CHIMPS2: Survey description and $^{12}\text{CO}$ 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 (CHIMPS2). CHIMPS2 is a survey that will observe the Inner Galaxy, the Central Molecular Zone (CMZ), and a section of the Outer Galaxy in $^{12}\text{CO}$, $^{13}\text{CO}$, and $^{18}\text{O}$ ($J = 3 \rightarrow 2$) 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 $^{12}\text{CO} J = 3 \rightarrow 2$ and cover $-3^\circ \leq l \leq 5^\circ$ and $|b| \leq 0.5$ 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) by gas density; and further relationships scaling the SFR with the quantity of dense gas \(n(H_2) \geq 3 \times 10^3\) 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; Knuijsen & Longmore 2014).

These two apparently contradictory results are supported when the clump-formation efficiency (SFE), or dense-gas mass fraction (DFMF) within individual molecular clouds is examined. The distribution of cloud CFEs is lognormal, with values varying by 2–3 orders of magnitude (Eden et al. 2012, 2013); however, the CFE is fairly constant when averaged over kiloparsec scales.

The distributions of the SFEs estimated from the ratio of infrared luminosity to cloud or clump gas mass, are also found to be lognormal (Eden et al. 2015), indicating that the central-limit theorem is at play in both cases, giving a well defined mean value when averaged over a large sample of clouds and a large area of the Galaxy. They also point to the spiral structures of the Milky Way having only a minor influence in enhancing the star formation, since triggering and local environment are only thought to cause 14–30 per cent of star formation (Thompson et al. 2012; Kendrew et al. 2012). There is some evidence that the clouds in the Central Molecular Zone (CMZ) exhibit low SFE as they are subject to mainly solenoidal turbulence (Federrath et al. 2016), as opposed to the compressive turbulence found in spiral-arm clouds. Therefore, to examine the internal physics, high-resolution observations of large samples of molecular clouds are required in different transitions and isotopologues such as the \(^{12}\)CO/\(^{13}\)CO (J = 3 → 2) Heterodyne Inner Milky Way Plane Survey (CHIMPS; Rigby et al. 2016), the CO High-Resolution Survey (COHRS; Dempsey et al. 2013), the FOREST Unbiased Galactic-plane Imaging survey with the Nobeyama 45-m telescope (FUGIN; Umemoto et al. 2017), and the Structure, Excitation, and Dynamics of the Inner Galactic Interstellar Medium survey (SEDIGISM; Schuller et al. 2017).

CHIMPS (Rigby et al. 2016) was a survey covering approximately 18 square degrees 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 → 2 rotational transitions of the CO isotopologues \(^{12}\)CO and \(^{13}\)CO, which have frequencies of 330.587 GHz and 329.391 GHz, respectively. The CHIMPS survey covered longitudes of \(\ell = 28^\circ – 46^\circ\) at latitudes of \(|b| < 0.5^\circ\).

COHRS (Dempsey et al. 2013) was also a JCMT-HARP survey of the inner Galactic Plane but in the J = 3 → 2 rotational transition of \(^{12}\)CO at a frequency of 345.786 GHz. The longitude range of the initial release covers \(\ell = 10^\circ.25 – 55^\circ.25\), with varying latitudes between \(|b| < 0.5^\circ\) and \(|b| < 0.25^\circ\). Full coverage details and a survey description can be found in Dempsey et al. (2013).

FUGIN (Umemoto et al. 2017) observed the inner Galaxy (\(\ell = 10^\circ – 50^\circ\), \(|b| < 1^\circ\)) and a portion of the Outer Galaxy (\(\ell = 198^\circ – 236^\circ\), \(|b| < 1^\circ\)) using the FOREST receiver (Minamidani et al. 2016) upon the Nobeyama 45-m telescope in the J = 1 → 0 transition of the three isotopologues, \(^{12}\)CO, \(^{13}\)CO, and \(^{15}\)O. The FUGIN survey is at an approximate resolution of 15 arcsecs, matching the CHIMPS and COHRS surveys, allowing for column density and temperatures to be calculated from a local thermodynamic equilibrium (LTE) approximation (Rigby et al. 2019).

SEDIGISM (Schuller et al. 2017) completes the isotopologue range of CO surveys by observing \(^{13}\)CO and \(^{15}\)O in the J = 2 → 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 \(|b| < 0.5^\circ\).

The coverage of the CHIMPS, COHRS, FUGIN, and SEDIGISM surveys are summarised 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 → 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 \(^{12}\)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>Isotopologue</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</th>
</tr>
</thead>
<tbody>
<tr>
<td>CHIMPS</td>
<td>$^{13}$CO/$^{14}$O</td>
<td>J = 3 → 2</td>
<td>28°–46°</td>
<td></td>
<td>15°</td>
<td>0.5 km s$^{-1}$</td>
<td>JCMT</td>
<td>(1)</td>
</tr>
<tr>
<td>COHRS</td>
<td>$^{12}$CO</td>
<td>J = 3 → 2</td>
<td>10°25–55:25</td>
<td></td>
<td>16°</td>
<td>1.0 km s$^{-1}$</td>
<td>JCMT</td>
<td>(2)</td>
</tr>
<tr>
<td>FUGIN Inner Gal.</td>
<td>$^{12}$CO/$^{13}$CO/$^{14}$O</td>
<td>J = 1 → 0</td>
<td>10°–50°</td>
<td></td>
<td>20°</td>
<td>1.3 km s$^{-1}$</td>
<td>NRO 45-m</td>
<td>(3)</td>
</tr>
<tr>
<td>FUGIN Outer Gal.</td>
<td>$^{12}$CO/$^{13}$CO/$^{14}$O</td>
<td>J = 1 → 0</td>
<td>198°–236°</td>
<td></td>
<td>20°</td>
<td>1.3 km s$^{-1}$</td>
<td>NRO 45-m</td>
<td>(3)</td>
</tr>
<tr>
<td>SEDIGISM</td>
<td>$^{13}$CO/$^{14}$O</td>
<td>J = 2 → 1</td>
<td>−60°–18°</td>
<td></td>
<td>30°</td>
<td>0.25 km s$^{-1}$</td>
<td>APEX</td>
<td>(4)</td>
</tr>
<tr>
<td>CHIMPS2 CMZ</td>
<td>$^{12}$CO/$^{13}$CO/$^{14}$O</td>
<td>J = 3 → 2</td>
<td>−5°–5°</td>
<td></td>
<td>15°</td>
<td>1.0/0.5/0.5 km s$^{-1}$</td>
<td>JCMT</td>
<td>(5)</td>
</tr>
<tr>
<td>CHIMPS2 Inner Gal.</td>
<td>$^{13}$CO/$^{14}$O</td>
<td>J = 3 → 2</td>
<td>5°–28°</td>
<td></td>
<td>15°</td>
<td>0.5 km s$^{-1}$</td>
<td>JCMT</td>
<td>(5)</td>
</tr>
<tr>
<td>CHIMPS2 Outer Gal.</td>
<td>$^{12}$CO/$^{13}$CO/$^{14}$O</td>
<td>J = 3 → 2</td>
<td>215°–225°</td>
<td></td>
<td>15°</td>
<td>1.0/0.5/0.5 km s$^{-1}$</td>
<td>JCMT</td>
<td>(5)</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) Schuller et al. (2017); (5) This paper

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>85.8</td>
<td>&lt; 0.05</td>
<td>$^{13}$CO and $^{14}$O</td>
</tr>
<tr>
<td>2</td>
<td>218.4</td>
<td>0.05–0.08</td>
<td>$^{13}$CO and $^{14}$O</td>
</tr>
<tr>
<td>4</td>
<td>50.0</td>
<td>0.12–0.20</td>
<td>$^{12}$CO</td>
</tr>
<tr>
<td>5</td>
<td>50.0</td>
<td>&gt; 0.20</td>
<td>$^{13}$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. The project was awarded 404 hours 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 $^{18}$O. Table 2 summarises the number of hours awarded in each band. Weather Bands 1 and 2 are required for $^{13}$CO and $^{14}$O observations, since these transitions sit on the shoulder of the 325-GHz atmospheric water-vapour absorption feature, while Bands 4 and 5 are utilised for the $^{12}$CO data. Observations began in June 2017 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 $^{18}$O and COHRS for the $^{12}$CO observations. Full details can be found in Rigby et al. (2016) and Dempsey et al. (2013); however, a brief description is included here, for completeness.

Following the CHIMPS strategy, CHIMPS2 is constructed of a grid of individual tiles orientated along Galactic coordinates. Tiles are $21 \times 21$ arcmin in size spaced 20 arcmin apart, so that a $3 \times 3$ set of nine tiles covers an area of ~1 square degree. The overlap allows for calibration adjustments between tiles and correction of edge-effects. The data have native angular resolution of 15 arcsec. The $^{13}$CO and $^{18}$O ($J = 3 \rightarrow 2$) lines are observed simultaneously with a 250-MHz frequency bandwidth, giving a native velocity resolution of 0.055 km s$^{-1}$. These data are binned to 0.5 km s$^{-1}$, covering the $V_{LSR}$ velocity ranges of $-$50 to 150 km s$^{-1}$ and $-$75 to 125 km s$^{-1}$, depending on the longitude of the observations. The data have antenna-temperature sensitivities of 0.58 K and 0.73 K in $^{12}$CO and $^{18}$O, corresponding to $H_2$ column densities of $3 \times 10^{20}$ cm$^{-2}$ and $4 \times 10^{21}$ cm$^{-2}$, assuming a typical excitation temperature of 10 K (see Rigby et al. 2019).

The COHRS data were observed in tiles up to $0.5 \times 0.5$ arcmin at a spatial resolution of 13.8 arcsec, and a raw spectral resolution of 0.42 km s$^{-1}$ in the velocity range $-$230 to 355 km s$^{-1}$. The data were binned spectrally to a resolution of 0.635 km s$^{-1}$. Taken across multiple weather bands, the sensitivity at this resolution is $\sim 0.3$ K (Park et al., in preparation). Since the original paper (Dempsey et al. 2013), new observations have been taken to complete a uniform latitude range of $|b| < 0.5$ km s$^{-1}$, to extend the longitude coverage to $|b| = 90.50$–62.25, and to re-observe the noisiest tiles (Park et al., in preparation).

The Inner Galaxy portion of the CHIMPS2 survey is an extension of the CHIMPS and COHRS projects into the inner 3 kpc of the Milky Way. This will extend these surveys to longitudes of $\ell = 5^\circ$ between latitudes of $|b| < 0.5$ km s$^{-1}$ from their current longitude limits of $\ell = 28^\circ$ and $\ell = 10^\circ$ for CHIMPS and COHRS, respectively. The observing strategy in this region matches that of the CHIMPS and COHRS surveys, although the $^{12}$CO tiles observed in CHIMPS2 will match the $21 \times 21$ arcmin tiles of CHIMPS.

The Outer Galaxy segment of CHIMPS2 covers the longitude and latitude ranges $215^\circ \leq \ell \leq 225^\circ$ and $-2^\circ \leq b \leq 0^\circ$, a sector partly covered by the FUGIN survey and entirely by the Herschel infrared Galactic Plane Survey (Hi-GAL; Molinari et al. 2010a,b), where over 1000 star-forming and pre-stellar clumps were identified (Elia et al. 2013). This regions is also entirely covered by the Forgotten Quadrant Survey in $^{12}$CO and $^{13}$CO $J = 1 \rightarrow 0$ (Benedettini et al. 2020). The $^{12}$CO emission is, however, quite sparse in this area of the Galaxy, and a corresponding blind survey of $^{13}$CO and $^{18}$O would result in many empty observing tiles. Therefore, using the relationship of $^{13}$CO brightness temperature from CHIMPS (Rigby et al. 2016) to that of $^{13}$CO from COHRS, as displayed in the left panel of Fig. 1, we are able to select regions that require $^{13}$CO and $^{18}$O follow-up. The threshold for this was determined to be at a $^{12}$CO brightness temperature of 5 K.

The final segment of CHIMPS2 covers the CMZ between longitudes of $\ell = \pm 5^\circ$ in the latitude range of $|b| < 0.5$ km s$^{-1}$. This range covers the 850-um continuum emission presented in Parsons et al. (2018). The extended velocity range of $\sim 550$ km s$^{-1}$ present in the CO emission from the Galactic Centre (Dame et al. 2001), requires the use of the 1-GHz bandwidth mode of HARP. In this mode, $^{13}$CO and $^{18}$O cannot be observed simultaneously. Therefore, the $^{13}$CO is observed as a blind survey, while $^{18}$O data are taken as follow-
Figure 1. Comparisons of brightness temperatures used to determine observing thresholds for CHIMPS2. Left panel: $^{12}$CO and $^{13}$CO $J=3\rightarrow2$ from COHRS and CHIMPS, respectively, used to select the detection threshold of $^{13}$CO for the Outer Galaxy segment. Right panel: $^{13}$CO and C$^{18}$O from CHIMPS used to select the detection threshold of C$^{18}$O for the CMZ segment.

up observations towards areas determined from the brightness-temperature relationship from CHIMPS (Rigby et al. 2016), displayed in the right panel of Fig. 1. A $^{13}$CO brightness-temperature threshold of 3 K was adopted.

The longitude coverage of the CHIMPS, CHIMPS2, and COHRS surveys are shown in Fig. 2. The FUGIN and SEDIGISM surveys are included due to the complementary nature of their observations. The CHIMPS2 latitude coverage in the Outer Galaxy follows that of Hi-GAL (Molinari et al. 2016) and is shown in Fig. 3, where the FUGIN survey latitude range is also displayed.

2.2 Science Goals

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

- Production of comparative samples of Galactic molecular clouds across a range of Galactic environments with cloud properties, analysed using complementary CO $J \geq 1 \rightarrow 0$ 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 (Szucs et al. 2014). Multi-transition models simulating observations, such as those of Peñaloza et al. (2017, 2018), will refine current LTE approximate methods (Rigby et al. 2019).

- 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 (Conijiras 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 $\sim 1$ 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. 2013). 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).
Fig. 3. The area of the Outer Galaxy covered by CHIMPS2 (green dashed) and FUGIN (yellow). FUGIN is extended to longitudes of \( \ell = 198^\circ \) to \( \ell = 236^\circ \). Hi-GAL covers the same area as CHIMPS2. The background image is the Planck dust opacity map (Planck Collaboration et al. 2014).

- 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 (Brunth & Federrath 2014; Federrath et al. 2016; Orkisz et al. 2017).

- 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).

- 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.

- 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 (Ragan et al. 2014; Zucker et al. 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. 2018). The gas flow into these clumps can be traced by the high-resolution CHIMPS2 data (e.g. Liu et al. 2018).

- 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 et al. 2017; Sormani et al. 2019; Arnaudtta 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 \(^{12}\text{CO}\) 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 appears as absorption lines in the reduced spectra and can bias baseline subtraction, flat-fielding using a variant of the Curtis et al. (2010) summation method, and masking of spectra affected by ringing in Receiver 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 \(^{12}\text{CO}\) (\(J = 3 \rightarrow 2\)) data (e.g. Oka et al. 2012). Cubes with both the ‘native’ spectral resolution and \( \Delta V = 1 \) km s\(^{-1}\) 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 baseline lines (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 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 \(^{12}\text{CO}\) CMZ tiles could not be flat fielded. In the best-determined flat fields, the corrections were typically less than 3 percent, 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 \( T_A^\prime \) scale. To convert this to the main-beam temperature scale, \( T_{\text{mb}} \), use the following relation \( T_{\text{mb}} = T_A^\prime / \eta_{\text{mb}} \), where \( \eta_{\text{mb}} \) is the main detector efficiency and has a value of 0.72 (Buckle et al. 2009).

4 RESULTS: \(^{12}\text{CO}\) IN THE CMZ

We are presenting the first results from the CHIMPS2 survey. These are the \(^{12}\text{CO}\) \( J = 3 \rightarrow 2 \) 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 \(\ell = 5^\circ\), \(|b|< 0.5\), 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 Gaussian in the negative wing due to non-Gaussian noise and non-Gaussian noise results in a future release, along with a kinematic and dynamic analysis of the CO-traced molecular gas in the CMZ.

### 4.2 Kinematic structure

#### 4.2.1 High-velocity-dispersion features

Fig. 10 contains the \(\ell - V_{\text{LSR}}\) 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; Bania’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 \(\ell \approx 358.5^\circ\) and \(1.5^\circ\); \(V_{\text{LSR}} \approx \pm 250\) km s\(^{-1}\) in Fig. 10 is thought to be caused by the dust lanes in the CMZ. The lateral sides are interpreted as the gas that is accreting onto the CMZ from the dust lanes (Sormani et al. 2019). The top and bottom sides
are caused by gas that is partly accreting onto the CMZ after travelling past the dust lanes (Sormani et al. 2018). This, combined with the efficient conversion of atomic to molecular gas, causes the velocity structure that we observe in the CMZ (Sormani et al. 2015a).

The longitudinal asymmetry of this region of bright CO emission with respect to $\ell = 0^\circ$, along with the velocity centroid offset of $\sim +40$ 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 $x_2$ orbit in a ring around the CMZ with semi-major axis $\sim 0.3$ kpc; and the several features that are narrow in $\ell$, but have large velocity dispersions; are shocks where the infalling material meets the CMZ on librations around an $x_2$ orbit (Kruijssen et al. 2015; Tress 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.

Figure 4. (a) The integrated emission from the $^{12}$CO $J = 3 \rightarrow 2$ CMZ data obtained as of October 2018. Each spectrum was integrated over all velocity channels; (b) Variance map of the $^{12}$CO $J = 3 \rightarrow 2$ CMZ data displayed in (a); (c) Herschel 500-μm surface brightness distribution from the Hi-GAL survey (Molinari et al. 2016); (d) CMZ ratio of $^{12}$CO $J = 3 \rightarrow 2$ integrated intensity (a) to Herschel Hi-GAL 500-μm surface brightness (c).

Bania’s Clump 2 can be seen as a high-velocity-dispersion cloud in Fig. 10 at $\ell = 3^\circ.2$ (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 et al. 2015b, 2019). Another high-velocity-dispersion cloud present in Fig. 10 is the $\ell = 1^\circ.3$ 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; Kakiuchi 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 $\ell - V_{\text{LSR}}$ 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 $V_{\text{LSR}} \sim -200$ km s$^{-1}$ running between $\ell \approx 35^\circ.9$ and $35^\circ.7$. 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) and Reid & Brunthaler (2020), who observed no evidence of an intermediate-mass black hole (IMBH) at the position of $\ell = -0^\circ.40, b = -0^\circ.22$ (Oka et al. 2016, 2017). Fig. 12 shows the
The $\ell-V_{\mathrm{LSR}}$ $^{12}$CO/500-µm ratio map (Fig. 8). Sources labelled with an asterisk were also detected by CuTEDX.

<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>*HI ι region; MMB G359.138+00.031</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>Tsuboi et al. 1991</td>
</tr>
<tr>
<td>359.617</td>
<td>−0.243</td>
<td>*BGPS G359.617-00.243; MMB G359.615-00.243</td>
<td>Caswell et al. 2010; Rosolowsky et al. 2010</td>
</tr>
<tr>
<td>359.633</td>
<td>−0.130</td>
<td>BGPS G359.636-00.131</td>
<td>Rosolowsky et al. 2010</td>
</tr>
<tr>
<td>359.750</td>
<td>−0.147</td>
<td>*AGAL G359.751-00.144</td>
<td>Contreras et al. 2013</td>
</tr>
<tr>
<td>359.787</td>
<td>−0.133</td>
<td>JCMT SCUBA source; BGPS G359.788-00.137</td>
<td>Di Francesco et al. 2008; Rosolowsky et al. 2010</td>
</tr>
<tr>
<td>359.870</td>
<td>−0.083</td>
<td>20-km s$^{-1}$ cloud: UCH ι regions and H$_2$O maser</td>
<td>Downes et al. 1979; Sjouwerman et al. 2002</td>
</tr>
<tr>
<td>359.895</td>
<td>−0.070</td>
<td>*AGAL G359.894-00.067</td>
<td>Contreras et al. 2013</td>
</tr>
<tr>
<td>359.977</td>
<td>−0.077</td>
<td>50-km s$^{-1}$ cloud: UCH ι regions and H$_2$O maser</td>
<td>Ekers et al. 1983; Reid et al. 1988</td>
</tr>
<tr>
<td>0.251</td>
<td>+0.016</td>
<td>*The Brick</td>
<td>Longmore et al. 2012</td>
</tr>
<tr>
<td>0.265</td>
<td>+0.036</td>
<td>*AGAL G000.264+00.032</td>
<td>Contreras et al. 2013</td>
</tr>
<tr>
<td>0.317</td>
<td>−0.200</td>
<td>AGAL 0.316-0.201; MMB</td>
<td>Urrutx et al. 2013</td>
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<tr>
<td>0.338</td>
<td>+0.052</td>
<td>*Dust-ridge b</td>
<td>Lis et al. 1999</td>
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<tr>
<td>0.377</td>
<td>+0.040</td>
<td>*MBB G000.376+00.040; BGPS G000.378+00.041</td>
<td>Caswell et al. 2010; Rosolowsky et al. 2010</td>
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<tr>
<td>0.380</td>
<td>+0.050</td>
<td>Dust-ridge c</td>
<td>Lis et al. 1999</td>
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<tr>
<td>0.412</td>
<td>+0.052</td>
<td>Dust-ridge d &amp; BGPS G000.414+00.051</td>
<td>Lis et al. 1999; Rosolowsky et al. 2010</td>
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<tr>
<td>0.483</td>
<td>+0.003</td>
<td>Sgr B1: off: UCH ι 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+00.188; BGPS G000.500+00.187</td>
<td>Caswell et al. 2010; Rosolowsky et al. 2010</td>
</tr>
<tr>
<td>0.526</td>
<td>+0.182</td>
<td>*AGAL G0.526+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 G000.629−00.062</td>
<td>Contreras et al. 2013</td>
</tr>
<tr>
<td>0.670</td>
<td>−0.030</td>
<td>*Sgr B2: UCH ι 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 G000.693−00.026</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 D1</td>
<td>Lis et al. 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 G001.647−00.062</td>
<td>Contreras et al. 2013</td>
</tr>
</tbody>
</table>

The $\ell-V_{\mathrm{LSR}}$ plots for the near 3-kpc arm and the Norma arm confirm the detection of these spiral arms. The near-3-kpc arm displays absorption in the CMZ region, with emission detected in positive longitudes. The Norma spiral arm is detected in absorption. There is no evidence in these data of the far 3-kpc arm, that Sanna et al. (2014) suggest crosses the CMZ region with absorption features within them and to allow kinematic analysis of the kinematics of the residual high-velocity-dispersion emission in the CMZ itself.
CHIMPS2 9

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 Central Molecular Zone (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 $^{18}$O ($J = 3 \rightarrow 2$) emission.

We present the $^{12}$CO $J = 3 \rightarrow 2$ data in the CMZ, covering approximately $-3^\circ \leq \ell \leq 5^\circ$ and $|b| \leq 0^\circ50$. The data have a spatial resolution of 15 arcsec, a spectral resolution of 1 km s$^{-1}$ over velocities of $|V_{LSR}| \leq 300$ 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-μm 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 $\ell - V_{LSR}$ 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 intermediate-mass black holes. 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 $^{18}$O CHIMPS2 data. Further combination with the complementary 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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DATA AVAILABILITY

The reduced CHIMPS2 $^{12}$CO CMZ data are available to download from the CANFAR archive. The data are available as mosaics, roughly $2\times 1^\circ$ in size, as well as the individual observations. Integrated $\ell - b$ and $\ell - V_{LSR}$ maps, displayed in Section 5 for the

https://www.canfar.net/citation/landing?doi=20.0004
Figure 6. The integrated emission of the map, split into 50-km s$^{-1}$ channels. The top map is $-250$ to $-200$ km s$^{-1}$; the second map is $-200$ to $-150$ km s$^{-1}$; the third map is $-150$ to $-100$ km s$^{-1}$; the fourth map is $-100$ to $-50$ km s$^{-1}$; the fifth map is $-50$ to 0 km s$^{-1}$; and the bottom map is 0 to 50 km s$^{-1}$.

whole CMZ are provided, as well as the $l-V_{LSR}$ maps for the individual cubes. The data are presented in FITS format.

The raw data are also downloadable from the JCMT Science Archive\(^3\) hosted by the Canadian Astronomy Data Centre using the Project ID M17BL004.

REFERENCES


\(^3\) http://www.cadc-ccda.hia-iha.nrc-cnrc.gc.ca/en/jcmt/

Cutri R. M., et al., 2003, VizieR Online Data Catalog, p. II/246
Figure 7. The integrated emission of $^{12}\text{CO} J = 3 \rightarrow 2$, split into 50-km s$^{-1}$ channels. From top to bottom, these are 50 to 100 km s$^{-1}$; 100 to 150 km s$^{-1}$; 150 to 200 km s$^{-1}$; 200 to 250 km s$^{-1}$; 250 to 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 4-sigma significance using CuTEX. The white circles are at the positions of several known dense clouds or clumps. Both samples are included in Table 4.
Figure 9. Left panel: the total column density found within the CuTEX sources in each temperature slice from the PPMAP analysis of the CMZ (Marsh et al. 2017). The minima from Fig. 8 are represented by blue points, whereas the maxima are red. Right panel: the cumulative distribution of the temperature contained within the CuTEX in the column-density weighted PPMAP temperature maps. The minima are represented by the blue dashed line, whereas the maxima are the red dot-dash line.

Figure 10. CMZ longitude-velocity map of $^{12}$CO $J=3 \rightarrow 2$ intensity integrated over latitude from data complete as of Sept 2018.
**Figure 11.** First moment map of the $^{12}$CO CMZ map in the region represented in Fig. 8.

**Figure 12.** Longitude-velocity map of the individual $^{12}$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.
Figure 13. As in Fig. 10 but with the spiral arms of Reid et al. (2016) overlaid and the velocity range restricted to $V_{LSR} \pm 100$ km s$^{-1}$. The arm segments are labelled as follows: 3-kpc near and far arms (3kN, 3kF; white dashed and white dot-dash, respectively), Carina near portion (CrN; pink dashed), Centaurus-Crux near (CN; pink dotted), Norma or 4-kpc (Nor; yellow dashed), Outer (Out; yellow dotted), Perseus (Per; blue dotted), Scutum near and far portions (ScN, ScF; blue dot-dash and blue dashed, respectively), and Sagittarius near and far portions (SgN, SgF; green dot-dash and green dashed, respectively). The Connecting Arm is out of this velocity range whilst the Outer Scutum-Centaurus, Carina far, an extension of the Connecting Arm, and Centaurus-Crux far arm segments currently have no parallax measurements and are not plotted.
Figure 14. Longitude-velocity maps isolated over the latitude and velocity range identified by Reid et al. (2016). Top panel: near 3-kpc arm. Second panel: far 3-kpc arm. Third panel: Norma spiral arms. Fourth panel: Perseus spiral arm. Fifth panel: far Sagittarius spiral arm. Bottom panel: Connecting Arm, which is limited to a longitude range of $\ell > 0.8$. The overlaid lines are the loci of the relevant spiral arms.


APPENDIX A: ORAC-DR PARAMETERS

The available recipe parameters are described in the REDUCE_SCIENCE_NARROWLINE documentation and summarised in the Classified Recipe Parameters appendix of Starlink Cookbook 204.

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
- PIXEL_SCALE = 6.0
- SPREAD_METHOD = gauss
- SPREAD_WIDTH = 9
- SPREAD_FWHM_OR_ZERO = 6
- TILE = 0
- CUBE_MAXSIZE = 1536
- CHUNKSIZE = 12288
- 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_LINEWIDTH = base

4 http://www.starlink.ac.uk/devdocs/sc20.htx/sc20.html
These too were constants, except BASELINE_LINEARITY_LINEWIDTH 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 normalised 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.

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

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

$$FLATFIELD = 1$$
$$FLAT_METHOD = \text{sum}$$
$$FLAT_REGIONS = -87.0:54.0,90.0:190.0$$
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