

# The Extended Halos of Molecular Clouds: Observations of C I and other species in Perseus, the Southern Coalsack, Chamaeleon and Lupus

Peter Wannier<sup>1</sup>, B-G Andersson<sup>2</sup>, Bryan Penprase<sup>3</sup> & Steve Federman<sup>4</sup>

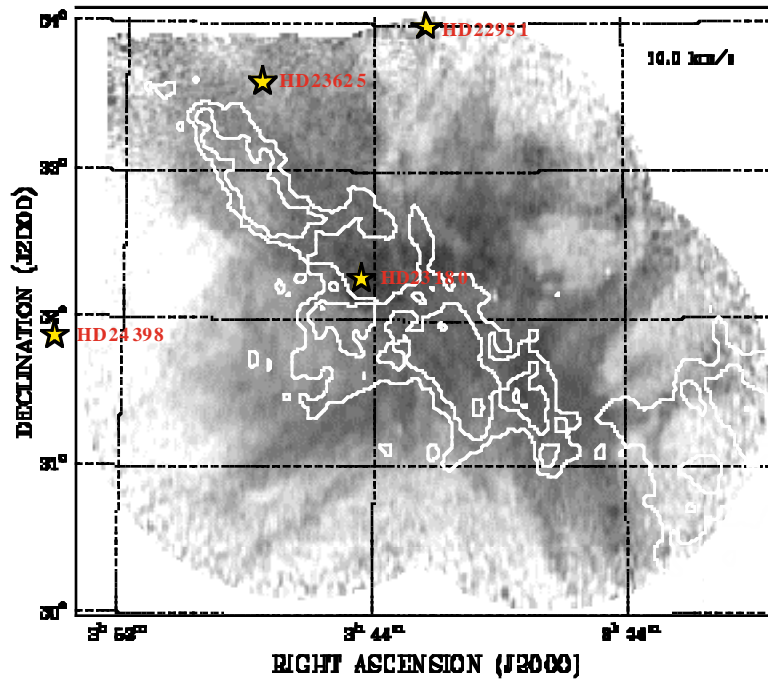
<sup>1</sup>Jet Propulsion Lab, Caltech, <sup>2</sup>Johns Hopkins Univ., <sup>3</sup>Pomona College, <sup>4</sup>Univ. of Toledo

Surrounding dense molecular clouds are extended halos of cool atomic and molecular gas (PDRs). We have used HST spectral line observations of the fine structure level populations of C I toward four stars in the Perseus region to precisely measure the fine structure excitation of atomic carbon (C I) (Wannier et al., 1999a). These results can be used to tightly constrain the gas pressure, and in combination with other observations, we show that the C I results can indicate the physical state of the atomic medium, and they can reveal much about the likely evolution of the central cloud.

Direct observations of the two fine structure emission lines at 492 and 809 GHz are possible, but very difficult to obtain using ground-based observatories (c.f. Zmuidzinas et al., 1986), with reliable calibration practical only from such sites as the Antarctica. For objects in the Northern Hemisphere, SOFIA observations of the C I fine structure lines will provide the capability of mapping the gas pressure in the extended halos of dense clouds.

HST absorption-line spectra provide accurate measurements of the fine structure excitation along selected sightlines, due to the availability of many spectral lines having wide ranges of line strengths, and resulting optical depths. Analysis of the C I excitation toward gas in the vicinity of the Perseus/B5 molecular cloud yield  $nT_{\text{kin}} = 2200 \pm 300 \text{ K cm}^{-3}$ . We derive  $T_{\text{kin}}$  on the same sightlines from optical observations of  $\text{C}_2$ , and from far-UV observations of  $\text{H}_2$ , yielding  $T_{\text{kin}} = 20\text{-}60\text{K}$ . Together with the observed pressure measurement, these yield a gas density  $n_{\text{tot}} = 35\text{-}110 \text{ cm}^{-3}$ .

**Figure 1.** The four stars discussed in this poster are located relative to the Perseus/B5 molecular cloud, seen in this figure (from Wannier et al., 1999b) by means of H I 21 cm emission (gray-scale) and  $^{13}\text{CO}$  2.6 mm emission (contours). The H I observations were obtained using the Synthesis Telescope and the 26m single-dish telescope of the Dominion Radio Astrophysical Observatory (DRAO). The  $^{13}\text{CO}$  observations were obtained at the AT&T Bell Laboratories 7-m antenna. The H I structure appears to be associated with the dense CO cloud, supporting the notion that it is part of an extended atomic halo, possibly consisting of an outflow.



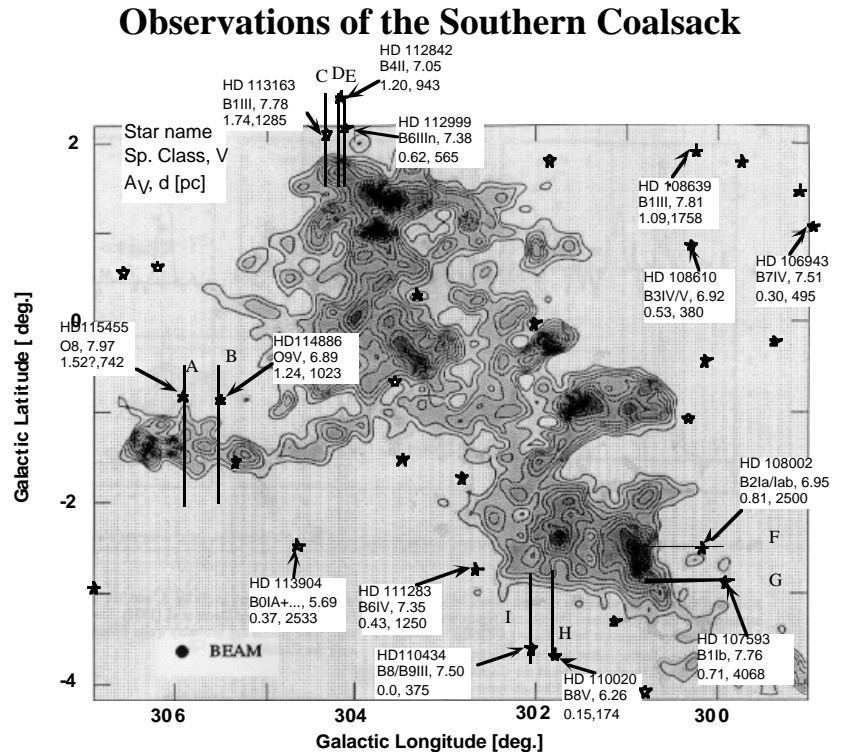
This gas density, in combination with molecular and atomic column densities ( $N_{\text{H}_2}$  and  $N_{\text{H I}}$ ) can yield the physical column length and the volume filling factor. The column length,  $L$ , implied

by far-UV observations of  $H_2$  falls in the range 3-10 pc, comparable to the extent on the sky of the gaseous halo and implying a volume filling factor of order unity for the diffuse molecular gas. This result is strengthened by our observations of 21-cm H I (Wannier et al., 1999b, see figure 1). The 10 km/s velocity channel map, corresponding to the Perseus radial velocity, shows a halo extending away from the dense CO cloud (Figure 1). The implied column density  $N_{H\text{I}}$  is somewhat larger (factor of 1 to 3) than  $N_{H_2}$ . Defining  $L = N_{\text{tot}}/n_{\text{tot}} = (N_{H_2} + N_{H\text{I}})/n_{\text{tot}}$ , we find values of  $L$  larger than the extent of the projected minor axis of the Perseus region. This result tightly constrains the volume-filling factor to a value close to unity. This further supports the notion of an extensive, uniformly-pressurized gaseous halo surrounding the B5 cloud.

The large volume filling factor also supports our analysis of the excitation of the C I fine structure levels, implying that they are predominately excited by collisions in the gas, and not by UV photons. We therefore also conclude that the ISRF does not exceed our assumed value by more than a factor 3. During the course of our analysis, we have shown that the rotational excitation of CO toward our B5 sightlines is unlikely to result from collisions, but rather is likely to result from the absorption of radio wavelength photons emitted by nearby denser CO-containing clouds.

We have used the Antarctic AST/RO submillimeter-wave observatory to obtain 11 strip-maps of 492 GHz C I emission. The strips were chosen so as to traverse the boundary of the dense molecular (CO) cloud, and to pass through sightlines toward hot background stars suitable for providing far-ultraviolet and optical wavelength absorption-line spectra of the intervening medium. Measurements of the gas temperature will be made from an analysis of  $H_2$  excitation, using the orbiting FUSE spectrometer, and C I excitation will be evaluated using proposed HST observations.

**Figure 2.** This contour map of CO emission from the Southern Coalsack (Nyman et al., 1989) locates the background stars used to study gas in the extended, low-density cloud halo. The stars are part of our GI program on the Far-Ultraviolet Spectroscopic Explorer (FUSE), to study the abundance and rotational excitation of  $H_2$ . Complementary HST (STIS) observations are planned. The heavy black lines indicate the extent of strip maps of submillimeter-wave (492 GHz) C I emission, made with the AST/RO telescope in the Antarctic. Together, these data sets provide detailed information about the physical state, kinematics and composition of the gas.



### References

- Nyman, L-Å, Bronfman, L. and Thaddeus, P., 1989, *A&A*, **216**, 185.  
Wannier, P. G., Andersson, B-G, Penprase, B, and Federman, 1999a, *S. R.*, *ApJ*, **510**.  
Wannier, PG, Moriarty-Schieven, GH, Andersson, B-G, Hilts, M & Langer, WD, 1999b (in prep).  
Zmuidzinas, J., Betz, A. L. and Goldhaber, D. M., 1986, *ApJ*, **307**, L75.