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A 3-mm molecular line study of the Central Molecular Zone of the Galaxy

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Abstract. We are studying the Central Molecular Zone (CMZ) in the inner few degrees around the Galactic Centre, by mapping multiple 3-mm molecular lines, with the 22-m Mopra telescope. During 2006, we covered a 5×5 arcmin^2 area of the Sagittarius B2 molecular cloud complex (Jones *et al.* 2008). We find substantial differences in chemical and physical conditions within the complex. We show some results here of Principal Component Analysis (PCA) of line features in this Sgr B2 area. During 2007 we covered the larger region of longitude -0.2 to 0.9 deg. and latitude -0.20 to 0.12 deg., including Sgr A and Sgr B2, in the frequency range 85.3 to 91.3 GHz. This includes lines of C_3H_2, CH_3CCH, $HOCO^+$, SO, $H^{13}CN$, $H^{13}CO^+$, SO, $H^{13}NC$, C_2H, HNCO, HCN, HCO^+, HNC, HC_3N, ^{13}CS and N_2H^+.

Keywords. ISM: molecules, radio lines: ISM, astrochemistry

1. Introduction

The Central Molecular Zone (CMZ) is the region within a few hundred parsec (a few degrees) of the Galactic Centre, which has strong molecular emission (Morris & Serabyn 1996), around 10% the molecular content of the whole Galaxy. The CMZ has extensive star formation, as shown by the mid-IR (Price *et al.* 2001) to sub-millimetre (Pierce-Price *et al.* 2000) dust emission. The conditions in the CMZ are characterised by high densities, large velocity dispersions, and high temperatures, compared to molecular clouds elsewhere in the Galaxy. The study of the CMZ provides a local analogue for the active nuclear regions of other galaxies.

The chemistry in the CMZ is complex, comparable to that of compact (~ 0.1 parcsec) "hot molecular cores", but extended over a scale several orders of magnitude larger, as shown, for example, in CH_3OH (Gottlieb *et al.* 1979) and HNCO (Dahmen *et al.* 1997)

The CMZ has been well studied in multiple CO lines (e.g. Nagai *et al.* 2007, Martin *et al.* 2004) giving a good estimate of the physical conditions. Particular, rich molecular regions of the CMZ, notably the hot cores Sgr B2(N) and Sgr B2(M), have had line surveys (e.g. Turner 1989, Belloche *et al.* 2007). However, due to observational limitations, there have not yet been studies which combine *large area coverage* of the CMZ and *large numbers of lines*, which is really needed to study the chemistry throughout the CMZ.

We are making a multi-line mapping survey of the CMZ, in the 3-mm band, with the Mopra 22-m telescope of the Australia Telescope National Facility. This project uses the new MMIC receiver (allowing easy tuning) and UNSW MOPS digital filterbank, which can cover up to 8 GHz bandwidth simultaneously. The broad band mode of the MOPS has up to 8192 channels of 0.27 MHz (~ 0.8 km s^{-1}), for each of four 2.2 GHz sub-bands. The zoom mode has up to four 137 MHz wide spectra of 4096 channels (~ 0.1 km s^{-1}) in each 2.2 GHz sub-band, making a maximum of 16 spectra over the 8 GHz. We use

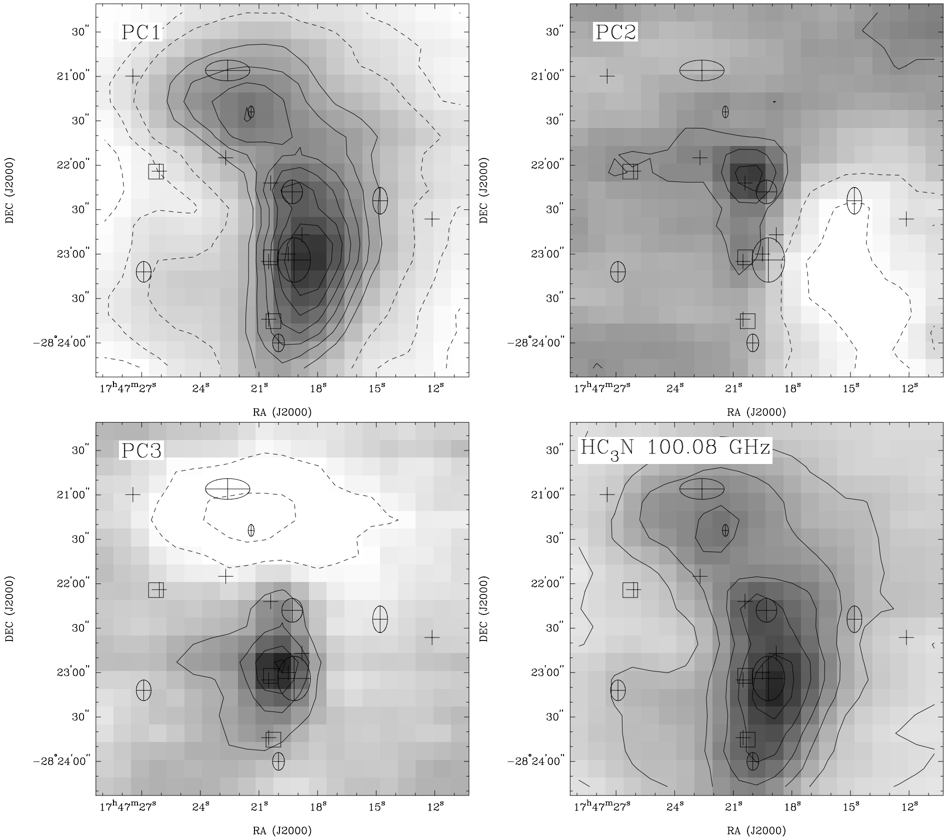

Figure 1. The images of the first three principal components (PC1, PC2, PC3). The ellipses with crosses indicate molecular peaks, the crosses radio sources, and the squares mid-IR sources. PC1 follows the ridge of molecular peaks, PC2 shows Sgr B2(N) and west ridge, and PC3 shows Sgr B2(M) and the north cloud. The integrated image of HC_3N at 100.08 GHz is shown in the last panel, demonstrating the similarity to PC1.

on-the-fly mapping, to cover large areas, in a similar way to the G333 survey of Bains *et al.* (2006). The resolution is around 35 arcsec (Ladd *et al.* 2005).

2. The Sagittarius B2 area

During 2006 we made observations with an early version of the MOPS system, of the 5×5 arcmin^2 area around Sgr B2. This included four tunings of the wide-band system covering most of the 3-mm band between 81.7 and 113.5 GHz, with ~ 6 km s^{-1} channels, and zoom mode observations of 24 lines with ~ 0.1 km s^{-1} channels. As this is a particularly strong, molecule rich area, we imaged the extended distribution of several dozen lines, and detected over 100 more lines mostly concentrated at the hot cores Sgr B2(N) and Sgr B2(M). These results are discussed in detail in Jones *et al.* (2008).

We have more recently used the Principal Component Analysis (PCA) technique, to provide an objective, quantitative way of describing the features in the integrated line images. In this context, the variation of the line images is explained in terms of principal component images, which describe the successively largest variance between the image data (e.g. Ungerechts *et al.* 1997, Meier & Turner 2005). The first principal component

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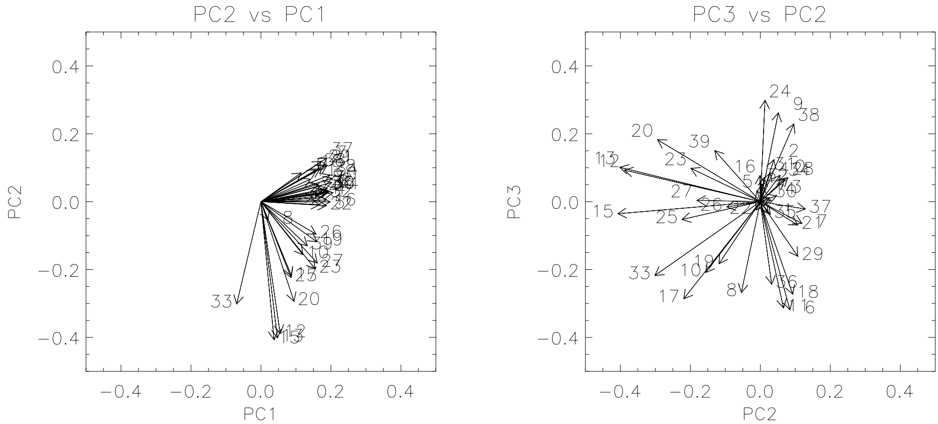

Figure 2. The eigenvector plots of component PC2 vs PC1 and PC3 vs PC2 for 40 lines in Sgr B2.

therefore provides a map of the main features, with the next few principal components describing the major differences in the data sets.

The PCA images are shown in Figure 1 with symbols showing the alignment with the features in Sgr B2. We summarise the molecular peaks found in Jones *et al.* (2008) as ellipses with crosses, with the mean and standard deviation of the fitted peak positions from multiple lines. Crosses mark the positions of radio sources from Hunt *et al.* (1999) and squares mark mid-IR sources from 21-μm MSX (Price *et al.* 2001). Sgr B2(N) is the radio source at the centre of the images, with Sgr B2(M) and Sgr B2(S) the radio and mid-IR sources in a line to the south.

Principal component 1 (PC1) traces the main molecular ridge line (ellipses) seen in most molecules, somewhat to the west of the radio and mid-IR peaks of Sgr B2(N), Sgr B2(M) and Sgr B2(S) and including the peak (which we call the north cloud) 1 arcmin north of Sgr B2(N). The molecular lines which have the strongest correlation with PC1 are the HC_3N lines at 90.98, 100.08 and 109.17 GHz, but many lines are similar including those of CH_3CN, CH_3OH, NH_2CN, CH_3CCH, NH_2CHO, H_2CS, CO, HNCO, SO and OCS.

PC2 traces Sgr B2(N) and the west ridge. HCN (88.63 GHz), HCO^+ (89.19 GHz) and HNC (90.66 GHz) have the strongest correlation with PC2, with a negative sign, due to strong absorption at the Sgr B2(N) hot core, and emission from the west ridge. Other lines, such as CS (97.98 GHz) and CN (113.17, 113.49 GHz), also show absorption at Sgr B2(N).

PC3 traces Sgr B2(M) and the north cloud. $HOCO^+$ (85.53 GHz) and HNCO (87.93 GHz) have strong negative correlation with PC3, due to strong emission from the north cloud. SO (86.09 GHz) and $C^{18}O$ (109.78 GHz) have strong positive correlation due to emission peaks at Sgr B2(M), while SiO (86.85 GHz) and N_2H^+ (93.17 GHz) have strong negative correlation due to absorption at Sgr B2(M).

The first three principal components explain 57, 12 and 9 percent, respectively, of the variance of the 40 integrated line images used here. The eigenvector plots of PC2 vs PC1 and PC3 vs PC2 are shown in Figure 2.

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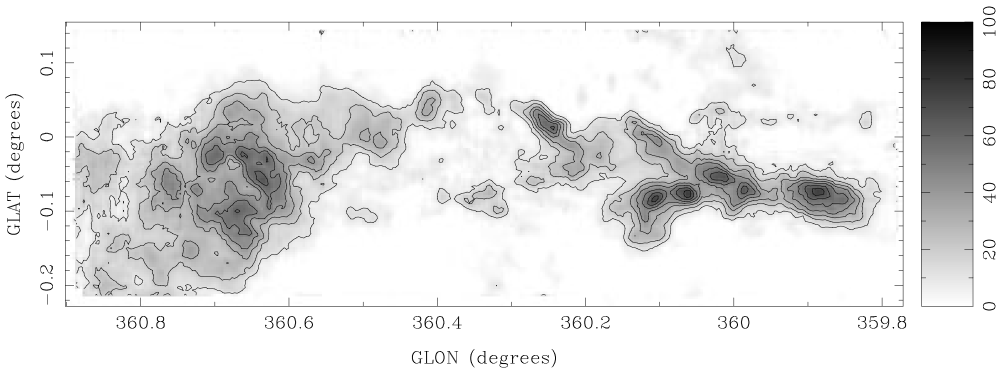

Figure 3. Integrated emission of N_2H^+ at 93.17 GHz, in the region of Sgr B ($l = 0.7$ deg.) and Sgr A ($l = 0.0$ deg.), from 2007 Mopra observations.

3. The Central Molecular Zone

During 2007 we started the large-scale imaging of the CMZ, with a single wide-band tuning covering the frequency range 85.3 to 91.3 GHz, and the area longitude -0.2 to 0.9 deg. and latitude -0.20 to 0.12 deg. This area includes Sgr A and Sgr B2, and we aim in 2008 to extend the longitude coverage to the area -0.7 to 1.7 deg., to include Sgr C and G1.6-0.025. These observations are with the full MOPS capability giving $\sim$ 0.8 km s^{-1} channels, which is quite sufficient given the large line-widths in the CMZ area. The frequency tuning was chosen to include the strongest lines in the 3-mm band, other than the CO lines which have been well covered by other projects (e.g Oka *et al.* 1998). We have imaged 18 lines: c-C_3H_2 (85.34 GHz), CH_3CCH (85.46 GHz), $HOCO^+$ (85.53 GHz), SO (89.06 GHz), $H^{13}CN$ (86.34 GHz), $H^{13}CO^+$ (86.75 GHz), SiO (86.85 GHz), $HN^{13}C$ (87.09 GHz), C_2H (87.32, 87.40 GHz), HNCO (87.93 GHz), HCN (88.63 GHz), HCO^+ (89.19 GHz), HNC (90.66 GHz), HC_3N (90.98 GHz), CH_3CN (91.99 GHz), ^{13}CS (92.49 GHz) and N_2H^+ (93.17 GHz).

Figure 3 shows the integrated N_2H^+ (93.17 GHz) emission, as an example of the Mopra CMZ survey data.

We are currently extending the Principal Component Analysis to the larger CMZ area, and studying images of line ratios, for example HCO^+/HCN and HNC/HCN, which are diagnostics of high-density conditions (cf. Baan *et al.* 2008).

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Discussion

CECCARELLI: I am curious what is the sensitivity that you reach in this survey?

JONES: It is a trade off between area and sensitivity. We're doing in this project on a large area, recognizing we are not probing the sensitivity as in a spectral line survey. For example, Sgr B2 has been observed with the IRAM 30 m where the 3mm band has much greater sensitivity. This means that we're getting things like methyl cyanide and methanol but not the more complex molecules. We see about hundred and fifty lines, but most of them are located in one point in Sgr B2 (N). We establish complex molecules there.

ZIURYS: Did you ever compare your maps with interferometer maps of the Galactic center such as those done by BIMA?

JONES: With 30 arc sec resolution, the BIMA interferometer maps correspond to about one or two beam areas, but they do match up.

ZIURYS: I'm just curious how much flux was resolved out in their data versus what you have?

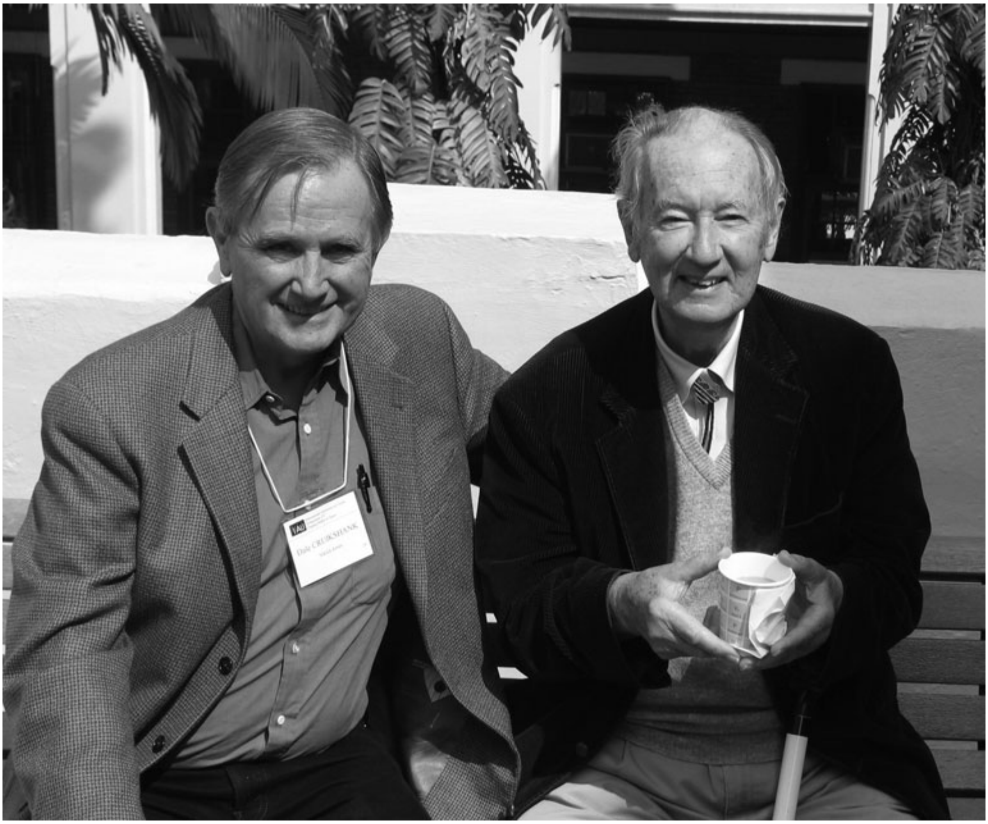
JONES: One of the advantages are having single dish observations is that we can put the single dish flux back into the interferometric data to get good interpretation of the data.

OLOFSSON: 8 GHz is fairly broad bandwidth. Do you have reliable baseline so that you can observe also very weak lines?

JONES: When we look at the strong continuum source such as Sgr B2 you do get some ripples in the baseline due to standing waves, so that can become a problem.

OLOFSSON: How about continuum free sources such as circumstellar envelopes?

JONES: The baseline is pretty flat over the full 8 GHz.



Dale Cruikshank (left) and Cliff Matthews (right).