TWO NEW RECOMBINATION-LINE RESULTS

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Abstract. This paper reports two new recombination-line results. The first is the detection of carbon line emission from the dark cloud near ϱ Ophiuchi, and the second discusses the origin of hydrogen recombination line emission associated with ionized gas outside known discrete continuum sources.

Current theories of heating and ionization processes in the interstellar medium suggest that many dark dust clouds should be sufficiently dense and cold, and have low enough velocity dispersions, that radio recombination-line emission should be detectable. Previous searches have proved negative (see Gordon, 1973), but a more recent search at 21 cm (the 166α and 167α lines) of four clouds by Brown and Knapp (1974) has shown the existence of a carbon emission line from one of them, the ϱ Ophiuchi cloud. The fact that only carbon, and not hydrogen, emission lines are seen suggests that the ionization is due to UV and not cosmic rays. Such UV could originate either in newly-formed stars in the cloud itself or in the early-type stars (such as ϱ Ophiuchi) near the cloud. The ϱ Ophiuchi cloud is the only dust cloud so far observed which is associated with such early-type stars.

The four clouds observed by Brown and Knapp contain large amounts of atomic hydrogen (Knapp, 1972), and the fact that ionized gas was seen in only one of the four clouds suggests that the processes responsible for ionization in dust clouds, and for the presence of atomic hydrogen, are not related.

The second recombination-line result comes from a new study by Jackson and Kerr of H110α recombination-line emission associated with ionized hydrogen outside of known discrete continuum sources. This type of distributed ionization has been studied by several workers at various wavelengths, mostly near 18–21 cm. Both the present observations, and earlier work of ours, were carried out near 6-cm wavelength. The use of a shorter wavelength gives the advantage of greater directional resolution and also ensures that the thermal component of the continuum emission is relatively more important. Unfortunately, the lines are more difficult to detect at the shorter wavelengths since the line brightness temperatures are roughly proportional to wavelength.

Our new observations were largely concerned with point-to-point variability of the emission. Figure 1 shows the results of integrating for 2 to $4\frac{1}{2}$ h on each of a series of positions approximately along the galactic equator from $l=23\overset{\circ}{.}92$ to $l=32\overset{\circ}{.}32$. Although the profiles are noisy, there are clear variations from position to position. Nine closely spaced positions were observed, the central one being $l=25\overset{\circ}{.}07$, $b=0\overset{\circ}{.}01$,

F. J. Kerr and S. C. Şimonson, III (eds.), Galactic Radio Astronomy, 81–85.

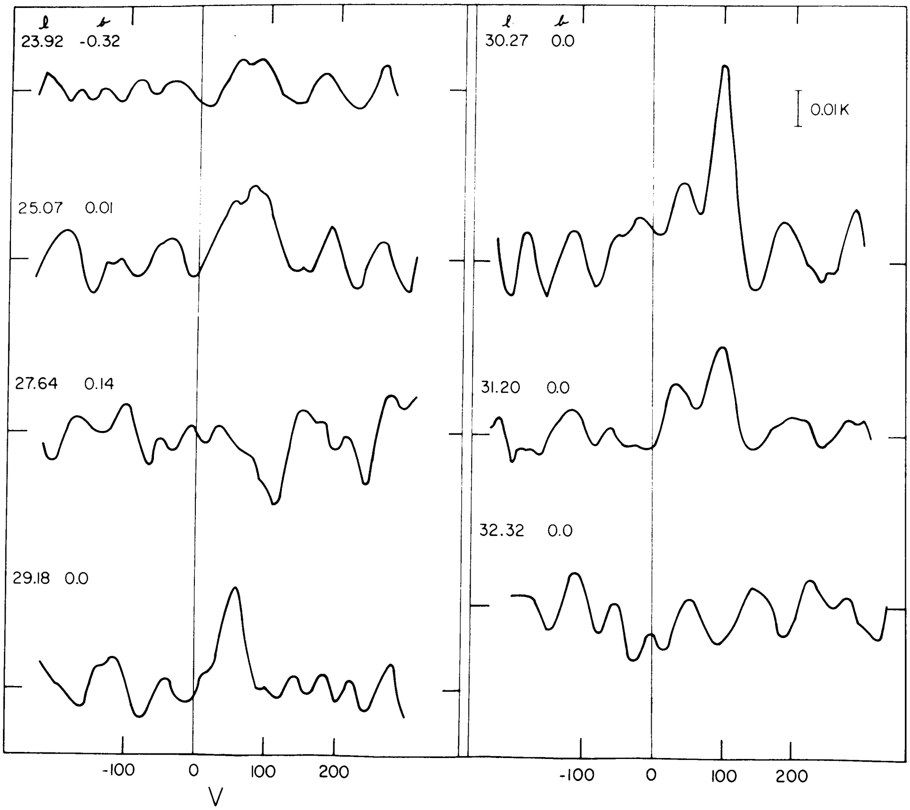

Fig. 1. Profiles of H110α recombination-line emission from a series of positions near the galactic equator between $l=23.92$ and $l=32.32$, The vertical axis is brightness temperature, and the horizontal axis is radial velocity in km s^{-1} relative to the local standard of rest after correction for 'standard' solar motion. The galactic coordinates for each profile are also indicated.

a position observed near 18-cm wavelength by Gottesman and Gordon (1970) and by Gordon and Gottesman (1971). We observed the nine closely spaced positions in order to build up a 6-cm profile corresponding to the beam size at 18 cm so that we could look at the spectral characteristics of the line radiation.

In Figure 2 is plotted the integrated line brightness L in K km s^{-1} against the concurrently observed 6-cm continuum temperature, T_b, for the seven positions of Figure 1. Despite the noise in the profiles, the correlation between L and T_b is quite good. A fit to the data is given by the line $L=2.3\ (T_b-0.7)$. If we identify the portion of T_b which correlates with L as the thermal component of the continuum emission, then we can infer that the residual portion of T_b, 0.7 K, represents the general non-thermal background over the whole region.

The slope $L/T_{th}=2.3$ allows us to derive an electron temperature $T_e=4400\pm600$ K as an average electron temperature for the distributed ionized gas in the region $l=24°-33°$. This computation assumes LTE, which seems to be a reasonable approximation, since the ratio of our value of L for $l=25.07$. $b=0.01$, with that ob-

https://doi.org/10.1017/S0074180900026309 Published online by Cambridge University Press

tained near 18 cm by Gordon and Gottesman (1971) agrees well with that predicted by LTE.

The fact that the LTE equation seems to be suitable for the emission, combined with the rapid point-to-point variability, the correlation with the continuum emission, and the relatively high associated electron temperatures all lead to the con-

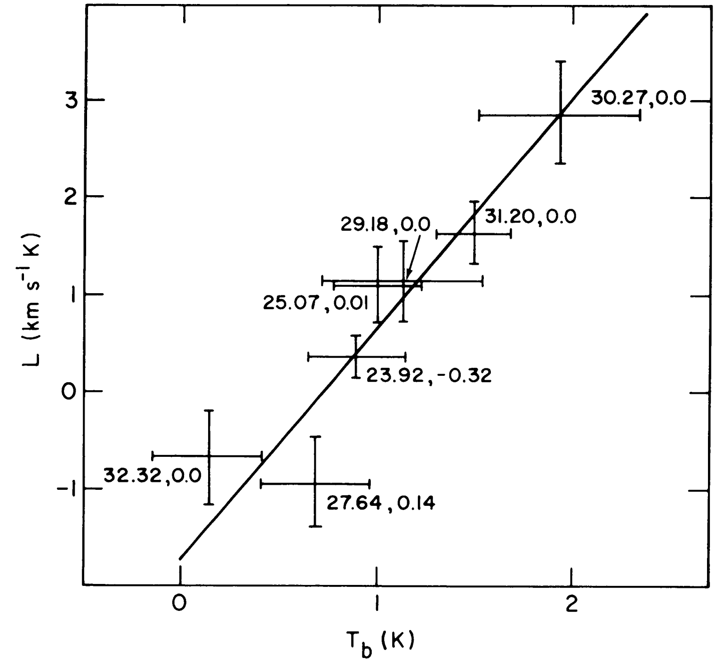

Fig. 2. Integrated H110α recombination-line emission, L, as a function of the continuum brightness temperature, T_b, at the same wavelength of observation, for the 7 positions whose profiles are given in Figure 1. The galactic coordinates for each position are indicated next to its plotted symbol. The estimated uncertainties in L and T_b are also indicated by error bars for each position. The straight line fit has the form $L = 2.3\,(T_b - 0.7)$.

clusion that most of the line radiation originates in small H II regions. Some calculations of the amount of line emission based on likely ionization around early-type stars come out a few times too low to explain our observations, using data for the solar neighborhood. However, we can reasonably assume that the small H II regions become more important in the inner regions of the Galaxy studied here; we know that a corresponding distribution is true for the giant H II regions.

Acknowledgements

The observations described herein were carried out with the 43-m telescope of the National Radio Astronomy Observatory. We thank the NRAO for the observing time to carry out these projects. The NRAO is operated by Associated Universities

Inc., under contract with the National Science Foundation. This research is supported by the NSF.

References

Brown, R. L. and Knapp, G. R.: 1974, *Astrophys. J.* **189**, 253.
Gordon, M. A.: 1973, *Astrophys. J.* **184**, 77.
Gordon, M. A. and Gottesman, S. T.: 1971, *Astrophys. J.* **168**, 361.
Gottesman, S. T. and Gordon, M. A.: 1970, *Astrophys. J. Letters* **162**, L93.
Knapp, G. R.: 1972, Ph.D. thesis, University of Maryland.

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DISCUSSION

Guélin: The proportionality of the integral of the radio recombination line strength to continuum temperature does not mean that the emitting electron gas is isothermal. Your temperature estimate may thus be not very meaningful.

Menon: Have you high enough angular resolution in the Orion nebula carbon observations to tell how the carbon is distributed? There is an H I emission cloud superimposed on the Orion nebula, corresponding to the dark bay, with the same velocity as the carbon line.

Zuckerman: At 2′ or 3′ resolution the carbon emission comes from all around the nebula. Most of it probably comes from the background molecular cloud, but some could be coming from the dark bay also.

Gordon: I have searched for recombination lines from five other dust clouds without success. Combining these results with those of Brown and Knapp, I feel that the detection in one of ten clouds searched means that the ϱ Oph dust cloud is indeed unusual and not characteristic of dust clouds in general.

Churchwell: It seems to me that the high-density model for the carbon recombination line does not answer two problems:

(1) If the carbon emission cloud is behind the H II gas in Orion A, how does one explain the increased line intensity of the carbon line at lower frequencies, particularly with LTE emission as you suggest?

(2) In W3 why does one not observe the carbon line in absorption at lower frequencies?

Zuckerman: In response to your question about the increased carbon line intensity in Orion A at low frequencies one must be careful to distinguish between non-LTE emission and stimulated emission. That is, although the latter may be unimportant this does not necessarily imply that I believe that the emission region is in LTE. Theoretical calculations by Dupree of the carbon level populations (the b_n's) indicate that they increase rapidly towards higher n. This would result in increased low frequency emission in the situation where only spontaneous emission contributes to the line intensities. As for W3 one would not necessarily expect to observe the carbon line in absorption at low frequencies for two reasons. Firstly, the central (bright) regions of the nebula fill only a small fraction of the beam of a single antenna at $\lambda \gtrsim 21$ cm, and, in any case, Dupree's calculations still suggest a small inversion of the levels even for dense clouds near $n \sim 166$.

J. R. Dickel: All the evidence we have seen today has pointed to the recombination lines arising in hot regions, but Gordon says he still favors cool regions. Would he comment as to why he favors low temperatures for the component emitting the diffuse recombination lines?

Gordon: I believe the source of the 'diffuse' recombination lines to be uncertain, both in $\langle T_e \rangle$ and $\langle n_e \rangle$. However, the beautiful analytical work for 3C 391 by Cesarsky and Cesarsky, leading to $\langle T_e \rangle \approx 20$ K, is difficult to refute. However, in other directions, different physical conditions may prevail; there the lines might be generated by weak H II regions.

Zuckerman: I don't favor Chaisson's interpretation of some of these re-combinations results. He has a preprint out where he's analyzed that same supernova and he finds that he can reproduce the observations with the hot gas, essentially the H II regions.