SURVEYS WITH HETERODYNE FOCAL PLANE ARRAYS AT MM WAVELENGTHS: QUARRY AT FCRAO

HANS UNGERECHTS
IRAM
Avenida Divina Pastora 7-NC, E-18012 Granada, Spain

1. Introduction

In early 1991 the focal plane array receiver QUARRY (Erickson *et al.*, 1992) for the 3 mm wavelength band went into operation on the FCRAO 14 m telescope. QUARRY uses 3×5 Schottky diode mixers with beams spaced $100'' \times 50''$ on the sky, while the beamwidth is $45''$ at 115 GHz. Maps sampled every full or half beamwidth are obtained by stepping the telescope to fill in the intermediate points. Backends used from the start were filterbanks with 32 channels of 250 kHz and 1 MHz for each receiver; and accordingly the first observations with QUARRY concentrated on galactic giant molecular clouds. More recently an autocorrelator (Predmore, 1994) has become available allowing a much wider range of targets including cold clouds requiring high spectral resolution and galactic surveys which need wide bandwidths.

The most extensive projects – or "surveys" – with QUARRY are large scale maps of GMC complexes using CO and other tracers, described in §2, and multiline studies of cloud cores with many molecular species, summarized in §3. A complete review of all projects with QUARRY is beyond the scope of this article; on the other hand details of several surveys are reported elsewhere in these proceedings (Gem OB 1: Carpenter, 1996; Second Galactic Quadrant: Heyer, 1996; and see the list of references).

2. Largescale Surveys of Clouds

A distinctive feature of CO surveys of GMCs with QUARRY is the large ratio of size covered to resolution or sampling. For example, the CO maps of Gem OB1, extend over about 180 pc $\times$ 220 pc sampled every 0.5 pc (Carpenter *et al.*, 1995a). The results are images of molecular clouds that are rich

TABLE 1. Largescale Surveys with QUARRY

Region	Molecule	Reference
Gem OB1	^{12}CO and ^{13}CO, [CS]	J. Carpenter *et al.* (1995a, 1995b, 1996)
"Ceph Bubble" & IC 1396	^{12}CO and ^{13}CO	N. Patel *et al.* (1994, 1995, 1996)
"Maddalena's" G216-2.5	^{12}CO and ^{13}CO [CS, $C^{18}O$, HCO^+]	Y. Lee *et al.* (1994)
Mon R2	^{12}CO	T. Xie *et al.* (1993, 1994, 1996)
Sh 140, Sh 155, Sh 235	^{12}CO and ^{13}CO	M. Heyer *et al.* (1996)
Galactic Center	^{12}CO and HCN	J. Jackson *et al.* (1996)
Second Galactic Quadrant	^{12}CO	M. Heyer (1996)

Note: lines in brackets [ ] were observed in restricted regions selected from the main survey.

in detail and reveal a wide range of processes at work shaping the clouds. Before QUARRY, some similar images of GMCs had been obtained; for example, ^{13}CO measurements of regions such as Orion A obtained with the Bell Labs Telescope (Bally *et al.*, 1987), and single-beam measurements of the ^{12}CO emission toward Orion A (Heyer *et al.*, 1992). We now have more and larger surveys with such characteristics, and for most ^{12}CO and ^{13}CO were mapped. An overview is given in Table 1, which gives full references; to save space in the following text these references are not always repeated when reporting results from one of these surveys.

For most of the clouds the ^{12}CO and ^{13}CO images look at first glance very similar. In ^{12}CO there are extended regions of low intensity emission and the strongest lines are found toward a relatively small fraction of lines of sight. The strongest ^{13}CO lines are generally seen where the main isotope is strong; the contrast to the low intensity extended emission is generally higher in ^{13}CO, and the area of detected emission is smaller in ^{13}CO. The latter is in part due to the lower signal-to-noise ratio of most ^{13}CO images, but there is also a substantial variation in the ^{12}CO to ^{13}CO intensity ratio (Carpenter *et al.*, 1995a).

Most of the cloud mass is in regions of low column density and temperatures of 10 K or less (e.g., Carpenter *et al.*, 1995a, Lee *et al.*, 1994). High column densities and larger temperatures are generally associated with H II-regions or star-forming activity. Densities averaged over a large complex like Gem OB1 are as low as 1 molecule cm^{-3}, only a few times the interstellar average, but more typically on the order of $100\,cm^{-3}$ for the extended emission of individual clouds and above $10^4\,\mathrm{cm}^{-3}$ in cloud cores.

Column densities can be compared to the total luminosity of the ^{12}CO emission to derive estimates of the X-ratio relating ^{12}CO luminosity and cloud mass: e.g., for Gem OB1 and G216−2.5 a typical value is $X = 1.0\ 10^{20}\,\mathrm{cm}^{-2}/(\mathrm{K\,km\,s}^{-1})$ with a spread of a factor of about 1.5. Many clouds with and without star formation appear approximately virialized when the mass from LTE column densities is related to the velocity dispersion seen in the line width, the major exception is, of course, Maddalena's cloud, G216−2.5, which has no signs of star formation but very broad lines (Maddalena and Thaddeus, 1985, Lee *et al.*, 1994).

It is not clear how typical these results are for the majority of clouds in the Galaxy: the clouds mapped with QUARRY were selected to be in the local arm or in the outer Galaxy, and the properties of the GMCs within the solar circle may be different.

The structure of the regions of strong CO emission can in some cases directly be linked to physical causes. Arcs or rings, sometimes only partial or broken into globules, are found around H II-regions (Gem OB1: Carpenter *et al.*, 1995a; IC1396: Patel *et al.*, 1995). In Mon R2 the ^{12}CO images show a shell swept up around the blue lobe of the bipolar outflow (Xie *et al.*, 1993). Other arcs and shells are found without an evident cause: e.g., in G216−2.5 an embedded shell of diameter $\approx 20\,\mathrm{pc}$ with a full three dimensional kinematic signature (Lee *et al.*, 1994). In both G216−2.5 and Mon R2, the large-scale structures of the clouds show the kinematics of a hemispherical expanding shell (Lee *et al.*, 1994; Xie and Goldsmith, 1994). Some morphological arcs and shells lack clear kinematic evidence for expansion. The globules around IC1396 appear on an expanding ring rather than a three dimensional shell, possibly because the H II-region formed in a molecular cloud that had previously been compressed with the formation of a much larger shell, the "Cepheus-Bubble", around which many more molecular clouds are found (Patel *et al.* 1995, Patel 1996).

Cores of enhanced density are indicated by strong ^{13}CO lines and high column densities. Some CO surveys have been followed by observations of the CS $J = 2 \to 1$ line in regions of high column density. In Gem OB1 eleven CS cores with masses 100 to $2000 M_\odot$ are located in the CO arcs and filaments (Carpenter *et al.*, 1995b). In G215−2.5 only a few CS cores of lower mass, $\approx 10 M_\odot$, are found which resemble cloud cores in cold dark clouds (Lee *et al.*, 1994).

To trace the relative amount of high density gas in clouds near the Galactic Center, Jackson *et al.* (1996) have surveyed CO and HCN and compared the results with active galactic nuclei. Around the Galactic Center the density peaks correlate with the CO luminosity peaks, and starburst galactic nuclei have a larger mass of dense gas, larger average density, and larger regions of high density.

The location of young stellar objects in the molecular clouds, in particular YSO candidates identified from the IRAS point source catalog, has been studied for Gem OB1, IC 1396, and Mon R2; there are no known YSOs associated with G215−2.5. In Gem OB1 the more luminous sources tend to be associated with more massive CS cores (Carpenter *et al.*, 1995b). In Mon R2 the IRAS sources are concentrated in the bright emission ridges (Xie, 1996); in IC 1396 they mostly fall onto the expanding ring of dense molecular gas (Patel *et al.*, 1995). On the other hand, sources of lower luminosity, as well as some bright sources, are more widely distributed and not necessarily associated with massive dense cores. A survey in the J, H, K, and L bands around Sh 247 in the Gem OB1 complex revealed four star clusters, all in massive CS cores (Carpenter *et al.*, 1995b).

A part of the CO survey of Mon R2 was used by Jarrett *et al.* (1994) for a comparison with the magnetic field morphology determined from polarimetric observations of stars: the magnetic field appears aligned with one of the prominent ridges or filaments in the CO map, coincident with the axis of the Mon R2 bipolar outflow, and on a smaller scale distorted or bent toward the long axis of the main cloud core.

In summary, the overall picture presented by the CO images of the large cloud complexes appears consistent with scenarios in which H II-regions (Elmegreen and Lada 1977) or stellar outflows and winds (Norman and Silk 1980), caused by one generation of stars, sweep up shells of enhanced density. Dense cloud cores form within these density enhancements, most of which soon form stars, which disperse the cores and subsequently cause new shells. G215−2.5 could be in a period between episodes of star formation (Lee *et al.* 1994).

3. Multiline "Chemistry" Surveys of Cloud Cores

In an attempt to study the relation between physical conditions and chemical abundance variations, QUARRY has been used to obtain fully sampled maps of many molecules and transitions in selected cloud cores. The early surveys with the filterbanks were of GMC cloud cores: the Orion A ridge (Ungerechts *et al.*, 1996), M17SW, and Cepheus A (Bergin *et al.*, 1996c); recently the autocorrelator has been used for the cold cloud cores TMC 1 and L183, a.k.a. L134N (Pratap, 1996) (compare Table 2). A similar study using single beam receivers on the IRAM 30 m telescope has been done of the NGC 7023 photodissociation region (Fuente *et al.*, 1993).

The molecules in the QUARRY surveys of GMC cores are CO, ^{13}CO, C^{18}O, CS, C^{34}S, HCO$^+$, H^{13}CO$^+$, N$_2$H$^+$, CN, C$_2$H, HCN, H^{13}CN, HNC, HN^{13}C, SO ,^{34}SO, SO$_2$, CH$_3$OH, C$_3$H$_2$, HC$_3$N, and CH$_3$CCH; except for

TABLE 2. QUARRY Chemistry Surveys of Cloud Cores

Source	Size of maps	Reference
GMC Cores:		
Orion A	$5' \times 12'$	(Ungerechts *et al.*, 1996)
M17SW	$4' \times 5'$	(Bergin *et al.*, 1996c)
Cepheus A	$4' \times 5'$	(Bergin *et al.*, 1996c)
Cold cloud cores:		
TMC 1	$4' \times 15'$	(Pratap, 1996)
L183 (L134N)	$8' \times 10'$	(Pratap, 1996)

C_3H_2 they are being mapped in the cold cores as well. For N_2H^+, CN, and C_2H hyperfine components are resolved, for CH_3OH, SO, CH_3CCH, and HC_3N several rotational transitions were mapped, which are sensitive to different excitation conditions. Finally, the HC_3N observations were complemented with observation of additional transitions at other observatories.

The strongest differences between maps of various species are found along the Orion A ridge. While all distributions are similar to first order – all show the ridge and the molecular bar – on a closer look they can be grouped into a range of morphological classes (Figure 1): i) distributions that are very strongly peaked toward KL and to a lesser degree toward Orion-1.5′S: CO, CH_3OH, SO, SO_2, HC_3N, HCN, and $H^{13}CN$; ii) those that very clearly show the ridge with moderate peaks at KL and Orion-1.5′S: CS, $C^{34}S$, and ^{13}CO; iii) maps that show the ridge but no predominant peak: especially CN, but also $C^{18}O$, and C_3H_2; iv) distributions that are strongest $\approx 4'$ north of KL around the radical-ion-peak "RIP" or show an overall north-south gradient: N_2H^+, $H^{13}CO^+$, C_2H, and $HN^{13}C$. Additionally some species have particularly low intensities toward the molecular bar around offsets (1.7′,−2.9′): HC_3N, N_2H^+, and $C^{34}S$. The distinction between the categories above is somewhat open, – HNC and CH_3CCH have characteristics of ii) and iv) – and if one examines all the details in the maps, each one shows some idiosyncrasy making it distinctly individual compared to all others.

Variations in temperatures can be estimated from the peak intensity and hence excitation temperature of the CO line for the outer layers of the cloud cores and from the relative strength of the K components of CH_3CCH for the denser cloud interior. All along the Orion ridge as well as for most positions in M17SW the interior temperature is lower, and in Orion both temperatures decrease with distance from KL (Bergin *et al.*, 1994).

The two HC_3N transitions mapped with QUARRY, $J = 10 \rightarrow 9$ and $12 \rightarrow 11$, when combined with maps of one lower, $4 \rightarrow 3$, and one higher

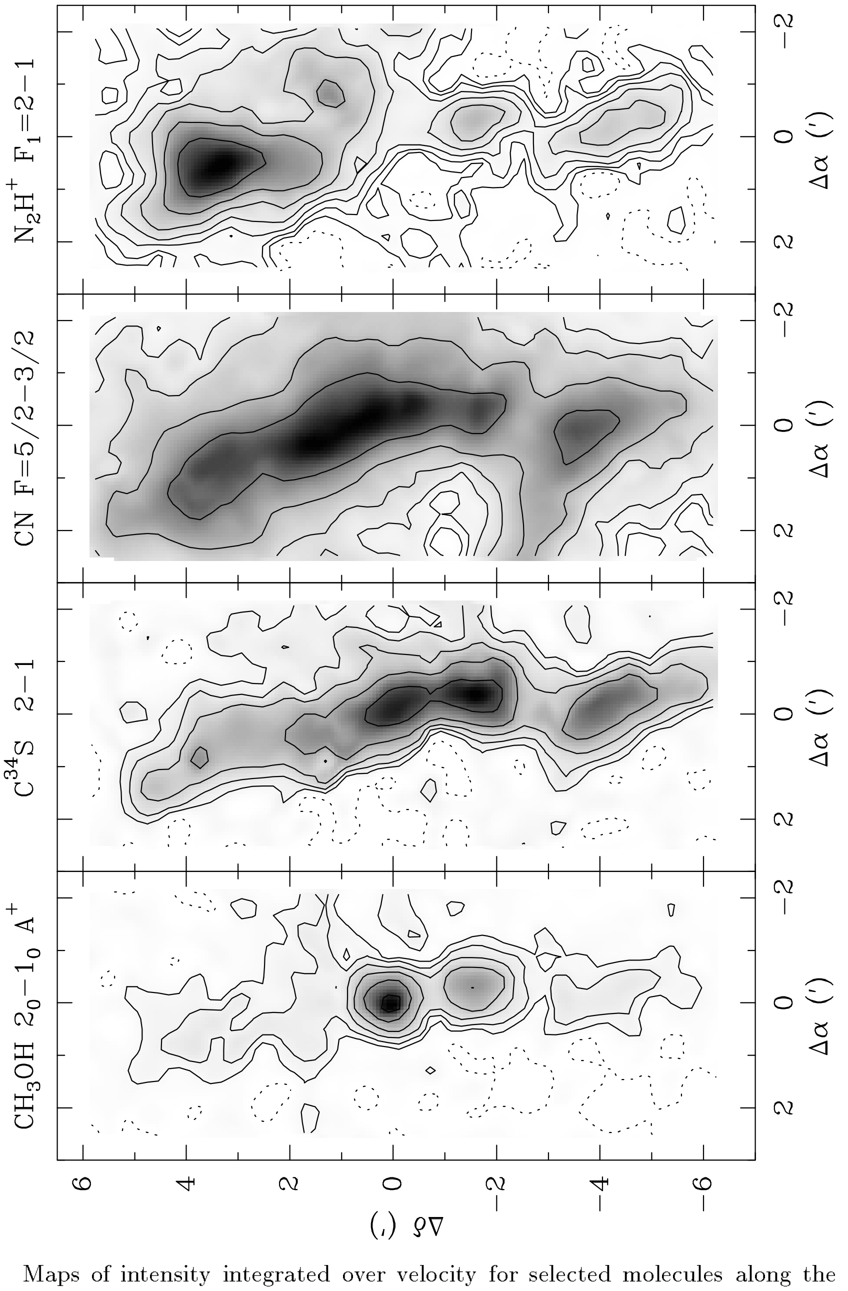

Figure 1. Maps of intensity integrated over velocity for selected molecules along the Orion A molecular ridge. These maps are representative of the different classes of distributions: i) CH_3OH $J_K = 2_0 \rightarrow 1_0 A^+$: strongly peaked toward Orion-KL (0,0) and 1.5′S; ii) $C^{34}S$ $J = 2 \rightarrow 1$: clearly outlining the ridge with moderate peaks at KL and 1.5′S; iii) CN $F = \frac{5}{2} \rightarrow \frac{3}{2}$: showing ridge and bar with no prominent peaks; iv) $N_2H^+ F_1 = 2 \rightarrow 1$: strongest around the RIP (radical-ion-peak) about 4′N of KL.

line, $16 \to 15$, provide an estimate of density. In all GMC cores studied, the derived densities are high, around $10^6\,\mathrm{cm}^{-3}$, with no systematic variation with position (Bergin *et al.*, 1996a). The kinematic evidence is consistent with the assumption that HC_3N and CH_3CCH trace conditions in the interior of the cores, from which the emission of most optically thin species in the survey arises. It is, therefore, reasonable to use the derived temperatures and densities with the observed intensities of optically thin lines to estimate molecular abundances relative to $C^{18}O$ (Bergin, 1996b).

The strongest abundance variations are the well-known enhancements toward KL and to a lesser degree toward Orion-1.5′S; this is the case for HC_3N, SO, CH_3OH, and HCN. A smaller, but distinct abundance variation corresponds to the NS-gradient or difference between the RIP and the cloud core 4′S of KL. These two cores have very similar densities as well as temperatures, but N_2H^+, $H^{13}CO^+$, C_2H, and to a lesser degree CH_3CCH and $HN^{13}C$ are more abundant around the RIP (Bergin, 1996b). Finally the relative weakness of some species toward the molecular bar translates into lower abundances than on the main ridge.

The strong enhancements around KL have, of course, for some time been explained by chemical processes directly linked to the massive star formation in this area (Blake *et al.*, 1987). The observed abundances in the more quiescent Orion ridge and the two other GMC cores are rather high when compared to models of the gas phase chemistry (Bergin *et al.*, 1995). Under the observed physical conditions, both a high C/O ratio and "early" times in the chemical evolution are necessary to match the observations (Bergin, 1996b). The observed secondary abundance variations – the NS contrast and the weakness of some species in the molecular bar – are possibly related to variations in the clumping and volume filling factor and in the UV radiation field.

4. Outlook

A 2×2 array with SIS receivers for the 3 mm band has been used on the Nobeyama 45 m telescope (Ukita and Tsuboi, 1994) and is to be replaced by a larger array. An 8-element SIS array for 1.3 mm will soon be available at the NRAO 12 m telescope (B. Latter and P. Jewell, priv. comm.). The next generation of focal plane arrays at 3 mm may directly employ HEMT amplifiers, offering the prospect of much lower noise temperatures than those of QUARRY as well as more elements. Especially when combined with faster observing modes like on-the-fly sampling, these systems may provide another order-of-magnitude gain in the speed of spectral-line observations at mm wavelengths.

The total area of CO emission in the composite galactic survey with the 1.2 m Columbia-Chile "Mini" telescopes (Dame *et al.*, 1987) is about 10 times larger than that of the second quadrant survey currently underway with QUARRY (Heyer, 1996). The next generation of focal plane arrays should enable us to map most of the galactic molecular gas with current telescopes of the 15 m size class with full sampling and angular resolution better than one arc minute.

Acknowledgments. I would like to thank everyone who helped with the GMC core "chemistry" survey or provided preprints, figures, or information: Ted Bergin, John Carpenter, Paul Goldsmith, Mark Heyer, Bill Irvine, Phil Jewell, Bill Latter, Amy Lovell, Phil Maloney, Doug McGonagle, Tim Paglione, Nimesh Patel, Preethi Pratap, Pete Schloerb, Ron Snell, Tao Xie, the FCRAO staff, and the QUARRY team.

References

Bally, J., Langer, W.D., Stark, A.A., and Wilson, R.W. (1987) *Ap.J.L.* **312**, L45
Bergin, E.A., Goldsmith, P.F., Snell, R.L., and Ungerechts, H. (1994) *Ap.J.* **431**, 674
Bergin, E.A., Langer, W.D., and Goldsmith, P.F. (1995) *Ap.J.* **441**, 222
Bergin, E.A., Snell, R.L., and Goldsmith, P.F., (1996a) *Ap.J.* **460**, 343
Bergin, E.A. (1996b) Poster Presentation at *this IAU symposium*
Bergin, E.A. *et al.* (1996c) in preparation for *Ap.J.*
Blake, G.A., Sutton, E.C., Masson, C.R., and Phillips, T.G. (1987) *Ap.J.* **315**, 621
Carpenter, J.M., Snell, R.L., and Schloerb, F.P. (1995a) *Ap.J.* **445**, 246
Carpenter, J.M., Snell, R.L., and Schloerb, F.P. (1995b) *Ap.J.* **450**, 201
Carpenter, J.M. (1996) Contributed Presentation at *this IAU symposium*
Dame, T.M. *et al.* (1987) *Ap.J.* **322**, 706
Elmegreen, B.G., and Lada, C.J. (1977) *Ap.J.* **214**, 725
Erickson, N.R. *et al.* (1992) *IEEE Trans. on Microwave Theory and Techniques* **40**, 1
Fuente, A., Martín-Pintado, J., Cernicharo, J., and Bachiller, R. (1993) *A.&A.* **276**, 473
Heyer, M.H., Morgan, J., Schloerb, F.P., Snell, R.L., and Goldsmith, P.F. (1992) *Ap.J.L.* **395**, L99
Heyer, M.H. (1996) Contributed Presentation at *this IAU symposium*
Heyer, M.H., Carpenter, J.M., and Ladd, E.F. (1996) *Ap.J.* **463**, 630
Jackson, J.M., Heyer, M.H., Paglione, T.A.D., & Bolatto, A.D. (1996) *Ap.J.L.* **456**, L91
Jarrett, T.H., Novak, G., Xie, T., and Goldsmith, P.F. (1994) *Ap.J.* **430**, 743
Lee, Y., Snell, R.L., and Dickman, R.L. (1994) *Ap.J.* **432**, 167
Maddalena, R.J., and Thaddeus, P. (1985) *Ap.J.* **294**, 231
Norman, C., and Silk, J. (1980) *Ap.J.* **238**, 158
Patel, N.A., Heyer, M.H., Goldsmith, P.F., Snell, R.L., Hezel, T., and Pratap, P. (1994) in *Clouds, Cores, and Low Mass Stars*, eds. D.P. Clemens and R. Barvainis, p. 81
Patel, N.A., Goldsmith, P.F., Snell, R.L., Hezel, T., and Xie, T. (1995) *Ap.J.* **447**, 721
Patel, N.A. (1996) Poster Presentation at *this IAU symposium*
Pratap, P. (1996) Poster Presentation at *this IAU symposium*
Predmore, C.R. (1994) in *Workshop on Multi-feed Systems for Radio Telescopes*, Astronomical Society of the Pacific Conference Series **75**, p. 259
Ukita, N., and Tsuboi, M. (1994) *Proceedings of the IEEE* **82**, 725
Ungerechts, H. *et al.* (1996) in preparation for *Ap.J.*
Xie, T., Goldsmith, P.F., and Patel, N. (1993) *Ap.J.L.* **419**, L33
Xie, T., and Goldsmith, P.F. (1994) *Ap.J.* **430**, 252
Xie, T. (1996) Poster Presentation at *this IAU symposium*