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DETECTION OF THE 370 MICRON $^3P_2$–$^3P_1$ FINE-STRUCTURE LINE OF [C I]

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ABSTRACT

We report here the first detection of the 370 μm (809 GHz) $^3P_2$–$^3P_1$ fine-structure transition of neutral carbon. The detection of this line confirms the (already strong) identification of the line seen at 492 GHz by Phillips *et al.* and reported in 1980 as the $^3P_1$–$^3P_0$ line of [C I]. The observations toward the core of the Orion molecular cloud show a line brightness temperature 1.7 ± 0.5 times that of the previously detected $^3P_1$–$^3P_0$ line. The center velocities and widths of the two [C I] lines are in good agreement. If both transitions arise in a single emission region that fills the beams used in the observations, an optically thin region with a temperature ≥ 300 K is the best explanation of the observed line ratio. The C I column density is then $\sim 10^{18}$ cm^{-2}. However, the observations are only $\sim 1.3\ \sigma$ from a brightness temperature and line intensity ratio which would allow an optically thick ~ 25 K region as the source of the [C I] emission. Source-dependent corrections to the observed ratio could push the result toward either a warm optically thin or cool optically thick medium as the line emitter. The most likely location for a warm optically thin region is in the interface between the Orion H II region and the massive molecular cloud that lies behind it. If the [C I] emission arises from a uniform, optically thick medium, it could not come from the 80–100 K gas at the core of OMC-1 or from the hot region immediately around the Kleinmann-Low nebula. The [C I] lines would have to arise in cooler gas, probably in the back half of the molecular cloud.

Subject headings: infrared: spectra — interstellar: matter — nebulae: Orion Nebula

I. INTRODUCTION

Neutral carbon has two transitions in the submillimeter region that arise from the fine-structure splitting of its ground state. The energy level spacing, $h\nu$, is approximately equal to kT in many interstellar clouds, and the critical density for population of the fine-structure levels is relatively low ($\sim 10^3$ cm^{-3}). The two submillimeter lines of C I are therefore important cooling lines in interstellar gas. The $^3P_1$–$^3P_0$ line at 492 GHz was first detected by Phillips *et al.* (1980) and is strong in many clouds where the low-J rotational transitions of CO also are strong (Phillips and Huggins 1981). Models of molecular clouds predict that UV radiation will cause much of the interstellar carbon to be in the form of C I at the edges of the clouds (see Langer 1976; Tielens and Hollenbach 1984, 1985*a*, *b*). The $^3P_1$–$^3P_0$ observations of Phillips *et al.* (1980) and Phillips and Huggins (1981) indicate that the abundance of C I is substantial ($N_{\rm C\,I} \approx 0.1\ N_{\rm CO}$) in many clouds and possibly could be comparable to the CO abundance. Such a large C I abundance would imply that neutral carbon exists throughout the clouds and would require a revision of current interstellar carbon chemistry models and/or of the commonly accepted chemical lifetime ($\gg 10^6$ yr) of giant molecular clouds.

Measurement of both the $^3P_1$–$^3P_0$ and $^3P_2$–$^3P_1$ transitions of C I completely characterizes the three-level system in the ground state since collisions cannot excite any other levels at the temperatures present in the dense interstellar medium. We report here the first observations of the $^3P_2$–$^3P_1$ transition. We have detected the line toward the center of the Orion molecular cloud (OMC-1). We discuss our result and compare it to the earlier measurement of the $^3P_1$–$^3P_0$ line (Phillips *et al.* 1980).

II. OBSERVATIONS

We observed the 370.414 μm (809.345 GHz; Saykally and Evenson 1980) $^3P_2$–$^3P_1$ transition of neutral carbon in 1984 January with the University of California, Berkeley submillimeter heterodyne spectrometer mounted on the University of Hawaii 88 inch (2.2 m) telescope on Mauna Kea. The spectrometer is the first of its type to mount at the Cassegrain focus of a telescope and weighs ~ 160 kg. The instrument is functionally similar to larger spectrometers used at coudé focus (Fetterman *et al.* 1981; Röser *et al.* 1984). It consists of an optically pumped far-IR molecular laser local oscillator (LO), a quasioptical diplexer to couple the LO and telescope signals, and an open structure Schottky-diode mixer. For the observations described here, the LO frequency was that of the $^{15}NH_3$ laser transition at 802.986 GHz. The open-structure mixer uses a corner reflector and a 4λ antenna contacted to a Schottky diode (Kräutle, Sauter, and Schultz 1977). The single-sideband noise temperature, measured at the telescope, ranged from 13,000 to 17,000 K. A filter spectrometer with 40 5 MHz channels analyzed the IF signal. At the line frequency, the velocity resolution was 1.85 km s^{-1}, and the total band observed was 75 km s^{-1} wide.

We observed by chopping the telescope secondary mirror between the source and (alternately) two off-source positions 6′ north and south of the Becklin-Neugebauer object in OMC-1. We determined the instrument boresight to $\pm 20''$ by

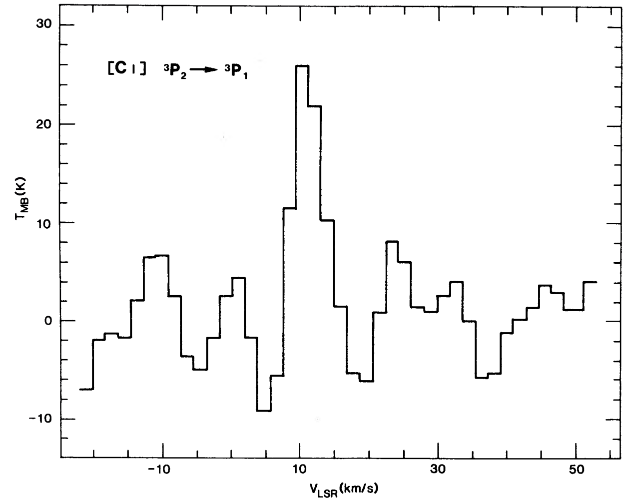

FIG. 1.—Spectrum of the $^3P_2 \rightarrow {}^3P_1$ transition of [C I] toward the Becklin-Neugebauer object in Orion. The horizontal scale is LSR velocity, and the vertical scale is Rayleigh-Jeans main beam brightness temperature.

scanning the beam across the limb of the Moon. The error in the boresighting dominated the other pointing uncertainties. The calculated beam size, based on the illumination pattern used, was 40″ full width to half-maximum. Subsequent measurement of the beam pattern on another telescope has confirmed the accuracy of the calculations. We derived the flux calibration by observing 273 K and 195 K loads and determined the 370 μm atmospheric transmission on the two nights when observations were possible by measuring the sky brightness temperature at several zenith angles. The zenith transmission was 30% on January 23 and 20% on January 25 UT. The line of sight transmission ranged from 10% to 25%. We obtained an estimate of the forward beam efficiency of the telescope plus spectrometer optics of $\eta_B \approx 0.4$ from observations of the Moon and the adjacent sky. The transmission uncertainty is $\pm 10\%$ and the beam efficiency estimate has an uncertainty on the order of $\pm 20\%$.

III. RESULTS

Figure 1 shows the spectrum of the $^3P_2$–$^3P_1$ line of [C I] toward the core of OMC-1. The vertical scale is Rayleigh-Jeans main beam brightness temperature ($T_{\rm MB}$), which is the antenna temperature corrected for atmospheric attenuation and forward beam efficiency. We have Hanning smoothed the spectrum to a resolution of 2.6 km s^{-1}. The baseline ripple apparent in Figure 1 is a factor ~ 3 higher than the statistical noise level which we measured separately in a series of short integrations. If we treat the baseline ripple as a random noise source, the line detection is at the 6σ level. The integration time was 96 minutes (on and off source). The apparent main beam temperature is $T_{\rm MB} = 24 \pm 4$ K. The true peak $T_{\rm MB}$, corrected for the finite resolution of the spectrometer and the measured width of the line, is 27 ± 5 K. The overall error, allowing for the calibration and transmission uncertainties, is ± 9 K. The Planck brightness temperature of the $^3P_2$–$^3P_1$ line is $T_B = 44 \pm 10$ K. The line width, corrected for the finite spectrometer resolution, is 5 ± 1 km s^{-1}, assuming a Gaussian line shape. This line width is in good agreement with the result of Phillips *et al.* (1980) for the $^3P_1$–$^3P_0$ line. The velocity of the $^3P_2$–$^3P_1$ line center is 11 km s^{-1} and agrees with both the $^3P_1$–$^3P_0$ center velocity and the velocity of the molecular cloud to within the combined statistical errors and the uncertainties in the [C I] and local oscillator laser line frequencies (± 3 MHz, Saykally and Evenson 1980; ± 0.5 MHz, this work). The baseline ripple apparent in Figure 1 is not entirely characterizable with the small number of channels observed. If we take our best guess as to its amplitude and phase and remove it from the spectrum, the best value of T_B is 35 ± 7 K, where the errors do not reflect the uncertainty involved in the ripple subtraction. The integrated line brightness will drop by approximately 10% (to 6×10^{-5} ergs cm^{-2} s^{-1} sr^{-1}) after the correction, and the observed line width will increase by $\sim 20\%$.

IV. DISCUSSION

The detection of the 809 GHz $^3P_2$–$^3P_1$ transition of [C I] provides conclusive confirmation of the identity of the 492 GHz line as the $^3P_1$–$^3P_0$ transition of [C I]. Although the high spectral density of molecular lines at lower frequencies (Sutton *et al.* 1984; Johansson *et al.* 1983) indicates that a mistaken identification is possible, the probability of such a coincidence is very low, especially for a relatively strong line such as the $^3P_1$–$^3P_0$ [C I] line. The detection of the $^3P_2$–$^3P_1$ line makes the probability of a misidentification virtually nil. We consider here the observed $^3P_2$–$^3P_1$/$^3P_1$–$^3P_0$ line ratio in relation to the simplest possible physical model of the [C I] emission region. The model consists of a region of uniform temperature, density, and optical depth. This region must have an extent significantly larger than the $^3P_1$–$^3P_0$ beam size ($\Theta_B = 2.5$) but smaller than twice the $^3P_2$–$^3P_1$ chopper throw ($2\Theta_{\rm chop} = 12'$).

a) A Single [C I] *Emission Region*

One limiting case for [C I] line parameters is a medium where both ground-state lines are optically thin, the levels are fully thermalized [$n(H_2) \geq 10^4$ cm^{-3}], and the kinetic temperature is high ($T_k \gg h\nu_{21}/k$). In this limit, the statistical weights determine the level populations, and these weights and the Einstein *A*-coefficients (2.7×10^{-7} s^{-1} for $^3P_2$–$^3P_1$, 7.9×10^{-8} s^{-1} for $^3P_1$–$^3P_0$; Nussbaumer 1971) determine the line flux and brightness temperature ratios (9.3 and 2.1, respectively, for $T > 500$ K). Another limiting case is an optically thick thermalized medium. In this limit, the line flux ratio is $\nu_{21}B(\nu_{21}, T)/\nu_{10}B(\nu_{10}, T) \leq 4.5$ ($= 3.1$ for $T = 25$ K), and the brightness temperature ratio is 1.0.

The observed $^3P_2$–$^3P_1$/$^3P_1$–$^3P_0$ line flux ratio is 10 ± 5. The observed brightness temperature ratio is 1.7 ± 0.5. Based on these ratios, the best derived temperature for the [C I] region is $T \geq 300$ for a fully thermalized gas. The line emission would then be optically thin. The combined calibration uncertainties for the two observed transitions, however, are substantial when compared to the range of variation in the line ratios for emission regions with reasonable physical parameters. As a result, the observed line flux and line brightness temperature ratios differ by only $\sim 1.3\ \sigma$ from the values expected from a cool ($\sim$ 25 K) optically thick emission region.

For an optically thin, thermalized gas, we derive from the $^3P_2$–$^3P_1$ line a total C I column density of 9×10^{17} cm^{-2} for $T_k \geq 300$ K. The C I column density increases only 30% to 1.2×10^{18} cm^{-2}, for $T_k = 80$ K. These column densities are comparable to those derived by Phillips *et al.* (1980) for OMC-1 from observations of the $^3P_1$–$^3P_0$ transition. They assumed a kinetic temperature of 20 K in the line formation region. At that temperature, the fraction of C I in the $J = 1$ state is the same as at 300 K but with most of the balance of C I in the $J = 0$ state instead of in $J = 2$. From the flux in the $J = 1$–0 line of $^{12}C^{18}O$ toward OMC-1 (Ulich and Haas 1976), we derive a column density of 3×10^{19} cm^{-2} for $^{12}C^{16}O$ assuming $^{12}C^{16}O/^{12}C^{18}O = 500$, $T = 80$ K, and that the $C^{18}O$ line is optically thin everywhere. This column density implies a C I relative abundance in a column toward the center of OMC-1 of $N(\text{C I}) \approx 0.04\ N(\text{CO})$. Much of the $C^{18}O$ emission may be from cooler line-of-sight material, however, in which case the CO column density will be lower (2×10^{19} cm^{-2} for $\langle T \rangle = 50$ K). On the other hand, the $C^{18}O$ emission may come from clumpy gas which is optically thick in spots. We can compare the C I column density with the hydrogen column density in the warm (100 K) core of the Orion molecular cloud using the far-IR dust continuum measurements (Werner *et al.* 1976; Werner *et al.* 1977; Jaffe *et al.* 1984), the relationship between UV and far-IR dust optical depth (Whitcomb *et al.* 1981), and the visual extinction to hydrogen column density ratio (Bohlin, Savage, and Drake 1978; see Hildebrand 1983). From the 100 μm flux toward BN-KL (Jaffe *et al.* 1984), we obtain a hydrogen column density of 3×10^{23} atoms cm^{-2}. This implies a C I abundance $\sim 3 \times 10^{-6}$ along the line of sight. If the [C I] emission arises predominantly in the H II/neutral interface region (Tielens and Hollenbach 1984, 1985*a*, *b*), the C I abundance in that region is substantially higher.

The interface between the Orion H II region and the dense molecular cloud behind it is the most likely site for a hot optically thin single component [C I] emission region. Far-IR [O I] and [C II] fine-structure line maps as well as C II radio recombination line results show that this interface region has a diameter of 4′–5′ (Naylor *et al.* 1982; Werner *et al.* 1984; Ellis and Werner 1984; Jaffe and Pankonin 1978). The fine-structure line results, chiefly the intensity ratios of the 63 μm and 145 μm lines of [O I] and the 158 μm line of [C II] and the brightness temperature of the 63 μm [C I] line, indicate temperatures in the range 200–600 K in the part of the interface where these lines are formed. The model predictions of Tielens and Hollenbach (1984, 1985*b*) for the interface region in OMC-1 match the intensities of these lines well and are consistent with the observed [C I] line ratio. They predict a temperature of 50 K and an optical depth of about 1 for the [C I] line region.

If the [C I] lines come from a cool (20–30 K) optically thick region, this region must lie along the line of sight to the H II region/molecular cloud interface and the core of the cloud around the Kleinmann-Low nebula. The bulk of the warm (80–100 K) molecular gas which dominates the emission from the OMC-1 cloud and the hot ($\sim$ 300 K) molecular gas in the core of the cloud, however, must not emit strongly in the [C I] lines. The [C I] emission would have to come from clumps with an area filling factor of ~ 0.2 or from a cool region on the far side of OMC-1.

b) *Source-dependent Corrections*

There are two source-dependent corrections to the observed $^3P_2$–$^3P_1$ and $^3P_1$–$^3P_0$ line parameters that will strongly affect the derived parameters for the [C I] emission region. Phillips and Huggins (1981) made an east-west strip map of the $^3P_1$–$^3P_0$ line in OMC-1 and detected emission on a scale size comparable to the $^3P_2$–$^3P_1$ chopper throw. Keene *et al.* (1984) show that the [C I] emission is extended in two additional molecular clouds, S140 and M17SW. The full width to half-power of the E-W $^3P_1$–$^3P_0$ main beam brightness temperature distribution in OMC-1 is 12′. The CO distribution in Orion, however, is elongated north-south (see Schloerb and Loren 1982). If the N-S [C I] $^3P_2$–$^3P_1$ distribution is similar to the E-W [C I] $^3P_1$–$^3P_0$ or N-S ^{12}CO and ^{13}CO $J = 1 \rightarrow 0$ distributions, the flux in the reference beams for the chopped $^3P_2$–$^3P_1$ observations was 50%–70% of the flux toward the source. A correction for this flux in the reference beams would make the $^3P_2$–$^3P_1$/$^3P_1$–$^3P_0$ ratio even higher than the high value observed and strengthen the case for a hot, optically thin emission region.

Beam dilution, the other source-dependent effect, will change the results in the opposite direction from the reference beam contamination effect. The $^3P_2$–$^3P_1$ and $^3P_1$–$^3P_0$ beam areas differ by a factor of 14. A compact source component would therefore have a very different effect on the line strength for the two lines. If all the [C I] emission came from a source, for example, the size of the far-IR continuum source ($\sim$ 60″), we would need to make a beam dilution correction to the line intensity ratio of a factor of 2. A 60″ diameter [C I] source with a peak surface brightness equal to that of the extended [C I] source will raise the $^3P_2$–$^3P_1$ line flux by $\sim$ 70% but raise that of the $^3P_1$–$^3P_0$ line by only $\sim$ 20%. If beam dilution is a severe problem, a combination of small, warm, and large, cool optically thick sources could mimic an intermediate-size optically thin source.

In addition to the above two corrections, a more unpredictable set of corrections are necessary if $\tau > 1$ for one or both of the [C I] lines and if there are multiple temperature and density components or temperature gradients in the emission region. It is then possible to construct models where self-absorption will allow optically thick lines from cold gas to have intensity and brightness temperature ratios that approximate those of warm optically thin emission regions. The evidence for warm externally heated gas on the near side of OMC-1, however, makes these self-absorption models unlikely choices for [C I] in this region.

The effects we have discussed here combine to make the observational situation very difficult. We could narrow the number of possible models if we could make more carefully matched $^3P_2$–$^3P_1$ and $^3P_1$–$^3P_0$ observations. By using the same (preferably long distance) beam switching technique, by observing both lines simultaneously, and mapping the 609 μm beam area at 370 μm, we would obtain much more certain values for the line flux and brightness temperature ratios.

Even so, the small variation in these parameters as a function of temperature and density in the physical region of interest in the interstellar medium may make it impossible to determine the true nature of the [C I] emission region by this method. It will certainly be useful to supplement the line ratio measurements with maps of the [C I] regions (see Keene *et al.* 1984) to allow the use of morphological arguments to help us distinguish between cool optically thick and warm optically thin emission regions. In addition, observations of isotopic variants of C I (i.e., ^{13}C I) may prove useful.

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