

Extremely Strong $^{13}\text{CO } J = 3 \rightarrow 2$ Line in the “Water Fountain” IRAS 16342–3814: Evidence for the Hot-Bottom Burning

Hiroshi IMAI and Sze Ning CHONG

Graduate School of Science and Engineering, Kagoshima University, 1-21-35 Korimoto, Kagoshima 890-0065
hiroimai@sci.kagoshima-u.ac.jp

Jin-Hua HE

Yunnan Astronomical Observatory/Key Laboratory for the Structure and Evolution of Celestial Objects,
Chinese Academy of Sciences, Kunming, Yunnan Province 650011, China

Jun-ichi NAKASHIMA and Chih-Hao HSIA

Department of Physics, The University of Hong Kong, Pokfulam Road, Hong Kong, China

Takeshi SAKAI

Institute of Astronomy, The University of Tokyo, 2-21-1 Osawa, Mitaka, Tokyo 181-0015

Shuji DEGUCHI

Nobeyama Radio Observatory, National Astronomical Observatory, Minamimaki, Minamisaku, Nagano 384-1305
and

Nico KONING

Department of Physics and Astronomy, University of Calgary, Calgary, AB T2N 1N4, Canada

(Received 2011 October 22; accepted 2012 March 15)

Abstract

We observed four “water fountain” sources in the CO $J = 3 \rightarrow 2$ line emission with the Atacama Submillimeter Telescope Experiment (ASTE) 10 m telescope in 2010–2011. The water fountain sources are evolved stars that form high-velocity collimated jets traced by H₂O maser emission. The CO line was detected only from IRAS 16342–3814. The present work confirmed that the ^{12}CO to ^{13}CO line intensity ratio is ~ 1.5 at the systemic velocity. We discuss the origins of the very low ^{12}CO -to- ^{13}CO intensity ratio, as possible evidence for “hot-bottom burning” in an oxygen-rich star, and the CO intensity variation in IRAS 16342–3814.

Key words: stars: AGB and post-AGB — stars: individual (IRAS 16342–3814)

1. Introduction

The “water fountain” sources are a rare group of asymptotic giant branch (AGB) or post-AGB stars that show H₂O maser emission with a total velocity width larger than that typically seen in 1612 MHz OH masers. Previous radio interferometric observations have revealed that the water fountains have highly collimated, fast jets traced by H₂O maser emission, while some of them still have circumstellar envelopes (CSEs), as seen around AGB and post-AGB stars (Imai et al. 2002; Claussen et al. 2009; Walsh et al. 2009; Day et al. 2010, see also a review of Imai et al. 2007). It has been suggested that the dynamical ages of the jets are shorter than 100 years (Imai et al. 2007). Thus, it is expected that the water fountains should shed light on the mechanism of jet launching found in planetary nebulae (PNe) and on that of the formation of asymmetric PNe (e.g., Sahai & Trauger 1998). However, because the volume of the maser emission regions is quite limited, observations of thermal emission such as CO and the dust continuum are essential for understanding the whole spatio-kinematical structures of the water fountains.

He et al. (2008) and Imai et al. (2009) reported the first example of CO emission towards a water fountain source, IRAS 16342–3814 (hereafter abbreviated as I16342), whose CO emission lines ($J = 2 \rightarrow 1$ and $J = 3 \rightarrow 2$ respectively)

were detected in single-dish observations. The failure of CO emission detection towards other water fountains (Imai et al. 2009) may be attributed to the following factors: they are located close to the galactic plane with heavy contamination from the interstellar CO emission, they are too distant ($D \gtrsim 2$ kpc), or the observed coordinates had large offsets from the true coordinates of the sources. Nevertheless, we can learn interesting properties of the CO emission from I16342. He et al. (2008) found a very low ^{12}CO -to- ^{13}CO line intensity ratio (~ 1.7). The $^{12}\text{C}/^{13}\text{C}$ abundance ratio is not only much lower than those towards interstellar clouds (~ 70 , e.g., Milam et al. 2005), but also lower than other AGB/post-AGB stars (e.g., Schöier & Olofsson 2000). Imai et al. (2009) also detected high-velocity wings in the $^{12}\text{CO } J = 3 \rightarrow 2$ spectrum, whose total velocity range is comparable to that of the H₂O maser spectrum.¹

In this paper, we report the results of additional observations of the CO $J = 3 \rightarrow 2$ lines towards I16342 with the Atacama Submillimeter Telescope Experiment (ASTE) 10 m telescope. They were conducted to reconfirm the low ^{12}CO -to- ^{13}CO line intensity ratio reported by He et al. (2008), but for the $J = 3 \rightarrow 2$ lines.

¹ In this paper, the CO spectrum published in Imai et al. (2009) is revised. See section 3.

Table 1. Parameters of the water fountain sources and ASTE observations in ^{12}CO emission.

IRAS name Other name	RA (J2000.0) Dec (J2000.0)	Year of observation	l^* ($''$)	V_{sys}^\dagger (km s^{-1})	$\Delta V_{\text{los}}^\ddagger$	D^\S (kpc)	t_{jet}^\parallel (yr)	Ref.**	Dur †† (hr)	On- ‡† point	rms (mK)
16342–3814 OH 344.1+5.8	16 ^h 37 ^m 39 ^s .91 –38°20′17″.3	2010 2011	2.4	50	240	2.0	100	2, 5	0.5 2.4	1 5	5 7
18043–2116 OH 009.1–0.4	18 ^h 07 ^m 20 ^s .85 –21°16′12″.0	2010	0.3	87	400	6.4	60	3, 7	1.25	5	6
18139–1816 OH 12.8–0.9	18 ^h 16 ^m 49 ^s .23 –18°15′01″.8	2010	0.12	56	50	~8	0	1	2.25	5	6
19190+1102	19 ^h 21 ^m 25 ^s .09 +11°08′41″.0	2010	0.28	28	130	8.6	60	4, 6	0.58 1.08	5 9	9 21

* Total angular length of the jet system.

† Systemic velocity of the jet system.

‡ Full range of the line-of-sight velocities of H_2O maser emission.

§ Distance to the source.

|| Dynamical age of the jet ($\approx l/\Delta V_{\text{los}}$).

** References of the jet parameters. 1: Boboltz and Marvel (2007); 2: Claussen, Sahai, and Morris (2009); 3: Deacon et al. (2007); 4: Day et al. (2010); 5: Imai et al. (2009); 6: Suárez, Gómez, and Miranda (2008); 7: Walsh et al. (2009).

†† Duration of the total observation time with ASTE.

‡‡ Number of points observed on and around the target, except an off-point.

2. Observations and Data Reduction

The new ASTE observations of the CO $J = 3 \rightarrow 2$ emission were conducted during LST 16:00–22:00/20:00–22:00 on 2010 August 16/17 and LST 13:00–21:00 on 2011 June 10. In 2010, the ^{12}CO $J = 3 \rightarrow 2$ emission at 345.79599 GHz was observed towards four water fountain sources, listed in table 1. In 2011, ^{13}CO $J = 3 \rightarrow 2$ emission at 330.587957 GHz was observed towards only I16342 so as to achieve a spectral noise level roughly equal to that of ^{12}CO .² The FWHM beam sizes of the ASTE telescope are $22''$ and $23''$ at the observed frequencies of 345 GHz and 330 GHz, respectively. The system temperature was between 210 and 420 K (single side band). The received signals were down-converted in frequency and transferred into three (in 2010) and four (in 2011) base band channels (BBCs), each of which had a band width of 512 MHz, corresponding to a velocity width of 445 km s^{-1} at 345 GHz. In 2010, the center frequencies of the BBCs were split by 100 MHz to check the intrinsic CO emission, which should be detected in different spectral channels, but at the same velocity ranges in the all BBCs.² In 2011, the center frequencies of the BBCs were set to the rest frequencies of ^{12}CO , ^{13}CO , C^{18}O ($J = 3 \rightarrow 2$), HCN , H^{13}CN , HC^{15}N ($J = 4 \rightarrow 3$), SO_2 (at 331.580 GHz), CS , HCO^+ , H^{13}CO^+ ($J = 4 \rightarrow 3$), and SiC_2 (at 357.473 GHz). However, except CO, no detection was confirmed in the $3\text{-}\sigma$ upper limit to 12–16 mK. This paper reports the results of the ^{12}CO and ^{13}CO observations. We used the MAC spectrometer to obtain a spectrum with 1024 spectral channels, corresponding to frequency and velocity spacings of 500 kHz and 0.45 km s^{-1} , respectively.

An antenna pointing check was made before every change from one target source to another. For this check, we used

² We tried to observe the ^{13}CO line on 2010 August 16, but the obtained data should be dropped out because later we confirmed that we observed it in a wrong frequency setup.

the CO emission towards the AGB stars II Lup and W Aql. The pointing offset derived in these measurements was always within $\sim 2''$, indicating that the pointing stability may be equal to this typical offset value in most of the observations. For antenna temperature calibration, ^{12}CO and ^{13}CO lines towards W28 were observed. Reduction of the spectral data was made using the NewStar package developed at the Nobeyama Radio Observatory.

Nine consecutive spectral channels were re-binned to a velocity resolution of 4.1 km s^{-1} to improve the signal-to-noise ratio. Comparing the antenna temperatures of the W28 CO lines with those obtained with the Caltech Submillimeter Observatory (CSO) 10 m telescope (Wang et al. 1994) and assuming an antenna aperture efficiency of ASTE ($\eta_{\text{MB}} = 0.59$; Imai et al. 2009), we set conversion factors of the antenna temperature scales in the BBCs. The original temperature scales were multiplied by these factors with values within a range of 1.0–1.3 to obtain corrected scales. The emission-free baseline had a linear gradient for the integrated spectrum of IRAS 16342–3814, and it was removed to obtain the final spectrum. On the other hand, gentle standing waves could be seen in the spectra of other sources. A higher order polynomial baseline was therefore removed. The baseline removal did not affect the identification of line features in the spectra because the wavelength of the standing waves is usually much broader than a typical line width ($\Delta V \leq 50 \text{ km s}^{-1}$).

Table 1 gives the parameters of the water fountain sources and the observations. The observations were made in the antenna-position switching mode; the number of points observed on and around the target source (> 1 for the cross-scan mode) is given in Column 11. Because all of the sources, except IRAS 16342–3814, are located very close to the galactic plane with intense background molecular emission, five-points or nine-points cross scans were adopted, in which the observed points were separated by $10''$ – $20''$ (see section 3).

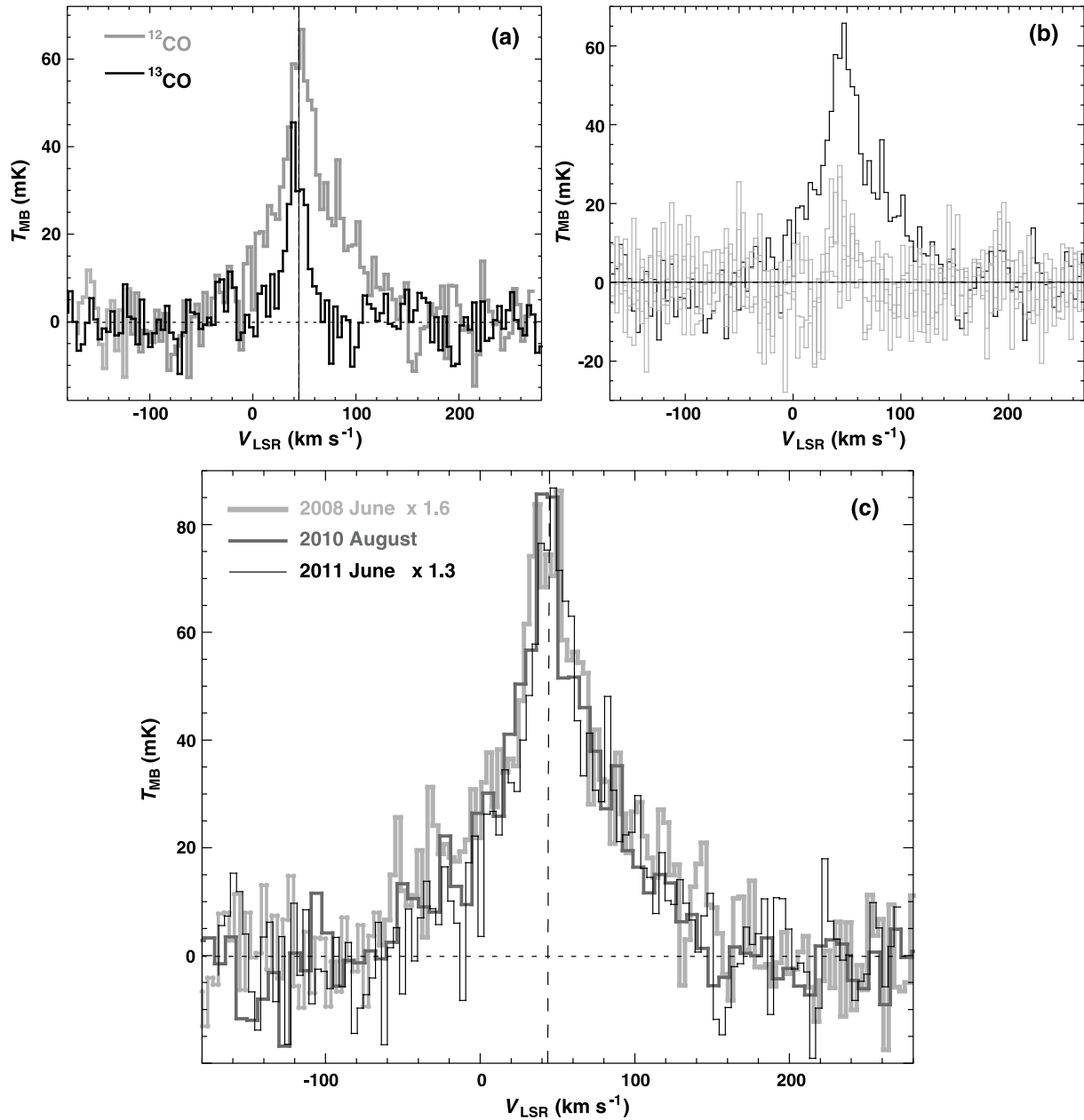


Fig. 1. Spectra of the CO $J = 3 \rightarrow 2$ emission lines toward IRAS 16342–3814. (a) Spectra of the ^{12}CO (gray thick line) and the ^{13}CO (black thick line) emission lines obtained in 2011 June. (b) Spectra of ^{12}CO at the source position (black line) and four offset positions (gray lines) in the cross-scans conducted in 2011 June. The separation between the on-source and offset positions was set to $11''$ and one of the cross arms was in the direction of the major axis of the IRAS 16342 jet. (c) ^{12}CO spectra obtained in 2008 June [a thick gray line, modified from Imai et al. (2009) and rescaled by a factor of 1.6], in 2010 August (thick black line), and in 2011 June (a thin black line, rescaled by a factor of 1.3). The horizontal gray dashed line shows the zero-temperature baseline.

Column 12 in table 1 gives the root-mean-square noise levels of the spectra.

3. Results

We searched for $^{12}\text{CO } J = 3 \rightarrow 2$ emission towards IRAS 18043–2116 (OH 009.1–0.4), IRAS 18139–1816 (OH 12.8–0.9), and IRAS 19190+1102 with the ASTE

telescope. However, after removing interstellar contamination by subtracting the off-point spectra in our cross-scans, no intrinsic CO emission could be recognized around the expected systemic velocities. The upper limit of CO $J = 3 \rightarrow 2$ emission is given by three times the root-mean-square noise level given in table 1.

Figure 1a shows the spectra of the ^{12}CO and $^{13}\text{CO } J = 3 \rightarrow 2$ lines toward IRAS 16342–3814. To obtain these spectra with improved sensitivity in 2010, two or three MAC spectra

Table 2. Parameters of Gaussian fitting to ^{12}CO and ^{13}CO emissions toward IRAS 16342–3814.

Molecule	Single Gaussian fitting			Two Gaussian fitting					
	$T_{\text{MB}}^{\text{peak}}$ (mK)	V_{sys} (km s $^{-1}$)	ΔV_{HWHM} (km s $^{-1}$)	Broad wing			Narrow peak		
				$T_{\text{MB}}^{\text{peak}}$ (mK)	V_{sys} (km s $^{-1}$)	ΔV_{HWHM} (km s $^{-1}$)	$T_{\text{MB}}^{\text{peak}}$ (mK)	V_{sys} (km s $^{-1}$)	ΔV_{HWHM} (km s $^{-1}$)
^{12}CO (in 2008)*	37 ± 1	47 ± 1	59 ± 2	23 ± 2	46 ± 3	105 ± 9	26 ± 3	46 ± 1	23 ± 3
^{12}CO (in 2010)	58 ± 3	49 ± 2	47 ± 3	45 ± 3	49 ± 2	71 ± 4	40 ± 6	46 ± 1	9 ± 2
^{12}CO (in 2011)	48 ± 2	52 ± 2	42 ± 3	32 ± 3	56 ± 3	70 ± 6	33 ± 5	48 ± 1	15 ± 3
^{13}CO (in 2011)	36 ± 3	44 ± 1	36 ± 3	—	—	—	—	—	—

* Observed on 2008 June 20–21 (Imai et al. 2009). The spectral synthesis shown in that paper is corrected.

covering different velocity ranges were synthesized.³ The spectrum obtained in 2011 was synthesized from only the data at the source position, and shown in figure 1a. The ^{12}CO spectra obtained in the three observations seem to be composed of two components: a wide wing ($V_{\text{LSR}} \lesssim 15 \text{ km s}^{-1}$ and $V_{\text{LSR}} \gtrsim 75 \text{ km s}^{-1}$) and a central sharp peak ($15 \lesssim V_{\text{LSR}} \lesssim 75 \text{ [km s}^{-1}\text{]}$). They look roughly symmetric around the systemic velocity ($V_{\text{LSR}} \simeq 45 \text{ km s}^{-1}$), but with some deviation, as mentioned later. Although cross-scan observations were performed, the CO emission was detected only at the position of I16342 (figure 1b). Although the emission seems to be marginally detected at points $12''$ away from the source position, this does not mean the existence of extended components, because even a perfect point source should be detected at these locations. The peak antenna temperature seems to exhibit temporal variation, the origin of which is discussed in subsection 4.3. The narrower and weaker ^{13}CO emission was also detected at the target position. The peak velocities of the ^{13}CO spectrum seem to be blue-shifted from that of ^{12}CO by $\sim 8 \text{ km s}^{-1}$. Although it is difficult to judge whether this shift is real, a comparison of the ^{12}CO spectrum with the ^{13}CO one supports a shift and the asymmetry of the former relative to the latter. They may indicate the optically thick property of the ^{12}CO line, which is discussed in subsection 4.2.

Table 2 gives the parameters of Gaussian fittings to the observed spectra in cases assuming one and two Gaussian components. Interestingly, the ^{12}CO -to- ^{13}CO line intensity ratio is very low (~ 1.5) around the systemic velocity. The derived intensity ratio is roughly consistent with that for the CO $J = 2 \rightarrow 1$ lines (He et al. 2008). The ^{13}CO line has a velocity width slightly larger than that of the narrow-peak component of the ^{12}CO spectrum. However, it is difficult to recognize the existence of high-velocity wings in the ^{13}CO spectrum.

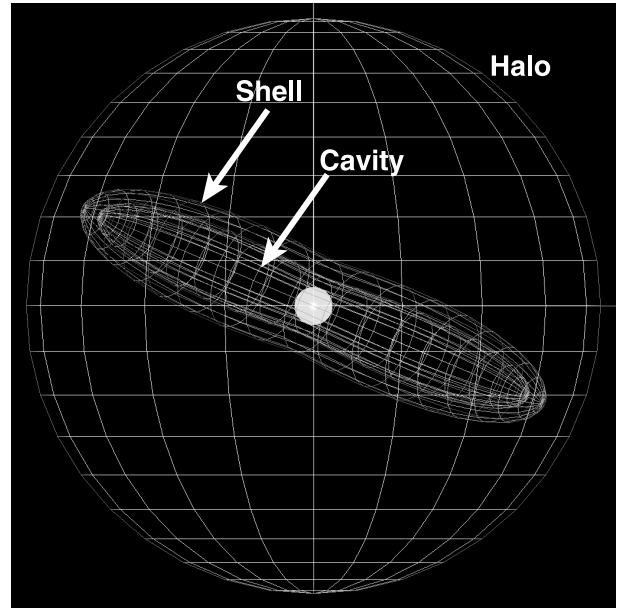


Fig. 2. SHAPE model of IRAS 16342–3814 consisting of a bipolar cavity embedded within a spherical halo of CO and dust. Surrounding the cavity is a thin dense shell, which represents material swept up by the jet. The inclination of the cavity/shell is $i = 30^\circ$.

4. Discussion

4.1. Origins of the High-/Low-Velocity Components in the CO Spectra

The ^{12}CO line profiles, as shown figure 1, exhibit both of a narrow component ($V_{\text{exp}} \lesssim 40 \text{ km s}^{-1}$) and very wide wings ($V_{\text{exp}} \gtrsim 100 \text{ km s}^{-1}$). The one-Gaussian model has a large deviation over the $3\text{-}\sigma$ noise level from the observed spectrum. In the case of an optically thick spherically expanding flow, as can be seen in CSEs of AGB stars, an observed CO emission shows a parabolic spectral profile (cf. Kemper et al. 2003). In contrast, the ^{12}CO line profile towards I16342 resembles a Gaussian rather than a parabolic shape. Taking into account the models for different opacity cases (e.g., De Beck et al. 2010), it suggests that at least the CO emission associated with the high-velocity jet has a Gaussian profile, which should be unresolved and optically thin. In fact, the jet and

³ In this step, we realized that the spectrum shown in Imai et al. (2009) was incorrectly synthesized from the spectra obtained from three BBCs. For two out of the three spectra covering different velocity ranges, the frequency scale was incorrectly converted to the velocity scale, leading to a velocity-averaged spectrum exhibiting a velocity width and a peak antenna temperature larger and less than the true ones, respectively. In this paper, the correctly synthesized spectrum is displayed.

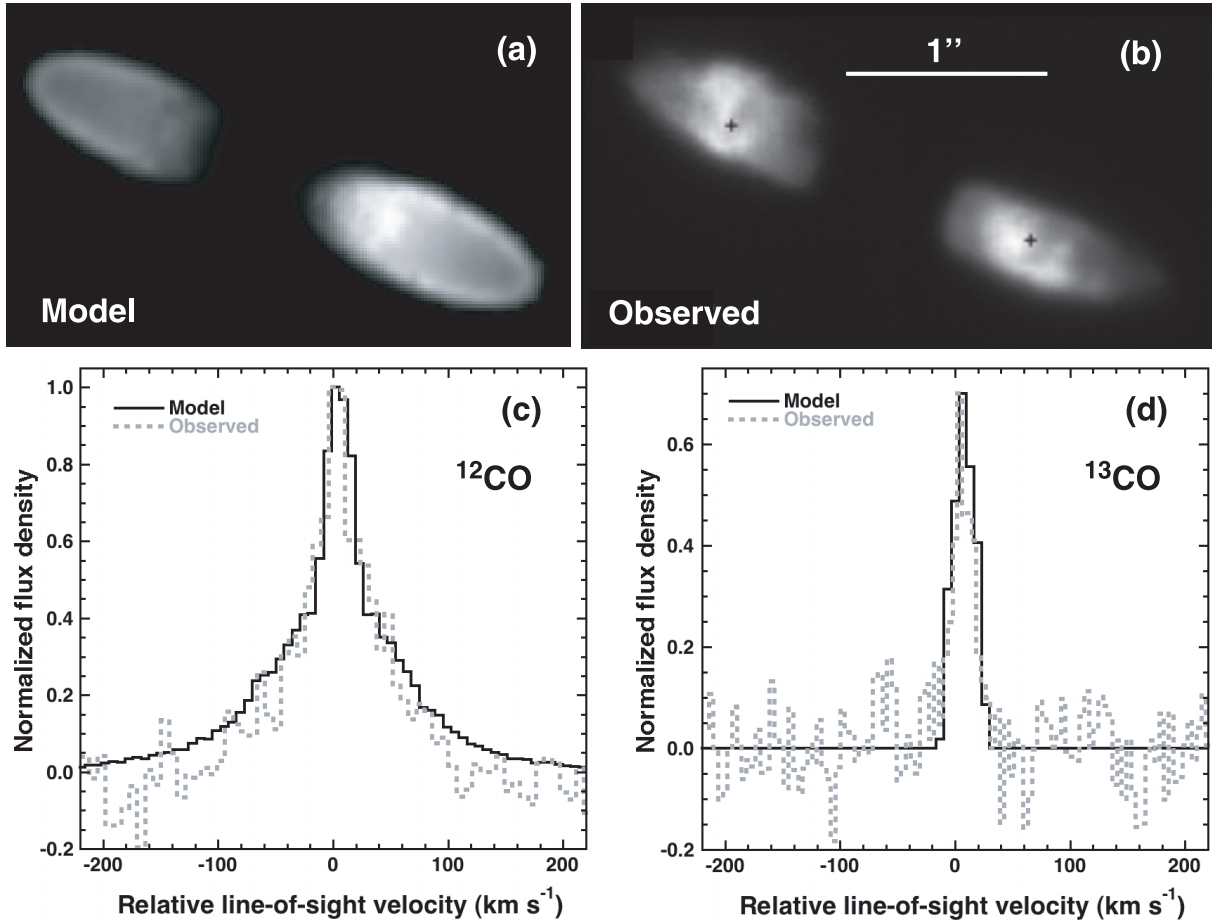


Fig. 3. Results from the SHAPE model compared with observations. (a) SHAPE rendering of the optical image model of IRAS 16342–3814. The image was created using radiative transfer within SHAPE. (b) Near-infrared image of IRAS 16342–3814 cited from Sahai et al. (2005). The image consists of light scattered off dust in the high density shells surrounding a tenuous interior. A plus symbol denotes an H₂O maser feature detected by Clausen, Sahai, and Morris (2009). (c) Comparison between the observed ¹²CO spectrum (gray dashed line) and that produced from the model (black solid line). (d) Comparison between the observed ¹³CO spectrum (gray dashed) and that produced from the model (black solid).

the equatorial flow should be smaller than the ASTE beam (Dijkstra et al. 2003; Sahai et al. 2005; Verhoelst et al. 2009). The existence of a central dark lane has also been confirmed in optical images (Sahai et al. 1999, 2005). Therefore, it is reasonable to assume that the observed CO emission in I16342 comes from both a fast bipolar flow and a slowly expanding torus/CSE around I16342.

On the other hand, the ¹³CO line profile, as shown figure 1, exhibits only a narrower component. If the both of the ¹²CO and ¹³CO lines have the same line profile, high-velocity wings of the latter line should also be detected over the 3- σ noise level. Actually, the absence or weakening of such wing components in the latter line is recognized. If supposing a common ¹²CO/¹³CO abundance ratio in the whole observed region, some opacity effects should be considered to explain the difference in the ¹²CO and ¹³CO profiles.

Using the morpho-kinematic software *SHAPE* (Steffen & López 2006; Steffen et al. 2011), we have reproduced both the physical and kinematic structure of I16342 with a single model. To constrain the geometrical and physical parameters, we made use of the near-infrared image of Sahai et al. (2005).

They suggested that the image represents light from a central star scattered by dust in dense shells surrounding a tenuous bipolar cavity. Our model therefore consists of a bipolar cavity extending 1'' on either side of the central star embedded within a spherical halo of radius $r_{\text{halo}} = 1''.5$ halo. The halo contains both CO and dust, and has a density profile of $\rho(\text{halo}) = \rho_{0,\text{halo}}(r/r_{0,\text{halo}})^{-2}$ ($0 \leq r \leq r_{0,\text{halo}}$). The surrounding cavity is a thin, dense shell of CO and dust; it is presumably swept up by the high-velocity jet. The cavity is inclined at $i = 30^\circ$ to the observer with a position angle of 67° . The geometry of the model is displayed in figure 2.

Using radiative transfer in *SHAPE*, to simulate the emission, absorption, and scattering for dust and the first two kinds of molecular particles with different opacities in a given temperature (see Steffen et al. 2011 for the technical details), this model produces the image displayed in figure 3a. The model is able to reproduce the general appearance of I16342 seen in the image from Sahai et al. (2005) (figure 3b) in scattered light, including the extent of both the lobes and dark equatorial waist. To constrain the kinematics of I16342, we used the results from our current study. The CO emission in our

model originates in the dense shell surrounding the cavity, and from the extended spherical halo. The velocity within the shell has the form $V_{\text{exp}}(\text{jet}) = 300 \text{ km s}^{-1} [r/1'']$. Since the cavity extends out to $1''$, the maximum speed of the jet is 300 km s^{-1} at the tip (cf. Claussen et al. 2009). The spherical halo is given a constant radial velocity of 15 km s^{-1} . With these kinematic parameters and the aforementioned physical model, SHAPE is able to reproduce the spectra for ^{12}CO and ^{13}CO in figures 3c and 3d, respectively. We find that because of the absence of high-velocity wings in the latter spectrum, ^{13}CO , a tracer of higher density gas, is not bright in the high-density shell, but only in the halo. ^{12}CO , on the other hand, is bright in both the shell and the halo. This suggests that a higher intensity ratio of ^{12}CO to ^{13}CO may exist in the shell where high temperatures ($> 600 \text{ K}$, see subsection 4.2) are expected and H_2O and OH maser actions are excited.

4.2. Extremely Low ^{12}CO to ^{13}CO Intensity Ratio

We confirmed a very low $^{12}\text{CO}/^{13}\text{CO}$ line intensity ratio (~ 1.5) for the $J = 3 \rightarrow 2$ and $J = 2 \rightarrow 1$ (He et al. 2008) transitions towards I16342. At first, one may suppose that this can be attributed to an opacity effect of these lines. To examine such a possibility, in other words whether even a typical $^{12}\text{CO}/^{13}\text{CO}$ abundance ratio, as seen in interstellar clouds (~ 70 , e.g., Milam et al. 2005), can explain such a low line intensity ratio, we performed other radiative-transfer simulations that repeatedly calculated the line opacities and the line intensity ratio. Note that SHAPE does not constrain the CO line opacities properly, because a line opacity in it is manually tuned to reproduce the observed brightness distribution of the line/continuum emission from the morpho-kinematical model. Thus, we resorted to another radiative transfer code, *RADEX*⁴ (van der Tak et al. 2007), which makes use of the molecular line database *LAMDA* (Schöier et al. 2005) and treats the radiative transfer and CO rotational level excitation in a self-consistent way. After many trials with changing input physical parameters, such as the volume density ($10^2 \text{ cm}^{-3} < n_{\text{H}_2} \leq 10^6 \text{ cm}^{-3}$), column density ($10^{12} \text{ cm}^{-2} < N_{\text{CO}} \leq 10^{18} \text{ cm}^{-2}$), and kinetic temperature ($10 \text{ K} < T_{\text{k}} \leq 1000 \text{ K}$), the results of the calculations are summarized as follows. Here, one assumes a velocity width of $\Delta V \simeq 10 \text{ km s}^{-1}$ and $N_{\text{CO}}/N_{\text{H}_2} \simeq 10^{-4}$. In the case of I16342, the spectral energy distribution (SED) indicates a blackbody temperature of the CSE of around $T \simeq 130 \text{ K}$, which was derived from fitting a single temperature SED to the data of IRAS,⁵ MSX6C,⁶ and AKARI⁷ Point Source Catalogs. Taking into account the size of the mid-infrared emission (Verhoelst et al. 2009) and the present ASTE observations, which gives an upper limit to the source size comparable to the ASTE beam size ($< 20''$), the CSE/jet may have a size in the range of 6000–10000 AU.

First, in the case of the volume density of hydrogen molecules close to the critical value, $n_{\text{H}_2} \simeq 2 \times 10^5 \text{ cm}^{-3}$, the CO $J = 3 \rightarrow 2$ lines become optically thick ($\tau \simeq 1$) in

a cloud with $N_{\text{CO}} \gtrsim 2 \times 10^{17} \text{ cm}^{-2}$ or $T_{\text{k}} \gtrsim 550 \text{ K}$. The former threshold value corresponds to a cloud size of $\sim 1000 \text{ AU}$ and a mass loss rate of $\sim 3 \times 10^{-5} M_{\odot} \text{ yr}^{-1}$. For the CSE of I16342 with the larger size, as mentioned above, the ^{13}CO opacity is estimated to be comparable to, or lower than, unity. On the other hand, the ^{12}CO emission has a lower critical density, and may have a larger distribution including the jet; therefore, the emitting region of the ^{12}CO line may have a lower temperature and the ^{12}CO line may be optically thick. This is consistent with the assumption of such an opacity difference from our SHAPE simulation (see subsection 4.1). Second, the $^{12}\text{CO}/^{13}\text{CO}$ line intensity ratio may have the observed small value *only* in the case where $T < 20 \text{ K}$ or $T > 550 \text{ K}$. Note that such low and high temperatures may appear, respectively, in the outer boundary of a CSE with a volume density lower than expected to excite the CO $J = 3 \rightarrow 2$ emission and at the innermost part of a CSE (e.g., within 100 stellar radii, Cooke & Elitzur 1985). Although tiny clumps to excite H_2O and OH maser meet such a physical condition, their volume fraction in the CSE should be extremely limited. Regardless, these temperature regions should be uncommon in the CSE. Third, in the physical conditions expected for the CSE of I16342, even if the ^{12}CO line is optically thick, a CO column density of $N_{\text{CO}} > 10^{19} \text{ cm}^{-2}$ is necessary to explain the observed intensity ratio if the CSE has a $^{12}\text{CO}/^{13}\text{CO}$ abundance ratio as seen in interstellar clouds (~ 70). For a moderate value ($N_{\text{CO}} \lesssim 10^{18} \text{ cm}^{-2}$), a much lower abundance ratio, 4 or lower, is required. These results support the extremely low $^{12}\text{CO}/^{13}\text{CO}$ abundance ratio in the CSE.

Applying a frequency correction described in equation (15) of De Beck et al. (2010), we derived a $^{12}\text{C}/^{13}\text{C}$ isotopic ratio of ~ 1.3 . Such an extremely low isotopic ratio has also been confirmed in J -type carbon-rich stars (Abia & Isern 2000; Olofsson & Nyman 1999). The J -type star has a lower stellar mass ($M_* \simeq 2\text{--}3 M_{\odot}$) and the ‘‘cold-bottom processing’’ is expected, in which the production of ^{13}C is enhanced, but not O (e.g., Abia & Isern 2000). On the other hand, an oxygen-rich star has a higher mass ($4 M_{\odot} \lesssim M_* \lesssim 7 M_{\odot}$) and the ‘‘hot-bottom burning’’ (HBB) is expected, in which the production of both ^{13}C and O is enhanced, so that ^{12}C is converted to these nucleons (see e.g., a review of Herwig 2005; De Beck et al. 2010). Therefore, the enhancement of ^{13}CO relative to ^{12}CO observed in O-rich stars should provide direct evidence for HBB in AGB nucleosynthesis. The present results towards I16342, which clearly has O-rich chemistry harboring H_2O and OH masers, may provide one of the most clear examples of the HBB signature. Some pre-planetary nebulae with O-rich chemistry show similar cases, and their progenitors are also suggested to be massive post-AGB stars (see also e.g., Nakashima et al. 2004; Nakashima & Deguchi 2006; Dinh-V-Trung 2009). Based on the stellar luminosity and the orbit in the Galaxy, it has been demonstrated that the water fountains should harbor intermediate-mass O-rich evolved stars, such as OH/IR stars and their posterity (e.g., Imai et al. 2002, 2007; Imai 2007). The possibility of HBB is consistent with this view. A direct determination of the original mass of the central star of I16342 is a future issue in theoretical and observational studies.

⁴ (<http://www.strw.leidenuniv.nl/~moldata/radex.html>).

⁵ Infrared Astronomical Satellite (http://irsa.ipac.caltech.edu/data/download/IRAS/iras_psc.tbl).

⁶ Midcourse Space Experiment (http://irsa.ipac.caltech.edu/data/MSX/docs/MSX_psc_es.pdf).

⁷ (<http://darts.isas.jaxa.jp/astro/akari/cas.html>).

4.3. Temporal Variation of the CO Profile

In general, it is difficult to precisely compare the peak (main beam) antenna temperatures, T_{MB} , found in different observation epochs. In the present observations, the peak value of T_{MB} is apparently enhanced by a factor of ~ 1.6 from the first to second epoch spectrum. Note that these T_{MB} scales had been corrected by using different flux calibrators (IRC +10216 in 2008 and W 28 in 2010 and 2011, respectively), while the scaling correction factors were smaller than 1.3 in the spectrum calibration of all observations. It has been expected that the flux calibrators provide T_{MB} scales with an uncertainty of $\sim 20\%$ (e.g., Wang et al. 1994). It has not yet been reported that these calibrator spectra are variable. Therefore, an intrinsic temporal variation of the I16342 CO spectrum cannot be ruled out.

However, we note that when the T_{MB} values are set to equal among the observations, the rescaled spectral profiles resemble each other over the whole velocity range within the rms noise levels. Figure 1c displays the ^{12}CO spectra obtained in 2008 June (Imai et al. 2009), 2010 August, and 2011 June. For a comparison of all spectra, the spectra in 2008 and 2011 were rescaled by factors of 1.6 and 1.3, respectively. As discussed in subsection 4.1, the CO emission may originate from both the fast jet and the slowly expanding CSE/torus, which should be physically independent. Taking into account a possible time scale of flux variation due to discontinuous stellar mass loss, or episodic events for mass eruption, as well as large physical sizes of the CO sources ($> 1000 \text{ AU}$), it is difficult to explain the T_{MB} variation by an intrinsic temporary variation. Alternatively, different antenna pointing offsets in the observations are expected to explain the similarity of the CO spectral profiles and the different antenna temperature scales. If the CO region is an ideal point source, such a large variation cannot be expected, because the pointing offsets should be much smaller than the beam size ($\lesssim 5''$). A simple Monte Carlo simulation, which decreased the antenna temperature scale, suggested that, for the ASTE's beam ($22''$), the source size should be larger than $5''$ (when assuming a point-symmetric, Gaussian brightness distribution) to reproduce the observed scale decrease. Figure 1b shows the spectra obtained from five-point scans conducted in 2011. The CO emission was detected only on the on-source point and the peak values of T_{MB} at the off-point positions are $\sim 40\%$ of that at the on-source point or lower. This indicates that the angular size of the CO emission, at least the low-velocity component, should be smaller than $\sim 10''$. The true angular scale of the observed CO emission can be easily measured by future interferometric observations.

4.4. Mass Loss Rate of IRAS 16342–3814

In this paper, we reestimate the mass-loss rate of the I16342 CO $J = 3 \rightarrow 2$ outflow from the revised ^{12}CO profile. With the assumption of unresolved, optically thick CO emission, as mentioned in subsection 4.2, we can derive the mass-loss rate in units of solar masses per year using the following formula (Ramstedt et al. 2008, see also Knapp & Morris 1985; Olofsson et al. 1993; Groenewegen et al. 1999; De Beck et al. 2010):

$$\dot{M} = s_J (I_{\text{CO}} B^2 D^2)^{a_J} V_{\text{exp}}^{b_J} f_{\text{CO}}^{-c_J}. \quad (1)$$

Here, I_{CO} is the velocity-integrated antenna temperature of the CO emission in K km s^{-1} , V_{exp} the expansion velocity of the CO emission in km s^{-1} , D the source distance in kpc, B the beam size of the telescope in arcsec, f_{CO} the abundance of CO molecules relative to H_2 , and $s_J \simeq 3.8 \times 10^{-11}$ a correction factor for the $J \rightarrow J - 1$ transition, and $a_J \simeq 0.91$, $b_J \simeq 0.39$, $c_J \simeq 0.45$ the coefficients derived for $J = 3 \rightarrow 2$, respectively. For I16342, $D = 2 \text{ kpc}$ is adopted. For ASTE, $B = 22''$ is adopted. For an O-rich circumstellar envelope harboring H_2O and OH maser emission, $f_{\text{CO}} \sim 10^{-4}$ is adopted. Using the Gaussian profile parameters listed in table 2 (here $V_{\text{exp}} \simeq \Delta V_{\text{HWHM}}$), the contributions to the mass-loss rates from the broad-wing and the central-peak components were calculated to be $\dot{M} \simeq 4.8 \times 10^{-5} M_{\odot} \text{ yr}^{-1}$ and $\dot{M} \simeq 3.8 \times 10^{-6} M_{\odot} \text{ yr}^{-1}$, respectively. The former value is much smaller than estimated with mid-IR emission ($\dot{M}_{\text{gas}} \approx 10^{-3} M_{\odot} \text{ yr}^{-1}$, Dijkstra et al. 2003), but indicates a major contribution to the total mass-loss rate of I16342. However, the CO emission contribution from the former component should be more carefully examined by high-resolution mapping.

5. Conclusions

Through a series of our ASTE observations, we detected the intrinsic CO emission from one source, I16342, out of 13 water fountain sources. We found a very low ^{12}CO to ^{13}CO line intensity ratio (~ 1.5). This may indicate an intrinsic property of the CO emission towards the water fountain, and indicates the presence of “hot-bottom burning” in stellar nucleosynthesis. Based on arguments from e.g., Imai, Sahai, and Morris (2007), the present results support that I16342 should be an oxygen-rich star with a mass of $4 M_{\odot} \lesssim M_* \lesssim 7 M_{\odot}$. I16342 may have a mass-loss rate of $\dot{M}_{\text{gas}} > 5 \times 10^{-5} M_{\odot} \text{ yr}^{-1}$. The detection of high-velocity wings in the ^{12}CO spectrum implies a possibility that the bipolar high-velocity jet plays a major role of final stellar mass loss. High angular resolution and sensitivity CO mapping observations, like those conducted with the Atacama Large Millimeter-submillimeter Array (ALMA), should dramatically increase the number of CO sources towards the water fountains within a few kilo parsecs with moderate mass-loss rates as AGB stars ($> 10^{-6} M_{\odot} \text{ yr}^{-1}$), and spatially resolve the high-velocity wing components in the CO spectra.

We deeply appreciate members of the ASTE team for their careful observations, preparation and kind operation support. The ASTE project is driven by Nobeyama Radio Observatory (NRO), a branch of National Astronomical Observatory of Japan (NAOJ), in collaboration with University of Chile, and Japanese institutes including the University of Tokyo, Nagoya University, Osaka Prefecture University, Ibaraki University, and Hokkaido University. Observations with ASTE were in part carried out remotely from Japan by using NTT's GEMnet2 and its partner R&E (Research and Education) networks, which are based on AccessNova collaboration of University of Chile, NTT Laboratories, and NAOJ. We thank T. Minamidani and H. Izumiura for introducing the radiative transfer calculation code (RADEX) and for giving fruitful comments on our work,

respectively. HI and SD have been financially supported by a Grant-in-Aid for Scientific Research from Japan Society for Promotion Science (20540234). JN is supported by a grant from the Research Grants Council of Hong Kong (project code:

HKU 704209P; HKU 704710P; HKU 704411P) and by the financial support from the Small Project Funding of HKU (project code: 201007176004).

References

- Abia, C., & Isern, J. 2000, *Mem. Soc. Astron. Ital.*, 71, 631
- Boboltz, D. A., & Marvel, K. B. 2007, *ApJ*, 665, 680
- Claussen, M., Sahai, R., & Morris, M. R. 2009, *ApJ*, 691, 219
- Cooke, B., & Elitzur, M. 1985, *ApJ*, 295, 175
- Day, F. M., Pihlström, Y. M., Claussen, M. J., & Sahai, R. 2010, *ApJ*, 713, 986
- De Beck, E., Decin, L., de Koter, A., Justtanont, K., Verhoelst, T., Kemper, F., & Menten, K. M. 2010, *A&A*, 523, A18
- Deacon, R. M., Chapman, J. M., Green, A. J., & Sevenster, M. N. 2007, *ApJ*, 658, 1096
- Dijkstra, C., Waters, L. B. F. M., Kemper, F., Min, M., Matsuura, M., Zijlstra, A., de Koter, A., & Dominik, C. 2003, *A&A*, 399, 1037
- Dinh-V-Trung 2009, *ApJ*, 692, 1382
- Groenewegen, M. A. T., Baas, F., Blommaert, J. A. D. L., Stehle, R., Josselin, E., & Tilanus, R. P. J. 1999, *A&AS*, 140, 197
- He, J. H., Imai, H., Hasegawa, T. I., Campbell, S. W., & Nakashima, J. 2008, *A&A*, 488, L21
- Herwig, F. 2005, *ARA&A*, 43, 435
- Imai, H. 2007, in *IAU Symp. 242, Astrophysical Masers and their Environments*, ed. J. Chapman & W. Baan (Cambridge: Cambridge University Press), 279
- Imai, H., He, J.-H., Nakashima, J., Ukita, N., Deguchi, S., & Koning, N. 2009, *PASJ*, 61, 1365
- Imai, H., Obara, K., Diamond, P. J., Omodaka, T., & Sasao, T. 2002, *Nature*, 417, 829
- Imai, H., Sahai, R., & Morris, M. 2007, *ApJ*, 669, 424
- Kemper, F., Stark, R., Justtanont, K., de Koter, A., Tielens, A. G. G. M., Waters, L. B. F. M., Cami, J., & Dijkstra, C. 2003, *A&A*, 407, 609
- Knapp, G. R. & Morris, M. 1985, *ApJ*, 292, 640
- Milam, S. N., Savage, C., Brewster, M. A., Ziurys, L. M., & Wyckoff, S. 2005, *ApJ*, 634, 1126
- Nakashima, J., & Deguchi, S. 2006, *ApJ*, 633, 282
- Nakashima, J., Deguchi, S., & Kuno, N. 2004, *PASJ*, 56, 193
- Olofsson, H., Eriksson, K., Gustafsson, B., & Carlström, U. 1993, *ApJS*, 87, 267
- Olofsson, H., & Nyman, L.-Å. 1999, *A&A*, 347, 194
- Ramstedt, S., Schöier, F. L., Olofsson, H., & Lundgren, A. A. 2008, *A&Ap*, 487, 645
- Sahai, R., Le Mignant, D., Sánchez Contreras, C., Campbell, R. D., & Chaffee, F. H. 2005, *ApJ*, 622, L53
- Sahai, R., te Lintel Hekkert, P., Morris, M., Zijlstra, A., & Likkell, L. 1999, *ApJ*, 514, L115
- Sahai, R., & Trauger, J. T. 1998, *AJ*, 116, 1357
- Schöier, F. L., & Olofsson, H. 2000, *A&A*, 359, 586
- Schöier, F. L., van der Tak, F. F. S., van Dishoeck, E. F., & Black, J. H. 2005, *A&A*, 432, 369
- Steffen, W., Koning, N., Wenger, S., Morisset, C., & Magnor, M. 2011, *IEEE Trans. Visualisation and Computer Graphics*, 17, 454 (arXiv:1003.2012S)
- Steffen, W., & López, J. A. 2006, *Rev. Mex. Astron. Astrofis.*, 42, 99
- Suárez, O., Gómez, J. F., & Miranda, L. F. 2008, *ApJ*, 689, 430
- van der Tak, F. F. S., Black, J. H., Schöier, F. L., Jansen, D. J., & van Dishoeck, E. F. 2007, *A&A*, 468, 627
- Verhoelst, T., Waters, L. B. F. M., Verhoeff, A., Dijkstra, C., van Winckel, H., Pel, J. W., & Peletier, R. F. 2009, *A&A*, 503, 837
- Walsh, A. J., Breen, S. L., Bains, I., & Vlemmings, W. H. T. 2009, *MNRAS*, 394, L70
- Wang, Y., Jaffe, D. T., Gref, U. U., & Evans, N. J., II 1994, *ApJS*, 95, 503