surveys.
| Species       | Transitions | Rest Freq. (MHz) | $E_c/k$ (K) | Observing date | FWHM beam (") | Rest Freq. (MHz) | $E_c/k$ (K) | Observing date | FWHM beam (") | Notes |
|---------------|-------------|-----------------|-------------|----------------|----------------|-----------------|-------------|----------------|----------------|-------|
| $^{13}$HCN    | $v = 0, J = 2 \rightarrow 1$ | 18196.2260      | 1.30994     | 2016Apr10      | 53             | 504.3(6.8)      | 13.7(1.5)   | -26.2(1.5)    | 10337(197)    | D     |
| $^{13}$CCCN   | $v = 0, J = 2 \rightarrow 1$ | 17633.7460      | 1.26928     | 2016Apr10      | 55             | 27.2(5.4)       | 13.1(1.6)   | -27.1(1.6)    | 306(157)      | D     |
| $^{13}$CCCN   | $v = 0, J = 2 \rightarrow 1$ | 18119.0430      | 1.30437     | 2016Apr10      | 54             | 24.3(3.3)       |             |               |                |       |
| $^{13}$CCCN   | $v = 0, J = 2 \rightarrow 1$ | 18120.7670      | 1.30445     | 2016Apr10      | 54             | 24.3(3.3)       |             |               |                |       |
| $^{13}$HCN    | $v = 0, J = 5 \rightarrow 4$ | 13313.3119      | 1.91685     | 2016Apr10      | 73             | 128.9(3.5)      | 15.5(2.1)   | -27.4(2.1)    | 306(157)      | F     |
| $^{13}$HCN    | $v = 0, J = 5 \rightarrow 4$ | 13353.9990      | 4.22232     | 2016Apr10      | 72             | 52.6(3.9)       | 15.2(2.0)   | -26.3(2.0)    | 1279(113)     | F     |
| $^{13}$HCN    | $v = 0, J = 13 \rightarrow 12$ | 14663.9936      | 4.92625     | 2016Mar25      | 66             | 64.7(5.4)       | 14.0(1.9)   | -26.4(1.9)    | 1463(157)     | F     |
| $^{13}$HCN    | $v = 0, J = 17 \rightarrow 16$ | 16919.9791      | 6.49617     | 2016Mar10      | 57             | 74.5(4.4)       | 13.6(1.6)   | -26.1(1.6)    | 1578(128)     | D     |
| $^{13}$HCN    | $v = 0, J = 16 \rightarrow 15$ | 18047.4697      | 7.36235     | 2016Mar10      | 54             | 82.6(6.7)       | 13.6(1.5)   | -26.0(1.5)    | 1629(194)     | D     |
| $c$-C$_3$H$_2$ | $J = 1(1,0) \rightarrow 0(1,0)$ | 18343.1430      | 3.23012     | 2016Apr10      | 73             | 20.0(3.9)       | 13.4(2.1)   | -26.3(2.1)    | 357(113)      | F     |
| C$_6$H$^+$    | $J = 6 \rightarrow 5$ | 16522.3290      | 2.77528     | 2016Mar16      | 59             | 14.6(4.0)       | 15.7(3.3)   | -28.7(3.3)    | 345(116)      | D     |
| C$_6$H$^+$    | $J = 11/2 \rightarrow 9/2, l = f$ | 15343.1726      | 24.51330    | 2016Mar25      | 63             | 20.9(5.3)       | 14.3(1.8)   | -27.7(1.8)    | 291(154)      | F     |
| C$_6$H$^+$    | $J = 11/2 \rightarrow 9/2, l = e$ | 15371.5462      | 24.52142    | 2016Mar25      | 63             | 12.1(3.8)       | 14.4(3.6)   | -26.0(3.6)    | 272(110)      | F     |
| C$_6$H$^+$    | $J = 13/2 \rightarrow 11/2, l = f$ | 18135.2758      | 25.38366    | 2016Apr10      | 54             | 16.1(3.6)       | 10.6(3.0)   | -26.4(3.0)    | 275(104)      | F     |
| C$_6$H$^+$    | $J = 13/2 \rightarrow 11/2, l = e$ | 18163.8788      | 25.39309    | 2016Apr10      | 53             | 25.3(5.4)       | 13.7(1.5)   | -26.6(1.5)    | 264(157)      | D     |
| C$_6$H$^+$    | $J = 11/2 \rightarrow 9/2, l = e$ | 15248.2791      | 21.2884     | 2016Mar25      | 64             | 33.2(5.3)       |             |               | 704(154)      | B     |
| C$_6$H$^+$    | $J = 13/2 \rightarrow 11/2, l = f$ | 18020.6059      | 29.9379     | 2016Apr10      | 54             | 24.4(6.7)       |             |               | 576(194)      | B     |
| C$_6$H$^+$    | $J = 13/2 \rightarrow 11/2, l = e$ | 18021.7828      | 29.9385     | 2016Apr10      | 54             | 24.4(6.7)       |             |               | 576(194)      | B     |
| C$_6$H$^+$    | $J = 27/2 \rightarrow 25/2$ | 13840.0020      | 5.40584     | 2016Mar25      | 61             | 14.8(3.7)       | 10.6(3.5)   | -29.1(3.5)    | 277(107)      | F     |
| C$_6$H$^+$    | $J = 29/2 \rightarrow 27/2$ | 17013.3256      | 6.22239     | 2016Mar25      | 57             | 17.1(3.6)       | 15.4(3.2)   | -25.0(3.2)    | 276(104)      | F     |
| C$_6$H$^+$    | $J = 31/2 \rightarrow 29/2$ | 18186.4740      | 7.9520      | 2016Mar25      | 57             | 15.8(5.1)       | 15.0(3.0)   | -26.4(3.0)    | 254(148)      | F     |
| SiS           | $v = 0, J = 1 \rightarrow 0$ | 18154.8880      | 0.87129     | 2016Apr10      | 53             | 480.6(6.4)      | 14.2(1.3)   | -26.2(1.3)    | 6692(186)     | D     |
| SiC$_2$       | $v = 0, J = 7(2,5) \rightarrow 7(2,6)$ | 15697.7396      | 40.16052    | 2016Mar25      | 62             | 22.3(5.6)       | 12.2(1.7)   | -25.6(1.7)    | 350(162)      | F     |
| SiC$_4$       | $J = 5 \rightarrow 4$ | 15337.6950      | 2.08240     | 2016Mar25      | 63             | 22.3(5.3)       | 14.3(1.8)   | -27.4(1.8)    | 400(154)      | F     |
Notes. The numbers in parentheses represent the 1σ errors. The rms noise of peak intensity is estimated from frequency ranges around each particular transition where the spectrum is apparently free of lines. The error for expansion velocity and LSR velocity is the velocity width of a channel. And the error of integrated intensity given here is the product of the rms noise of peak intensity and the width of the line for about 29 km s⁻¹.

Each column represents the following information, Col. (1): molecule name; Col. (2): transition; Col. (3): rest frequency; Col. (4): $E_u/k$, the upper level energy in K; Col. (5): observing date; Col. (6): FWHM beam; Col. (7): peak intensity of main beam temperature; Col. (8): expansion velocity; Col. (9): LSR velocity; Col. (10): integrated intensity. (D) The lines fitted with double peaked profiles are marked with “D”. (F) The lines fitted with flat-topped profiles are marked with “F”. (B) The blended transitions are marked with “B”. (S) Transitions that are smoothed to improve signal to noise ratio are marked with “S”.