A Three Dimensional View of Gomez’s Hamburger

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ABSTRACT
Unraveling the 3D physical structure, the temperature and density distribution, of protoplanetary discs is an essential step if we are to confront simulations of embedded planets or dynamical instabilities. In this paper we focus on Submillimeter Array observations of the edge-on source, Gomez’s Hamburger, believed to host an overdensity hypothesised to be a product of gravitational instability in the disc, GoHam b. We demonstrate that, by leveraging the well characterised rotation of a Keplerian disc to deproject observations of molecular lines in position-position-velocity space into disc-centric coordinates, we are able to map out the emission distribution in the (r, z) plane and (x, y, z) space. We show that $^{12}$CO traces an elevated layer of $z/r \sim 0.3$, while $^{13}$CO traces deeper in the disc at $z/r \lesssim 0.2$. We localize emission associated with GoHam b, finding it at deprojected radius of $\sim 500$ au and at polar angle of $\pm 30^\circ$ from the disc major axis. At the spatial resolution of $\sim 1.5''$, GoHam b is spatially unresolved, with an upper limit to its radius of $<190$ au.

Key words: (stars:) circumstellar matter – stars: formation – accretion, accretion discs

1 INTRODUCTION

High angular resolution observations of the dust in protoplanetary discs, both at mm and NIR wavelengths, have shown a stunning variety of features such as concentric rings and spirals (Andrews et al. 2018; Avenhaus et al. 2018). These structures hint at highly dynamic environments where the dust distributions are sculpted by changes in the gas pressure distribution. The precise cause for the perturbations in the gas is hard to constrain, with multiple scenarios possible including embedded planets (e.g. D’Elias et al. 2015b; Keplinger et al. 2018; Fedele et al. 2018; Zhang et al. 2018), (magneto-)hydrodynamical instabilities (Flock et al. 2015) or gravitational instabilities (D’Elias et al. 2015a; Dong et al. 2018; Hall et al. 2016; Meru et al. 2017). Differentiating between these scenarios requires an intimate knowledge of the underlying gas structure and, in particular, how that structure changes from the midplane, as traced by the mm continuum emission, to the disc atmosphere, populated by the small sub mm grains which efficiently scatter stellar NIR radiation.

This is routinely attempted by using observations of different molecular species believed to trace distinct vertical regions in the disc. This is due to a combination of both optical depth effects and changes in physical conditions with height in the disc which make certain regions more conducive to the formation of particular species. However, it is only with high spatial resolution data that we are beginning to be able to directly measure the height at which molecular emission arises (Rosenfeld et al. 2013; de Gregorio-Monsalvo et al. 2013; Pinte et al. 2018), verifying predictions from chemical models.

A more direct approach is the observation of high inclination discs where the emission distribution can be mapped directly. Unlike continuum emission which suffers from extremely high optical depths due to the long path lengths for edge on discs (Guilloteau et al. 2016; Louvet et al. 2018), the rotation of the disc limits the optical depth of molecular emission in a given spectral channel. This allowed Dutrey et al. (2017) to map the $^{12}$CO $J = 2 - 1$ and CS $J = 5 - 4$ emission distribution in the $(r_{\text{disc}}, \z_{\text{disc}})$ plane, calling this a tomographically reconstructed distribution, for the edge-on disc colloquially known as the Flying Saucer (2MASS J16281370-2431391).

In addition to allowing access to the $(r_{\text{disc}}, \z_{\text{disc}})$ plane, Matr` a et al. (2017) demonstrated how similar techniques can be used to deproject a cut across the disc major axis into the $(r_{\text{disc}}, |\y_{\text{disc}}|)$ plane. The absolute value of $\y_{\text{disc}}$ arises because it is impossible to distinguish between the near and far side of the disc ($\pm \y_{\text{disc}}$) from their projected line of sight.
velocities alone. Using this technique, the authors were able to extract the azimuthal emission distribution along the line of sight revealing a clump of CO emission. Application of this technique to a vertically extended source enables the extraction of a full 3D emission distribution.

In this paper we apply these techniques to Submillimeter Array (SMA) observations of Gomez’s Hamburger, an edge-on circumstellar disc. In section 2 we describe the observations and data reduction. In Section 3 we provide an overview of the deprojection techniques used and their application to Gomez’s Hamburger. A discussion of these results and a summary conclude the paper in Sections 4 and 5, respectively.

2 SUMMARY OF OBSERVATIONS

At an inclination of $i \approx 86^\circ$ and a distance of 250 ± 50 pc, Gomez’s Hamburger (GoHam, IRAS 18059-3211) offers a rare opportunity to study the chemical and physical structure of an edge-on disc. Although originally classified as an evolved A0 star surrounded by a planetary nebula, follow-up observations using the Submillimeter Array (SMA) showed CO emission in the distinct pattern of Keplerian rotation about GoHam. These and subsequent observations firmly establish GoHam as a 2.5 ± 0.5 $M_\odot$ A-type star at a distance of 250 ± 50 pc surrounded by a massive, $M_{\text{disk}} \sim 0.2 M_\odot$, circumstellar disc (Bujarrabal et al. 2008, 2009; Wood et al. 2008; De Beck et al. 2010). This identification is further justified with the exquisite observations from the NICMOS instrument on the Hubble Space Telescope (HST) which show the distinct flared geometry associated with protoplanetary discs (Bujarrabal et al. 2009).

Figure 1. Summary of the observations. Panel (a) shows the 1.3 mm continuum emission. The black contours show steps of 20σ starting at 10σ, where $\sigma = 1.13$ mJy beam$^{-1}$. Central panels (b) and (c) show the rotation maps for the $^{12}$CO and $^{13}$CO emission, respectively. The black contours show the integrated intensities for the two lines in steps of 10% of their peak values, 4.90 Jy beam$^{-1}$ km s$^{-1}$ and 3.51 Jy beam$^{-1}$ km s$^{-1}$. The right most panels, (d) and (e) show the effective width of the line, with the integrated intensity contours overlaid. The synthesized beams are shown in the bottom left of each panel.

2.1 Data Reduction

The data were obtained from the SMA archive and calibrated using the MIR software. The interested reader is referred to the original papers, Bujarrabal et al. (2008, 2009), for a thorough overview of the calibration process. After calibration, the data were exported to CASA v5.6.0 where two rounds of self-calibration were performed on the continuum, with phase-solutions applied to the spectral line windows. The phase center was adjusted so that the center of the continuum was in the image center.

After experimenting with various imaging properties, both the $^{12}$CO and $^{13}$CO transitions were imaged at their native channel spacing of 203 kHz (264 m s$^{-1}$) with a Briggs weighting scheme and a robust parameter of 0.5. This resulted in synthesized beams of $1.53'' \times 1.11''$ at 0.4" for $^{12}$CO and $1.57'' \times 1.15''$ at 2.0" for $^{13}$CO. The measured RMS in a line free channel was found to be 132 mJy beam$^{-1}$ and 120 mJy beam$^{-1}$ for the $^{12}$CO and $^{13}$CO. Channel maps were created both at the native channel spacing and down-sampled by a factor of two to increase the signal to noise ratio.

Moment maps were also generated for the data using the Python package bettermoments (Teague & Foreman-Mackey 2018). Integrated intensity maps were created using a threshold of 2σ for both molecules, while the rotation map used the quadratic method described in (Teague & Foreman-Mackey 2018) without the need for any σ-clipping. Rather than using the intensity weighted velocity dispersion (second moment) which is typically very noisy and incurs a large uncertainty (Teague 2019a), we use the ‘effective line width’ implemented in bettermoments. This calculates an effective

1 https://www.cfa.harvard.edu/cgi-bin/sma/smaarch.pl
2 https://www.cfa.harvard.edu/~cqi/mircook.html
line width using $\Delta V_{\text{eff}} = M_0 / \sqrt{\pi} \sigma F_{\nu}^{\text{max}}$, where $M_0$ is the integrated intensity and $F_{\nu}^{\text{max}}$ is the line peak. For a Gaussian line profile, this returns the true Doppler width of the line. Both transitions show a peak at the disc center, gradually decreasing in the outer disc. However, at this spatial resolution the line profile is dominated by systematic broadening effects from the imaging.

### 2.2 Observational Results

Using the 2D-Gaussian fitting tool in CASA the integrated flux of the 1.3 mm continuum was found to be 293 ± 4 mJy, consistent with Bujarrabal et al. (2008). Integrating over an elliptical region with a major axis of 14″, a minor axis of 7″ and a position angle of 175°, and clipping all values below 2σ, the $^{12}$CO integrated flux was found to be 37.2 Jy km s$^{-1}$. For the $^{13}$CO, integrating over an elliptical mask with a major axis of 12″ and a minor axis of 4.2″ a position angle of 175°, again clipping all values below 2σ, resulted in an integrated flux of 16.5 Jy km s$^{-1}$.

A summary of the moment maps alongside the continuum image is shown in Fig. 1. The continuum is clearly detected and considerably smaller in extent than the gas component. Assuming a source distance of 250 pc (Bujarrabal et al. 2008), the gaseous disc extends 1500 au in radius. For both transitions the southern side of the disc is observed to be considerably brighter than the northern side, in addition to a slight north-south asymmetry in the continuum emission. In addition, the east-west asymmetry in the $^{13}$CO integrated intensity suggests that the eastern side of the disc is tilted towards the observer.

Figure 2 shows the channel maps, downsampled in velocity by a factor of two, for the $^{12}$CO emission, top, and the $^{13}$CO emission, bottom. Both lines show the distinct ‘butterfly’ emission morphology characteristic of a rotating disc. The $^{12}$CO emission is more extended, both in the radial and vertical directions, as would be expected given its larger abundance. The $^{13}$CO emission also splits into two lobes, most clearly seen in the channels at 1.62 km s$^{-1}$ and 3.73 km s$^{-1}$, due to the elevated emission surface, while the $^{13}$CO appears more centrally peaked.

To find the systemic velocity of the disc, we fit the rotation maps, maps of the line center, $V_0$, shown in Fig. 1, using the Python package eddy (Teague 2019b). At these large inclinations, vertically extended emission, as expected for $^{12}$CO and to a lesser extent, $^{13}$CO, will result in ro-

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**Figure 2.** Top: Channel maps of the $^{12}$CO emission, downsampled to 528 m s$^{-1}$ channel spacing for presentation. Solid lines show contours starting at $3\sigma$ and increasing in steps of $3\sigma$, where $\sigma = 87$ mJy beam$^{-1}$. The synthesized beams are shown in the left rows. The dotted lines show the orientation of the major and minor axes of the disc. The central velocity of the channel is shown in the top right of each panel. Bottom: As above, but for $^{13}$CO emission. The solid lines are contours of $\sigma$ where $\sigma = 75$ mJy beam$^{-1}$. Note the substantial increase in brightness in the southern side of the disc.
Inclination and $v_{\text{LSR}}$ is the systemic velocity. For Keplerian rotation we know that,

$$v_\phi(r, z) = \sqrt{\frac{GM_*}{r^2 + z^2}} \rac{z}{\sqrt{r^2 + z^2}}. \quad (2)$$

where $r$ and $z$ are the cylindrical radius and height in the disc, respectively, dropping the disc subscript for brevity. Substituting this into Eqn. 1 and noting that for an edge-on disc, such that $i > 90^\circ$, $x_{\text{sky}} = r \cos \phi$ and $z = y_{\text{sky}}$, then we find,

$$v_0 - v_{\text{LSR}} = \sqrt{\frac{GM_*/x_{\text{sky}}^2}{(r_0 - v_{\text{LSR}})^2}} - y_{\text{sky}}^2. \quad (3)$$

As both $x_{\text{sky}}$ and $y_{\text{sky}}$ are readily measured in the image plane, we can rearrange for $r$ giving,

$$r = \sqrt{\frac{GM_*/x_{\text{sky}}^2}{(v_0 - v_{\text{LSR}})^2}} - y_{\text{sky}}^2. \quad (4)$$

If cylindrical rotation is assumed, i.e. that there is no $z$ dependence in $v_\phi$ in Eqn. 2, the $y_{\text{sky}}^2$ correction term vanishes, recovering the result from Dutrey et al. (2017).

Noting that $r = \sqrt{x_{\text{disc}}^2 + y_{\text{disc}}^2}$, we can additionally infer something about the line-of-sight distance of the emission,

$$|y_{\text{disc}}| = \sqrt{\frac{GM_*/x_{\text{sky}}^2}{(v_0 - v_{\text{LSR}})^2}} - y_{\text{sky}}^2 - z_{\text{sky}}^2. \quad (5)$$

as used in Matr`a et al. (2017). However, as there is a degeneracy in the side of the disc the emission arises, $xy$, this recovers an average of both sides of the disc. Again, if the cylindrical rotation is assumed, the $y_{\text{sky}}^2$ correction term vanishes in Eqn. 5. Figure 3 shows how pixels would be deprojected into the $(x_{\text{disc}}, |y_{\text{disc}}|)$ plane. It illustrates that the velocity resolution sets the ‘azimuthal’ sampling, i.e. how many spokes there are, while the pixel size (or spatial resolution) will set sampling along these spokes. As, such, both spatial and spectral resolution are required for an accurate deprojection of the data.

We note that these derivations assume that the disc is completely edge-on and in Keplerian rotation. Dutrey et al. (2017) showed how changes in the inclination can affect the deprojection. The authors found that for only moderate deviations from edge-on, i.e. $i \gtrsim 80^\circ$, the tomographically reconstructed distribution (TRD, see also section 3.1) provided a good representation of the underlying physical structure. One half of the disc, either where $z > 0$ or $z < 0$, would be brighter, with this brighter half corresponding to the side of the disc which is closer to the observer. In addition, the vertical extent of the emitting layer would broaden in the $z$ direction, before eventually splitting into two distinct arms when $i \lesssim 80^\circ$ and the near and far sides of the disc are spatially resolved.

**Figure 3.** The deprojection of pixels assuming a 0.25″ pixel size and a 250 m s$^{-1}$ velocity spacing from Eqn. 5. The velocity resolution sets the number of ‘spokes’ in the deprojection, while the pixel scaling sets the sampling along each spoke.

### 3 DEPROJECTION TO DISC-CENTRIC COORDINATES

If the velocity structure of the source is known, it is possible to deproject observations of an edge-on disc in position-velocity (PPV) space, $(x_{\text{sky}}, y_{\text{sky}}, v_0)$, into 3D disc-centric coordinates, $(x_{\text{disc}}, y_{\text{disc}}, z_{\text{disc}})$. Both Dutrey et al. (2017) and Matr`a et al. (2017) discuss similar deprojections, the former into an azimuthally averaged $(r_{\text{disc}}, z_{\text{disc}})$ plane, and the latter into the $(x_{\text{disc}}, |y_{\text{disc}}|)$ plane for a cut at a constant $z$ through the disc. In this section we discuss both deprojections and include a correction due to changes in the rotation velocity as a function of height rather than assuming cylindrical rotation.

At any given voxel (a pixel in PPV space), the projected line of sight velocity, $v_0$, is given by,

$$v_0 = v_\phi \cos \phi \sin i + v_{\text{LSR}}. \quad (1)$$

where $v_\phi$ is the rotation velocity, $\phi$ is the azimuthal angle (not to be confused with the polar angle which is measured in the sky-plane rather than the disc-plane), $i$ is the disc inclination and $v_{\text{LSR}}$ is the systemic velocity. For Keplerian rotation we know that,

$$v_\phi(r, z) = \sqrt{\frac{GM_*}{r^2 + z^2}} \frac{z}{\sqrt{r^2 + z^2}}. \quad (2)$$

where $r$ and $z$ are the cylindrical radius and height in the disc, respectively, dropping the disc subscript for brevity. Substituting this into Eqn. 1 and noting that for an edge-on disc, such that $i > 90^\circ$, $x_{\text{sky}} = r \cos \phi$ and $z = y_{\text{sky}}$, then we find,

$$v_0 - v_{\text{LSR}} = \sqrt{\frac{GM_*/x_{\text{sky}}^2}{(r_0 - v_{\text{LSR}})^2}} - y_{\text{sky}}^2. \quad (3)$$

As both $x_{\text{sky}}$ and $y_{\text{sky}}$ are readily measured in the image plane, we can rearrange for $r$ giving,

$$r = \sqrt{\frac{GM_*/x_{\text{sky}}^2}{(v_0 - v_{\text{LSR}})^2}} - y_{\text{sky}}^2. \quad (4)$$

If cylindrical rotation is assumed, i.e. that there is no $z$ dependence in $v_\phi$ in Eqn. 2, the $y_{\text{sky}}^2$ correction term vanishes, recovering the result from Dutrey et al. (2017).

Noting that $r = \sqrt{x_{\text{disc}}^2 + y_{\text{disc}}^2}$, we can additionally infer something about the line-of-sight distance of the emission,

$$|y_{\text{disc}}| = \sqrt{\frac{GM_*/x_{\text{sky}}^2}{(v_0 - v_{\text{LSR}})^2}} - y_{\text{sky}}^2 - z_{\text{sky}}^2. \quad (5)$$

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3.1 Tomographically Reconstructed Distribution

As the disc is expected to be highly inclined, \(i \sim 85^\circ\) (Bujarrabal et al. 2008, 2009), we use the deprojection techniques described in Section 3 to explore the three dimensional structure of the disc, starting with the TRD as used for the Flying Saucer in Dutrey et al. (2017). We take the geometrical properties inferred from forward modelling a full 3D model presented in Bujarrabal et al. (2008, 2009) which assumed Keplerian rotation around a 2 \(M_\odot\) central star and a disc inclined at 85\(^\circ\), observed at a position angle of 175\(^\circ\).

Using Eqn. 4, each pixel is deprojected into \((r_{\text{disc}}, z_{\text{disc}})\) space, before being binned into bins equal in size to the pixel. In each bin, we take the maximum value, converting it to brightness temperature using the full Planck law.

Figure 4 shows the TRD for \(^{12}\text{CO}\), left, and \(^{13}\text{CO}\), right, taking the peak brightness temperature in each bin. Immediately we see that \(^{12}\text{CO}\) traces an elevated region of \(z / r \sim 0.3\), while \(^{13}\text{CO}\) appears to trace a region closer to the midplane, confined to \(z / r \lesssim 0.2\). The drop off of signal within the inner 1\(''\) is due to convolution effects, as described in Dutrey et al. (2017). The asymmetry above the midplane is due to the deviation from a directly edge-on disc with a similar effect seen in the Flying Saucer, where the level of difference between the positive and negative values is consistent with the \(i \sim 85^\circ\) inclination measured for the source.

3.2 Line-of-Sight Deprojection

In Bujarrabal et al. (2009) it was argued that there was an enhancement of \(^{13}\text{CO}\) at an offset of \(r \sim 1''\). To explore whether this can be observed with the above techniques, we follow Matrà et al. (2017) and use Eqn. 5 to deproject cuts along the major axis of the disc into the \((\Delta x_{\text{disc}}, \Delta y_{\text{disc}})\) plane.

The disc was split into six equally thick slices of 0.8\(''\) spanning ±2\(''\) about the disc midplane. For each slice, every PPV voxel above a SNR of 2 was deprojected into disc coordinates then linearly interpolated onto a regular grid with the results shown in Fig. 5. The same procedure was performed for \(^{13}\text{CO}\), however with narrower slices of 0.6\(''\) spanning ±1.5\(''\) with the results shown in Fig. 6.

As with the TRD, the western side of the \(^{12}\text{CO}\) emission, positive \(z\) values, panels (c), (f) and (g), is considerably brighter than the eastern side, negative \(z\) values, due to the slight deviation from a completely edge-on disc (Dutrey et al. 2017). It is also clear that at large separations from the disc midplane, the inner edge of the \(^{12}\text{CO}\) emission moved outwards, most clearly seen in panels (b) and (g) of Fig. 5. Some azimuthal structure is tentatively observed at higher altitudes for \(^{12}\text{CO}\), namely in panel (f). Given the orientation of the disc, the gas rotates in a clockwise direction. Although the \(^{13}\text{CO}\) data is noisier, some features are still observable. As with the \(^{12}\text{CO}\), at higher altitudes the emission peaks at \(r \sim 3''\), while becoming more centrally peaks at lower \(z\) value.

Both \(^{12}\text{CO}\) and \(^{13}\text{CO}\) show an enhancement in emission close to the disc midplane, at \((\Delta x_{\text{disc}}, |\Delta y_{\text{disc}}|, z_{\text{disc}}) \approx (2'', 1'', 0'')\), marked in Figures 5 and 6 by the black dashed circle. Bujarrabal et al. (2009) previously reported an enhancement in \(^{13}\text{CO}\) emission at an offset position of \((\delta x_{\text{sky}}, \delta y_{\text{sky}}) \approx (1.5'', -2.5'')\), with later observations of 8.6 \(\mu\)m and 11.2 \(\mu\)m PAH emission revealing a similar apparent over-density (Berné et al. 2015).

4 DISCUSSION

In the previous section we have shown that assuming that an edge-on disc is in Keplerian rotation allows one to deproject pixels in position-position-velocity space into disc-centric position-position-position space. In this section we discuss the implication of these deprojections.

4.1 GoHam b

Previous studies of GoHam have detected a significant enhancement in emission in the southern half of the disc, dubbed GoHam b, seen in \(^{13}\text{CO}\) emission and 8.6 \(\mu\)m and 11.2 \(\mu\)m PAH emission (Bujarrabal et al. 2009; Berné et al. 2015). They find that this excess emission could be explained with a gaseous over-density containing a mass of 0.8 to 11.4 \(M_{\text{Jup}}\), spread uniformly over a spherical region with a radius of ∼ 0.6'' (∼ 150 au). Furthermore, based on models of the disc structure, it is estimated that the disc of GoHam is marginally gravitationally unstable, with Toomre parameter \(Q \lesssim 2\) (Berné et al. 2015). In circumstellar discs gravitational instabilities can lead to growth of local, gravitationally bound over-densities (i.e., to disc fragmentation; Gammie 2001; Rice et al. 2003). It has been hypothesized that such self-gravitating over-densities could be precursors to giant planets (Boss 1997, 1998). In fact, formation by gravitational instability is favoured for giant planets on wide orbits (e.g. Morales et al. 2019). This poses the question of whether GoHam b may be a young protoplanet formed via gravitationally instability.

To test this hypothesis, we need to understand the three dimensional structure of the edge-on disc, which can be achieved using the deprojection techniques discussed above. In panels (c) through to (f) of Figure 6, the right half of the disc (corresponding to the southern half of the disc on the sky) is considerably brighter than the left half which we interpret as GoHam b. A similar asymmetry is seen in the \(^{12}\text{CO}\) emission, however at a much lower significance. Importantly, the deprojection shows that the excess in emission is localized in all three dimensions, further confirming it as a local over-density and not due to chance line of sight projection effects. These properties are consistent with what would be expected from an object formed via gravitational fragmentation of the disc.

This source appears with a diameter of ≈ 2'', meaning that it is spatially unresolved in our observations, consistent with the 1.2'' diameter previously reported (Berné et al. 2015). The center of the feature is found at \((\Delta x_{\text{disc}}, |\Delta y_{\text{disc}}|) \approx (1.8'', 1.0'')\) relating to \((r_{\text{disc}}, \phi_{\text{disc}}) \approx (500 \, \text{au}, \pm 30')\), where the ambiguity in \(\phi_{\text{disc}}\) comes from the degeneracy in \(\gamma_{\text{disc}}\). Better spatial and spectral resolution of the data would allow to constrain the location and size of GoHam b.

4.2 Utility in Determining Chemical Stratification

As previously discussed in Dutrey et al. (2017), these deprojection techniques allow us to directly access the vertical
Figure 4. TRD using the method in Dutrey et al. (2017) for $^{12}$CO, left, and $^{13}$CO, right. Each pixel shows the maximum $T_B$ value. Black contours are from 10 K in steps of 2 K. The beam size is shown in the bottom right of each panel. The dashed lines show $z/r = 0.3$ in the left panel and $z/r = 0.2$ in the right. Note that asymmetry about the $z = 0$ line due to the deviation from a completely edge-on disk.

Figure 5. Deprojected $^{12}$CO emission assuming Keplerian rotation. The left panel shows the zeroth moment (integrated intensity) map of $^{12}$CO. The six annotated slices, (b) through (g), show the centre of the cuts which make up the two columns to the right. For the deprojected data, regions where $|x| < 0.5''$ and $|y| < 0.5''$ are masked. The height of each cut relative to the disc midplane is shown in the top right of each panel. Note that negative $x$ values are to the north of the disc center. In panels (b) through (g) the black dashed lines are lines of constant cylindrical radius. The dashed circle, centered at (1.8'', 1''), highlights GoHam b.

The stratification of molecular species, an essential data product with which to confront astrochemical models. Figure 7 demonstrates this using TRDs of $^{12}$CO and $^{13}$CO emission from GoHam. Due to the large difference in the abundance of the two isotopologues and the resulting optical thickness of their lines, their emission traces different radial and vertical regions in the disc.

A more common method to probing chemical stratification in discs uses the asymmetry of the line emission about the disc major axis in a moderately inclined disc to infer the height of the emission surface (e.g. Rosenfeld et al. 2013; Pinte et al. 2018). However, observations of edge-on discs aided by the deprojection techniques have two distinct advantages over such methods. Firstly, the technique for moderately inclined discs can only be applied to bright lines such that the emission in any given channel is well defined. This criteria leaves only $^{12}$CO and $^{13}$CO as viable choices, meaning that less abundant molecules believed to arise from elevated regions, such as CH$_3$CN (Loomis et al. 2018), are unable to be tested. Conversely, for an edge-on disc there is no requirement on the significance of the detection; if the
molecular emission can be detected in the channel maps, it can be deprojected into disc-centric coordinates.

Secondly, the deprojection techniques described in Section 3 do not require any assumptions about the optical depth of the lines to be made as all pixels can be deprojected to fill in the \((r_{\text{disc}}, z_{\text{disc}})\) plane. This can be clearly seen in Figure 7 where the \(^{12}\text{CO}\) emission is detected in the midplane, where usually it is hidden due to high optical depths. We note that Dullemond et al. (2020) showed it is possible access similar information for moderately inclined sources if the spatial resolution of the data allowed for the top and bottom half of the disk to be spatially resolved.

Observations of edge-on sources, such as GoHam and The Flying Saucer, therefore represent the most robust approach to mapping the radial and vertical chemical structure in protoplanetary discs.

4.3 The Prospect for Mapping the Disc Mass

With multiple transitions of a molecule observed in an edge-on source, it is possible to go beyond merely mapping out the emission distribution. For example, excitation analyses can be performed to extract local excitation temperatures and volume densities (e.g. Bergner et al. 2018; Loomis et al. 2018; Teague et al. 2018). By first deprojecting the data into 3D disc-centric coordinates, one can be certain that the emission being compared arises from the same location; an assumption always made but extremely hard to verify in less inclined sources. In other words, highly-inclined sources provide access to the disc vertical structure, without losing access to the disc azimuthal structure.

With the deprojection, it is also possible to calculate the volume of the emitting area. Thus, if the local \(^2\text{H}_2\) density can be constrained using molecules which are not in thermodynamic equilibrium (non-LTE; such as CS in the outer disk, Teague et al. 2018), this can be readily mapped to a gas mass. With a temperature of the gas and local mass to hand, it is possible to determine, in a spatially-resolved manner, if and where the disc is gravitationally unstable. This could be done simply by calculating the local Toomre (1964)
$Q$ parameter. Such a constraint on disc stability would be valuable in inferring the nature and origin of GoHam b.

5 SUMMARY AND CONCLUSIONS

We have used the deprojection techniques previously presented in Dutrey et al. (2017) and Matr` a et al. (2017) to provide a three dimensional view of the massive disc, Gomez’s Hamburger using archival SMA observations of 12CO and 13CO.

The deprojected data reveals a clear difference between the 12CO and 13CO emission regions with the 12CO tracing a considerably elevated region of $z/r \sim 0.3$, while the 13CO arises from much lower regions, $z/r \lesssim 0.2$, as expected from the higher abundance of 12CO compared to 13CO.

When deprojecting the data into the $(x_{\text{disc}}, y_{\text{disc}})$ plane, a clear feature in the southern side of the disc in 13CO which is interpreted as the previously detected overdensity, GoHam b. With this deprojection, it is possible to localise the emission to $(r_{\text{disc}}, \phi_{\text{disc}}) \approx (500 \text{ au}, \pm 30^\circ)$, with the accuracy ultimately limited by the spatial and spectral resolution of the data.

We conclude with a discussion on the utility of these observational techniques in mapping the physical and chemical structure in protoplanetary discs. With access to the full 3D structure of the disc, future observations will be able to map out the gas temperature and density as has never been done before.

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