Probing the Initial Conditions of Clustered Star Formation – Large Scale On-the-Fly Mapping of Orion B at FCRAO

Naomi A. Ridge
FCRAO, 619 Lederle GRC, University of Massachusetts, Amherst, MA 01003, USA.

Edwin A. Bergin & S. T. Megeath
Harvard-Smithsonian CfA, 60 Garden St., Cambridge, MA 02138, USA.

Abstract. In order to obtain a census of the pre-stellar and star-forming molecular cores, we have begun an unbiased survey in CS and N$_2$H$^+$ of the L1630 and L1641 molecular clouds. The use of these two molecular species enables us to quantify and disentangle the effects of depletion often seen in CS observations of dense cores. The spectral line data will provide essential kinematical information not present in similar studies of the sub-millimeter dust-continuum, enabling us to examine the overall core to core velocity dispersion and study the effects of infall and outflows around known sub-mm and infra-red sources. Here we present our initial observations of part of L1630, taken during the commissioning phase of the FCRAO On-the-Fly Mapping system.

1. Introduction

CS is an often used tracer of dense gas in molecular clouds (e.g. Lada et al. 1991 (LEF); Lada et al. 1997). These and similar studies have shown that the CS emission is not uniformly distributed, but confined to dense cores which constitute just a small fraction of the total cloud volume and mass. LEF were able to identify all previously known dense regions of star-formation in their CS study of L1630, as well as finding many previously unknown condensations due to their CS emission. It has now become customary to search for star-forming cores using CS.

However, recent chemical models (summarized by Bergin 2000) have shown that CS is likely to be depleted due to freezing onto dust grains in the densest regions of pre-star-forming cores and therefore may not be the best tracer of dense star-forming gas. An alternative molecule to use as a tracer for dense gas is N$_2$H$^+$. N$_2$H$^+$ traces similar excitation conditions to CS, but chemically responds differently to variations in density. As a result, CS is more likely to trace post-star-forming gas while N$_2$H$^+$ traces the pre-star-forming cores.

We have therefore begun an unbiased study of two clustered star forming regions, L1630 and L1641 in both CS and N$_2$H$^+$. By mapping the regions in both lines (which can be observed simultaneously at FCRAO) we hope to be able to identify both the youngest cores, which have undergone collapse but not yet
formed stars (traced by the N$_2$H$^+$) and post-star-forming cores (traced by the CS), and look for evidence of the freezing out of CS. The combination of the optically thick CS and optically thin N$_2$H$^+$ will also enable us to search for evidence for infall in the clusters. This essential kinematical information complements existing (sub)-millimetre dust continuum observations of these cluster-forming regions. Here we present initial maps of the region surrounding LBS 23 and NGC 2068.

2. Observations

The observations were made with the FCRAO 14m telescope during the commissioning period of an On-the-Fly (OTF) mapping scheme in 2002 January. OTF mapping with the 16-element SEQUOIA$^1$ array receiver provides fast, high-quality and high-sensitivity imaging. Using the newly commissioned Dual-IF correlator with 25MHz total bandwidth and 1024 channels (providing an effective velocity resolution of 0.08 kms$^{-1}$), the two lines were observed simultaneously. Maps were obtained by scanning in the RA direction, and an “off” source reference scan was obtained after every two rows. Each $10' \times 10'$ submap required 3 repeats to build up the required sensitivity. The area shown here therefore represents a total of 18 hours of on-source observing. System temperatures during the observations were around 200 K.

Maps obtained by this method are not evenly sampled due to the rotation of the sky with respect to the array, and a convolution and regridding algorithm has to be applied to the data in order to obtain spectra on a regularly sampled grid.

3. Initial Results

Figure 1a shows an overlay of N$_2$H$^+$ 1–0 integrated intensity on a map of the CS 2–1 integrated intensity, in the region of LBS 23 and NGC 2068. These maps cover $\sim$ 600 square arcminutes and represent a pilot study of a much larger project. The emission maps shown here contain $\sim$ 4000 spectra at 25$''$ spacing (Nyquist sampling), each with an rms sensitivity of $\leq$0.1 K per 25 kHz channel.

Our pilot study has already shown some intriguing results. The N$_2$H$^+$ emission is less extended than the CS and a clear offset is seen between the peaks of the N$_2$H$^+$ and CS emission. This offset is not due to pointing error, as the data were obtained simultaneously with the dual-IF system. Figure 1b shows the area around LBS 23 in more detail. Triangles indicate the positions of sub-mm continuum sources found by Lis, Menten & Zylka (1999) and the stars show the positions of the sub-mm sources with IRAS detections. The sub-mm sources form a chain along the bright CS ridge, but their positions seem to correspond more closely to the N$_2$H$^+$ peaks, indicating that N$_2$H$^+$ is a better tracer of the youngest star-forming cores than CS.

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$^1$SEQUOIA was successfully upgraded to a 32-element dual-polarisation system in March 2002, providing even faster mapping capabilities.
Figure 1. Left: \(^2\text{H}^+\) contours overlaid on a grey-scale map of CS 2–1 emission. Right: Enlarged map of the \(^2\text{H}^+\) (contours) and CS (grey-scale) of the region around LBS23. The symbols indicate the positions of sub-mm sources detected by Lis, Menten & Zylka (1999). The (0,0) position corresponds to the position of LBS 23, \(\alpha = 05:43:34, \delta = -00:11:12\) (1950; LEF).

The left panel of Figure 2 shows the CS map overlaid on a 2MASS K-band image. The NGC 2068 cluster is located to the north-east of the CS core, in a region cleared of molecular gas as traced by CS. Bright stars are seen in several regions of high CS column density. The CS channel maps in the right panel of Figure 2 show structure not visible in the integrated intensity. Four arched filaments stretch out from the NGC 2068 region, while the LBS 23 region appears more diffuse. The northern region (around the NGC 2068 cluster) is present in more of the channels, indicating a higher CS line-width than the more quiescent southern region.

4. Project Goals

We are currently in the process of extending our survey to north to include the NGC 2071 region, and also to the Orion Nebula Cluster region, L1641-South cluster, the NGC 2023/4 region and the L1641 streamer. This ambitious project, includes a range of star-forming environments, from relatively quiescent to huge cluster-forming regions. In total our survey will cover approximately 9 sq. degrees.

The results from our pilot study already demonstrate the utility of chemistry as a tool for star formation studies. Using only CS as a tracer will bias a core sample to warmer or less dense regions (where depletion is less evident). The combination of CS and \(^2\text{H}^+\) maps probes a wider range of conditions. L1630
Figure 2. Left: CS 2–1 contours overlaid on a 2MASS K-band image. Right: 0.5 km s$^{-1}$ channel-maps of CS integrated emission, from 8–12.5 km s$^{-1}$
and L1641 are known to contain varied star-forming activity (Allen 1996), and therefore these data will allow for a more complete comparison of the distribution of molecular gas to known star-forming sites.

These two tracers are also routinely used for infall studies and CS is a common tracer of outflows. The huge area of our survey will enable us to look for these phenomena on scales previously beyond the capability of millimetre observatories.

Our project goals are:

• To compare and contrast core properties (mass, dynamics, densities) in the differing environments of L1630 and L1641.

• With the use of 2MASS and existing (sub-)millimetre continuum data, to investigate how core morphological and kinematical properties are related to the YSO population, and look for spectral and chemical signatures which trace different modes (clustered vs. distributed) of star formation.

• To investigate the effects of CS depletion, and look for an evolutionary trend in depletion between the cores, by combining the CS and N$_2$H$^+$ data.

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