

Infall and Outflow Motions towards a Sample of Massive Star Forming Regions from the RMS Survey

N. Cunningham,^{1,2,3*} S L. Lumsden,³ T. J. T. Moore,⁴ L T. Maud,⁵ I. Mendigutía^{6,3}

¹*Institut de Radioastronomie Millimétrique (IRAM), 300 rue de la Piscine, 38406 Saint Martin d’Hères, France*

²*Green Bank Observatory, 155 Observatory Rd, P.O. Box 2, Green Bank, WV, 24944, USA*

³*School of Physics and Astronomy, University of Leeds, LS2 9JT, UK*

⁴*Astrophysics Research Institute, Liverpool John Moores University, IC2, Liverpool Science Park, 146 Brownlow Hill, Liverpool L3 5RF, UK*

⁵*Leiden Observatory, Leiden University, PO Box 9513, 2300 RA Leiden, The Netherlands*

⁶*Centro de Astrobiología, Departamento de Astrofísica (CSIC-INTA), ESA-ESAC Campus, P.O. Box 78, 28691 Villanueva de la Cañada, Madrid, Spain.*

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ABSTRACT

We present the results of an outflow and infall survey towards a distance limited sample of 31 massive star forming regions drawn from the RMS survey. The presence of young, active outflows is identified from SiO (8-7) emission and the infall dynamics are explored using HCO⁺/H¹³CO⁺ (4-3) emission. We investigate if the infall and outflow parameters vary with source properties, exploring whether regions hosting potentially young active outflows show similarities or differences with regions harbouring more evolved, possibly momentum driven, “fossil” outflows. SiO emission is detected towards approximately 46% of the sources. When considering sources with and without an SiO detection (i.e. potentially active and fossil outflows respectively), only the ¹²CO outflow velocity shows a significant difference between samples, indicating SiO is more prevalent towards sources with higher outflow velocities. Furthermore, we find the SiO luminosity increases as a function of the *Herschel* 70 μm to *WISE* 22 μm flux ratio, suggesting the production of SiO is prevalent in younger, more embedded regions. Similarly, we find tentative evidence that sources with an SiO detection have a smaller bolometric luminosity-to-mass ratio, indicating SiO (8-7) emission is associated with potentially younger regions. We do not find a prevalence towards sources displaying signatures of infall in our sample. However, the higher energy HCO⁺ transitions may not be the best suited tracer of infall at this spatial resolution in these regions.

Key words: stars: formation – interstellar medium: jets and outflows – interstellar medium: molecules

1 INTRODUCTION

Infall and outflow motions are an important part of the star-formation process. However, a comprehensive understanding of both processes, particularly towards massive star forming regions, is still lacking. This is due, in part, to the larger distances and typically more clustered and complex nature of such regions, making it difficult to disentangle the infall and outflow properties of individual objects in a given cluster.

Observationally, young stellar objects (YSOs) of all masses are known to drive bipolar molecular outflows and SiO emission has been effectively used to detect outflows driven by low ($M_{sun} < 2 M_*$), intermediate ($2 M_* < M_{sun} < 8 M_*$) and high-mass ($M_{sun} > 8 M_*$) stars (e.g., Gibb et al. 2004; Gibb et al. 2007; Duarte-Cabral et al.

2014; Klaassen et al. 2012; Cunningham et al. 2016). The passage of fast shocks are required to disrupt and release SiO from the solid grains into the gas phase (e.g., Gusdorf et al. 2008; Guillet et al. 2009; Schilke et al. 1997; Flower & Pineau des Forêts 2012). Thus, SiO emission, particularly the higher energy transitions, is likely to be an excellent tracer of an active outflow located close to the stellar driving source. Gibb et al. (2004) found SiO emission was preferentially detected towards Class 0 sources in their sample of low-mass stars. Furthermore, those sources with an SiO detection were associated with higher outflow velocities and higher densities, suggesting shock velocity and ambient density are likely to play an important role in the production of SiO in the early stages of low-mass star-formation. Bon-temps et al. (1996) observed more powerful outflows to be associated with Class 0 sources in their sample of 45 embedded YSOs. Similarly, a decrease of the outflow force with source

* E-mail: cunningham@iram.fr

evolution was observed by Mottram et al. (2017) towards a sample of Class 0 and Class I sources. In the high-mass regime, Gibb et al. (2007) found SiO emission was preferentially detected towards sources with higher outflow velocities, but were unable to establish the evolutionary nature of individual sources. Further work by Klaassen et al. (2012) found an increase in the integrated intensity of the SiO emission with evolutionary stage, contrary to the observations in the low-mass regime, detecting both infall and outflow signatures towards ultra-compact H_{II} (UCH_{II}) regions. As CO is more readily excited in the ambient medium, it has been suggested (e.g., Klaassen et al. 2012; Bally et al. 1999) that emission from CO may potentially trace a remnant, momentum driven, outflow cavity that is no longer being actively driven by the central star. In comparison, SiO, which requires a fast shock and higher critical density to be excited, may be tracing an active outflow close to the central star. A major aim of this work is to explore systematic differences in the environment, age and evolutionary nature between massive star forming regions hosting outflows traced by both CO and SiO emission (i.e. potentially active outflows) compared with regions that have an outflow traced by CO and show no associated SiO emission (i.e. potentially momentum driven fossil outflows).

In addition, we purposely observed the dense-gas tracer HCO⁺ as a means of probing the infall dynamics in these regions. Infall is believed to form an important role in the high-mass star formation process. However, exactly how mass is accumulated on the clump/cloud scales and finally accreted onto the central cores in massive star forming regions is still unclear (e.g. see Motte et al. 2017 for a recent review). There are two dominant theoretical scenarios for the formation of massive stars; turbulent core accretion McKee & Tan (2003) and competitive accretion Bonnell et al. (2001). In the former, the infall dynamics would likely be localized on individual core/binary type scales, whereas in the latter the cloud and high mass protostars form simultaneously (e.g. Tigé et al. 2017) and global collapse on clump/cloud scales is expected. In this formation scheme, the gas is likely to be channeled along converging flows onto central clouds that are undergoing global collapse on parsec scales. Several recent observations (e.g. Peretto et al. 2014; Williams et al. 2018) have observed velocity gradients along filamentary structures converging onto a central hub. In the observations presented here, we expect to probe signatures of global infall on scales of 1-2 pc, if present.

We present the results of an HCO⁺, H¹³CO⁺ J=4-3, and SiO J=8-7 molecular line survey performed using the James Clerk Maxwell Telescope (JCMT) towards a sample of 33 high-mass star forming regions selected from the RMS MSX survey (Lumsden et al. 2013). In Section 2 we summarize the observations presented in this paper. The results are presented in Section 3, the discussion in Section 4 and the main conclusions of the work are outlined in Section 5.

2 SAMPLE AND OBSERVATIONS

2.1 Sample selection

The sample includes 33 massive star forming regions, selected from a previous outflow survey by Maud et al.

(2015b), where 27 of the sources observed have an outflow detection traced by ¹²CO (3-2). For completeness, we also include 6 regions that have no confirmed ¹²CO (3-2) outflow detection in Maud et al. (2015b), but have associated C¹⁸O (3-2) emission (see Maud et al. 2015a) and therefore retain a dense massive core. All sources are part of the RMS survey and were selected to probe both evolutionary nature and cover a range in luminosity. The sample includes; 20 YSOs, 11 compact H_{II} and 2 H_{II}/YSO RMS classified regions (Lumsden et al. 2013). Objects labeled as H_{II}/YSO regions were found to display characteristics of both YSOs and compact H_{II} regions (see Lumsden et al. 2013 for a full discussion of the classification of RMS sources). Furthermore, the source selection was chosen to be distance limited (<4.5 kpc) to minimise distance-related bias. However, since the observations were undertaken, the distances of two sources, G020.7617 and G045.0711, have been corrected. The distance to G020.7617 has been updated to the far kinematic distance of 11.8kpc, and the distance to G045.0711 has been corrected to 7.75±0.4kpc (Wu et al. 2014, obtained from parallax and proper motion measurements). To keep the sample distance limited we omit these sources from the remaining analysis. Table 1 presents the source properties taken from the RMS survey. The sources are labelled by their Galactic name (Column 1), and properties such as the RMS survey classification (e.g., YSO and H_{II}), source V_{LSR}, distance and bolometric luminosity are given. Where possible the IRAS name and/or more commonly used name(s) for each source are provided.

2.2 JCMT observations

SiO J=8-7, H¹³CO⁺ J=4-3 and HCO⁺ J=4-3 were observed using the Heterodyne Array Receiver program (HARP) (Buckle et al. 2009) at the 15 m James Clerk Maxwell Telescope¹ (JCMT) as part of the projects M09AU18 (SiO J=8-7, and H¹³CO⁺ J=4-3) and M10AU04 (HCO⁺ J=4-3). Due to time limitations, only 25 sources were observed as part of project M10AU04 (HCO⁺ J=4-3). Project M09AU18 was observed between 12/04/2009 - 05/04/2010, and project M10AU04 between 16/04/2010 and 01/09/2010. The HARP array consists of 16 receiver elements but during both projects receiver H14 was not operational and is subsequently missing from the data. The observations were taken in position switched jiggle chop mode (Buckle et al. 2009), creating ~2 arcminute by 2 arcminute maps. We observed each source for between 30-60 minutes, and the pointing was checked every hour on a known bright molecular source and is accurate to within ~5". H¹³CO⁺ and SiO were observed simultaneously in the same frequency set-up, where the Auto-Correlation Spectral Imaging System (ACSIS) was configured with an operational bandwidth of 1000 MHz×2048 channels, providing a velocity resolution of 0.42 km s⁻¹. For HCO⁺ the bandwidth was set-up at 250 MHz×4096 channels, providing a velocity resolution of

¹ The James Clerk Maxwell Telescope has historically been operated by the Joint Astronomy Centre on behalf of the Science and Technology Facilities Council of the United Kingdom, the National Research Council of Canada and the Netherlands Organisation for Scientific Research.

Table 1. Source parameters for all objects in the sample taken from the RMS survey online archive (http://rms.leeds.ac.uk/cgi-bin/public/RMS_DATABASE.cgi).

Source Name	RMS Classification	RA (J2000)	Dec (J2000)	V_{LSR} (km s $^{-1}$)	Distance (kpc)	Luminosity (L_{\odot})	IRAS/Common Name
CO outflow detection ^a							
G010.8411−02.5919	YSO	18:19:12.09	-20:47:30.9	12.3	1.9	2.4e+04	18162-2048
G012.9090−00.2607	YSO	18:14:39.56	-17:52:02.3	36.7	2.4	3.2e+04	18117-1753/ W33A
G013.6562−00.5997	YSO	18:17:24.38	-17:22:14.8	47.4	4.1	1.4e+04	18144-1723
G017.6380+00.1566	YSO	18:22:26.37	-13:30:12.0	22.1	2.2	1.0e+05	18196-1331
G018.3412+01.7681	YSO	18:17:58.11	-12:07:24.8	33.1	2.8	2.2e+04	18151-1208
G020.7617−00.0638	HII/YSO	18:29:12.36	-10:50:38.4	56.9	11.8 ^b	1.3/3.6e+04	
G043.3061−00.2106 ^c	HII	19:11:16.97	+09:07:28.9	59.6	4.4	1.1e+04	19088+0902
G045.0711+00.1325	HII	19:13:22.10	+10:50:53.4	59.2	7.8 ^b	6.2e+05	19110+1045
G050.2213−00.6063	YSO	19:25:57.77	+15:02:59.6	40.6	3.3	1.3e+04	19236+1456
G078.1224+03.6320	YSO	20:14:25.86	+41:13:36.3	-3.9	1.4	4.0e+03	20126+4104
G079.1272+02.2782	YSO	20:23:23.83	+41:17:39.3	-2.0	1.4	1.6e+03	20216+4107
G079.8749+01.1821	HII	20:30:27.45	+41:15:58.5	-4.3	1.4	1.1e+03	20286+4105
G081.7133+00.5589	HII	20:39:02.36	+42:21:58.7	-3.8	1.4	1.9e+03	
G081.7220+00.5699	HII	20:39:01.01	+42:22:50.2	-4.7	1.4	1.2e+04	DR21 OH
G081.7522+00.5906	YSO	20:39:01.98	+42:24:59.1	-4.0	1.4	9.0e+03	
G081.7624+00.5916	YSO	20:39:03.72	+42:25:29.6	-4.4	1.4	2.6e+03	
G081.8652+00.7800	YSO	20:38:35.36	+42:37:13.7	9.4	1.4	3.6e+03	
G081.8789+00.7822	HII	20:38:37.71	+42:37:58.6	8.1	1.4	1.1e+04	
G083.0936+03.2724	HII	20:31:35.44	+45:05:45.8	-3.1	1.4	1.2e+04	
G083.7071+03.2817	YSO	20:33:36.51	+45:35:44.0	-3.6	1.4	3.9e+03	
G083.7962+03.3058	HII	20:33:48.02	+45:40:54.5	-4.3	1.4	4.8e+03	
G103.8744+01.8558	YSO	22:15:09.08	+58:49:07.8	-18.3	1.6	6.8e+03	22134+5834
G109.8715+02.1156	YSO	22:56:17.98	+62:01:49.7	-11.1	0.7	1.5e+04	22543+6145/Cep A
G192.6005−00.0479	YSO	06:12:54.01	+17:59:23.1	7.4	2.0	4.5e+04	06099+1800/ S255 IR
G194.9349−01.2224	YSO	06:13:16.14	+15:22:43.3	15.9	2.0	3.0e+03	06103+1523
G203.3166+02.0564	YSO	06:41:10.15	+09:29:33.6	7.4	0.7	1.8e+03	06384+0932/NGC2264-C
G207.2654−01.8080	HII/YSO	06:34:37.74	+04:12:44.2	12.6	1.0	1.3/9.1e+03	06319+0415
No CO outflow detection ^a							
G080.8645+00.4197	HII	20:36:52.16	+41:36:24.0	-3.1	1.4	9.1e+03	
G080.9383−00.1268	HII	20:39:25.91	+41:20:01.6	-2.0	1.4	3.2e+04	
G081.7131+00.5792	YSO	20:38:57.19	+42:22:40.9	-3.6	1.4	4.9e+03	
G196.4542−01.6777	YSO	06:14:37.06	+13:49:36.4	18.0	4.1 ^b	5.4e+04	06117+1350
G217.3771−00.0828	HII	06:59:15.73	-03:59:37.1	25.1	1.3	8.0e+03	06567-0355
G233.8306−00.1803	YSO	07:30:16.72	-18:35:49.1	44.6	3.3	1.3e+04	07280-1829

Notes

(a) The CO outflow sources have either a confirmed $^{12}\text{CO}(3-2)$ outflow or in the case of two sources, G017.6380 and G083.7962, show evidence of an outflow, whereas the No CO outflow sources have no observed emission consistent with an outflow in Maud et al. (2015b). (b) The distance to G020.7617 has been updated to the far distance since the observations were undertaken. A distance of 7.75 ± 0.4 kpc to G045.0711 has recently been identified through measurements of parallax and proper motions by Wu et al. (2014). The distance to G196.4542 has been since updated to $4.05^{+0.65}_{-0.49}$ kpc (Asaki et al. 2014). The corrected distances for these sources are used in the remainder of the analysis.

(c) G043.3061-00.2106 was observed as part of the ^{12}CO outflow survey (Maud et al. 2015b). However, as G043.3061-00.2106 was not observed in the C^{18}O core properties survey by Maud et al. (2015a), this source was subsequently excluded from the $^{12}\text{CO}(3-2)$ outflow survey (Maud et al. 2015b). Inspection of the $^{12}\text{CO}(3-2)$ data shows emission indicative of outflow motions, thus we include this source as a CO outflow candidate in this work.

0.05 km s^{-1} . At the observed frequency range of ~ 345 GHz the JCMT has a beam size of $\sim 15''$. The average atmospheric opacity ($\tau_{(225\text{GHz})}$) obtained from the Caltech Submillimeter Observatory (CSO) during both sets of observations was 0.07.

The HARP/ACIS data reduction was undertaken using the Starlink software packages SMURF, KAPPA, and GAIA (Jenness et al. 2015). The data were initially

converted to spectral (RA-DEC-velocity) cubes using the SMURF command MAKECUBE. The data were gridded on to cubes with a pixel size of $7.5''$ by $7.5''$ using the function “SincSinc”, which is a weighting function using a $\text{sinc}(\pi x \text{sinc} \pi x)$ kernel. The noisy channels at the edges of the band were removed, and a linear baseline was subtracted. The data were converted from the antenna temperature scale T_A^* (Kutner & Ulich 1981) to main-

beam brightness temperature T_{mb} using $T_{mb} = T_A^*/\eta_{mb}$, where the main beam efficiency η_{mb} has a value of 0.61 (Buckle et al. 2009). To increase the signal to noise ratio of the SiO (8-7) line, we re-sampled the velocity resolution to 1.68 km s^{-1} using the KAPPA command SQORST. The 1σ rms $T_{mb(\text{rms})}$ per channel was determined from line free channels excluding any noisy pixels towards the edges of the map; the typical values are 0.08 K, 0.04 K, and 0.6 K for H^{13}CO^+ (0.42 km s^{-1}), SiO (1.68 km s^{-1}) and HCO^+ (0.05 km s^{-1}), respectively. As mentioned in the previous section, the HCO^+ observations were not completed towards all sources in this survey; sources that were not observed are noted in Table 2.

2.3 Archival data

To complement the JCMT HARP observations, we utilise archival far-infrared (IR) data. The far-IR $70\mu\text{m}$ observations, performed with the ESA *Herschel Space Observatory*² (Pilbratt et al. 2010) using the PACS instrument (Poglitsch et al. 2010), were obtained from the *Herschel* archive in standard product generation form³. The majority of the data were taken from the HOBYS (Motte et al. 2010) or HiGal (Molinari et al. 2010) surveys. Only two regions, G018.3412 and G078.1224, were not observed as part of these two surveys, and were observed under the PIs; Krauss (observation ID:1342191813) and Cesaroni (observation ID:1342211514) respectively (see Table 2 for a summary of the sources covered).

3 RESULTS

3.1 Determining the source extents and properties from the HCO^+ and H^{13}CO^+ emission

The extent of the H^{13}CO^+ emission is determined from dendrogram fits made to the H^{13}CO^+ zeroth order moment maps, using the python based dendrogram fitting application, *astrodendro*⁴. An H^{13}CO^+ detection is assigned based on a $\geq 5\sigma$ detection over a minimum of 4 contiguous pixels (approximately equivalent to the beam area of 4.45 pixels). The rms noise per pixel in the integrated intensity maps is obtained using $\Delta I = T_{mb(\text{rms})} \Delta v \sqrt{N_{\text{chan}}}$, where $T_{mb(\text{rms})}$ is the rms noise level in K per channel, Δv is the velocity resolution in km s^{-1} (0.42 km s^{-1} for H^{13}CO^+) and N_{chan} is the number of channels used to integrate the emission. The number of channels is determined from the minimum and maximum velocity in the H^{13}CO^+ cubes that contain emission above the 3σ limit. A sample of the H^{13}CO^+ zeroth order moment maps with the HCO^+ emission overlaid are

shown in Figure 1 with the remainder provided in the online data. The HCO^+ and H^{13}CO^+ spectra (shown in Figure 2) display the average emission per pixel extracted from the sum of all pixels within the H^{13}CO^+ dendrogram fitted mask. The Gaussian fits of the H^{13}CO^+ spectra, presented in Table A1 of the Appendix, are extracted from the the sum of the emission over the region.

We detect H^{13}CO^+ emission towards 28 of the 31 distance limited RMS sources observed. For the three undetected sources (G233.8306, G081.7131, and G083.9383) no H^{13}CO^+ emission is detected in a single pixel above the 3σ limit. Towards several sources we find the peak of the H^{13}CO^+ emission is offset by more than the FWHM of the JCMT beam ($>14.5''$) from the RMS position. Furthermore, towards two sources, G081.7522 and G203.3166, two H^{13}CO^+ features are identified in the dendrogram fit. One component is associated with the RMS source position and a second structure is located in an offset position ($>14.5''$ from the RMS position). We discuss the offset components in more detail below.

3.1.1 H^{13}CO^+ offset components

An offset component is identified if the centre of the pixel containing the peak of the H^{13}CO^+ integrated intensity emission is spatially offset by more than a beam FWHM ($14.5''$) from the RMS source position (see Figure B1 in the online data for the HCO^+ and H^{13}CO^+ zeroth order moment maps towards the offset sources). In total six H^{13}CO^+ offset components are identified:

(i) Towards G079.8749, only one H^{13}CO^+ component is identified and is offset from the RMS source position by $\sim 24''$, located at R.A. (J2000) $20^{\text{h}}30^{\text{m}}29.5^{\text{s}}$, Dec. (J2000) $+41^{\circ}15'51.4''$. However, there is a clear enhancement in the H^{13}CO^+ emission towards the RMS source position in agreement with previous ammonia VLA observations (Lu et al. 2014). We therefore split the H^{13}CO^+ emission into two separate components, a smaller one associated with the RMS source position, and a second larger component located in the offset position now labelled G079.8749-OFFSET.

(ii) Towards G081.7522, two H^{13}CO^+ components are identified; one feature coincident with the RMS source position and a second offset by $\sim 30''$ to the south of the RMS position located at R.A. (J2000) $20^{\text{h}}39^{\text{m}}00.3^{\text{s}}$, Dec. (J2000) $+42^{\circ}24'36.4''$. We label the second offset component G081.7522-OFFSET. This source, located in the northern part of the DR 21 filament, was identified as a mm-continuum source (N43) by Motte et al. (2007) and does not have an outflow association in either SiO (2-1) (Motte et al. 2007) or CO (2-1) Schneider et al. (2010).

(iii) Towards G081.7624, only one H^{13}CO^+ component is present, located $\sim 22''$ to the north of the RMS source position at R.A. (J2000) $20^{\text{h}}39^{\text{m}}03.3^{\text{s}}$, Dec. (J2000) $+42^{\circ}25'50.6''$, and is now labelled G081.7624-OFFSET. This component also resides in the northern part of the DR 21 filament and was identified as a mm-continuum source (N53) by Motte et al. (2007). This H^{13}CO^+ feature has associated SiO (2-1) emission (Motte et al. 2007) and a CO (2-1) outflow (Schneider et al. 2010). Furthermore, the ^{12}CO (3-2) emission in Maud et al. (2015b) is also coincident with the

² *Herschel* is an ESA space observatory with science instruments provided by European-led Principal Investigator consortia and with important participation from NASA.

³ <http://www.cosmos.esa.int/web/herschel/science-archive>

⁴ This research made use of *astrodendro*, a Python package to compute dendrograms of Astronomical data (<http://www.dendrograms.org/>)

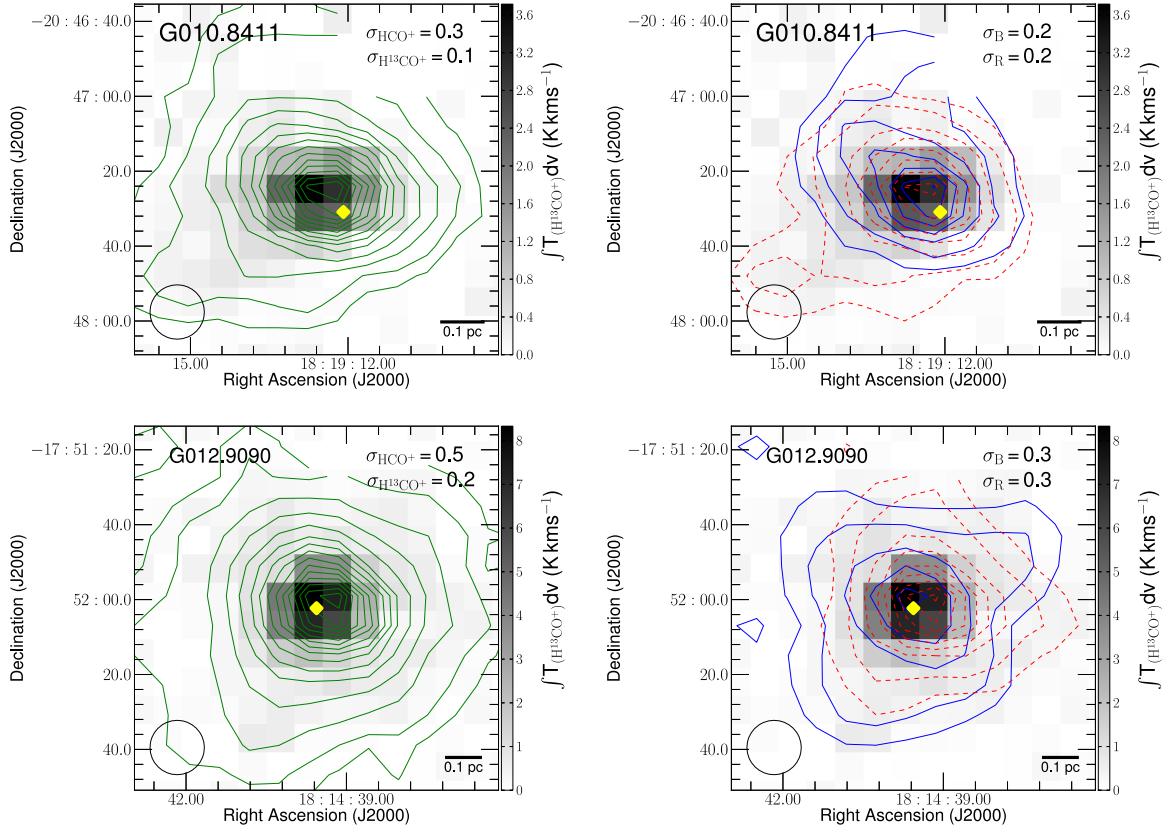


Figure 1. H^{13}CO^+ and HCO^+ zeroth order moment maps. The H^{13}CO^+ maps are shown in greyscale and are the total integrated emission ($\int T_{mb} dv$ in units of K km s^{-1}), integrated from the minimum to maximum channels with 3σ emission. The yellow diamonds mark the RMS source positions. The JCMT beam is shown in the bottom left corner, and the source name is shown in the top left corner. **Left:** The HCO^+ emission is overlaid in green solid contours for the total moment maps (again integrated from the minimum and maximum channels with 3σ emission in the HCO^+ maps) where the 1σ rms (in units of K km s^{-1}) for the HCO^+ (σ_{HCO^+}) and the H^{13}CO^+ ($\sigma_{\text{H}^{13}\text{CO}^+}$) integrated intensity maps are given in the top right corner. The HCO^+ contour levels are from $1\sigma \times (5, 10, 20, \dots)$ to peak in-steps of 10σ . **Right:** The red- and blue-shifted HCO^+ emission is shown by the red (dashed) and blue (solid) contours, respectively. The blue- and red-shifted contours are taken from the minimum and maximum channels with 3σ emission respectively, excluding the central emission which is defined by the H^{13}CO^+ FWHM (see Table A1 for the H^{13}CO^+ FWHM values). The 1σ levels for the red- (σ_{R}) and blue-shifted (σ_{B}) emission are given in the top right corner, where the contour levels are from $1\sigma \times (5, 10, 20, \dots)$ to peak in-steps of 10σ . The velocity ranges used to integrate the HCO^+ emission are $9.5\text{--}15.6 \text{ km s}^{-1}$ for G010.8411, and $30.3\text{--}44.0 \text{ km s}^{-1}$ for G012.9090. The remainder of the sources are presented in the online data.

offset component and we associate the outflow properties to G081.7624-OFFSET in this work.

(iv) For G081.8789 and G081.8652, which were observed in the same JCMT map, the dendrogram fit reveals only one H^{13}CO^+ feature, located between the two RMS positions, $\sim 40''$ from G081.8789, and $\sim 20''$ from G081.8652 at R.A. (J2000) $20^{\text{h}}38^{\text{m}}36.3^{\text{s}}$, Dec. (J2000) $+42^{\circ}37'30.3''$. While H^{13}CO^+ emission extends over both sources, there appears to be no obvious enhancement towards either RMS source, this is consistent with the C^{18}O emission in this region (Maud et al. 2015a). The peak of the H^{13}CO^+ emission is coincident with W75N, which hosts multiple mm continuum peaks and outflow emission (e.g., Minh et al. 2010). Furthermore, the ^{12}CO (3-2) emission in Maud et al. (2015b) is also coincident with W75N and we associate the outflow properties to W75N in this work. Given the source confusion in this field, W75N was not listed as an MSX point source. We label this H^{13}CO^+ component as W75N but class it as

an offset source for the remainder of the analysis as it does not coincide with a listed RMS point source position.

(v) Towards G083.7071, only one H^{13}CO^+ component is identified, offset from the RMS position by $\sim 16''$. The peak of the H^{13}CO^+ emission is located at R.A. (J2000) $20^{\text{h}}33^{\text{m}}35.2^{\text{s}}$, Dec. (J2000) $+45^{\circ}35'36.5''$. This component is not coincident with any previously known source and is labelled G083.7071-OFFSET.

(vi) Towards G203.3166, two H^{13}CO^+ components are identified in the dendrogram fit; the first feature is coincident with the RMS source position and the second component is offset by $\sim 37''$ to the south east of the RMS position. The offset component, labeled G203.3166-OFFSET, is located at R.A. (J2000) $06^{\text{h}}41^{\text{m}}12.1^{\text{s}}$, Dec. (J2000) $+09^{\circ}29'11.3''$, and is coincident with the position of C-MM3 (see Cunningham et al. 2016 and references therein).

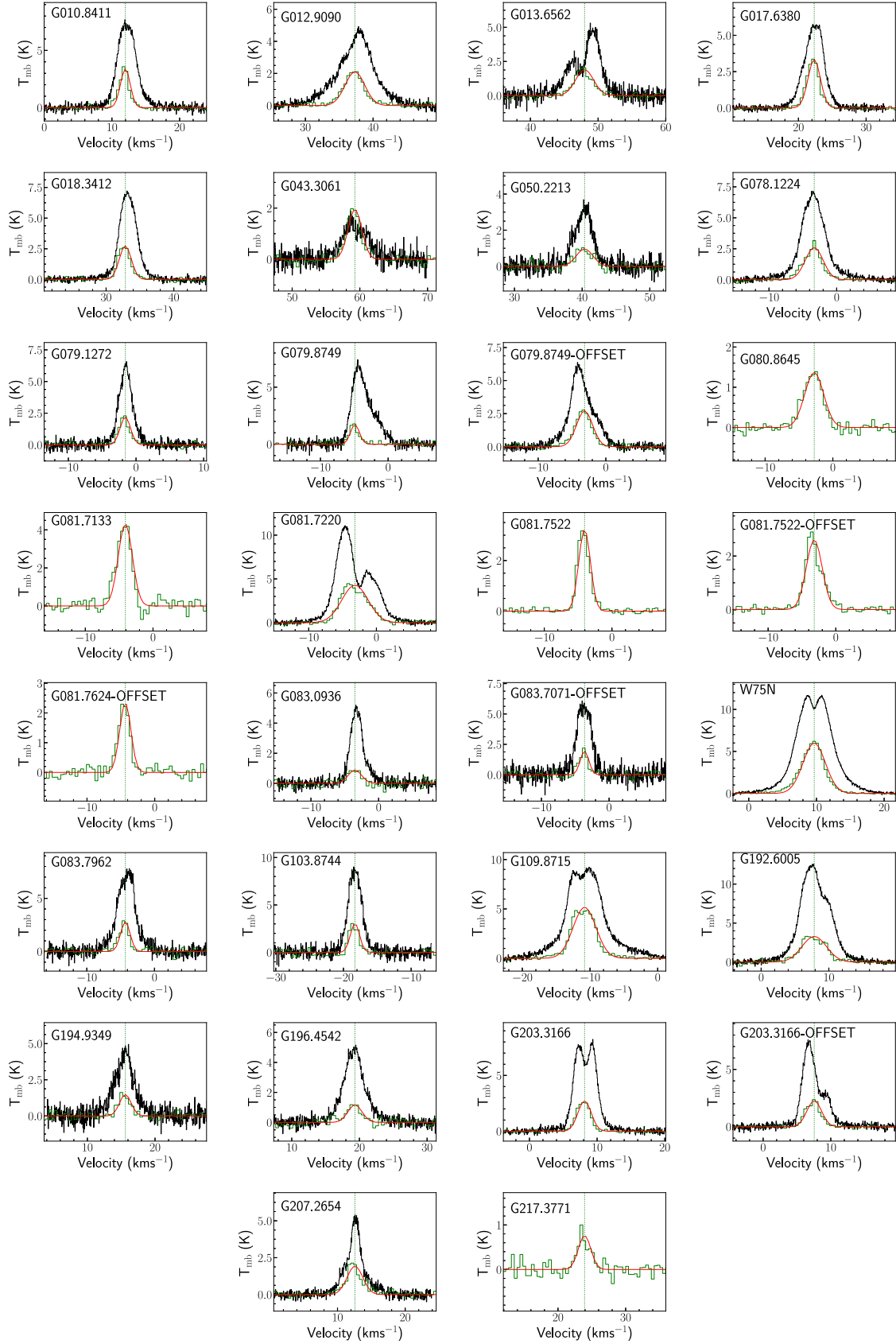


Figure 2. HCO^+ (solid black line) and H^{13}CO^+ (solid green line) $J=4-3$ spectra averaged over all pixels within the dendrogram fitted masks. The solid red line shows the Gaussian fits to the H^{13}CO^+ emission (calculated from Table A1 of the appendix). The green dotted line is at the position of the H^{13}CO^+ V_{LSR} taken from Table A1. Both the H^{13}CO^+ spectra and respective Gaussian fit have been multiplied by a factor of 4. The velocity scale is the same for all plots, and is the H^{13}CO^+ $V_{\text{LSR}} \pm 12 \text{ km s}^{-1}$. Sources where no HCO^+ observations were undertaken are missing the HCO^+ spectra.

3.1.2 HCO⁺ column density estimates

We estimate the HCO⁺ column density, assuming that the H¹³CO⁺ emission is optically thin, following,

$$N_{\text{H}^{13}\text{CO}^+} = \frac{8\pi\kappa\nu^2}{hc^3} \frac{1}{g_u A_{ul}} Q(T_{\text{ex}}) e^{\frac{E_u}{kT_{\text{ex}}}} \int T_{\text{mb}} dv, \quad (1)$$

where $\int T_{\text{mb}} dv$ is either the average of the H¹³CO⁺ integrated intensity (where the emission is the average over all pixels in the dendrogram fit) or the peak H¹³CO⁺ integrated intensity extracted at the peak of the H¹³CO⁺ emission, and $N_{\text{H}^{13}\text{CO}^+}$ is then the average or peak column density. $Q(T_{\text{ex}})$ is the partition function, and is well approximated by $Q(T_{\text{ex}}) = (kT_{\text{ex}})/(hB)$ for linear rotators, where B is the rotational constant and T_{ex} is the excitation temperature. A_{ul} is the Einstein A coefficient in s⁻¹, g_u is the degeneracy of the upper energy state and E_u is the energy of the upper state. We assume a value of 44 K for the excitation temperature as used by [Klaassen & Wilson \(2007\)](#). Furthermore, towards a similar sample of RMS selected young massive star forming regions ([Cunningham 2015](#)) an average rotational temperature of 44 K was derived from the CH₃CN (J=5-4) ladder. The HCO⁺ column densities are estimated assuming an abundance ratio between H¹³CO⁺ and HCO⁺ to be 65 ([Rygl et al. 2013](#)) and are given in Table 3. In addition, we also provide mass estimates for individual sources in Table 3. The masses are taken from [Maud et al. \(2015a\)](#), derived using the 850 μ m SCUBA fluxes. For sources not listed in [Maud et al. \(2015a\)](#), we follow the same procedure and extract the 850 μ m fluxes from [Di Francesco et al. \(2008\)](#) checking that the SCUBA positions are coincident with the position of the offset emission. The mass estimates are used in Sections 4.2, 4.3, and 4.3.1 for comparison with the SiO luminosities, and are used in the bolometric-luminosity-to-mass ratio in Figure 4.

3.2 Detecting active outflow signatures with SiO

A source is determined to have an SiO detection if a minimum 3σ detection is obtained in at least one pixel in the SiO integrated intensity maps. The integrated SiO intensity is extracted from the zeroth order moment maps, where the velocity range is determined using either the velocity of the upper and lower channels above 3σ in the SiO channel maps (where possible) or from the ¹²CO linewidths taken from [Maud et al. \(2015b\)](#). Furthermore, only pixels situated within the respective H¹³CO⁺ integrated intensity mask are considered (this was done to eliminate the possibility of a spurious detection that may appear towards the edge of the maps being identified as a detection). The SiO luminosity (in units of K km s⁻¹ kpc²) is calculated from $L_{\text{SiO}} = \int T_{\text{mb}(\text{SiO})} dv \times 4\pi d^2$, where $\int T_{\text{mb}(\text{SiO})} dv$ is the SiO integrated intensity extracted from the sum of the pixels in the zeroth order moment maps (see Table 3 for individual source values and Figure B2 of the online data for individual SiO integrated intensity maps), and d is the distance to the respective source. For sources without an SiO detection, we estimate the 3σ upper limits using the rms in a single pixel. For the 6 sources without a CO outflow detection a velocity interval of 26 km s⁻¹ (the average ¹²CO linewidth of the SiO

non-detections) is used to estimate the upper limit of the SiO luminosity.

SiO J=8-7 is detected towards 14 (~45%) of the 31 RMS sources observed (excluding both sources, G045.0711 and G020.7617, that fall outside of the distance limits), see Table 2 for a list of detections towards individual sources. We do not detect SiO emission towards the 6 sources without a confirmed CO outflow in [Maud et al. \(2015b\)](#). We detect SiO emission towards 3 of the 6 defined OFFSET sources, G203.3166-OFFSET, G081.7624-OFFSET and W75N. Therefore, we detect SiO emission, including the offset sources, towards 17(46%) of the distance limited sample (see Table 4).

For completeness, we also provide an estimate of the average SiO column density (N_{SiO}) and average abundance (X_{SiO}) in Table 3. We calculate the SiO column density using Equation 1 substituting the values for SiO (8-7). For the SiO abundance, we derive the N_{H_2} column density using the ¹²CO (3-2) column densities given in [Maud et al. \(2015b\)](#), averaged over the blue- and red-shifted outflow lobes. The CO (3-2) column densities were used because the SiO emission is likely to be produced as a result of shocks in the jet/outflow and is not expected to be associated with the compact continuum emission tracing the core. However, in doing this we also assume that SiO arises from the same component in the outflow as the CO emission, which may not be the case.

3.3 Infall signatures determined from the HCO⁺ and H¹³CO⁺ emission

Both HCO⁺ (4-3) and H¹³CO⁺ (4-3) are dense-gas tracers ($n_{\text{crit}} \sim 8 \times 10^6 \text{ cm}^{-3}$) and, as such, their emission can be used to probe the dynamics of the dense-gas, such as infall or expansion. Infall is typically interpreted if a blue asymmetry, either from a double-peaked line profile with a brighter blue peak or a single-peak profile, is observed in the optically thick HCO⁺ transition, and is offset from the optically thin isotopologue, H¹³CO⁺, which shows only a single peaked component at rest velocity (e.g. [Myers et al. 1996](#)). A single-peak in the optically thin H¹³CO⁺ (4-3) line allows us to distinguish between self absorption and multiple line of sight components in the optically thick HCO⁺ profile. The predominance of either a blue or red asymmetry is quantified by the skewness parameter ([Mardones et al. 1997](#)) which is estimated from,

$$\delta V = \frac{V_{\text{thick}} - V_{\text{thin}}}{\Delta V_{\text{thin}}}, \quad (2)$$

where V_{thick} and V_{thin} are the LSR velocities at line peak for the optically thick HCO⁺ (4-3) and optically thin H¹³CO⁺ (4-3) transitions, respectively. The velocity difference is then normalized by the FWHM of the optically thin H¹³CO⁺ line (ΔV_{thin}). The H¹³CO⁺ FWHM and V_{LSR} are taken from the Gaussian fits presented in Table A1 of the Appendix and V_{thick} is taken from the position of the brightest emission peak in the HCO⁺ spectrum. To explore the presence of global infall in these regions, the spectra shown in Figure 2 are extracted from the average of the emission over all pixels within the dendrogram-fitted masks. The result is then the dimensionless skewness parameter δV . A

Table 2. Summary of the molecular-line detections towards the sources surveyed. Column 1 gives the Galactic name, sources where a H^{13}CO^+ component was detected more than $14.5''$ offset from the RMS source position are labelled Galactic name-OFFSET. Column 2 gives the RMS classification of the source. Columns 3, 4, and 5 give the corresponding detection (Y), non-detection (N) or were not observed (-) of SiO, H^{13}CO^+ and HCO^+ respectively. Columns 6 and 7 are the asymmetries estimated from the H^{13}CO^+ and HCO^+ spectra extracted from both the average emission over the whole source and peak of the H^{13}CO^+ emission, where N, R and B represent no asymmetry, red asymmetry and blue asymmetry, respectively. Column 8 is the detection (Y), and non-detection (N) of *Herschel* $70\mu\text{m}$, within $14.5''$ of the peak of the H^{13}CO^+ component. Sources not available or present in the online data by either survey are noted by (-).

Source Name	RMS Type	SiO (8-7)	H^{13}CO^+ (4-3)	HCO^+ (4-3)	Line Asymmetry ^a		<i>Herschel</i> $70\mu\text{m}$ flux
					Average	Peak	
CO outflow detection							
G010.8411	YSO	N	Y	Y	N	N	-
G012.9090	YSO	Y	Y	Y	N	N	Y
G013.6562	YSO	Y	Y	Y	R	N	Y
G017.6380	YSO	N	Y	Y	N	B	Y
G018.3412	YSO	Y	Y	Y	N	N	Y
G043.3061	HII	Y	Y	Y	B	R	Y
G050.2213	YSO	Y	Y	Y	N	N	Y
G078.1224	YSO	Y	Y	Y	N	N	Y
G079.1272	YSO	Y	Y	Y	N	N	Y
G079.8749	HII	N	Y	Y	R	R	Y
G079.8749-OFFSET	-	N	Y	Y	N	B	Y
G081.7133	HII	Y	Y	-	-	-	Y
G081.7220	HII	Y	Y	Y	B	B	Y
G081.7522	YSO	Y	Y	-	-	-	Y
G081.7522-OFFSET	-	N	Y	-	-	-	Y
G081.7624	YSO	N	N	-	-	-	Y
G081.7624-OFFSET	-	Y	Y	-	-	-	Y
G081.8652 ^b	YSO	N	N	Y	-	-	N ^c
W75N ^b	-	Y	Y	Y	R	N	Y
G081.8789 ^b	HII	N	N	Y	-	-	N ^c
G083.0936	HII	N	Y	Y	N	N	-
G083.7071	YSO	N	N	Y	N	N	-
G083.7071-OFFSET	-	N	Y	Y	N	B	-
G083.7962	HII	N	Y	Y	R	N	-
G103.8744	YSO	N	Y	Y	N	B	Y
G109.8715	YSO	Y	Y	Y	N	B	Y
G192.6005	YSO	Y	Y	Y	N	N	Y
G194.9349	YSO	N	Y	Y	N	N	Y
G203.3166	YSO	Y	Y	Y	R	R	Y
G203.3166-OFFSET	-	Y	Y	Y	B	N	Y
G207.2654	HII/YSO	Y	Y	Y	N	N	Y
No CO outflow detection							
G080.8645	HII	N	Y	-	-	-	Y
G080.9383	HII	N	N	-	-	-	Y
G081.7131	YSO	N	N	-	-	-	Y
G196.4542	YSO	N	Y	Y	N	N	-
G217.3771	HII	N	Y	-	-	-	Y
G233.8306	YSO	N	N	-	-	-	Y

Notes

(a) The line asymmetry is given for both the average and peak emission, and is denoted by a B for a blue asymmetry where $\delta V \leq -0.25$, R for red asymmetry where $\delta V \geq 0.25$, and N for no asymmetry.

(b) These sources are all spatially located within ~ 1 arcminute. The H^{13}CO^+ emission peaks between the two RMS sources, $\sim 40''$ from G081.8789, and $\sim 20''$ from G081.8652. While H^{13}CO^+ emission does extend over the whole region, there appears to be no obvious extension or enhancement towards either RMS source, therefore the H^{13}CO^+ component is associated with the offset position, W75N, and G081.8789 and G081.8652 are classed as non-detections and their HCO^+ properties are not estimated.

(c) *Herschel* $70\mu\text{m}$ emission extends over both sources, however the dendrogram fit cannot separate the emission from the dominant $70\mu\text{m}$ component in the field which is associated with the offset position, W75N.

Table 3. Physical properties estimated for the sources. The 3σ upper limits (represented by $<$) are provided for sources that have no detected emission. Where (-) represents sources for which no estimate of the property was possible.

Source Name	Peak N_{HCO^+} (cm^{-2}) ($\times 10^{13}$)	Average N_{HCO^+} (cm^{-2}) ($\times 10^{13}$)	Average N_{SiO} (cm^{-2}) ($\times 10^{12}$)	Average X_{SiO} ($\times 10^{-9}$)	Mass (M_{\odot})	$\int T_{\text{SiO}} dv$ (K km s^{-1})
SiO Detection						
G012.9090	24.2±8.6	5.4±2.4	3.4±0.7	1.1±0.2	1167	25.4
G013.6562	5.1±0.7	4.5±0.4	2.0±0.4	0.5±0.2	1385	5.2
G018.3412	12.1±0.7	4.3±0.3	1.6±0.4	1.1±0.2	224	1.0
G043.3061	4.8±1.3	3.5±0.4	0.8±0.2	–	595	3.2
G050.2213	2.7±0.9	2.1±0.5	2.0±0.4	2.5±0.7	397	1.2
G078.1224	17.6±0.8	6.1±0.3	4.3±0.7	6.7±1.1	90	53.1
G079.1272	4.1±0.7	3.0±0.4	1.8±0.2	5.4±1.1	24	2.1
G081.7133	11.5±1.3	8.0±0.8	3.4±0.7	1.8±0.2	367	35.0
G081.7220	69.9±2.0	15.2±0.5	10.0±1.3	18.0±2.9	312	132.0
G081.7522	10.7±0.8	4.9±0.3	2.0±0.7	1.1±0.2	272	1.2
G081.7624-OFFSET	6.12±0.9	3.4±0.5	4.0±0.7	3.6±0.7	201	44.6
W75N	102.1±1.5	17.5±0.3	6.7±0.2	2.5±0.2	647	98.3
G109.8715	62.3±1.4	15.4±0.4	6.5±0.9	1.8±0.2	112	85.8
G192.6005	14.7±1.0	10.5±0.6	2.5±0.7	3.4±0.9	130	17.2
G203.3166	11.4±0.8	4.7±0.2	1.8±0.5	19.8±4.3	61	19.6
G203.3166-OFFSET	8.9±0.6	4.3±0.2	2.2±0.4	–	33	11.8
G207.2654	7.1±1.5	4.0±0.5	2.2±0.7	5.6±1.4	172	4.4
SiO Non-detection						
G010.8411	12.2±1.5	4.3±0.4	<1.3	–	139	<0.9
G017.6380	19.1±0.7	5.4±0.2	<1.3	–	374	<0.8
G079.8749	2.7±0.7	2.0±0.4	<1.1	–	–	<0.7
G079.8749-OFFSET	16.1±1.3	5.7±0.3	<1.1	–	–	<0.7
G081.7522-OFFSET	10.8±1.0	5.4±0.3	<1.3	–	–	<0.9
G083.0936	2.4±1.3	1.6±0.6	<0.9	–	–	<0.5
G083.7071-OFFSET	2.5±0.9	2.2±0.6	<1.3	–	–	<0.8
G083.7962	3.5±0.9	3.5±0.6	<1.3	–	–	<0.9
G103.8744	4.5±1.1	3.7±0.8	<1.6	–	91	<1.0
G194.9349	3.1±0.9	2.3±0.6	<1.3	–	–	<0.9
No SiO or CO Outflow Detected						
G080.8645	6.3±0.7	3.4±0.3	<1.3	–	137	<0.8
G196.4542	3.5±0.9	2.1±0.5	<1.6	–	167	<1.0
G217.3771	1.8±0.9	1.2±0.4	<1.3	–	–	<0.8

Table 4. Summary of the outflow and infall detections

Source Type	Total	SiO 3σ	Total HCO^+ Observed	Blue Asymmetric ^a Profile	
				Ave	Peak
YSO	20	10	16	0	3
HII	10	3	6	2	1
HII/YSO	1	1	1	0	0
OFFSET	6	3	4	1	2
Total (%)	37	17(46%)	27(73%)	3(12%)	6(24%)

Notes

(a) The asymmetry is derived for 25 sources using the H^{13}CO^+ and HCO^+ emission extracted from both the average (Ave) and peak (Peak) spectra. Where the average spectra are taken from the emission averaged over all pixels taken from the dendrogram fits and the peak spectra are taken from the pixel at the peak of the H^{13}CO^+ emission.

significant blue or red excess is defined as $\delta V \leq -0.25$ or $\delta V \geq 0.25$, respectively (Mardones et al. 1997). Of the sources where it was possible to determine the asymmetries, 3 objects show a blue excess indicative of infall and 5 show a red excess (expansion) and 17 show no red or blue excess. All 3 sources with a blue excess have a corresponding SiO detection and 3 of the 5 sources with a red excess have an SiO detection (see Table 2 for individual sources). The number of sources with an infall detection is consistent with the number of sources without an infall detection given the Poisson errors of 3 ± 1.7 and 5 ± 2.25 respectively. However, as the emission is extracted from the full source extent and likely encompasses multiple protostars, this may add noise and mask the signs of global infall. Therefore, we also assess the asymmetry considering the spectra from the H^{13}CO^+ peak position, finding a total of 6 sources (see Table 2) with a blue asymmetry and 3 with a red asymmetry. Only a single source G081.7220 displays a blue asymmetry in both the averaged and peak spectra. Furthermore, the Poisson errors are again

consistent for sources displaying a blue and red asymmetry of 6 ± 2.5 and 3 ± 1.7 , respectively. This suggests that the majority of sources in our sample show no preference for global infall motions. However, an important consideration is the sensitivity for infall asymmetry to line optical depth, excitation temperature, and density. [Smith et al. \(2013\)](#) find an increase in the blue asymmetry of the optically thick line with decreasing beam size, suggesting that matching the beam size with the energy of line transition will increase the detection of infall signatures. Furthermore, as noted we are likely sensitive to multiple sources within the JCMT beam which can add noise to the observations. Future higher spatial resolution observations, resolving individual protostars, will be able to directly test this. It should also be noted that HCO^+ is a known tracer of outflow emission in massive star forming regions (e.g. [Walker-Smith et al. 2014](#)), and several of the regions display broad line wings in the HCO^+ spectra which can be clearly seen in Figure 2 (e.g. G109.8715). In addition, several sources show an offset between the red- and blue-shifted HCO^+ emission in Figure B1 of the online data (e.g. G050.2213, G192.6005, and G207.2654), again suggesting that the HCO^+ emission is influenced by the outflow in several regions. Furthermore, sources that display no asymmetric line profile in the HCO^+ spectra, taken over the whole source extent, but show a blue asymmetric profile in the spectra taken from the peak, tend to show multiple components in the red- and blue-shifted HCO^+ emission maps (e.g. G017.6562 and G083.7071-OFFSET). This may add to the lack of consistency between the presence of asymmetry in the peak and average spectral line profiles.

3.4 Far-IR associations

We obtain $70\mu\text{m}$ *Herschel* PACS fluxes for 25 of the 31 RMS sources with available data in the archive. The $70\mu\text{m}$ flux was extracted using dendrogram fits, again using the python package *astrodendro*. The minimum number of contiguous pixels was set to the beam area of the *Herschel* map and the minimum detection was set to 5σ . The rms noise for each source was determined from an aperture local to that source and not from the entire map, therefore larger regions with higher levels of emission may have higher noise estimates. We assign *Herschel* $70\mu\text{m}$ emission to an H^{13}CO^+ component if the peak of the $70\mu\text{m}$ emission is within $14.5''$ of the peak of the H^{13}CO^+ component (see Table 2 for the association of a $70\mu\text{m}$ component with a respective H^{13}CO^+ component). Of the 25 RMS sources with available *Herschel* $70\mu\text{m}$ data, 23 have an associated *Herschel* peak. Only G081.8652, and G081.8789 do not have an associated $70\mu\text{m}$ component. However, as with the H^{13}CO^+ emission towards these sources, $70\mu\text{m}$ emission extends over both RMS source positions but there is no obvious enhancement towards either RMS source and the peak of the $70\mu\text{m}$ emission coincides with the offset H^{13}CO^+ component, W75N. All of the OFFSET sources have an associated $70\mu\text{m}$ component within $14.5''$ of the identified H^{13}CO^+ peak⁵. The sum of the $70\mu\text{m}$ flux, within the dendrogram mask, is converted to a luminosity through

$L_{70\mu\text{m}} = 4\pi d^2 \cdot F_{70\mu\text{m}}$, using a $25\mu\text{m}$ bandwidth for the *Herschel* $70\mu\text{m}$ PACS filter.

4 DISCUSSION

4.1 Comparison of SiO-detected and non-detected source properties

SiO emission is detected towards approximately 46% of the sources. Table 5 presents the average, median, and standard deviation of the source properties (e.g., bolometric luminosity, distance, and HCO^+ column density) for the SiO-detected and non-detected samples. For completeness we also include sources without an SiO or a CO outflow detection. We perform Kolmogorov-Smirnov (KS) tests to determine if the source properties of the SiO-detected and non-detected sources are drawn from the same underlying distribution. The returned p -value from the KS test gives the confidence level at which the null hypothesis (i.e. that the two samples originate from the same underlying distribution) can be rejected. A value of ≤ 0.01 is associated with a high confidence that the two populations originate from different underlying distributions. We find no difference in the distance to sources with or without an SiO detection. The median distance is 1.4kpc for both samples. If the emission traced by SiO is considerably smaller than the beam, suggesting a very young outflow, then beam dilution may be responsible for the remainder of the SiO non-detections. However, this would need to be tested with higher angular resolution observations. We note that several of the SiO non-detections have the weakest H^{13}CO^+ emission in the sample, but there is no obvious difference in the masses or bolometric luminosities between populations. Therefore, the lack of an SiO detection towards these sources should not be due to sensitivity limitations in the sample.

We find no significant differences between the source properties of the SiO-detected and SiO non-detected populations (see Table 5 for a list of all returned p -values). If we compare the outflow properties taken from [Maud et al. \(2015b\)](#), such as the outflow velocity, momentum, force, mass and energy, we find only the CO outflow velocity has a p -value ≤ 0.01 between the SiO-detected and SiO non-detected sample. Furthermore, only sources with an SiO detection have a ^{12}CO (3-2) total linewidth $> 35 \text{ km s}^{-1}$, suggesting SiO emission is a more efficient tracer of high-velocity outflows. This is consistent with the CO outflow velocity ranges observed by [Gibb et al. \(2007\)](#) towards a sample of young massive stars, where sources with detected SiO (5-4) have associated outflows with a total maximum CO velocity of $> 36 \text{ km s}^{-1}$. This suggests that the detection of the higher J transitions of SiO is an indication of the presence of a high-velocity outflow and is consistent with the expected shock velocities ($> 25 \text{ km s}^{-1}$) required to disrupt dust grains (e.g. [Schilke et al. 1997](#)). For the remaining CO outflow properties we find no difference between the SiO-detected and non-detected samples. However, we find the

$70\mu\text{m}$ emission is not directly associated with the offset position C-MM3

⁵ It should be noted that for G203.3166-OFFSET when observed at higher spatial resolution (e.g. [Cunningham et al. 2016](#)) the

Table 5. Summary of properties between SiO-detected and non-detected sources.

Source properties	SiO-detected ^a		No SiO Detected ^a		No SiO or CO Detected ^a		KS-test ^b	
	Mean	Median	Mean	Median	Mean	Median	No SiO	No SiO or CO
Distance (kpc)	1.9±1.1	1.4	1.6±0.3	1.4	2.1±1.1	1.4	0.45	0.63
L* (L _⊙ × 10 ³)	13±12	11	15±27	5	20±18	11	0.52	0.51
H ¹³ CO ⁺ FWHM ^c (km s ⁻¹)	2.9±0.8	2.7	2.0±0.5	1.9	2.7±0.5	2.5	0.05	0.11
C ¹⁸ O FWHM (km s ⁻¹)	2.9±0.7	2.6	2.6±0.7	2.7	–	–	0.48	–
L _{70μm} (L _⊙ × 10 ²)	27±30	18	17±34	2	18±15	10	0.21	0.33
Mass (M _⊙)	364±378	224	201±124	139	107±64	137	0.91	0.18
Average N _{HCO+} (cm ⁻² × 10 ¹³)	6.9±4.7	4.7	3.6±1.5	3.6	2.3±0.9	2.1	0.29	0.06
Peak N _{HCO+} (cm ⁻² × 10 ¹³)	22.1±27.4	11.4	7.7±6.0	4.2	3.9±1.9	3.5	0.12	0.04
¹² CO linewidth (km s ⁻¹)	48±19	56	26±6	25	–	–	0.009	–

Notes

(a) The mean is given with ± standard deviation. For the No SiO Detected sample the mean and median values are estimated considering sources without an SiO-detection that have a CO outflow detection. For the No SiO or CO Detected column the mean and median values are estimated considering only those sources with no SiO and no CO outflow.

(b) The results of the KS test for the No SiO column is considering sources with and without an SiO detection that have a CO outflow detection. The No SiO or CO is considering all sources without an SiO detection, including those sources with no CO outflow in Maud et al. (2015b).

(c) The H¹³CO⁺ FWHM presented here is extracted from the dendrogram fits to the full source extent.

total outflow-mass between the two populations has a p -value ≥ 0.9999 , thus the outflow-masses estimated from the CO emission are drawn from the same distribution.

4.2 SiO luminosity as a function of source properties

We perform Spearman rank correlations along with linear regression fits to the estimated source properties as a function of the SiO luminosity with the outcomes presented in Table 6. We assume that a correlation is significant, given the small sample sizes, if a P-value of ≤ 0.01 is found and a correlation coefficient (R) of > 0.53 is obtained. The H¹³CO⁺ FWHM, HCO⁺ column density (both the peak and average), ¹²CO (3-2) total linewidth or outflow velocity, outflow force and energy are all found to correlate with the SiO luminosity and are presented in Figure 3. We find no correlation between the bolometric luminosity, source mass, outflow-mass, or momentum with the SiO luminosity.

The correlation of the SiO luminosity with the H¹³CO⁺ FWHM was also observed by Klaassen et al. (2012) in their sample of high mass star forming regions. Furthermore, for both the SiO-detected and non-detected sources, the H¹³CO⁺ FWHM is greater than would be estimated considering only the linewidth-size relation (Larson 1981), and may then be a measure of the turbulence in these regions. This would suggest an increase in turbulence with increasing SiO luminosity, which may be a product of the shocks associated with the production of SiO. However, no correlation is observed between the C¹⁸O FWHM from Maud et al. (2015a) and the SiO luminosity. Towards several sources (e.g. G050.2213, G192.6005, and G207.2654) the HCO⁺ red- and blue-shifted emission (see Figure B1 in the online data) appears to be offset, indicating the HCO⁺ emission is tracing the outflows in these sources. Thus, it may also be the case that the H¹³CO⁺ emission is sensitive to the outflows

in these regions. A correlation is observed between the SiO luminosity and the HCO⁺ column density, which suggests a preference for increased SiO emission towards sources with higher densities, as seen in the low mass regime (Gibb et al. 2004). Furthermore, we find the SiO luminosity is correlated with the CO outflow velocity, again showing the association of SiO emission with high velocity outflows as seen in previous works (e.g. Gibb et al. 2007).

4.3 SiO luminosity with source evolution

SiO emission was predominantly detected towards Class 0 sources in the low-mass regime (Gibb et al. 2004) suggesting a preference for SiO emission towards younger, denser sources with faster outflows. However, in the high-mass regime the evolutionary sequence and outflow properties are less constrained, and previous works have found the observed SiO luminosity and integrated intensity to both increase and decrease as a function of evolution (e.g. Klaassen et al. 2012; Sánchez-Monge et al. 2013; Leurini et al. 2014). In this work we aim to establish if an evolutionary trend, as seen in the low-mass regime, does transfer to the high-mass regime. With this in mind, we purposely selected a sample of massive star forming regions from the RMS survey with a range of luminosity and evolutionary stage (categorised into two evolutionary stages in the RMS survey; massive YSOs (MYSOs) and compact HII regions, see Lumsden et al. 2013). A KS test shows no significant difference in the SiO luminosity between the MYSOs and HII regions. Moreover, the SiO luminosities of the OFFSET and HII/YSO sources also show no obvious differences compared with the MYSO sample.

4.3.1 Evolutionary indicators

We adopt the approach used by Sánchez-Monge et al. (2013) and López-Sepulcre et al. (2011) and compare the bolomet-

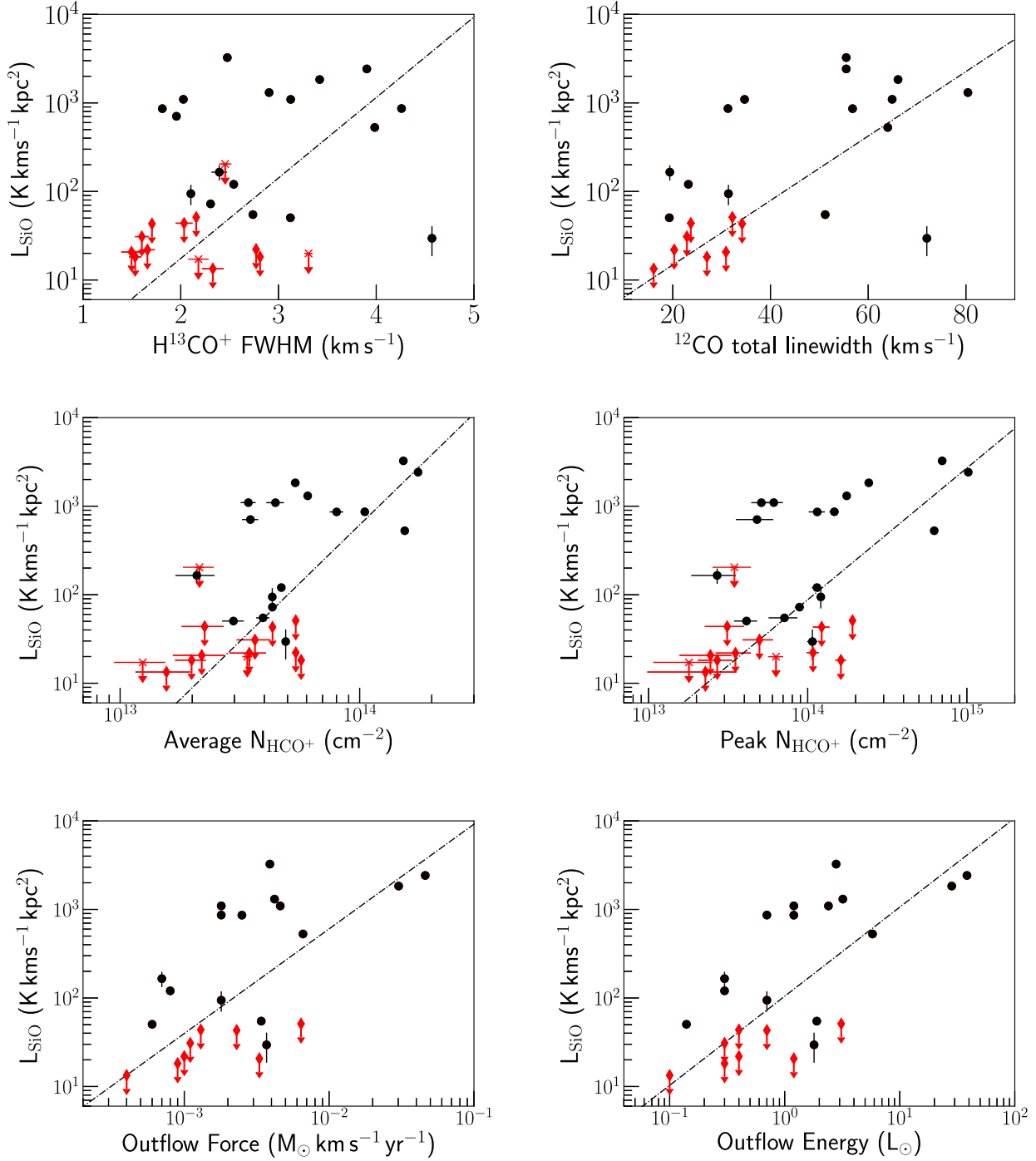


Figure 3. SiO luminosity as a function of source properties, for those parameter relationships given in Table 6 with a P-value ≤ 0.01 and a correlation coefficient > 0.53 . The plots include the H^{13}CO^+ FWHM, ^{12}CO (3-2) total linewidth or outflow velocity, average and peak HCO^+ column density, outflow force and outflow energy. The black circles represent those sources with an SiO detection above 3σ that have a confirmed CO outflow detection in Maud et al. (2015b). The red diamonds and red crosses represent the 3σ upper limits for non-detected SiO sources with and without a CO outflow respectively. The black dashed lines are linear regression fits (provided in Table 6) to the data. For sources that show no L_{SiO} error bars the errors are smaller than the symbols. It should be noted that the errors in the SiO luminosity do not account for uncertainties in source distance, and should be seen as minimal errors.

Table 6. Spearman rank correlation statistics for source properties as a function of the SiO luminosity. The P-value represents the probability of a correlation arising by chance, R is the resultant correlation coefficient, and N is the number of sources in each sample and the linear fit for SiO luminosity relationship is also given for properties showing a correlation. The Spearman rank probability of false correlation, the linear correlation coefficient and the resulting linear regression fit were derived using the ASURV package (Feigelson & Nelson 1985; Isobe et al. 1986; Lavalley et al. 1992) considering the 3σ upper limits only. The linear fits are for the \log_{10} of the SiO luminosity and the \log_{10} of the source properties (excluding the H^{13}CO^+ FWHM and ^{12}CO (3-2) linewidth). The H^{13}CO^+ FWHM is extracted from the dendrogram fits to the full source extent.

Correlation with L_{SiO}	N	P-value	R	Linear fit
L_* (L_{\odot})	32	0.509	–	–
H^{13}CO^+ FWHM (km s^{-1})	30	≤ 0.003	0.66	$\text{Log}_{10}(L_{\text{SiO}}) = (0.91 \pm 0.18) \times \text{H}^{13}\text{CO}^+ \text{ FWHM} - 0.58$
C^{18}O FWHM (km s^{-1})	23	0.121	–	–
$L_{70\mu\text{m}}$ (L_{\odot})	29	0.049	–	–
Mass (M_{\odot})	23	0.033	–	–
N_{HCO^+} Peak (cm^{-2})	30	0.003	0.59	$\text{Log}_{10}(L_{\text{SiO}}) = (1.49 \pm 0.38) \times \text{Log}_{10}(N_{\text{HCO}^+}) - 18.89$
N_{HCO^+} Average (cm^{-2})	30	0.003	0.64	$\text{Log}_{10}(L_{\text{SiO}}) = (2.63 \pm 0.62) \times \text{Log}_{10}(N_{\text{HCO}^+}) - 34.05$
^{12}CO linewidth (km s^{-1})	23	≤ 0.004	0.62	$\text{Log}_{10}(L_{\text{SiO}}) = (0.04 \pm 0.01) \times ^{12}\text{CO} \text{ linewidth} + 0.44$
M_{total} (M_{\odot})	23	0.54	–	–
P_{total} ($M_{\odot} \text{ km s}^{-1}$)	23	0.08	–	–
E_{total} (ergs)	23	0.02	–	–
\dot{M}_{total} ($M_{\odot} \text{ yr}^{-1}$)	23	0.11	–	–
\dot{P}_{total} ($M_{\odot} \text{ km s}^{-1} \text{ yr}^{-1}$)	23	0.01	0.60	$\text{Log}_{10}(L_{\text{SiO}}) = (1.18 \pm 0.32) \times \text{Log}_{10}(\dot{P}_{\text{total}}) + 5.14$
\dot{E}_{total} (L_{\odot})	23	0.004	0.67	$\text{Log}_{10}(L_{\text{SiO}}) = (1.00 \pm 0.25) \times \text{Log}_{10}(\dot{E}_{\text{total}}) + 2.02$

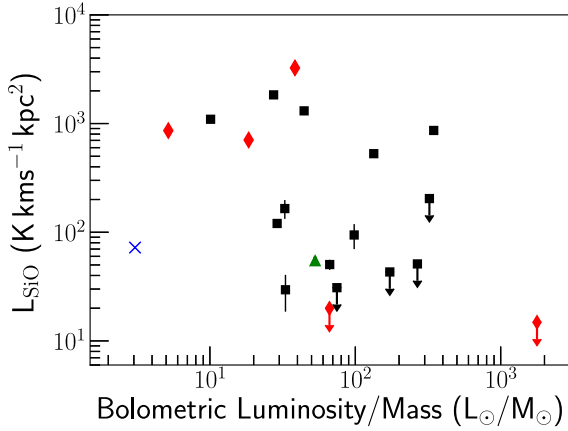


Figure 4. SiO luminosity as a function of bolometric luminosity-to-mass ratio (L_{bol}/M_{\odot}). The black squares, red diamonds, and green triangle represent YSOs, HII, and HII/YSO sources with an SiO detection, respectively. Sources without an SiO detection are represented as upper limits using the same colours/symbols as for the SiO-detected sources. The blue cross represents the offset source G203.3166-OFFSET, where the bolometric luminosity estimate is taken from Cunningham et al. (2016). We do not have bolometric luminosity estimates for the remaining OFFSET sources, and as such, are subsequently missing from the figure.

ric luminosity-to-mass ratio (L_{bol}/M_{\odot}), suggested as an indicator of the age of a given source, to the SiO luminosity in Figure 4. Molinari et al. (2008) showed that as a source evolves the luminosity is expected to increase more rapidly than the core envelope mass, which is expected to decrease only slightly due to mass loss from winds and jets. An increase in the bolometric luminosity-to-mass ra-

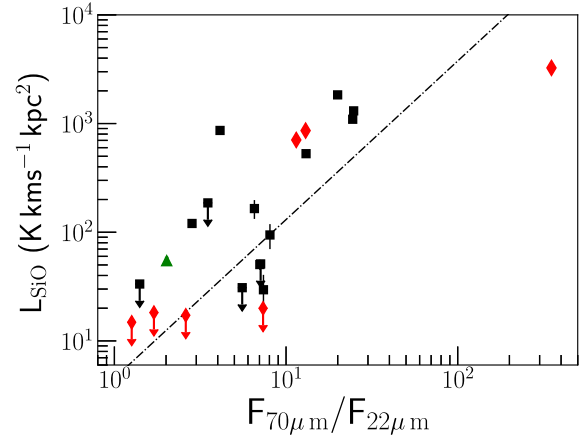


Figure 5. SiO luminosity as a function of the F70/F22 colour ratio. The symbols and colours are the same as in Figure 4. The offset sources are not included as their $22\mu\text{m}$ fluxes were not available. The linear fit is shown by the black dashed line and has a correlation coefficient of $R=0.76$ and a linear fit given by $\text{Log}_{10}(L_{\text{SiO}}) = (1.46 \pm 0.30) \times \text{Log}_{10}(F70/F22) + 0.66$.

tio would potentially indicate a more advanced evolutionary stage. We find that all of the SiO non-detected sources have higher ($>50 L_{\odot}/M_{\odot}$) bolometric-to-luminosity ratios. The result of the KS test returns a p -value of 0.009 between the SiO-detected and SiO non-detected samples, suggesting they are drawn from different populations. However, it should be noted that the sample size for the non-detected sources is low and includes 3 of those sources without either an SiO detection or an associated CO outflow. As with the bolometric luminosity, we find no difference between the

RMS classifications. This was previously observed by both [Urquhart et al. \(2014\)](#) and [Maud et al. \(2015a\)](#), where no indistinguishable differences in the bolometric luminosity-to-mass ratios between the MYSOs and compact HII regions from the RMS survey were found. This suggests that these sources are either likely to be at a similar evolutionary stage or it may be the case that the luminosity for this IR-bright stage has stopped rapidly increasing and the bolometric luminosity-to-mass ratio may not be sensitive enough to distinguish the evolutionary stages in this sample. For the offset source G203.3166-OFFSET or CMM-3⁶ this source shows the smallest bolometric luminosity-to-mass ratio in the sample, in agreement with it being a young protostar (e.g. [Cunningham et al. 2016](#); [Watanabe et al. 2015](#)).

In addition, we use the ratio of mid- to far-IR colours as a potential indication of age in these sources. In Figure 5 we plot the ratio of the 70 μ m flux estimated from the *Herschel* data with the 22 μ m WISE flux (F70/F22)⁷. As a source evolves and the emission moves to shorter wavelengths, we would expect the F70/F22 colour ratio to decrease. A Spearman rank correlation test gives a correlation coefficient of 0.76 and probability of a false correlation given by <0.001 between the SiO luminosity and the F70/F22 colour ratio. Thus, the SiO luminosity is stronger in the redder, potentially younger, more embedded sources. This may indicate that the colour ratio is more sensitive to evolution in these sources. However, a KS test between the SiO-detected and SiO non-detected sources only gives a *p*-value of ~ 0.06 and is therefore not significant between the populations, which may again be a result of these sources being at a similar evolutionary stage. [Csengeri et al. 2016](#) noted that the bolometric luminosity-to-mass ratio can be dominated by the most massive IR-bright source in the region, the F70/F22 colour ratio is also likely to suffer from this. Furthermore, as suggested by [Maud et al. \(2015b\)](#) there is evidence that several of these regions are likely to host multiple outflows at this spatial resolution (e.g. G081.7220/DR21 OH; [Girart et al. 2013](#), CMM-3 in NGC2264-C; [Watanabe et al. 2017](#)). Additionally, we are assuming that the SiO emission is associated with the IR-bright RMS source in all regions, which was not the case towards G203.3166/NGC2264-C ([Cunningham et al. 2016](#)). This is likely to add scatter to the statistics.

5 CONCLUSIONS

We present the results of a JCMT SiO (8-7), H¹³CO⁺ and HCO⁺ (4-3) survey towards a distance limited sample of 31 massive star-forming regions drawn from the RMS survey. The presence of a young, active outflow is associated with the detection of SiO (8-7) emission and we use previous ¹²CO (3-2) data ([Maud et al. 2015b](#)) to determine outflow properties and identify potential fossil outflows. We explore the presence of possible global infall from the HCO⁺ and H¹³CO⁺ (4-3) emission. Our results are summarized below.

⁶ The bolometric luminosity for this source is taken from [Cunningham et al. \(2016\)](#) and the mass is taken from the SCUBA mass estimated here.

⁷ The WISE flux is extracted directly from the RMS survey database, for one source, G012.9090, which does not have a WISE flux, the MSX 21 μ m flux is used.

(i) We detect SiO (8-7) emission towards $\sim 46\%$ of the sources, where the lack of an SiO detection does not appear to be due to sensitivity limitations or distance to the sources. We find only the CO outflow velocity shows a significant difference between SiO-detected (i.e. a potentially active outflow) and SiO non-detected (i.e. a potentially fossil remnant driven outflow) sources. Thus, the detection of SiO is an indication of the presence of a high velocity, likely active outflow and is consistent with the expected shock velocities required to disrupt dust grains. In addition, correlations between the SiO luminosity and the H¹³CO⁺ FWHM, HCO⁺ column density, ¹²CO (3-2) total outflow velocity, outflow force and energy are found. Thus, the production and strength of the SiO emission is increased towards potentially more turbulent regions with increased column densities. Similarly, regions with faster and more powerful outflows are more likely to produce stronger SiO emission, as observed in the low mass regime. However, it is possible the H¹³CO⁺ is also tracing the outflow emission in these sources.

(ii) We find tentative evidence from the bolometric luminosity-to-mass ratio and F70/F22 colour ratios that sources with an SiO detection are associated with potentially younger, more embedded regions. However, if multiple outflows are present or the SiO emission is not associated with the RMS source this would likely add scatter to the statistics. Higher resolution observations are required to fully explore this.

(iii) We do not find a significant number of blue asymmetric profiles, indicative of global infall, towards these sources. However, HCO⁺ (4-3) may not be best suited tracer, at this spatial resolution, to detect global infall signatures in these sources. Higher spatial resolution observations, where infall motions onto individual protostars can be resolved, will be able to directly probe this.

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SUPPORTING INFORMATION

Additional supporting information may be found in the online version of this article: **Appendix B**. HCO⁺, H¹³CO⁺ and SiO emission maps. Please note: Oxford University Press is not responsible for the content or functionality of any supporting materials supplied by the authors. Any queries (other than missing material) should be directed to the corresponding author for this article.

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APPENDIX A: H¹³CO⁺ GAUSSIAN FITS

Presented below are the resulting Gaussian fits to the H¹³CO⁺ spectra.

Table A1. Fitted parameters from a single Gaussian fit to the sum of the H^{13}CO^+ (4-3) line emission extracted from all pixels within H^{13}CO^+ (4-3) 5σ masked regions. Column 1 is the galactic name, Column 2 is the RMS classification, and Column 3 gives the total number of pixels in the H^{13}CO^+ (4-3) masks used to extract the emission. Columns 4, 5, 6 and 7 give peak, central velocity, FWHM and integrated intensity from a single Gaussian fit to the sum of the H^{13}CO^+ (4-3) emission extracted from all pixels within the masked region.

Source Name	Type	No of pixels	summed T_{mb} (K)	V_{LSR} (km s^{-1})	δV (km s^{-1})	summed $T_{mb} dv$ (K km s^{-1})
CO Outflow						
G010.8411-02.5919	YSO	17	14.38±0.76	11.98±0.04	1.71±0.10	26.12±2.11
G012.9090-00.2607	YSO	38	19.94±0.58	37.32±0.05	3.42±0.11	72.65±3.21
G013.6562-00.5997	YSO	4	1.90±0.12	48.00±0.10	3.13±0.23	6.32±0.62
G017.6380+00.1566	YSO	33	27.57±0.77	22.33±0.03	2.16±0.07	63.38±2.71
G018.3412+01.7681	YSO	21	14.37±0.56	32.84±0.04	2.10±0.10	32.19±1.91
G043.3061-00.2106	HII	6	2.92±0.21	59.28±0.08	2.40±0.20	7.45±0.81
G045.0711+00.1325	HII	13	6.97±0.14	59.10±0.06	6.20±0.15	45.98±1.43
G050.2213-00.6063	YSO	4	0.96±0.15	40.36±0.23	2.90±0.54	2.97±0.72
G078.1224+03.6320	YSO	22	14.26±0.46	-3.32±0.05	3.12±0.12	47.39±2.35
G079.1272+02.2782	YSO	5	2.74±0.26	-1.58±0.09	1.81±0.20	5.28±0.77
G079.8749+01.1821	HII	5	2.16±0.29	-4.90±0.10	1.54±0.24	3.53±0.71
G079.8749+01.1821-OFFSET	-	19	12.84±0.49	-3.14±0.05	2.81±0.12	38.44±2.25
G081.7133+00.5589	YSO	8	8.63±0.53	-4.09±0.08	2.47±0.18	22.76±2.14
G081.7220+00.5699	HII	53	58.83±1.32	-3.17±0.05	4.57±0.12	286.36±9.84
G081.7522+00.5906	YSO	23	18.58±0.70	-4.04±0.04	2.03±0.09	40.11±2.29
G081.7522+00.5906-OFFSET	-	20	13.02±0.51	-3.19±0.05	2.77±0.12	38.43±2.28
G081.7624+00.5916-OFFSET	YSO	19	11.11±0.94	-4.34±0.08	1.96±0.19	23.2±3.03
G081.8652+00.7800	YSO	-	-	-	-	-
W75N	-	56	83.83±0.75	9.67±0.017	3.90±0.04	348.53±4.78
G081.8789+00.7822	HII	-	-	-	-	-
G083.0936+03.2724	HII	4	0.89±0.22	-3.50±0.29	2.33±0.67	2.22±0.84
G083.7071+03.2817	YSO	-	-	-	-	-
G083.7071+03.2817-OFFSET	-	4	1.95±0.35	-3.62±0.13	1.50±0.31	3.11±0.85
G083.7962+03.3058	HII	4	2.78±0.33	-4.31±0.10	1.66±0.23	4.91±0.88
G103.8744+01.8558	YSO	5	3.80±0.55	-18.30±0.11	1.60±0.27	6.49±1.44
G109.8715+02.1156	YSO	71	91.63±1.31	-10.80±0.03	3.99±0.07	388.87±8.49
G192.6005-00.0479	YSO	5	4.11±0.14	7.84±0.07	4.26±0.17	18.65±0.98
G194.9349-01.2224	YSO	4	1.48±0.27	15.61±0.18	2.03±0.43	3.20±0.89
G203.3166+02.0564	YSO	50	34.05±1.06	8.15±0.04	2.31±0.08	83.60±3.96
G203.3166+02.0564-OFFSET	-	28	15.87±0.56	7.55±0.04	2.54±0.10	42.96±2.32
G207.2654-01.8080	HII/YSO	12	5.77±0.45	12.58±0.10	2.74±0.24	16.83±1.98
No CO Outflow						
G080.8645+00.4197	HII	11	3.76±0.22	-2.75±0.095	3.31±0.22	13.26±1.17
G080.9383-00.1268	HII	-	-	-	-	-
G081.7131+00.5792	YSO	-	-	-	-	-
G196.4542-01.6777	YSO	4	1.16±0.18	19.34±0.18	2.46±0.43	3.20±0.89
G217.3771-00.0828	HII	4	0.76±0.17	23.93±0.25	2.18±0.58	1.76±0.62
G233.8306-00.1803	YSO	-	-	-	-	-

APPENDIX B: H^{13}CO^+ , HCO^+ AND SiO ZEROth ORDER MOMENT MAPS

This paper has been typeset from a $\text{T}_{\text{E}}\text{X}/\text{L}^{\text{A}}\text{T}_{\text{E}}\text{X}$ file prepared by the author.

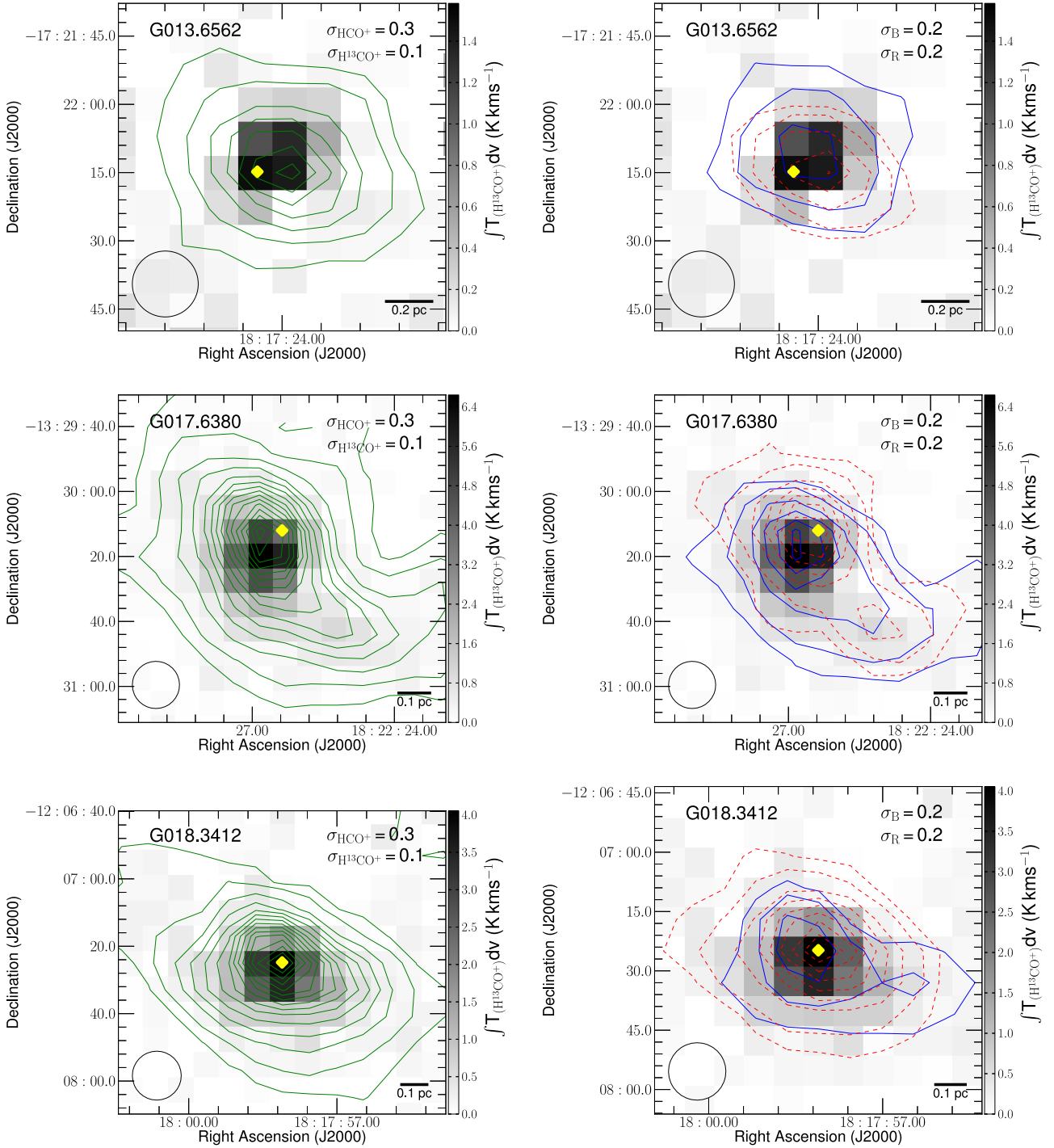


Figure B1. H¹³CO⁺ and HCO⁺ zeroth order moment maps. The total integrated H¹³CO⁺ emission is shown in greyscale, integrated from the minimum to maximum channels with a 3 σ detection. The yellow diamonds and crosses are the RMS source position(s) and offset position, respectively. The JCMT beam is shown in the bottom left corner, and the source name is shown in the top left corner. **Left:** The total integrated HCO⁺ emission is overlaid in green solid contours (again integrated from the minimum and maximum channels with a 3 σ detection). The 1 σ rms (in units of K km s^{−1}) for both the HCO⁺ (σ_{HCO^+}) and H¹³CO⁺ ($\sigma_{\text{H}^{13}\text{CO}^+}$) integrated intensity maps are given in the top right corner. The HCO⁺ contour levels are from 1 $\sigma \times$ (5, 10, 20, ... to peak in-steps of 10 σ). **Right:** The red- and blue-shifted HCO⁺ emission is shown by the red (dashed) and blue (solid) contours, respectively. The blue- and red-shifted contours are taken from the minimum and maximum channels with 3 σ emission, respectively, excluding the central velocity range defined by the H¹³CO⁺ FWHM (see Table A1 for the H¹³CO⁺ FWHM values). The 1 σ levels for the red- (σ_{R}) and blue-shifted (σ_{B}) contours are given in the top right corner, where the contour levels are from 1 $\sigma \times$ (5, 10, 20, ... to peak in-steps of 10 σ). The velocity ranges used for the total integrated HCO⁺ emission are 45.0–51.0 km s^{−1} for G013.6562, 18.9–25.7 km s^{−1} for G017.6380, and 30.2–36.4 km s^{−1} for G018.3412.

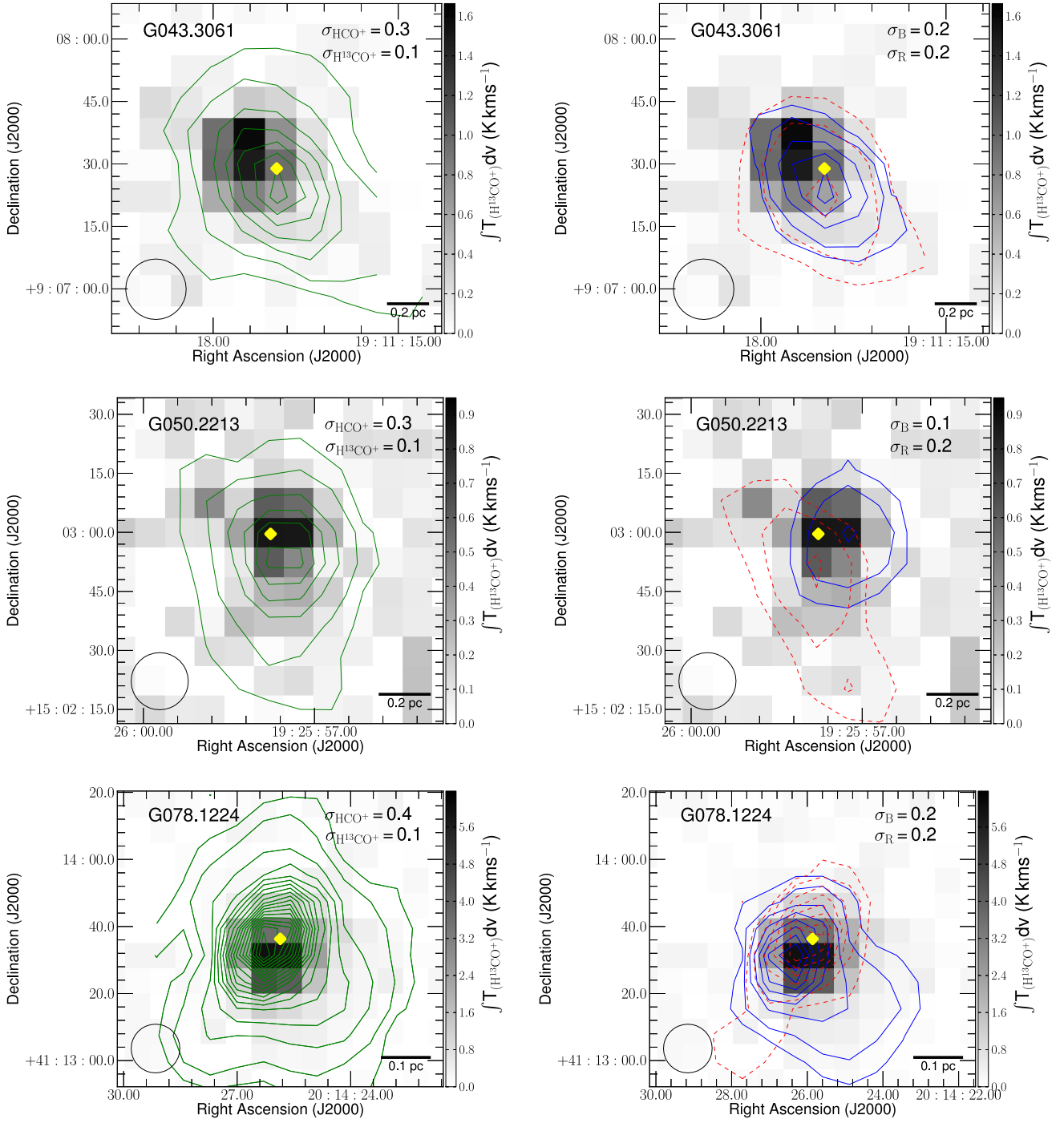


Figure B1 – *continued* – The velocity ranges used to integrate the total emission are $55.7\text{--}62.7\text{ km s}^{-1}$ for G043.3061, $38.1\text{--}43.3\text{ km s}^{-1}$ for G050.2213, and $-8.1\text{--}1.6\text{ km s}^{-1}$ for G078.1224.

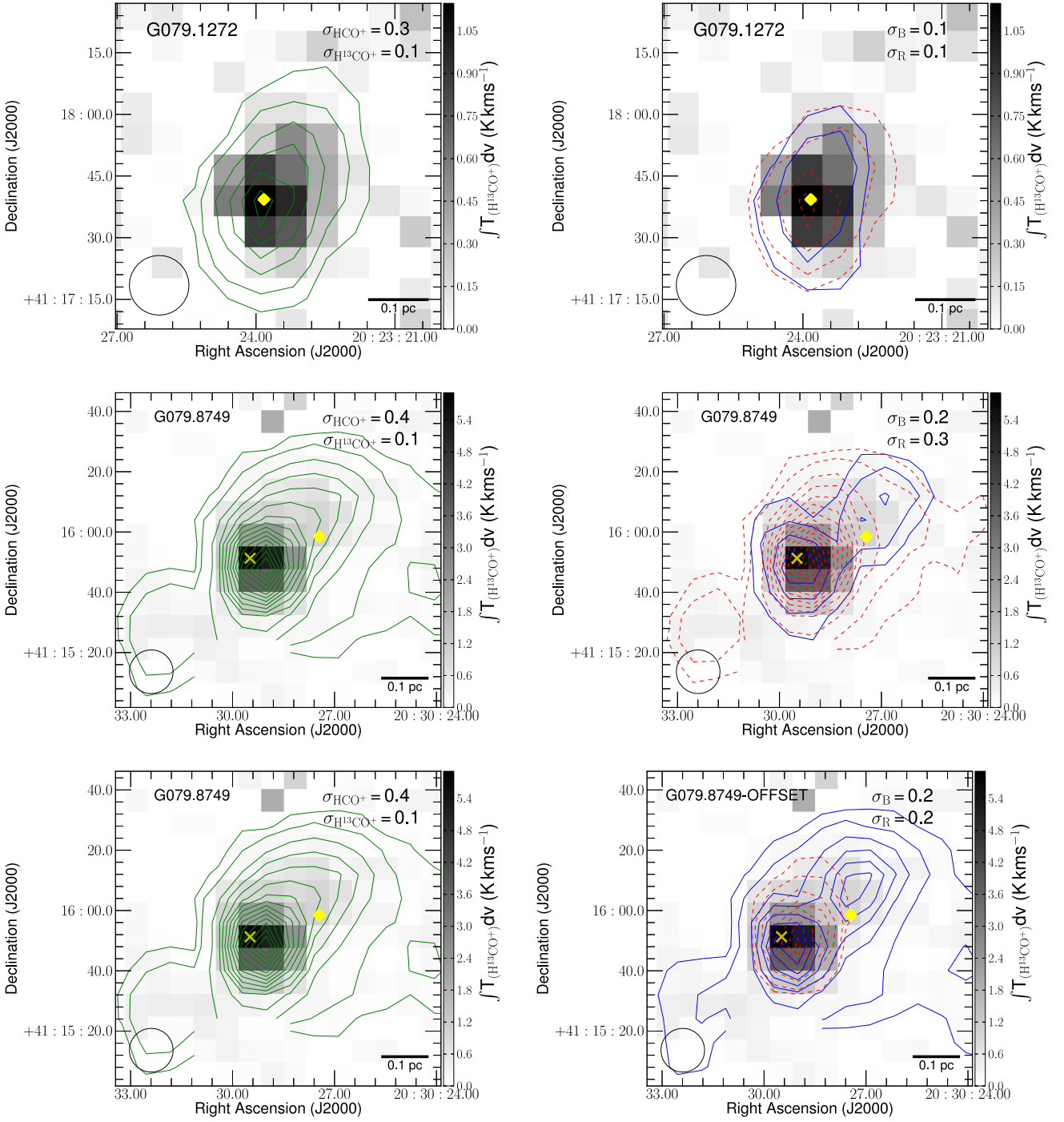


Figure B1 – *continued* – The velocity ranges used to integrate the total emission are -3.3 – 0.9 km s $^{-1}$ for G079.1272, -7.7 – 0.9 km s $^{-1}$ for both G079.8749 and G079.8749-OFFSET.

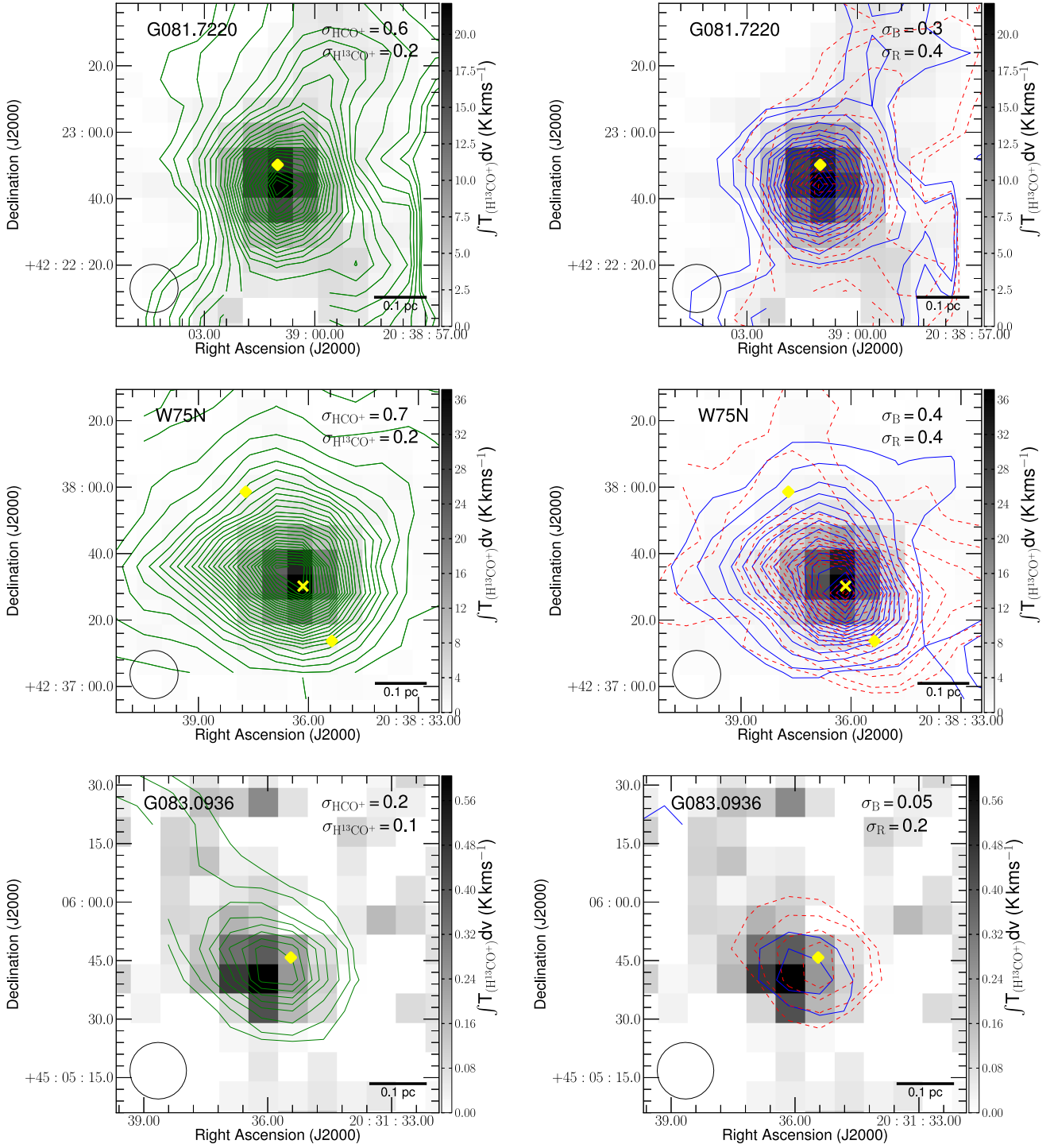


Figure B1 – *continued* – The velocity ranges used to integrate the total emission are -9.5 – 4.8 km s^{-1} for G081.7220, 0.8 – 18.1 km s^{-1} for W75N, and -5.1 – -0.1 km s^{-1} for G083.0936.

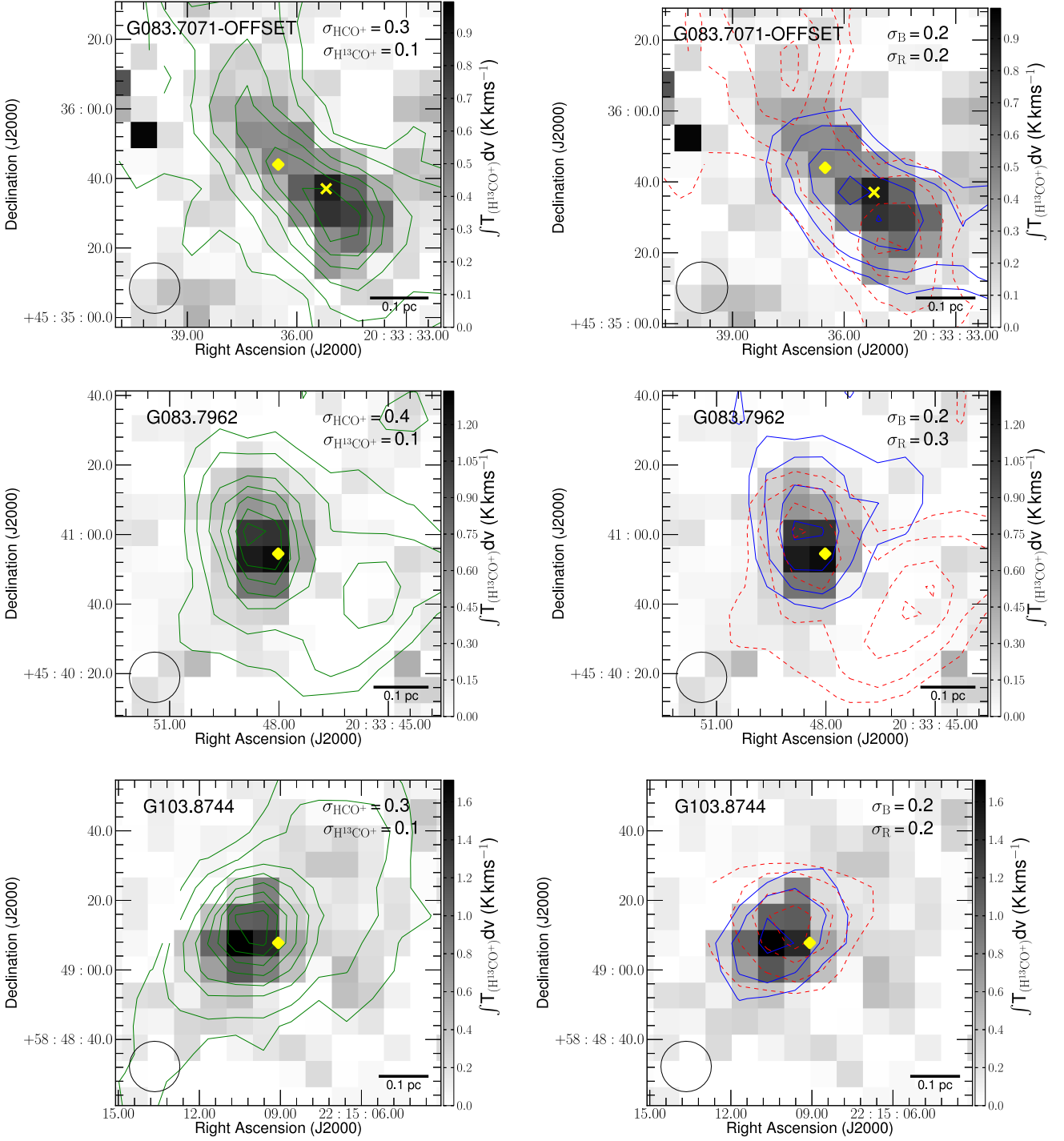


Figure B1 – *continued* – The velocity ranges used to integrate the total emission are -5.8 – -1.3 km s^{-1} for G083.7071-OFFSET, -6.2 – -0.3 km s^{-1} for G083.7962, and -20.2 – -16.3 km s^{-1} for G103.8744.

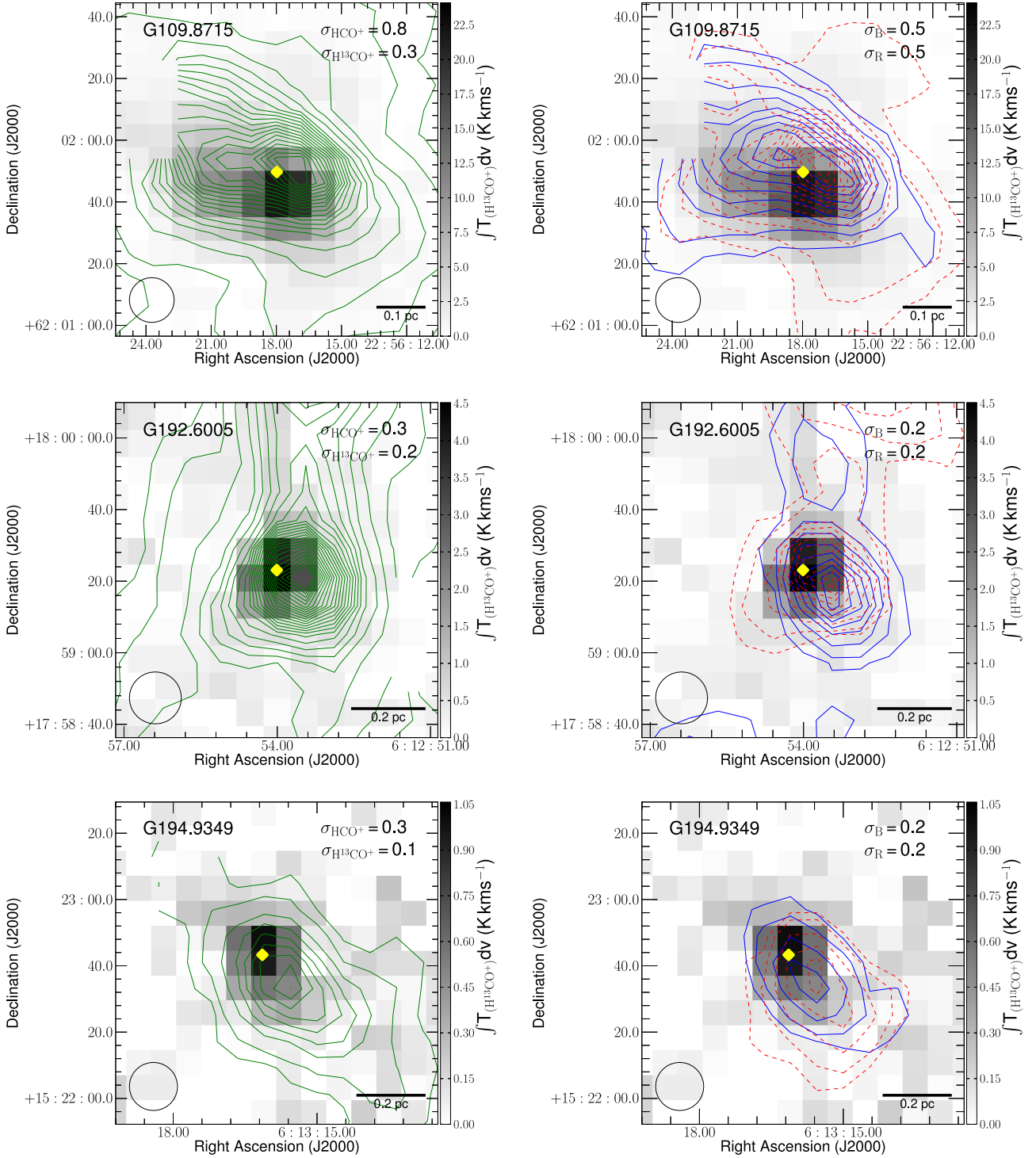


Figure B1 – *continued* – The velocity ranges used to integrate the total emission are -19.1 – -1.1 km s^{-1} for G109.8715, 2.8 – 12.7 km s^{-1} for G192.6005, and 12.2 – 18.9 km s^{-1} for G194.9349.

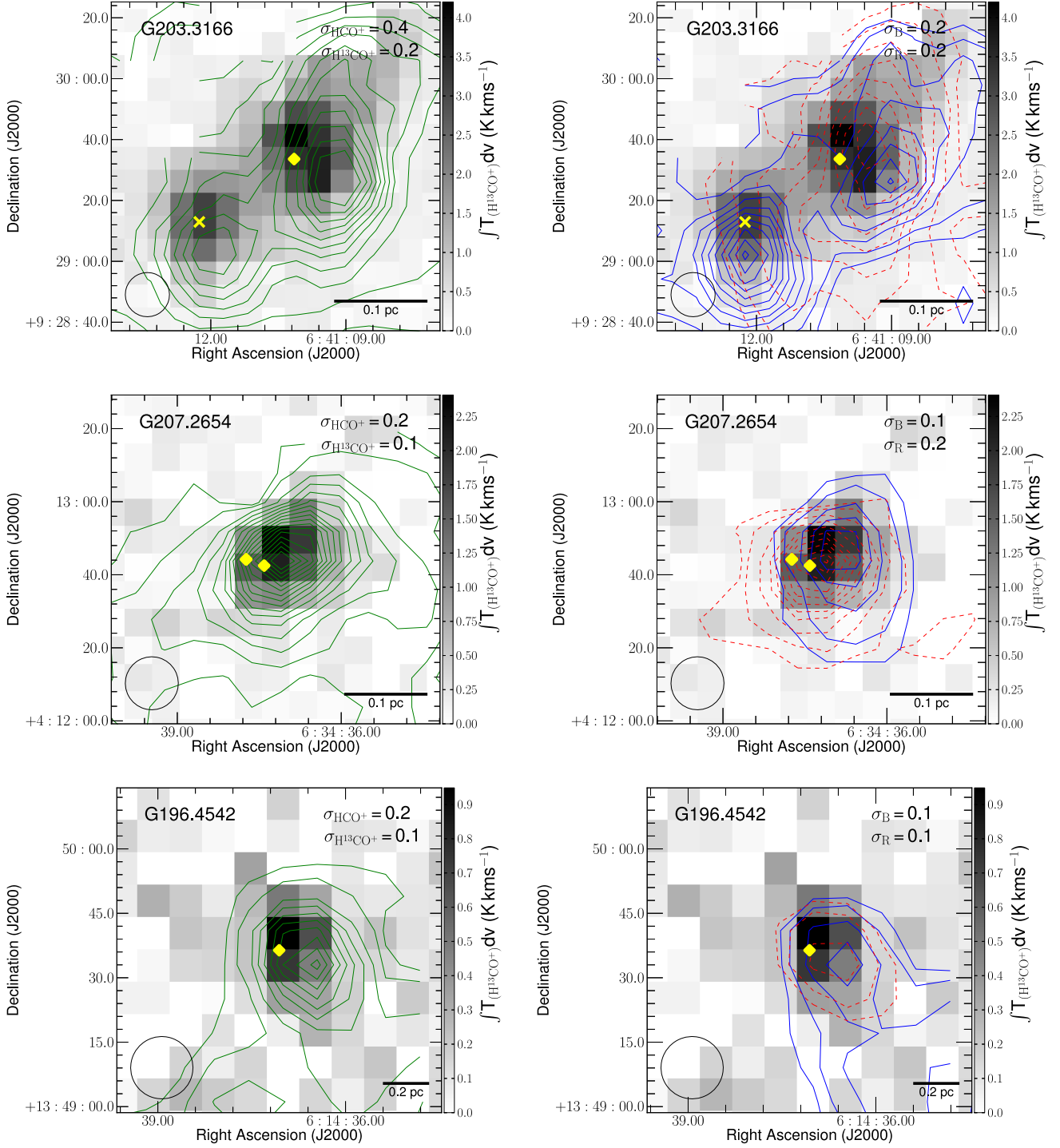


Figure B1 – *continued* – The velocity ranges used to integrate the total emission are $4.2\text{--}12.6\text{ km s}^{-1}$ for G203.3166, $9.2\text{--}17.7\text{ km s}^{-1}$ for G207.2654, and $16.6\text{--}22.0\text{ km s}^{-1}$ for G196.4542. We do not include a separate map for G203.3166-OFFSET as the emission ranges are similar.

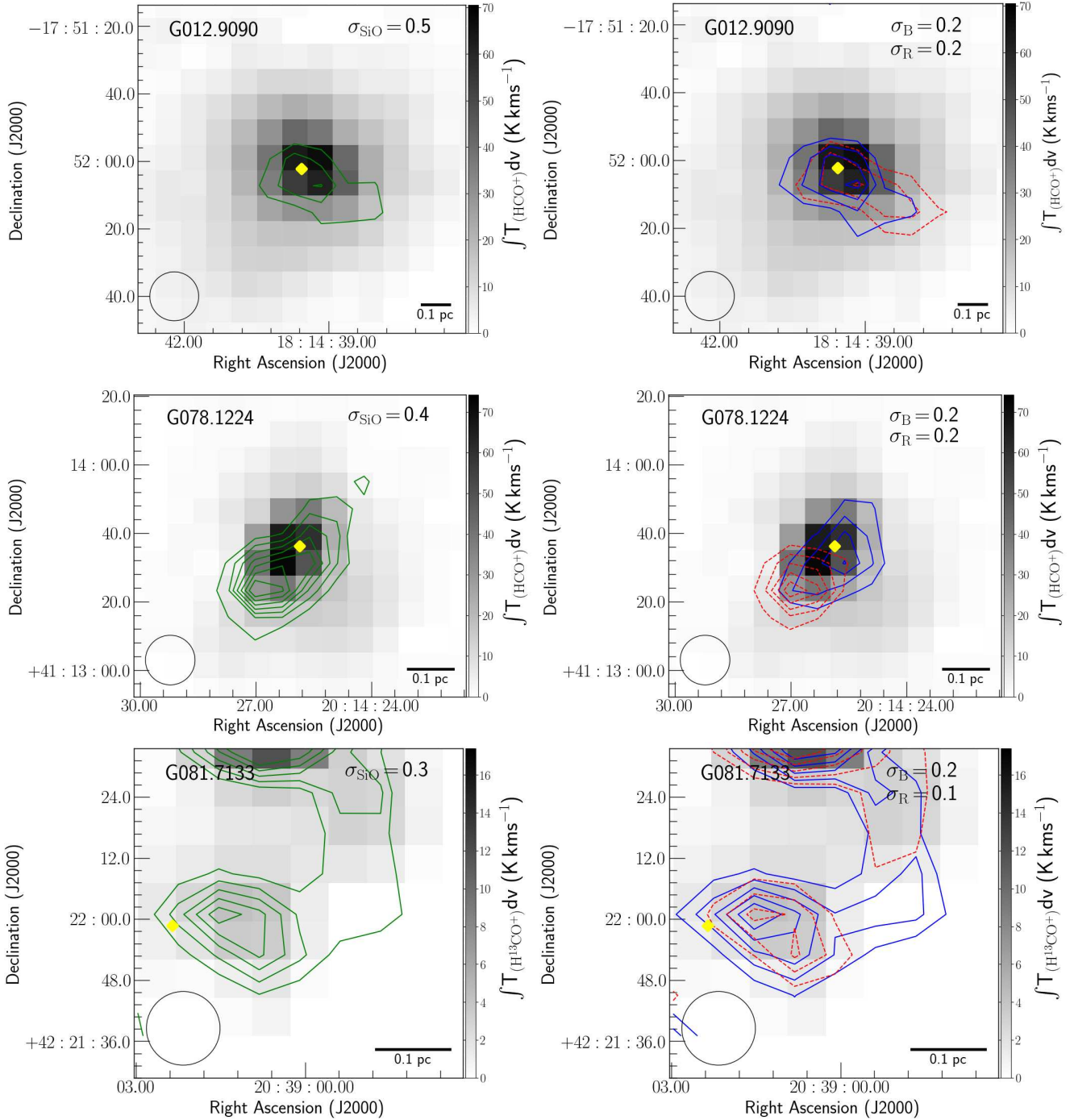


Figure B2. SiO and HCO⁺ zeroth order moment maps. The total integrated HCO⁺ emission is shown in greyscale (apart from sources where no HCO⁺ emission was observed and the H¹³CO⁺ emission is displayed), integrated from the minimum to maximum channels with a 3σ detection (and is the same as given in Figure. B1). The yellow diamonds and crosses are the RMS source position(s) and offset position, respectively. The JCMT beam is shown in the bottom left corner, and the source name is shown in the top left corner. For sources with SiO emission extending over less than four pixels we show only the total integrated emission as shown in the left column, and for sources with emission extending over more than 4 pixels we show the red- and blue-shifted SiO contours as shown in the right column here. **Left:** The total integrated SiO emission is overlaid in green solid contours (again integrated from the minimum and maximum channels with a 3σ detection). The 1σ rms (in units of K km s^{-1}) for the SiO (σ_{SiO}) integrated intensity is given in the top right corner. The contour levels are from $1\sigma \times (3, 5, 7, 9, \dots)$ to peak in-steps of 2σ . **Right:** The red- and blue-shifted SiO emission is given by the red (dashed) and blue (solid) contours, respectively. The blue- and red-shifted contours are taken from the minimum and maximum channels with 3σ emission to the source V_{LSR} (taken from Table A1), respectively. The 1σ levels for the red- (σ_{R}) and blue-shifted (σ_{B}) emission are given in the top right corner, where the contour levels are from $1\sigma \times (3, 5, 7, \dots)$ to peak in-steps of 2σ . The velocity ranges used for the total integrated SiO emission are $25.1.0\text{--}46.9.0 \text{ km s}^{-1}$ for G012.9090, $-25.2\text{--}16.8 \text{ km s}^{-1}$ for G078.1224, and $-13.2\text{--}3.6 \text{ km s}^{-1}$ for G081.7133.

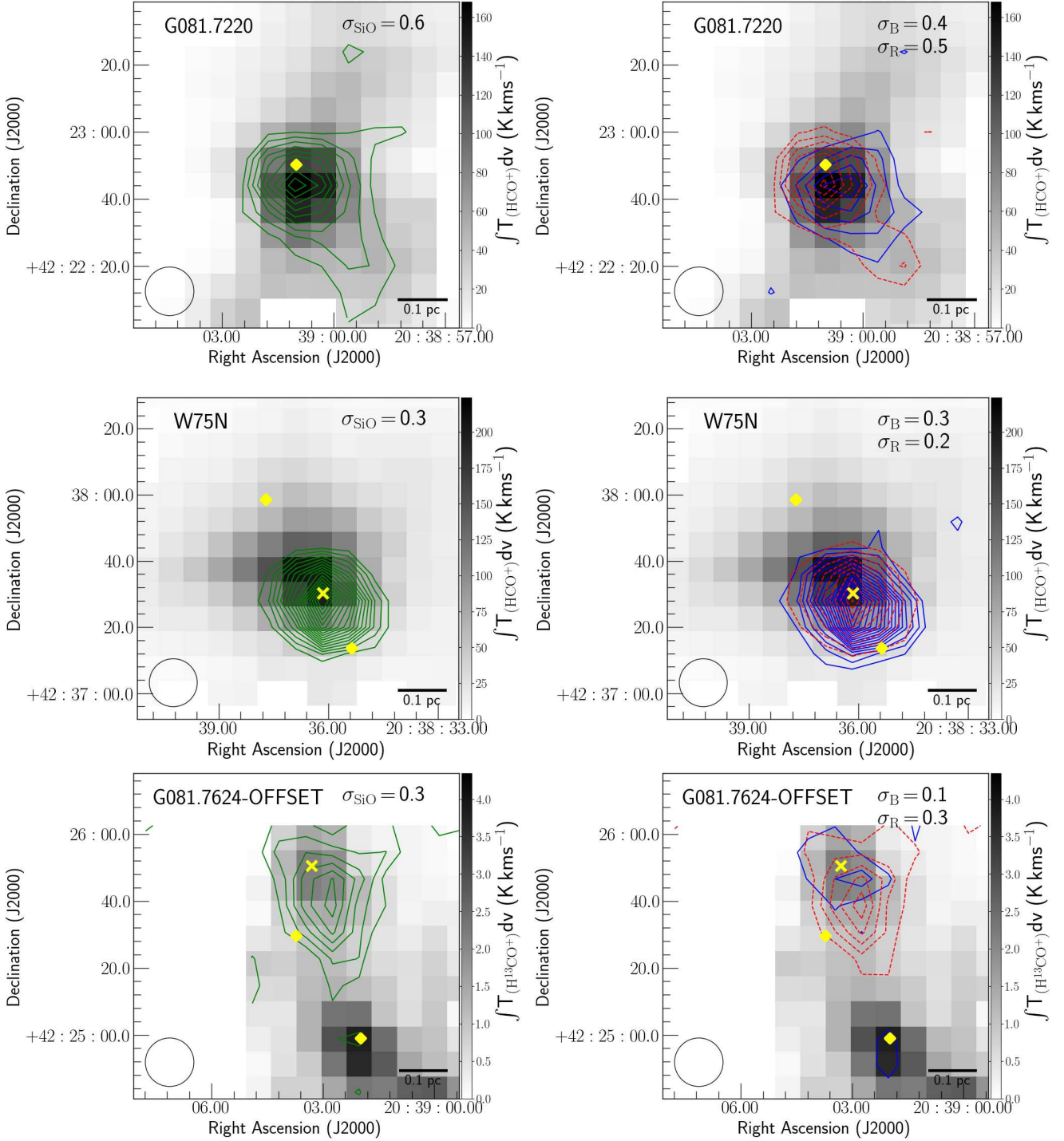


Figure B2 – *continued* – The velocity ranges used for the total integrated SiO emission are -16.6 – 8.6 km s^{-1} for G081.7220, -10 – 21.9 km s^{-1} for W75N and -8.2 – 22.0 km s^{-1} for G081.7624-OFFSET.

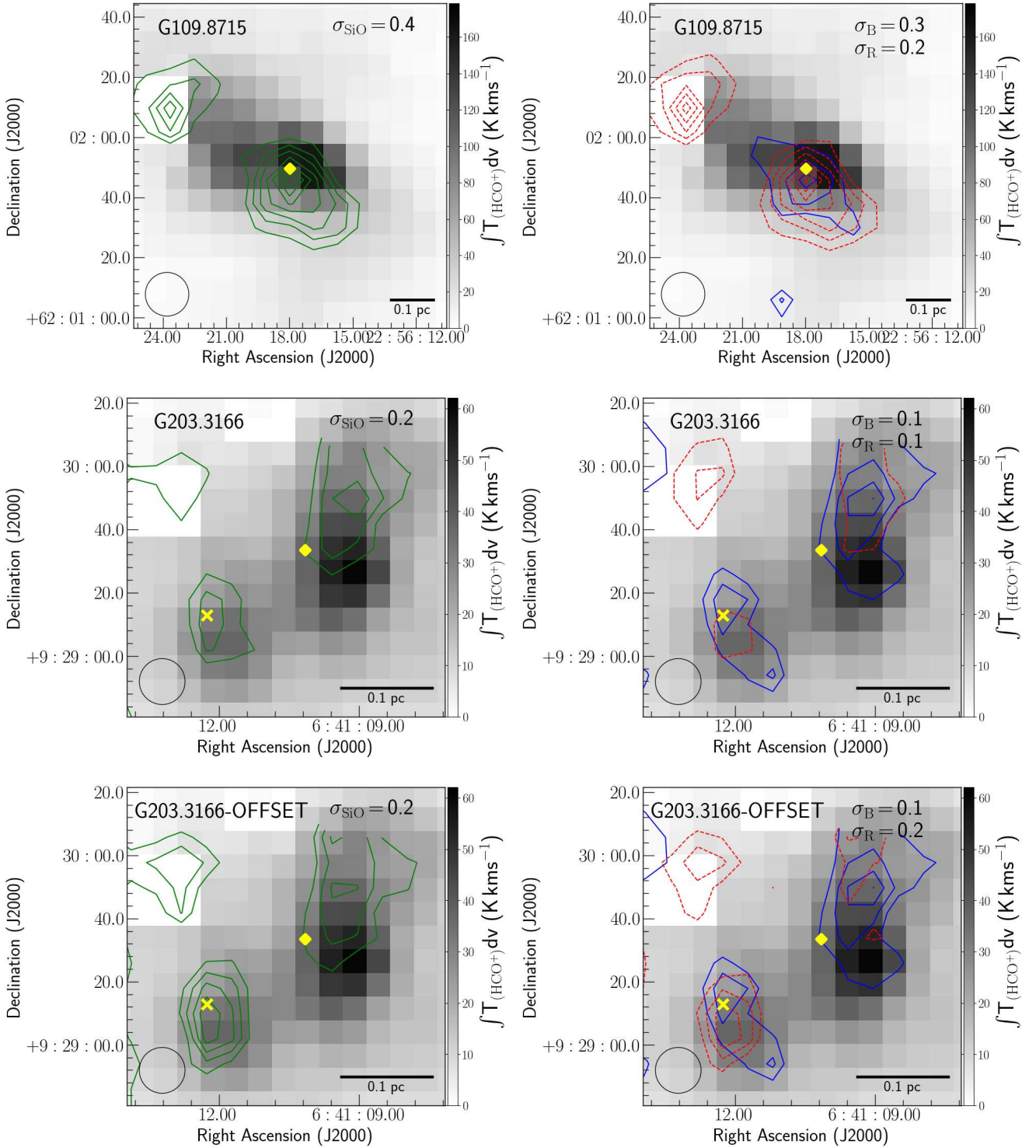


Figure B2 – *continued* – The velocity ranges used for the total integrated SiO emission are -18.2 – 0.3 km s^{-1} for G109.8715, 1.6 – 15.1 km s^{-1} for G203.3166, and 3.3 – 25.6 km s^{-1} for G203.3166-OFFSET.

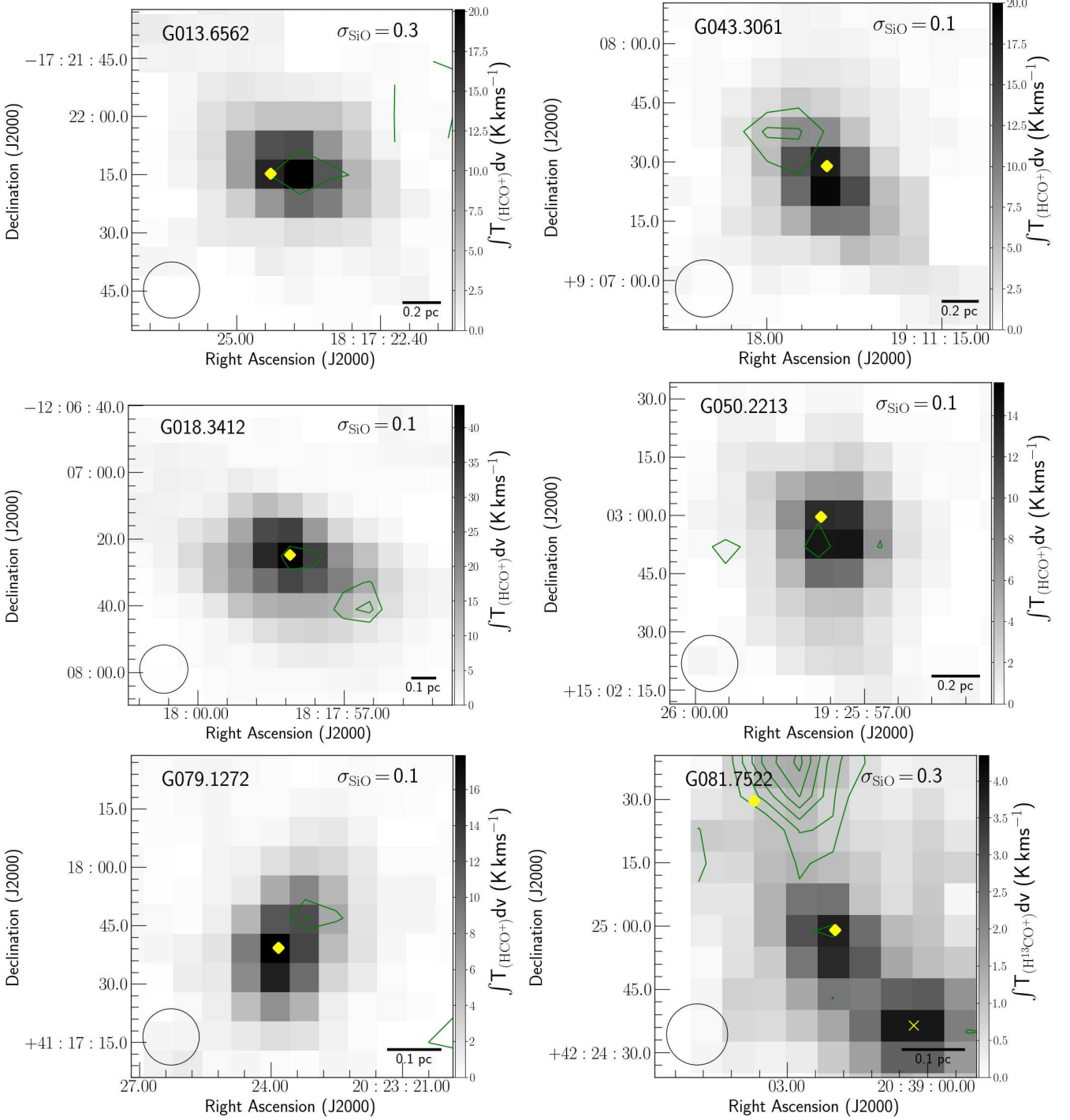


Figure B2 – continued – The velocity ranges used to integrate the emission are 33.0–43.6 km s⁻¹ for G013.6562, 30.5–37.3 km s⁻¹ for G018.3412, 57.5–64.2 km s⁻¹ for G043.3061, 37.0–42.0 km s⁻¹ for G050.2213, -1.5–5.2 km s⁻¹ for G079.1272 and -8.2–5.2 km s⁻¹ for G081.7522. It should be noted that for G081.7522, the velocity range used is the same as for G081.7624-OFFSET as the SiO emission towards G081.7522 is weaker it is difficult to estimate the SiO velocity range for this source.

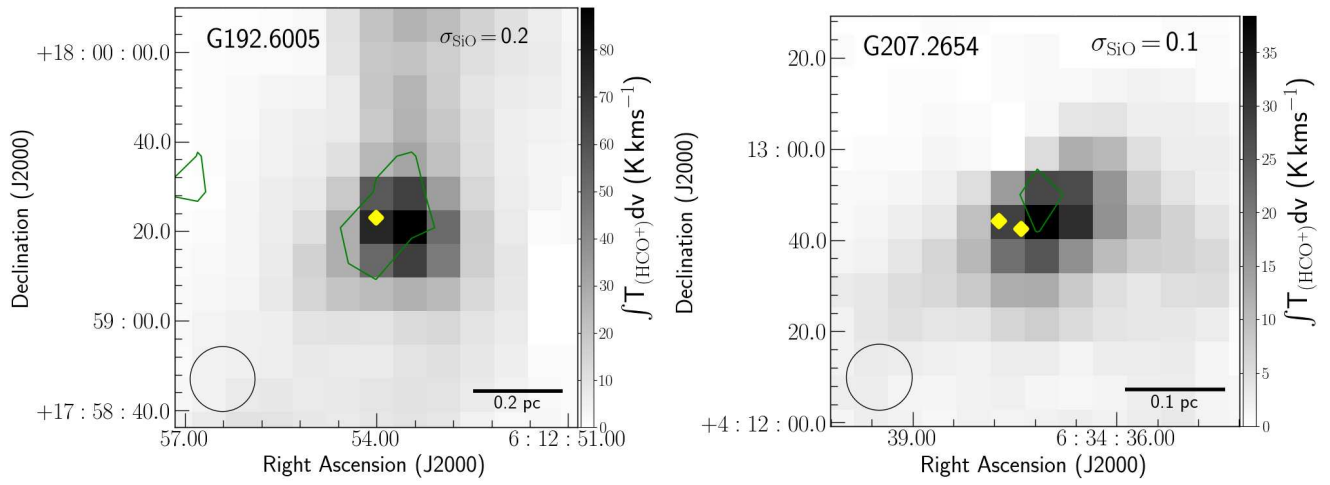


Figure B2 – *continued* – The velocity ranges used to integrate the emission are 6.8–11.9 km s⁻¹ for G192.6005, and 11.8–15.2 km s⁻¹ for G207.2654.