CHIMPS2: Survey description and $^{12}$CO emission in the Galactic Centre

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CHIMPS2: survey description and $^{12}$CO emission in the Galactic Centre


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ABSTRACT

The latest generation of Galactic Plane surveys is enhancing our ability to study the effects of galactic environment upon the process of star formation. We present the first data from CO Heterodyne Inner Milky Way Plane Survey 2 (CHIMPS2). CHIMPS2 is a survey that will observe the Inner Galaxy, the Central Molecular Zone (CMZ), and a section of the Outer Galaxy in $^{12}$CO, $^{13}$CO, and C$^{18}$O ($J = 3 \rightarrow 2$) emission with the Heterodyne Array Receiver Program on the James Clerk Maxwell Telescope (JCMT). The first CHIMPS2 data presented here are a first look towards the CMZ in $^{12}$CO ($J = 3 \rightarrow 2$) and cover $−3^\circ \leq \ell \leq 5^\circ$ and $|b| \leq 0.5^\circ$ with angular resolution of 15 arcsec, velocity resolution of 1 km s$^{-1}$, and rms $\Delta T_A^*$ = 0.58 K at these resolutions. Such high-resolution observations of the CMZ will be a valuable data set for future studies, whilst complementing the existing Galactic Plane surveys, such as SEDIGISM, the Herschel infrared Galactic Plane Survey, and ATLASGAL. In this paper, we discuss the survey plan, the current observations and data, as well as presenting position–position maps of the region. The position–velocity maps detect foreground spiral arms in both absorption and emission.

Key words: molecular data – surveys – stars: formation – ISM: molecules – Galaxy: centre.

1 INTRODUCTION

The formation of stars from molecular gas is the key process driving the evolution of galaxies from the early Universe to the current day. However, the regulation of the efficiency of this process (the star formation efficiency, SFE) on both the small scales of individual clouds and the larger scales of entire galaxies, is poorly understood.

In the era of ALMA, single-dish surveys play an essential role for understanding star formation in the context of Galactic environment. Advances in array detectors have enabled large surveys of the Galactic Plane to be completed in a reasonable time, producing large samples of regions for statistical analysis (e.g. Urquhart et al. 2018). By doing this, we can measure the relative impact on the SFE of Galactic-scale processes, e.g. spiral arms, or the pressure and turbulence within individual clouds.

However, untangling star formation on larger and smaller scales is complicated by the different sampling rates on these scales. Studies of extragalactic systems have produced empirical relationships, such as the Kennicutt–Schmidt (K–S) relationship (Kennicutt 1998), which scales the star formation rate (SFR) with gas density; and further relationships scaling the SFR with the quantity of dense gas ($n(\text{H}_2) \geq 3 \times 10^4$ cm$^{-3}$; Gao & Solomon 2004; Lada et al. 2012). These correlations, though, break down on scales of 100–500 pc, a scale where the enclosed sample of molecular clouds is small (Onodera et al. 2010; Schruba et al. 2010; Kruijssen & Longmore 2014).

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These two apparently contradictory results are supported when the clump-formation efficiency (CFE), or dense-gas mass fraction (DGMF) within individual molecular clouds is examined. The distribution of cloud CFEs is lognormal, with values varying by the clump-formation efficiency (CFE), or dense-gas mass fraction $a$ Table 1.

The distributions of the SFEs estimated from the ratio of infrared luminosity to cloud or clump gas mass, are also found to be lognormal

$$\text{CHIMPS2 Outer Gal. } 12\text{CO}/13\text{CO}/C_{18}O$$

$$\text{CHIMPS2 Inner Gal. } 13\text{CO}/C_{18}O$$

$$\text{FUGIN Inner Gal. } 12\text{CO}/13\text{CO}/C_{18}O$$

$$\text{COHRS } 12\text{CO}$$

$$\text{FUGIN Outer Gal. } 12\text{CO}/13\text{CO}/C_{18}O$$


Studies of other Galactic-scale mechanisms, such as shear, have found conflicting evidence for impact on the star formation (Dib et al. 2012; Ragan et al. 2016, 2018). The CHIMPS survey covered longitudes of $\ell = 3\rightarrow 2$ rotational transition of the CO isotopologues $^{13}$CO and $^{13}$CO, which have frequencies of 330.587 and 329.331 GHz, respectively. The CHIMPS survey covered longitudes of $\ell = 28\rightarrow 46$ at latitudes of $|b| < 0.50$.

COHRS (Dempsey et al. 2013) was also a JCMT-HARP survey of the inner Galactic Plane but in the $J = 3\rightarrow 2$ rotational transition of $^{12}$CO at a frequency of 345.786 GHz. The longitude range of the initial release covers $\ell = 10.25\rightarrow 55.25$, with varying latitudes between $|b| < 0.50$ and $|b| < 0.25$. Full coverage details and a survey description can be found in Dempsey et al. (2013).

FUGIN (Umemo et al. 2017) observed the inner Galaxy ($|b| < 0.50$), and a portion of the Outer Galaxy ($|b| < 1.0$) using the FOREST receiver (Minamidani et al. 2016) upon the Nobeyama 45-m telescope (FUGIN; Umemo et al. 2017), and the Structure, Excitation, and Dynamics of the Inner Galactic Interstellar Medium survey (SEDIGISM; Schiller et al. 2017).

CHIMPS (Rigby et al. 2016) was a survey covering approximately 18 deg$^2$ of the northern inner Galactic Plane. The survey was conducted with the Heterodyne Array Receiver Program (HARP; Buckle et al. 2009) upon the James Clerk Maxwell Telescope (JCMT) in the $J = 3\rightarrow 2$ rotational transition of the CO isotopologues $^{13}$CO and $^{13}$CO, and $^{13}$CO, which have frequencies of 330.587 and 329.331 GHz, respectively. The CHIMPS survey covered longitudes of $\ell = 28\rightarrow 46$ at latitudes of $|b| < 0.50$.

SEDIGISM (Schiller et al. 2017) completes the isotopologue range of CO surveys by observing $^{13}$CO and $^{13}$CO in the $J = 2\rightarrow 1$ rotational transition. SEDIGISM is observed at the APEX telescope at a resolution of 30 arcsec. The longitude range is $-60^\circ \leq \ell \leq 18^\circ$, and latitude range is $|b| < 0.50$.

The coverage of the CHIMPS, COHRS, FUGIN, and SEDIGISM surveys are summarized in Table 1, along with the CHIMPS2 survey regions introduced in this paper.

In this paper, we describe the CHIMPS2 survey and present the first data resulting from it, being the $^{12}$CO $J = 3\rightarrow 2$ emission from the CMZ. The structure of this paper is as follows: Section 2 introduces the CHIMPS2 survey, the observing strategy and science goals. Section 3 describes the data and the data reduction, whilst Section 4 introduces the intensity maps from the $^{13}$CO CMZ portion of the CHIMPS2 survey, and Section 5 provides a summary.

### Table 1. Summary of the observation parameters for the CHIMPS, COHRS, FUGIN, and SEDIGISM surveys, including CHIMPS2 for comparison.

<table>
<thead>
<tr>
<th>Survey</th>
<th>Observed isotopologues</th>
<th>Transition</th>
<th>Longitude range</th>
<th>Latitude range</th>
<th>Angular resolution</th>
<th>Velocity resolution</th>
<th>Telescope</th>
<th>Reference(^a)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CHIMPS</td>
<td>$^{13}$CO$^{18}$O</td>
<td>$J = 3\rightarrow 2$</td>
<td>28–46$^\circ$</td>
<td>$</td>
<td>b</td>
<td>&lt; 0.5$</td>
<td>15 arcsec</td>
<td>0.5 km s$^{-1}$</td>
</tr>
<tr>
<td>COHRS</td>
<td>$^{12}$CO</td>
<td>$J = 3\rightarrow 2$</td>
<td>10.25–55.25</td>
<td>$</td>
<td>b</td>
<td>&lt; 0.5$</td>
<td>16 arcsec</td>
<td>1.0 km s$^{-1}$</td>
</tr>
<tr>
<td>FUGIN Inner Gal.</td>
<td>$^{12}$CO$^{13}$CO$^{18}$O</td>
<td>$J = 1\rightarrow 0$</td>
<td>10–50$^\circ$</td>
<td>$</td>
<td>b</td>
<td>&lt; 1.0$</td>
<td>20 arcsec</td>
<td>1.3 km s$^{-1}$</td>
</tr>
<tr>
<td>FUGIN Outer Gal.</td>
<td>$^{12}$CO$^{13}$CO$^{18}$O</td>
<td>$J = 1\rightarrow 0$</td>
<td>198–236$^\circ$</td>
<td>$</td>
<td>b</td>
<td>&lt; 1.0$</td>
<td>20 arcsec</td>
<td>1.3 km s$^{-1}$</td>
</tr>
<tr>
<td>SEDIGISM</td>
<td>$^{13}$CO$^{18}$O</td>
<td>$J = 2\rightarrow 1$</td>
<td>$-60$–$18$</td>
<td>$</td>
<td>b</td>
<td>&lt; 0.5$</td>
<td>30 arcsec</td>
<td>0.25 km s$^{-1}$</td>
</tr>
<tr>
<td>CHIMPS2 CMZ</td>
<td>$^{12}$CO$^{13}$CO$^{18}$O</td>
<td>$J = 3\rightarrow 2$</td>
<td>$-5$–$5^\circ$</td>
<td>$</td>
<td>b</td>
<td>&lt; 0.5$</td>
<td>15 arcsec</td>
<td>1.0/0.5 km s$^{-1}$</td>
</tr>
<tr>
<td>CHIMPS2 Inner Gal.</td>
<td>$^{13}$CO$^{18}$O</td>
<td>$J = 3\rightarrow 2$</td>
<td>5–28$^\circ$</td>
<td>$</td>
<td>b</td>
<td>&lt; 0.5$</td>
<td>15 arcsec</td>
<td>0.5 km s$^{-1}$</td>
</tr>
<tr>
<td>CHIMPS2 Outer Gal.</td>
<td>$^{12}$CO$^{13}$CO$^{18}$O</td>
<td>$J = 3\rightarrow 2$</td>
<td>215–225$^\circ$</td>
<td>$&lt; 2.0$</td>
<td>15 arcsec</td>
<td>1.0/0.5 km s$^{-1}$</td>
<td>JCMT (5)</td>
<td></td>
</tr>
</tbody>
</table>

\(^a\)References for survey information: (1) Rigby et al. (2016), (2) Dempsey et al. (2013), (3) Umemoto et al. (2017), (4) Schiller et al. (2017), (5) This paper. bottom
Table 2. The time awarded to the CHIMPS2 project within each JCMT weather band, and the corresponding sky opacity.

<table>
<thead>
<tr>
<th>Weather band</th>
<th>Hours awarded</th>
<th>Sky Opacity ( \tau_{225} )</th>
<th>CO isotopologue</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>85.5</td>
<td>&lt;0.05</td>
<td>(^{12})CO and C(^{13})O</td>
</tr>
<tr>
<td>2</td>
<td>218.4</td>
<td>0.05–0.08</td>
<td>(^{12})CO and C(^{13})O</td>
</tr>
<tr>
<td>4</td>
<td>50.0</td>
<td>0.12–0.20</td>
<td>(^{13})CO</td>
</tr>
<tr>
<td>5</td>
<td>50.0</td>
<td>&gt;0.20</td>
<td>(^{12})CO</td>
</tr>
</tbody>
</table>

2 CHIMPS2

CHIMPS2 is the follow-up to the CHIMPS and COHRS surveys and is a Large Program on the JCMT.\(^1\) The project was awarded 404 h across four of the five JCMT weather bands to observe parts of the Inner and Outer Galaxy and the CMZ in the \( J = 3 \rightarrow 2 \) transition of \(^{12}\)CO, \(^{13}\)CO, and C\(^{18}\)O. Table 2 summarizes the number of hours awarded in each band. Weather Bands 1 and 2 are required for the \(^{13}\)CO and C\(^{18}\)O observations, since these transitions sit on the shoulder of the 325-GHz atmospheric water-vapour absorption feature, while Bands 4 and 5 are utilized for the \(^{12}\)CO data. Observations began in 2017 June and are still ongoing.

2.1 Observing strategy

The CHIMPS2 survey contains three components, the Inner and Outer Galaxy and the CMZ, with slightly differing observing strategies employed in each portion. The general observing strategy is to follow that of CHIMPS for \(^{13}\)CO and C\(^{18}\)O and COHRS for the \(^{12}\)CO observations, since these transitions sit on the longitude of the observations. The data have antenna-temperature sensitivity at this resolution is 0.055 km s\(^{-1}\).

The CHIMPS2 survey contains three components, the Inner and Outer Galaxy and the CMZ, with slightly differing observing strategies employed in each portion. The general observing strategy is to follow that of CHIMPS for \(^{13}\)CO and C\(^{18}\)O and COHRS for the \(^{12}\)CO observations, since these transitions sit on the shoulder of the 325-GHz atmospheric water-vapour absorption feature, while Bands 4 and 5 are utilized for the \(^{12}\)CO data. Observations began in 2017 June and are still ongoing.

2.2 Science goals

The science goals of the CHIMPS2 project are multifaceted, and intended to give us a greater understanding of the effect of environment on the star formation process. The main goals are outlined below.

(i) Production of comparative samples of Galactic molecular clouds across a range of Galactic environments with cloud properties, analysed using complementary CO \( J = 1 \rightarrow 0 \) surveys such as FUGIN (Umemoto et al. 2017) and Milky Way Imaging Scroll Painting (MWISP; Gong et al. 2016; Su et al. 2019). Line-intensity ratios are found to be robust indicators of excitation conditions (e.g. Nishimura et al. 2015), with simulations validating these methods (Szücs, Glover & Klessen 2014). Multitransition models simulating observations, such as those of Pe˜naloza et al. (2017), Pe˜naloza et al. (2018), will refine current LTE approximate methods (Rigby et al. 2019).

(ii) Combine with Hi-GAL (Molinari et al. 2016; Elia et al. 2017), JCMT Plane Survey (JPS; Moore et al. 2015; Eden et al. 2017), ATLASGAL (Contrares et al. 2013; Urquhart et al. 2014), and other continuum data to map the SFE and DGMF in molecular gas and constrain the mechanisms chiefly responsible for the regulation of SFE. The dense-gas SFE is largely invariant on \( \sim \)kpc scales in the Inner Galaxy disc (Moore et al. 2012; Eden et al. 2015) but falls significantly within the central 0.5 kpc (Longmore et al. 2013; Urquhart et al. 2014).
Comparisons of brightness temperatures used to determine observing thresholds for CHIMPS2. Left-hand panel: $^{12}$CO and $^{13}$CO $J = 3 \rightarrow 2$ from COHRS and CHIMPS, respectively, used to select the detection threshold of $^{13}$CO for the Outer Galaxy segment. Right-hand panel: $^{13}$CO and $^{18}$O from CHIMPS used to select the detection threshold of $^{18}$O for the CMZ segment.

The area of the Galaxy covered by the CHIMPS2 survey (green segments). Complementary surveys are shown for comparison of their longitude coverage, COHRS (red), CHIMPS (white), yellow (FUGIN), and SEDIGISM (blue). The background image is the artist’s impression of the Milky Way by Robert Hurt of the Spitzer Science Center, made in collaboration with Robert Benjamin.

Comparing these regions, along with the Outer Galaxy, where the metallicity is much lower (Smartt & Rolleston 1997), and the bar-swept radii will increase our understanding of the impact of environment on the star formation process. Variations within the CMZ may also provide insight into high-redshift star formation, since the physical condition of the clouds in this region are similar to those in galaxies at $z \sim 2$–3 (Kruijssen & Longmore 2013). (iii) Analyse the turbulence within molecular clouds and its relationship to the large variations in SFE and DGMF/CFE between one cloud and another (Eden et al. 2012, 2013, 2015). The ratio of compressive to solenoidal turbulence in molecular clouds to the CFE and SFE may determine how the internal physics of molecular clouds is altering the star formation (Brunt & Federrath 2014; Federrath et al. 2016; Orkisz et al. 2017).

(iv) Determine Galactic structure as traced by molecular gas and star formation, and the relationship between the two. The CHIMPS survey found significant, coherent, inter-arm emission (Rigby et al. 2016), identified as a connecting spur (Stark & Lee 2006) of the type identified in external systems (e.g. Elmegreen 1980).

(v) Use comparable neutral-hydrogen data (e.g. THOR; Beuther et al. 2016) to constrain cloud-formation models and relate turbulent conditions within molecular clouds to those in the surrounding neutral gas. The first stage of the macro star formation process is the conversion of neutral gas into molecular gas and therefore clouds (Wang et al. 2020). The comparison of the THOR survey with CHIMPS2 data will allow estimates of the efficiency of this process, as well as the underlying formation process (e.g. Bialy et al. 2017) to be made.

(vi) Study the relationship of filaments to star formation, and of gas flow within filaments to accretion and mass accumulation in cores and clumps. The filaments in question cover different scales. Several long (>50 pc) filamentary structures have been identified...
Table 3. The off positions for the CMZ observations in the CHIMPS2 survey.

<table>
<thead>
<tr>
<th>Galactic longitude (°)</th>
<th>Galactic latitude (°)</th>
</tr>
</thead>
<tbody>
<tr>
<td>−2.50</td>
<td>2.50</td>
</tr>
<tr>
<td>0.75</td>
<td>−2.75</td>
</tr>
<tr>
<td>2.60</td>
<td>2.50</td>
</tr>
<tr>
<td>3.00</td>
<td>−2.50</td>
</tr>
<tr>
<td>5.00</td>
<td>2.50</td>
</tr>
</tbody>
</table>

(Ragan et al. 2014; Zucker, Battersby & Goodman 2015), and the CHIMPS2 data will allow for a determination of how much molecular gas is contained within these structures. On smaller scales, Herschel observations have shown a web of filamentary structures (e.g. André et al. 2010; Schisano et al. 2014) in which star-forming clumps are hosted (Molinari et al. 2010b). The gas flow into these clumps can be traced by the high-resolution CHIMPS2 data (e.g. Liu et al. 2018).

(vii) Test current models of the gas kinematics and stability in the Galactic-centre region, the flow of gas from the disc, through the inner 3-kpc region swept by the Galactic Bar and into the CMZ. Models of the gas flows into the centres of galaxies give signatures of these flows (e.g Krumholz, Krujissen & Crocker 2017; Armillotta et al. 2019; Sormani et al. 2019; Tress et al. 2020), and the CHIMPS2 data can determine the mass-flow rate, the nature of the flows and the star-forming properties of these clouds.

3 DATA AND DATA REDUCTION

The data reduction for the 12CO component of the CHIMPS2 survey broadly followed the approach used for COHRS (Dempsey et al. 2013), namely using the REDUCE_SCIENCE_NARROWLINE recipe of the ORAC-DR automated pipeline (Jenness & Economou 2015), and employing the techniques described by Jenness et al. (2015). The pipeline invoked the Starlink applications software (Currie et al. 2014), including ORAC-DR, from its 2018A release. However, some new or improved ORAC-DR code was developed to address specific survey needs.

Since the original COHRS reductions were completed, many improvements have been made to the reduction recipe, yielding better-quality products. These include automated removal of emission from the reference (off-position) spectrum that appear as absorption lines in the reduced spectra and can bias baseline subtraction, flat-fielding using a variant of the Curtis, Richer & Buckle (2010) summation method, and masking of spectra affected by ringing in Receptor H07 (Jenness et al. 2015).

The reduced spectral (position, position, velocity) cubes were re-gridded to 6-arcsec spatial pixels, convolved with a 9-arcsec Gaussian beam, resulting in 16.6-arcsec resolution. This produces an improvement on existing 12CO ($J = 3 \rightarrow 2$) data (e.g. Oka et al. 2012). Cubes with both the ‘native’ spectral resolution and $\Delta V = 1$ kms$^{-1}$ were generated. The cleaning came first because it included the identification and masking of spectra that contained some extraneous signal comprising alternate bright and dark spectral channels. A first-order polynomial was used to fit the baselines (aligning with COHRS; Dempsey et al. 2013), although in the CMZ half of the baselines did require fourth-order polynomials.

The reduction of each map was made twice. The first pass used fully automated emission detection and baseline fitting, or adopted the recipe parameters of an abutting reduced tile. A visual inspection of the resultant spectral cube, tuning through the velocities and plotting the tile’s integrated spectrum, enabled refined baseline and flat-field velocity range recipe parameters to be set. Also, any residual non-astronomical artefacts from the raw time series not removed in the quality-assurance phase of the reductions, and contamination from the off-position spectrum were assessed. In some cases of the former, such as transient narrow spikes, these were masked in the raw data.
4 RESULTS: $^{12}$CO IN THE CMZ

We are presenting the first results from the CHIMPS2 survey. These are the $^{12}$CO $J = 3 \rightarrow 2$ emission within the CMZ. They provide a first look at the potential science that can be achieved with such data, which have greater resolution and/or trace higher densities than other large-scale CO surveys of the CMZ across the transition ladder ($J = 1 \rightarrow 0$; Bally et al. 1987; Oka et al. 1998; Dame et al. 2001; Barnes et al. 2015; $J = 2 \rightarrow 1$; Schuller et al. 2017; $J = 3 \rightarrow 2$; Oka et al. 2012). The data will be combined with the corresponding CHIMPS2 $^{13}$CO $J = 3 \rightarrow 2$ results in a future release, along with a kinematic and dynamic analysis of the CO-traced molecular gas in the CMZ.

4.1 Intensity distribution

Panel (a) of Fig. 4 shows the map of integrated intensity of $^{12}$CO $J = 3 \rightarrow 2$ in the CMZ region between $\ell = 357^\circ$ and $\ell = +5^\circ$, $|b| \leq 0.5$, constructed from data obtained up to the end of 2018. Panel (b) of Fig. 4 shows the $^{12}$CO $J = 3 \rightarrow 2$ intensity variance array mosaic and hence the relative noise levels in each constituent tile within the CMZ survey region.

A histogram of the voxel values of the map in Panel (a) of Fig. 4 is displayed in the top panel of Fig. 5. The distribution is modelled by a Gaussian function with a mean of 0.05 K and a standard deviation of 0.58 K. The data distribution departs from the Gaussian in the negative wing due to non-Gaussian noise and non-uniform noise across the data set. In the positive wing, the excess comes from the real emission and the aforementioned noise. A histogram of the rms noise values from the variance maps in Panel (b) of Fig. 4 are displayed in the bottom panel of Fig. 5. Each pixel in these variance maps represents one complete spectrum from the data cube. The values in the histogram are the square root of those in the map, giving the standard deviation. The distribution peaks at 0.38 K, comparable with the value obtained from the Gaussian fit in the emission in the top panel of Fig. 5.

500-μm continuum-emission data from the Herschel Hi-GAL project (Molinari et al. 2010a, 2011b) at 37-arcsec resolution are displayed in Panel (c) of Fig. 4. Panel (d) of Fig. 4 shows the distribution of the ratio of $^{12}$CO $J = 3 \rightarrow 2$ integrated intensity to 500-μm continuum surface brightness. The ratio values (while arbitrary) range from ~0.1 to 2.0 – a factor of ~20.

Figs 6 and 7 show the $^{12}$CO $J = 3 \rightarrow 2$ emission integrated over 50-km s$^{-1}$ velocity windows within the range $-250$ to $300$ km s$^{-1}$, with no emission detected at velocities lower than $-250$ km s$^{-1}$.

Fig. 8 is the same as Panel (d) in Fig. 4 but with the longitude range limited to $\ell = -1^\circ$ to $1^\circ$. A number of compact minima coincident with bright regions in both the continuum and CO-line maps can be seen by eye and appear to represent high column-density objects in which the CO emission is reduced due to, e.g. high optical depth. In order to produce an objective list of these sources, we applied the CUTEX object-detection package (Molinari et al. 2011a, 2017) to the inverted (reciprocal) ratio image. CUTEX was chosen as it was designed to deal with extended backgrounds in Herschel data. The detection thresholds were four times the rms noise in the second derivative (curvature) data and a minimum of four contiguous pixels. The resulting sample was then filtered to remove sources smaller than 35 arcsec in either axis, to represent the 500-μm Herschel beam size. The detected sources are marked in Fig. 8 as cyan squares and listed in Table 4.

As can be seen, not all the visible compact minima were detected by CUTEX, including several well-known sources. Table 4 lists several

data before the second reduction. Approximately 7 per cent of the tiles exhibited reference emission, which was removed by ORAC-DR using an algorithm that will be described in a forthcoming paper on the COHRS Second Release (Park et al., in preparation). The off-positions employed in the CHIMPS2 CMZ data are listed in Table 3.

Only 2 of 75 $^{12}$CO CMZ tiles could not be flat fielded. In the best-determined flat-fields, the corrections were typically less than 3 per cent, although receptor H11 was circa 8 per cent weaker than the reference receptor. Example sets of recipe parameters are given in Appendix A.

All intensities given in this paper are on the $T_A^*$ scale. To convert this to the main-beam temperature scale, $T_{\text{mb}}$, use the following relation $T_{\text{mb}} = T_A^*/\eta_{\text{mb}}$, where $\eta_{\text{mb}}$ is the main detector efficiency and has a value of 0.72 (Buckle et al. 2009).
of the latter that can be picked out in Fig. 8, including The Brick ($\ell \simeq 0.25$), the clouds of the dust ridge at $\ell = 0.3-0.5$, Sgr B2 at $\ell \simeq 0.7$, the 50- and 20-km s$^{-1}$ clouds at $\ell = 359.9-360.0$, Sgr C at $\ell \simeq 359.4$, as well as the southern part of the loop structure discussed by Molinari et al. (2011b), Henshaw et al. (2016), and others, in terms of clouds orbiting the central potential. The known objects from Table 4 that were not detected by CUTEK, are plotted in Fig. 8 as white circles. In addition to these two sets of objects, there are at least as many that can be picked out by eye. This simple analysis thus has considerable potential as a discovery channel for finding previously unknown dense, compact sources in such data and will be investigated further in future work. Here, we briefly investigate whether or not such sources tend to be colder than their surroundings.

The source extraction with CUTEK was repeated on the data in Fig. 8 but, rather than the reciprocal map above, now the maxima were detected. The positions of both CUTEK samples were used to extract temperature and column densities from the results of Marsh et al. (2017), produced by the PPMAP procedure outlined in Marsh, Whitworth & Lomax (2015). The left-hand panel of Fig. 9 shows the total column density contained within the sources at each temperature within the PPMAP grid. There are 12 temperatures, evenly separated in log space between 8 and 50 K. The peak total column density is found at 18.4 K for the minima, compared with 21.7 K for the maxima. The positions of the same sources were used to extract values from the column-density-weighted mean temperature maps produced by PPMAP, and the cumulative distributions of these values are shown in the right-hand panel of Fig. 9.

The distribution of temperatures at the positions of the $^{12}$CO/500-$\mu$m minima in Fig. 8 is weighted to lower values than that of the maxima. The former are therefore tracing denser, colder structures, probably with high optical depths in $^{12}$CO and perhaps some degree of freeze-out of CO molecules on to dust grains. The minima generally form quite compact features that pick out many of the dense clouds studied by, e.g. Walker et al. (2018). By induction, high values, which tend to be extended, should therefore correspond to warmer areas of low $^{12}$CO optical depth.
**Figure 7.** The integrated emission of $^{12}$CO $J = 3 \rightarrow 2$, split into 50-km s$^{-1}$ channels. From top to bottom, these are 50–100 km s$^{-1}$; 100–150 km s$^{-1}$; 150–200 km s$^{-1}$; 200–250 km s$^{-1}$; and 250–300 km s$^{-1}$.

**Figure 8.** A close-up of the central portion of Panel (d) of Fig. 4. The cyan squares are compact sources detected at 4σ significance using CUTEX. The white circles are at the positions of several known dense clouds or clumps. Both samples are included in Table 4.
Table 4. Known compact sources in the $^{12}$CO/500-μm ratio map (Fig. 8). Sources labelled with an asterisk were also detected by CUTEX.

<table>
<thead>
<tr>
<th>Galactic longitude (°)</th>
<th>Galactic latitude (°)</th>
<th>Source name and notes</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>359.137</td>
<td>+0.030</td>
<td>H II region; MMB G359.138+0.031</td>
<td>Walsh et al. (1998), Caswell et al. (2010)</td>
</tr>
<tr>
<td>359.440</td>
<td>−0.103</td>
<td>Sgr C</td>
<td>Tsuibo et al. (1991)</td>
</tr>
<tr>
<td>359.617</td>
<td>−0.243</td>
<td>BGPS G359.617−0.243; MMB G359.615−0.243</td>
<td>Caswell et al. (2010), Rosolowsky et al. (2010)</td>
</tr>
<tr>
<td>359.633</td>
<td>−0.130</td>
<td>BGPS G359.636−0.131</td>
<td>Rosolowsky et al. (2010)</td>
</tr>
<tr>
<td>359.750</td>
<td>−0.147</td>
<td>AGAL G359.751−0.144</td>
<td>Contreras et al. (2013)</td>
</tr>
<tr>
<td>359.797</td>
<td>−0.070</td>
<td>AGAL G359.894−0.067</td>
<td>Contreras et al. (2013)</td>
</tr>
<tr>
<td>0.253</td>
<td>+0.016</td>
<td>The Brick</td>
<td>Longmore et al. (2012)</td>
</tr>
<tr>
<td>0.317</td>
<td>−0.200</td>
<td>AGAL 0.316−0.201; MMB</td>
<td>Urquhart et al. (2013)</td>
</tr>
<tr>
<td>0.338</td>
<td>+0.052</td>
<td>Dust-ridge b</td>
<td>Lis et al. (1999)</td>
</tr>
<tr>
<td>0.377</td>
<td>+0.040</td>
<td>MMB G000.376+0.040; BGPS G000.378+0.041</td>
<td>Caswell et al. (2010), Rosolowsky et al. (2010)</td>
</tr>
<tr>
<td>0.380</td>
<td>+0.050</td>
<td>Dust-ridge c</td>
<td>Lis et al. (1999)</td>
</tr>
<tr>
<td>0.412</td>
<td>+0.052</td>
<td>Dust-ridge d &amp; BGPS G000.414+0.051</td>
<td>Lis et al. (1999), Rosolowsky et al. (2010)</td>
</tr>
<tr>
<td>0.483</td>
<td>+0.003</td>
<td>Sgr B1-off; UCH II regions and H$_2$O maser</td>
<td>Lu et al. (2019)</td>
</tr>
<tr>
<td>0.497</td>
<td>+0.188</td>
<td>MMB G000.496+0.188; BGPS G000.500+0.187</td>
<td>Caswell et al. (2010), Rosolowsky et al. (2010)</td>
</tr>
<tr>
<td>0.526</td>
<td>+0.182</td>
<td>AGAL 0.526+0.182</td>
<td>Contreras et al. (2013)</td>
</tr>
<tr>
<td>0.613</td>
<td>+0.135</td>
<td>2MASS J17463693−2820212</td>
<td>Cutri et al. (2003)</td>
</tr>
<tr>
<td>0.629</td>
<td>−0.063</td>
<td>AGAL G000.629−0.062</td>
<td>Contreras et al. (2013)</td>
</tr>
<tr>
<td>0.670</td>
<td>−0.030</td>
<td>Sgr B2; UCH II regions</td>
<td>Ginsburg et al. (2018)</td>
</tr>
<tr>
<td>0.687</td>
<td>−0.013</td>
<td>JCMT SCUBA-2 source</td>
<td>Parsons et al. (2018)</td>
</tr>
<tr>
<td>0.695</td>
<td>−0.022</td>
<td>AGAL G000.693−0.026</td>
<td>Contreras et al. (2013)</td>
</tr>
<tr>
<td>0.958</td>
<td>−0.070</td>
<td>JCMT SCUBA-2 source</td>
<td>Parsons et al. (2018)</td>
</tr>
<tr>
<td>1.003</td>
<td>−0.243</td>
<td>Sgr D</td>
<td>Lizt (1992)</td>
</tr>
<tr>
<td>1.123</td>
<td>−0.110</td>
<td>Sgr D UCHII + H$_2$O</td>
<td>Downes &amp; Maxwell (1966), Mehringer et al. (1998)</td>
</tr>
<tr>
<td>1.393</td>
<td>−0.007</td>
<td>Sgr D8</td>
<td>Eckart et al. (2006)</td>
</tr>
<tr>
<td>1.651</td>
<td>−0.061</td>
<td>AGAL G001.647−0.062</td>
<td>Contreras et al. (2013)</td>
</tr>
</tbody>
</table>

4.2 Kinematic structure

4.2.1 High-velocity-dispersion features

Fig. 10 contains the $\ell - V_{LSR}$ distribution of the $^{12}$CO $J = 3 \rightarrow 2$ intensity, integrated over the whole latitude range. The main features are labelled in Fig. 10 and are the parallelogram-like structure; Banía’s Clump 2; the Connecting Arm, the dust lanes fuelling the CMZ; and a series of supernova remnants.

The bright, high-velocity-dispersion emission between $\ell \simeq 358.5$ and $1.5$; $V_{LSR} \sim \pm 250$ km s$^{-1}$ in Fig. 10 that resembles a parallel-
Figure 10. CMZ longitude–velocity map of \(^{12}\text{CO} J = 3 \rightarrow 2\) intensity integrated over latitude from data complete as of 2018 September.

Figure 11. First moment map of the \(^{12}\text{CO}\) CMZ map in the region represented in Fig. 8.

Figure 12. Longitude–velocity map of the individual \(^{12}\text{CO}\) tile containing the reported position of the IMBH CO\(^{−}0.40–0.22\) (Oka et al. 2016, 2017). The expected longitude range is marked by the green rectangle.

The expected longitude range is marked by the green rectangle.

The longitudinal asymmetry of this region of bright CO emission with respect to \(\ell = 0^\circ\), along with the velocity centroid offset of \(\sim 40 \text{ km s}^{-1}\) seen in Fig. 10, was previously explained as the result of gas responding to an asymmetry in the Galactic potential in \(m = 1\) mode oscillation with respect to the Galactic disc (e.g. Morris \\& Serabyn 1996). However, the positional asymmetry has been recently suggested by Sormani et al. (2018) to be due to non-steady flow of gas in the bar potential. In these models, a combination of hydrodynamical and thermal instabilities mean that the gas flow into the CMZ is clumpy and unsteady. This structure leads to transient asymmetries in the inward flow, which we observe, the authors argue, as the longitudinal asymmetry in the gas distribution. Also, structures similar to those observed at the top and bottom edges of the parallelogram feature are detected in the simulations, where they correspond to far- and near-side shocks at the leading edges of the rotating bar. The bright compact structures within this structure are the molecular clouds on librations around \(x_2\) orbits in a ring around the supermassive black hole (SMBH).
the CMZ with semimajor axis $\sim0.3$ kpc; and the several features that are narrow in $\ell$, but have large velocity dispersions, are shocks where the infalling material meets the CMZ or librations around an $x^2$ orbit (Kruijssen, Dale & Longmore 2015; Tresse et al. 2020). The velocity offset is displayed in Fig. 11. This is the first-moment map of the sub-region in Fig. 8, created using the SPECTRAL-CUBE package (Ginsburg et al. 2019) and reflecting the centroid velocity at each pixel.

Bania’s Clump 2 can be seen as a high-velocity-dispersion cloud in Fig. 10 at $\ell = 3.2$ (Bania 1977). The line width of Bania’s Clump 2 appears to cover over 100 km s$^{-1}$ (Stark & Bania 1986), with very narrow longitude coverage (Liszt 2006) but high-resolution data have found that the velocity range is made up of many lower linewidth components (Longmore et al. 2017). Clouds such as these are the signature of shocks as clouds collide with the dust lane, as opposed to the turbulence of individual clouds (Sormani, Binney & Magorrian 2015b; Sormani et al. 2019). Another high-velocity-dispersion cloud present in Fig. 10 is the $\ell = 1.3$ complex (Bally et al. 1988; Oka et al. 1998). The high-velocity dispersion has three potential causes. The first is a series of supernova explosions (Tanaka et al. 2007), with the alternatives reflecting the acceleration of gas flows along magnetic field lines due to Parker instabilities (Suzuki et al. 2015; Kakuuchi et al. 2018) or collisions between gas on the dust lanes and the gas orbiting the CMZ (Sormani et al. 2019). Neither of these two structures shows signatures of ongoing star formation (Tanaka et al. 2007; Bally et al. 2010), with no associated 70-μm Hi-GAL compact sources (Elia et al. 2017), which are considered to be a signature of active star formation (Ragan et al. 2016, 2018).

The Connecting Arm (Rodriguez-Fernandez et al. 2006) is also visible in the $\ell - V_{LSR}$ diagram. Though described as a spiral arm, it is in fact a dust lane at the near side of the CMZ (e.g. Fux 1999; Marshall et al. 2008; Sormani et al. 2018), with a symmetrical dust lane found at the far side of the CMZ. We also see the latter in Fig. 10 as the curved feature at $V_{LSR} \sim -200$ km s$^{-1}$ running between $\ell \simeq 359^\circ$ and $357^\circ$. These dust lanes are signatures of accretion into the CMZ (Sormani & Barnes 2019), fuelling episodic star formation in this region (Krumholz et al. 2017).

We also confirm the findings of Tanaka (2018), who observed no evidence of an intermediate-mass black hole (IMBH) at the position of $\ell = -0.40$, $b = -0.22$ (Oka et al. 2016, 2017). Fig. 12 shows the $\ell - V_{LSR}$ $^{12}$CO intensity distribution of the observed tile that would contain this IMBH. There are no large-velocity-dispersion features that are indicative of an accreting IMBH being present in the $\ell - V_{LSR}$ maps.

### 4.2.2 Foreground features

The $\ell - V_{LSR}$ plot (Fig. 10) also shows several clear features with narrow velocity widths, in absorption and emission, probably corresponding to foreground structures, namely spiral arms. We can use these features to constrain the loci of these arms as they cross the CMZ. Several of the arm features modelled in Reid et al. (2016) are plotted on the same data, restricted to $V_{LSR} \pm 100$ km s$^{-1}$, in Fig. 13.

At the $\ell = 0^\circ$ position, there are three features in absorption at $V_{LSR} \simeq -60$, $-30$ and $-10$ km s$^{-1}$, with one emission feature at $\sim +10$ km s$^{-1}$. All of these appear to have substructure and...
possibly shallow gradients and are somewhat discontinuous across the longitude range. Following Bronfman et al. (2000) and Sanna et al. (2014), we can postulate that the $-60$ km s$^{-1}$ feature is the near 3-kpc arm and the $-30$ km s$^{-1}$ feature is the Norma arm.

To identify these features, more-precise $\ell - V_{\text{LSR}}$ plots were made, integrating over the latitude and velocity range identified for these arms in Reid et al. (2016). Fig. 14 displays the $\ell - V_{\text{LSR}}$ plots for the near 3-kpc arm, far 3-kpc arm, Norma arm, Perseus arm, and the far Sagittarius arm. The latitude and velocity ranges of the five spiral arms are: $\pm 0.2^\circ$ and $-80$ to $-20$ km s$^{-1}$, $\pm 0.1^\circ$ and $30$ to $80$ km s$^{-1}$, $\pm 0.2^\circ$ and $-50$ to $10$ km s$^{-1}$, $-0.1^\circ$ to $0^\circ$ and $-30$ to $30$ km s$^{-1}$, and $-0.1^\circ$ to $0^\circ$ and $-10$ to $50$ km s$^{-1}$, for the near 3-kpc, far 3-kpc, Norma, Perseus, and far Sagittarius arms, respectively.

The $\ell - V_{\text{LSR}}$ plots for the near 3-kpc arm and the Norma arm confirm the detection of these spiral arms. The near-3kpc arm displays absorption in the CMZ region, with emission detected in positive longitudes. There is no evidence in these data of the far 3-kpc arm, that Sanna et al. (2014) suggest crosses $\ell = 0^\circ$ at $+56$ km s$^{-1}$.

The Perseus spiral arm and the far segment of the Sagittarius arm both have emission that corresponds to the loci of these arms, in the positive longitudes at velocities $V_{\text{LSR}} \approx +10$ km s$^{-1}$. We are therefore unable to confirm which of these spiral arms we have detected.

We have also produced the $\ell - V_{\text{LSR}}$ plot for the Connecting Arm, using the Reid et al. (2016) latitude and velocity ranges of $-0.5$ to $0.3$ and $200$ to $270$ km s$^{-1}$. We detect this structure, the near-side dust lane down which material streams from distances of 3 kpc into the CMZ (e.g. Cohen & Davies 1976; Rodriguez-Fernandez et al. 2006; Sormani & Barnes 2019).

In future work, we will extract the detected narrow arm features from the $^{12}$CO data cubes in order to analyse the molecular-gas properties within them and to allow kinematic analysis of the kinematics of the residual high-velocity-dispersion emission in the CMZ itself.

5 SUMMARY

We introduce the CO Heterodyne Inner Milky Way Plane Survey (CHIMPS2). CHIMPS2 will complement the CHIMPS (Rigby et al. 2016) and COHRS (Dempsey et al. 2013) surveys by observing the CMZ, a segment of the Outer Galaxy, and to connect the CMZ to the current CHIMPS and COHRS observations in $^{12}$CO, $^{13}$CO, and C$^{18}$O ($J = 3 \rightarrow 2$) emission.
We present the \(^{12}\)CO \(J = 3 \rightarrow 2\) data in the CMZ, covering approximately \(-3\degree \leq \ell \leq 5\degree\) and \(|b| \leq 0.50\). The data have a spatial resolution of 15 arcsec, a spectral resolution of 1 km s\(^{-1}\) over velocities of \(|V_{\text{LSR}}| \leq 300\) km s\(^{-1}\), an rms of 0.58 K on 7.5 arcsec pixels and are available to download from the CANFAR archive.

Taking the ratio of the integrated-intensity to the 500-\(\mu\)m continuum surface brightness from Hi-GAL, we find that the result correlates well with dust temperature. The minima tend to coincide with compact, dense, cool sources; whereas the maxima correspond to warmer, more-extended regions.

We investigate the kinematic structure of the CMZ data through the use of \(\ell - V_{\text{LSR}}\) plots. We are able to distinguish the high-velocity-dispersion features in the Galactic Centre, such as Bania’s Clump 2. We find no evidence for the existence of IMBHs. We find evidence for spiral arms crossing in front of the Galactic Centre in both absorption and emission, detecting the near 3-kpc spiral arm, along with the Norma spiral arm, and evidence for emission in the space occupied by the far Sagittarius arm and the Perseus arm.

These data provide high-resolution observations of molecular gas in the CMZ, and will be a valuable data set for future CMZ studies, especially when combined with the future \(^{13}\)CO and C\(^{18}\)O CHIMPS2 data. Further combination with the complimentary data sets from existing surveys in the molecular gas, such as SEDIGISM, and in the continuum from Hi-GAL and ATLASGAL will further increase the value.

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Chapin E., Gibb A. G., Jenness T., Berry D. S., Scott D., Tilanus R. P. J., 2013, Starlink User Note 258, the Sub-Millimetre User Reduction Facility. Joint Astronomy Centre

DATA AVAILABILITY

The reduced CHIMPS2 \(^{12}\)CO CMZ data are available to download from the CANFAR archive.\(^2\) The data are available as mosaics, roughly \(2\degree \times 1\degree\) in size, as well as the individual observations. Integrated \(\ell - b\) and \(\ell - V_{\text{LSR}}\) maps, displayed in Section 5 for the whole CMZ are provided, as well as the \(\ell - V_{\text{LSR}}\) maps for the individual cubes. The data are presented in FITS format.

2https://www.canfar.net/citation/landing?doi=20.0004


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in the *Classified Recipe Parameters* appendix of Starlink Cookbook 20.¹

We first list the parameters that were constant throughout the survey and will be applied to all $^{12}$CO data in the CHIMPS2 survey. The following parameters controlled the creation of the spectral cubes with *SMURF:MAKECUBE* (Chapin et al. 2013; Jenness et al. 2013), and the maximum size of input data before they were processed in chunks.

```
CUBE_WCS = GALACTIC
PIXELSCALE = 6.0
SPREAD_METHOD = gauss
SPREAD_WIDTH = 9
SPREAD_FWHM_OR.ZERO = 6
TILE = 0
CUBE_MAXSIZE = 1536

CHUNKSIZE = 12288
```

The following parameters controlled the creation of the longitude–velocity maps and spectral-channel re-binning for the tiling of a large number of tiles.

```
REBIN = 1.0
LV_IMAGE = 1
LV_AXIS = skylat
LV_ESTIMATOR = sum
```

To guide the automated rejection of spectra affected by artefacts extraneous noise the following parameters were used.

```
BASELINE_LINEARITY = 1
BASELINE_LINEARITY_LINEARWIDTH = base
BASELINE_REGIONS = -406.8:-272.0,124.0:377.5
BASELINE_LINEARITY_MINRMS = 0.080
HIGHFREQ_INTERFERENCE = 1
HIGHFREQ_RINGING = 0
LOWFREQ_INTERFERENCE = 1
LOWFREQ_INTERFERENCE_THRESH_CLIP = 4.0
```

These too were constants, except BASELINE_LINEARITY_LINEARWIDTH was sometimes set to a range to be excluded from the non-linearity tests if there was a single continuous section of emission, otherwise BASELINE_REGIONS was used inclusively. HIGHFREQ_RINGING was only enabled (set to 1) when ringing (Jenness et al. 2015) was present in HARP Receptor H07. LOWFREQ_INTERFERENCE_THRESH_CLIP was set higher – 6, 8, or 10 – as needed for $^{12}$CO observations in the CMZ.

The following three parameters controlled how the receptor-to-receptor flat-field was to be determined. The responses are normalized to Receptor H05, except in 15 cases in where H05 had failed quality-assurance criteria and H10 was substituted. In three CMZ cases the index method was preferred, using well-determined flat ratios from the same night. The regions used to derive the flat-field were estimated by averaging all the spectra in the first pass of a reduction, then tuning through border velocity channels until there was deemed to be sufficient signal that was not overly concentrated, typically when the mean flux exceeded 0.2 K.

```
FLATFIELD = 1
FLAT_METHOD = sum
```

¹http://www.starlink.ac.uk/devdocs/sc20.htx/sc20.html

For $^{12}$CO observations in the CMZ, the following parameters related to the baseline fitting were used.

```
BASELINE_METHOD = auto
BASELINE_ORDER = 1
FREQUENCY_SMOOTH = 25
BASELINE_NUMBIN = 128
BASELINE_EMISSION_CLIP = 1.0,1.3,1.6,2.0,2.5
```

In some cases the baseline order was required to be set to 4.

```
BASELINE_ORDER = 4
```

The velocity coverage of the output data products in the CMZ were determined to be −407 to 355, and assigned to the FINAL_LOWER VELOCITY and FINAL_UPPER VELOCITY parameters.

The velocity limits containing all identified emission with a margin for error were set by MOMENTS_LOWER VELOCITY and MOMENTS_UPPER VELOCITY to aid in the creation of moments’ maps, such the integrated emission.

The final set of parameters were only applicable when there was noticeable contamination from the reference (off-position).

```
CLUMP_METHOD = clumpfind
SUBTRACT_REF_EMISSION = 1
REF_EMISSION_MASK_SOURCE = both
REF_EMISSION_COMBINE_REFFPOS = 1
REF_EMISSION_BOXSIZE = 19
```

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