LARGE SCALE MAPPING OF THE \( \rho \) OPHIUCHI REGION BY SWAS

Di Li\textsuperscript{1}, Paul F. Goldsmith\textsuperscript{2,3}, and Gary J. Melnick\textsuperscript{1}

\textsuperscript{1}Harvard-Smithsonian Center for Astrophysics, Cambridge, MA, U.S.A.
\textsuperscript{2}Astronomy Department, Cornell University Ithaca, NY, U.S.A.
\textsuperscript{3}National Astronomy and Ionosphere Center, Ithaca, NY, U.S.A.

Abstract

We have completed a 3 square degree CI \( ^3P_1-^3P_0 \) map of the \( \rho \) Ophiuchi region using SWAS. The remarkably stable receiver and backends systems of SWAS allow for uniformly calibrated data set on this scale. Combined with \( ^{12}\text{CO}, \, ^{13}\text{CO}, \, \text{and} \, \text{18o} \) maps made using FCRAO, this data set will facilitate a thorough study of the physics and the chemistry in this nearby star forming region.

Key words: Radio lines: ISM – ISM: individual (\( \rho \) Ophiuchi)

1. The Ophiuchi Region

At only 125 pc from the Earth (de Geus 1989), the \( \rho \) Ophiuchi molecular cloud is one of the closest regions of active star formation. This region has been the focus of numerous observational investigations, as witnessed by mapping efforts by Wilking & Lada (1983) and Loren et al. (1989), to give only some references with extensive mapping data. At the same time, it was recognized to be an interesting area for studying stars at the earliest phases of their evolution, and also properties of interstellar dust (e.g. Vrba, Strom, & Strom 1976). More recently, there has been a reawakening of interest, as witnessed by ISO observations in the infrared (Abergel et al. 1996; Liseau et al. 1999).

Its overall size of approximately 15 pc and its proximity present us a unique opportunity for studying both large scale structure and resolved dense cores. Our goal is to map the region in CI and three CO isotopologues (CO, \( ^{13}\text{CO}, \, \text{and} \, \text{18o} \)). The optically thick J=1-0 line of \( ^{12}\text{CO} \) provides information on the kinetic temperature of clouds, and thus sheds light into the cloud thermal balance. The lines with modest opacity such as CI fine structure line \( ^3P_1-^3P_0 \) and \( ^{13}\text{CO} \) J=1-0, are ideal for studying the large scale structure, particularly the effects of nearby ionizing sources, such as HD 147889. The largely optically thin tracer of \( \text{18o} \) 1-0 should provide a relatively complete census of cores from scale sizes of 1 pc to 0.03 pc.

We focus on the CI mapping of the \( \rho \) Ophiuchi region in this discussion.

2. Observations

The Submillimeter Astronomy Wave Satellite (SWAS) is particularly suitable to carry out large scale mapping in CI. At 492 GHz, its 54×68 cm antenna gives a relatively large beam of 3.5×5.0 FWHM. The off–axis Cassegrain design provides a 90% main beam efficiency, minimizing the sidelobe pickup. Although CI can be observed from ground based telescopes, the opacity and instability of the atmosphere at this frequency make it hard to perform position switching with large throws. Finally, the acousto–optical spectrometer (AOS) on board SWAS has proven to be extremely stable. This is important for maintaining high quality of the overall calibration for a data set taken over a time span of a couple of years.

From February 1999 to March 2002, SWAS has taken data toward 4345 individual positions with 1.6′ spacing. The Nyquist sampled maps cover a region of 3 square degrees including the \( \rho \) Oph A cloud and Lynds 1689. The 18o data were only available from the Five College Radio Astronomy Observatory (FCRAO) during roughly the same period as the SWAS observations. \( ^{12}\text{CO} \) and \( ^{13}\text{CO} \) maps cover the same 3 square degree region. The \( \text{18o} \) data were only...
Figure 1. The CI and $^{13}$CO spectra from the maps of the ρ Ophiuchi clouds. The map center is at (16$^h$26$^m$25$^s$.4, -24$^\circ$23$'$02$''$) (J2000). Given in the top of each box is the angular offset ($\Delta$RA, $\Delta$DEC). All spectra have been convolved with a Gaussian beam of 4.25$'$ FWHM and corrected for the main beam efficiencies of the respective telescopes. The $^{13}$CO line intensities have been reduced by a factor of 2 in order to be shown on the same scale with CI.

taken toward selected areas with high column density. The details of these data will be discussed elsewhere.

3. CLOUD TEMPERATURE AND CI COLUMN DENSITY

For a spectral line with modest opacity like CI, the column density derived from the line integrated intensity can be parameterized as the following

$$ N_{CI} = N_1 F_r F_b F_u , $$

where

$$ N_1 (cm^{-2}) = 5.94 \times 10^{15} \int T_{mb} dV \ (km \ s^{-1}) $$

is the column density in the $^3P_1$ level (Frerking et al. 1989),

$$ F_r = \frac{\int \tau dv}{\int (1 - e^{-\tau}) dv} $$

accounts for the line opacity,

$$ F_b = \left[ 1 - \frac{e^{\frac{h\nu}{kT_x}} - 1}{e^{\frac{h\nu}{kT_{bg}}} - 1} \right]^{-1} $$

accounts for the non-zero background temperature $T_b$, and

$$ F_u = \frac{1}{3} e^{23.6/T_x} + 1 + \frac{5}{3} e^{-38.8/T_x} $$

converts the population in the $^3P_1$ level to the total population.

Both $F_b$ and $F_u$ diverge for excitation temperatures $T_x < 5$ and remains essentially constant for $T_x > 20$. For an average density of $n \sim 10^4$ cm$^{-3}$ and and a nominal carbon abundance $[C^0]/[CO] \sim 0.1$, the CI $^3P_1$–$^3P_0$ line is close to being thermalized based on Large Velocity Gradient calculations. The opacity of this line can then be estimated using the antenna temperature and the gas temperature under these conditions. It is, therefore, important to determine the gas temperature.

For cloud surfaces, the $^{12}$CO 1–0 antenna temperatures provides a measure of the gas temperature due to its large opacity. The temperatures thus obtained show a relatively smooth distribution in the range 20 to 25 Kelvins for the bulk part of the clouds. Patches of temperature enhancement (30–40 K) appear around the center of ρ Oph A and along some cloud edges of both ρ Oph A and L1689. A comprehensive explanation for the temperature structure should include both internal and external heating. Particularly, the heating of the cloud edges, if proven exclusively due to external heating, could provide us a measure of the UV enhancement (Li & Goldsmith 2002). The change in the UV field must be tied with the gas density and with the $[C^0]/[CO]$ ratio in a consistent manner in developing a completed physical and chemical model of the region.

Overall, the physical conditions of ρ Oph clouds produce thermalized CI emission at relatively warm temperatures ($T_x > 20$ K), which restricts the variation in the combined factor $F_r F_b F_u$ to be no more than 5%. One major uncertainty in the derived $N(CI)$ lies in the significant opacity close to cloud centers, where the CI line may become optically thick and the CO line shows self-absorption. For cloud edges, the CO line may not be thick enough to allow an accurate determination of gas temperatures. At the cloud edges, the density also drops so that the CI line may no longer be thermalized.

The derived CI column density shows a striking correlation in morphology with that of the $^{13}$CO (Figure 2). In low extinction regions, ring like structures around (120$, 0'$) and (-10$, -15'$) are seen both in $^{13}$CO and in CI. In
high extinction regions, CI and $^{13}$CO peak at the same locations both in L1689 and $^{^0}$ Oph A.

4. Discussion

According to van Dishoeck and Black (1988), the fractional abundance of CI increases from very low visual extinction ($A_v$) and to a peak at about $A_v = 2$ for an average interstellar radiation field. CI disappears in highly extinguished regions before $A_v$ reaches 10. Apparently, a large portion of the clouds are darker than $A_v = 10$ with the central extinction of $^{^0}$ Oph A being a couple of hundred. If only a skin of CI is seen toward the line of sights with large $A_v$, we would expect a more uniform image of CI column density. Similar phenomena are also observed in other regions, particularly those with stronger UV fields, such as M17 (Howe et al. 2000) and Orion (Plume et al. 2000). To explain the presence of CI in high extinction regions, suggestions have been made in terms of clumpy structure and/or dynamics, which allow UV to penetrate further. We will study the spatial correlation scales of CI and CO, which could test the plausibility of these two types of models.

As whole, CI and CO data form a valuable data set, which allow us to pursue a consistent picture of the large scale structure and chemistry of the $^{^0}$ Ophiuchi region.

Acknowledgements

This work was supported by NASA's SWAS contract NAS5-30702. The Five College Radio Astronomy Observatory is supported by NSF grant AST 97-25951. The National Astronomy and Ionosphere Center is operated by Cornell University under a Cooperative Agreement with the National Science Foundation.

References

Abergel, A., et al. 1996, A&A, 315, L329

de Geus, E., de Zeeuw, P., & Lub, J. 1989, A&A, 216, 44

Frerking, M. A., Keene, J., Blake, G. A., & Phillips, T. G. 1989, ApJ, 344, 311

Howe, J. et al. 2000, ApJ, 539, L137

Kenyon, S.J., Lada, E.A., & Barsony, M. 1998, ApJ, 115, 252

Li, D., & Goldsmith, P.F. 2002, submitted to ApJ

Liseau, R., et al. 1999, A&A, in press

Loren, R.B. 1989, ApJ, 338, 902

Motte, F., André, P., & Neri, R. 1998, A&A, 336, 150

Plume, R. et al. 2000, ApJ, 539, L133
Wilking, B.A. & Lada, C.J. 1983, ApJ, 274, 698
van Dishoeck, E. F. & Black, J. H. 1988, ApJ, 334, 771
Vrba, F.J., Strom, S.E., & Strom, K.M. 1976, AJ, 81, 317
