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HETERODYNE SPECTROSCOPY OF THE 158 MICRON C II LINE IN M42

R. T. BOREIKO, A. L. BETZ, AND J. ZMUIDZINAS
Space Sciences Laboratory, University of California, Berkeley
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ABSTRACT

We have obtained velocity-resolved spectra of the ^{12}C II 157.8 μm $^2P_{3/2}$–$^2P_{1/2}$ fine-structure line in the M42 region of Orion. Observations at 0.8 km s^{-1} resolution with a laser heterodyne spectrometer show multiple velocity components in some locations, with typical linewidths of 3–5 km s^{-1}. Spectra of θ^1C and BN–KL also show weak emission from the $F = 2$–1 hyperfine component of the equivalent ^{13}C II line. From the observed ^{12}C II/^{13}C II line intensity ratios, we deduce that the ^{12}C II emission is optically thick with $\tau \approx 5$ at both positions. Excitation temperatures of 128 K and 90 K, together with column densities of $\sim 1 \times 10^{19}$ cm^{-2} and $\sim 4 \times 10^{18}$ cm^{-2}, are derived for θ^1C and BN–KL, respectively.

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

I. INTRODUCTION

Line emission from the C II $^2P_{3/2}$–$^2P_{1/2}$ fine-structure transition at 157.8 μm (1900 GHz) is well recognized as a major coolant for the diffuse neutral regions of interstellar gas clouds (Dalgarno and McCray 1972). Observations with airborne telescopes have shown C II emission to be strong and pervasive in molecular cloud regions exposed to ultraviolet radiation (Russell *et al.* 1980, 1981; Kurtz *et al.* 1983; Crawford *et al.* 1986; Melnick *et al.* 1986). Heretofore, interpretation of the C II data for galactic clouds has been hampered by inadequate resolution of line profiles. Typically, only integrated intensities have been obtained, and other physical parameters, such as optical depth, temperature, column density, and velocity structure, have not been determined uniquely (Watson 1984; Stacey 1985). The observed C II emission has generally been interpreted as optically thin, which then leads to an estimated gas temperature >200 K. A quantitative estimate of the C II optical depth would require the detection of at least two line components with different intrinsic line strengths. The 157.8 μm line of ^{12}C II has only one spectral component, but the ^{13}C II line could serve as the other, given a known ^{12}C/^{13}C isotopic ratio. If the optical depth of the ^{12}C II emission could be determined and the line profile resolved, then the line intensity could be used to derive both the excitation temperature and abundance of C$^+$. The M42 region of Orion is probably the best source for initial observations of this kind.

This *Letter* describes the first observations of the 157.8 μm C II line with a heterodyne spectrometer capable of providing 0.8 km s^{-1} resolution. Several positions in the Orion molecular cloud have been observed, and the results provide some significant new insights on the abundance and excitation of ionized carbon in this region.

II. INSTRUMENTATION AND CALIBRATION

The instrument used for the observations discussed here is an airborne far-infrared heterodyne receiver (Betz and Zmuidzinas 1984). The local oscillator (LO) is a CH_2F_2 optically pumped laser at 1891.2743 GHz (Petersen, Scalabrin, and Evenson 1980), which is 9.3 GHz away from the rest frequency of the ^{12}C II transition at 1900.5369 GHz (Cooksy *et al.* 1986). The mixer is a GaAs Schottky diode (University of Virginia type 1E7A) in a corner-reflector mount. The system noise temperature, with the mixer at ambient temperature and the 9.3 GHz IF amplifier cooled to 77 K, was measured to be 32,000 K (SSB) during the observations. The IF signal is analyzed by a 40 channel bank of 5 MHz filters which provides 0.8 km s^{-1} resolution over a range of 32 km s^{-1}, and a 64 channel bank of 20 MHz filters which gives 3 km s^{-1} resolution spanning 200 km s^{-1}. The narrow filters provide good resolution for the C II line, while the wide filters give a broader view of the spectrum that facilitates the measurement of continuum levels.

At 158 μm the transmission of a 1 m path at sea level is typically less than 0.5 because of water vapor absorption, so it is essential to observe the C II line from a high altitude. The instrument was therefore flown aboard the NASA Kuiper Airborne Observatory (KAO) at an altitude of 12.5 km, where the line-of-sight transmission is $\sim$0.94. From scans of the lunar limb, the telescope beamwidth was measured to be approximately 43″ and the coupling efficiency $\sim$0.6. Pointing accuracy is estimated to be 15″. The chopping secondary mirror was used with an 8′ E–W throw to alternate between on-source and off-source positions at 2 Hz. The lack of significant distortion in the measured profiles, such as would be produced by strong emission in the reference beam from different velocity or linewidth components, indicates that the throw was adequate.

Absolute flux calibration was obtained from measurements of the Moon, for which a physical temperature of 394 K and an emissivity of 0.98 were assumed (Linsky 1973). The double-sideband measurement was corrected to a corresponding single-sideband value by using the unequal, but known, transmissions of both the aircraft pressure window and the atmosphere in the signal and image sidebands. The Moon is an appropriate source for intensity calibration for observations such as these where the spatial extent of the line emission encompasses both the main beam and inner sidelobes. A blackbody source was used as a secondary standard throughout the observations to maintain the initial lunar calibration. The statistical and systematic uncertainty in the calibration arising from all sources except the unknown spatial distribution of the radiation within our beam is estimated to be no greater than 10%. The velocity scale is determined from the known line and LO frequencies, and is accurate to better than 0.4 km s^{-1}.

III. OBSERVATIONS

The data were obtained on the night of 1987 February 9, at four locations within the Orion complex: 15″ west of θ^1C (hereafter referred to simply as θ^1C), BN–KL, and 2′ and 4′ east of θ^1C. Figure 1 shows the spectra obtained in the 40 × 5 MHz filterbank, with the position of the strongest hyperfine component of the ^{13}C II line indicated. The $^{13}C^+$ ion has nuclear-spin splitting of the fine-structure levels which leads to three emission components at velocities of 11.2, 63.2, and −65.2 km s^{-1} relative to the ^{12}C II line center (Cooksy *et al.* 1986). The relative intensities of the three components are 0.44, 0.20, and 0.36, respectively. Table 1 lists various parameters measured from the specta.

The continuum temperature was obtained from an average of the data in the 64 × 20 MHz filterbank excluding the channels containing the line and has been corrected to a SSB value. Previous measurements of the continuum by Werner *et al.* (1976) show a maximum near (but not at) BN–KL, with $T_A^* = 4.5 \pm 1$ K (interpolated for 158 μm) within a 1′ beam. The continuum drops off sharply from the peak, and consequently the 10″–15″ uncertainty in our viewing direction may be responsible for the lower continuum temperature measured near BN–KL in the present set of observations. In the vicinity of θ^1C, there is no corresponding discrepancy, probably because the emission is more uniform over a spatially extended (> 1′) region. Slight offsets in pointing will not materially affect the observed intensity of the C II line, since the fine-structure emission is much more extended than the continuum emission. However, because of this difference in spatial distributions, the line intensity estimates would not necessarily be accurate if they were derived solely from the line-to-continuum ratios, especially if the continuum intensity is derived from data obtained at a different spatial resolution.

The integrated line intensity has previously been measured at low spectral resolution to be ~3.5 × 10^{-3} ergs s^{-1} cm^{-2} sr^{-1}

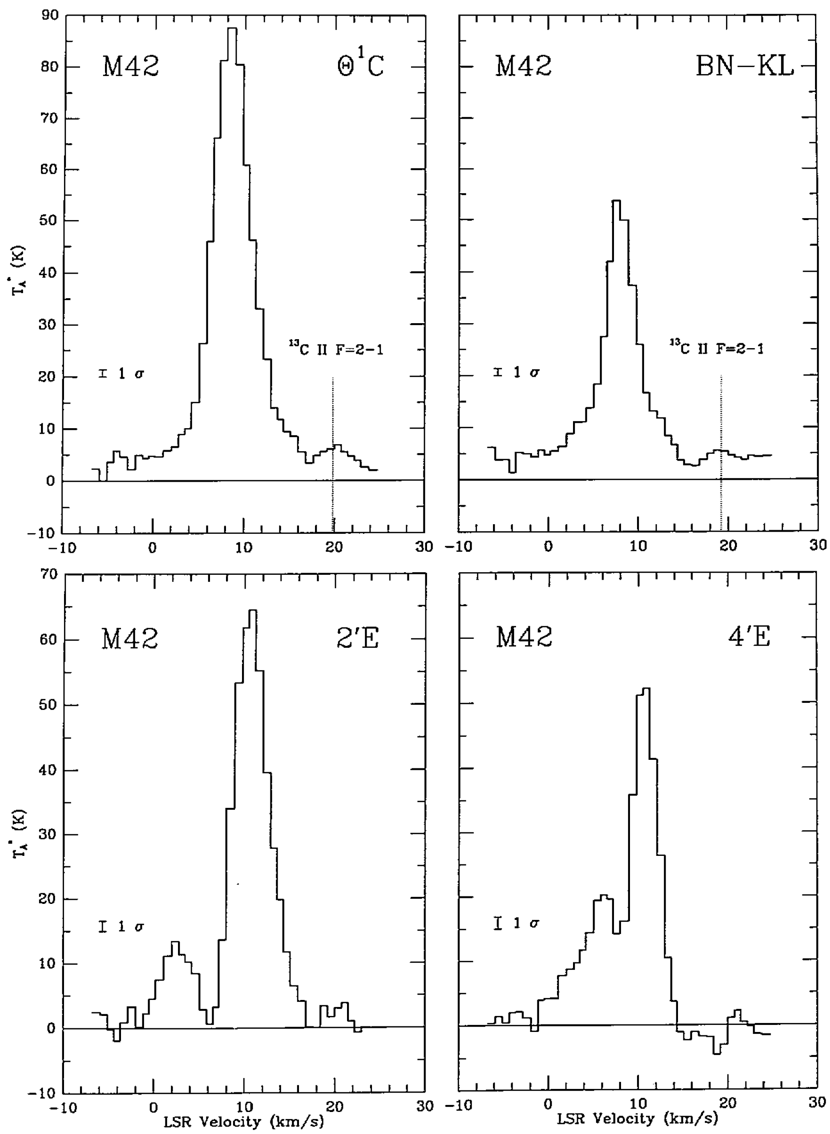

FIG. 1.—Spectra of the $^2P_{3/2}$–$^2P_{1/2}$ line of C II at 0.8 km s^{-1} resolution from four positions in M42. Integration times are 16 minutes for θ^1C and BN–KL, 12 minutes for 2′E, and 8 minutes for 4′E.

TABLE 1

OBSERVED C II LINE PARAMETERS

Position	V_{LSR} (km s^{-1})	Line Width (km s^{-1}, FWHM)	T_A^* (K)	T_b (K)	Integrated Intensity (ergs s^{-1} cm^{-2} sr^{-1})	Continuum (K)
			^{12}C II			
θ^1C	8.59(0.05)	5.0(0.1)	87.7(1.2)	127.9(1.3)	$3.26(0.04) \times 10^{-3}$	1.70(0.08)
BN–KL	8.05(0.05) 8.01(0.15)	2.7(0.2) 7.5(0.6)	51.2(1.1)	89.2(1.2)	$1.64(0.05) \times 10^{-3}$	2.40(0.08)
2′E	10.79(0.05) 2.45(0.24)	4.5(0.1) 3.8(0.6)	64.1(1.8) 13.1(1.8)	103.1(1.9) 44.0(2.6)	$2.20(0.04) \times 10^{-3}$ $0.43(0.04) \times 10^{-3}$	0.39(0.10)
4′E	10.87(0.07) 5.76(0.42)	3.0(0.2) 6.7(0.9)	51.8(2.3) 19.9(2.3)	89.8(2.5) 53.0(2.9)	$2.03(0.05) \times 10^{-3}$	0.33(0.10)
			^{13}C II $F = 2$–1			
θ^1C	8.8(0.5)	3.3(1.2)	3.6(1.1)	27.9(2.7)	$7.6(2.5) \times 10^{-5}$	1.70(0.08)
BN–KL	8.0(0.8)	1.9(1.8)	1.8(1.6)	23.1(8.2)	$3.4(2.5) \times 10^{-5}$	2.40(0.08)

NOTES.—(1) T_A^* is corrected for the continuum. (2) The continuum values listed are corrected for transmission of the pressure window in each of the two infrared sidebands and represent the antenna temperature T_A^* of the continuum in each sideband. (3) Values in parentheses represent 1 σ statistical uncertainties.

(Russell *et al.* 1980), for an assumed uniform beam over the 4′ × 8′ field of view centered on the continuum peak. This value is larger than that derivable from the present data over an equivalent beamsize, if the C II line has its maximum intensity at the position of θ^1C. Recently, Crawford *et al.* (1986) have reported an integrated intensity at the Trapezium of 5.5×10^{-3} ergs s^{-1} cm^{-2} sr^{-1}. The data, shown by Lugten (1987), were obtained at 25 km s^{-1} resolution and calibrated using the line-to-continuum ratio. After deconvolving the instrumental response function from the C II data, Crawford *et al.* (1986) estimated the intrinsic linewidth to be 7 ± 2 km s^{-1}, which is in reasonable agreement with the more precise value of 5.0 ± 0.1 km s^{-1} presented here.

The rest of the parameters given in Table 1 for θ^1C and BN–KL are derived from least-squares fitting of one or more Gaussian profiles to the data. The ^{12}C II profile in BN–KL shows clear evidence for two components with significantly different widths. These two components fit the data to within statistical uncertainties. The velocity and width for the two components are tabulated separately, but the amplitude and integrated intensity represent the combined values. Similarly, two components are evident in the spectra obtained 2′ and 4′ east of θ^1C. For these data, the component centers and widths were obtained from the fits, while the T_A^* values represent measured peak values.

All of the parameters for the $F = 2$–1 ^{13}C II lines, with the exception of integrated intensity, were obtained from a fit to a Gaussian. The statistical significance of the lines was conservatively found to be 4 σ and 1.3 σ for θ^1C and BN–KL, respectively, from the ratio of signal to noise within a Gaussian filter having the same width and V_{LSR} as the ^{12}C II line, but centered at the expected location of a ^{13}C II component. The weaker $F = 1$–1 and $F = 1$–0 hyperfine components of the ^{13}C II line are not within the bandpass of the high-resolution filterbank, and were not detected in the wideband filterbank because of insufficient resolution and signal-to-noise ratio.

The identification of the weak detected features with ^{13}C II rests on several points. First, the location of the features relative to the ^{12}C II lines is correct and is fixed relative to the main lines rather than being at a common velocity for θ^1C and BN–KL, as would be the case if they were due to a separate velocity component within the gas. Second, the width of the small line is approximately proportional to that of the associated ^{12}C II line, but is always less, as would be expected if the two lines were produced in the same gas, but one was broadened as a result of having significantly greater optical depth. Finally, the integrated intensity of the feature in the BN–KL spectrum is smaller than that in θ^1C, following the behavior of the ^{12}C II line, which is consistent with the two regions having similar optical depths.

IV. ANALYSIS AND CONCLUSIONS

a) Optical Depth

The detection of ^{13}C II allows the optical depth in the ^{12}C II line to be determined, provided that the $F = 2$–1 ^{13}C II line is optically thin, and the ^{12}C/^{13}C isotopic ratio is known. The line center optical depths for the θ^1C and BN–KL positions are given in Table 2. The derived parameters are obtained from the data in Table 1 by using a value of 60 for the ^{12}C/^{13}C isotopic ratio (Wannier 1980), and 0.444 for the fractional intensity of the $F = 2$–1 ^{13}C II hyperfine component (Cooksy *et al.* 1986). The conclusion from our data is that the ^{12}C II line is definitely optically thick ($\tau = 5.6 \pm 1.7$) at line center for θ^1C and is likely to be thick for BN–KL as well. Our deduced values are somewhat higher than the previous upper limit ($\tau < 2$ [Crawford *et al.* 1986], revised to $\tau < 3[1\ \sigma]$ [Lugten 1987]) derived from the nondetection of either of the two most separated ^{13}C II hyperfine components. The optical depths quoted here, based on the detection of the $F = 2$–1 ^{13}C II hyperfine component, depend only on the ratio of observed antenna temperatures, and hence are insensitive to systematic

TABLE 2

DERIVED PHYSICAL PARAMETERS

Position	$\tau_{^{12}C\ II}$	T_{ex} (K)	N (cm^{-2})
θ^1C	5.6	128	1×10^{19}
BN–KL	4.8	90	4×10^{18}

errors in calibration. The derived values for optical depth and column density depend approximately linearly on the isotopic ratio, while the excitation temperature is insensitive to this parameter.

Supporting evidence for our comparatively high value for the optical depth is provided by the relative linewidths of the ^{12}C II and ^{13}C II lines. The ratio of the apparent FWHM of a line with $\tau \approx 5$ to its intrinsic width is 1.7 for a Gaussian line originating in a homogeneous medium. This is comparable to the ratio of measured half-widths of the ^{12}C II and ^{13}C II lines (1.5 for θ^1C and 1.4 for BN–KL), as would be expected if the two lines originate in the same gas.

b) *Excitation Temperature*

Theoretical models of the Orion photodissociation region (e.g., Tielens and Hollenbach 1985) have generally concluded that the C II line is optically thin with an excitation temperature of at least 250 K. These two parameters are coupled, however, and cannot be determined simultaneously from measurements of a single C II line. However, because we estimate the line optical depth independently of the line intensity, the line excitation temperature can be calculated directly. In addition, because the critical density for the $^2P_{3/2}$–$^2P_{1/2}$ transition is only $\sim 10^3$ cm^{-3}, the level populations will likely have their equilibrium values, and the derived excitation temperature can be interpreted as the gas kinetic temperature. Our deduced values are listed in Table 2 for the positions noted. Because the ^{12}C II lines are optically thick, the uncertainty in excitation temperature is less than $\sim 10\%$ determined from the calibration accuracy. The temperatures are considerably lower than those previously assumed and appear to indicate that C II is more in equilibrium with the cooler molecular component than the warmer atomic gas in the ionization interface region. For comparison, Stacey (1985) calculates that the gas temperature in the photodissociation region is ~ 350 K, based on the intensities of the 145 μm O I and 158 μm C II lines. However, the calculation assumed that both lines were optically thin. A lower gas temperature would be indicated if C II were taken to be optically thick. Perhaps a better estimate for the atomic gas temperature can be derived from the integrated intensity and estimated linewidth of the 63 μm O I line observed by Crawford *et al.* (1986). If the line is optically thick as suggested by Stacey (1985), then an excitation temperature of 180 ± 40 K is indicated, which is reasonably consistent with the C II results presented here.

Our analysis assumes that the C II emission fills the beam uniformly. Should the emission arise from discrete clumps that do not fill the beam, then the derived excitation temperature would represent only a lower limit. The optical depth within the clumps, however, would not change significantly since the beam filling factor would be expected to be the same for both the ^{12}C II and ^{13}C II lines.

c) *Column Densities*

Column densities for C II toward the θ^1C and BN–KL positions are listed in Table 2. For the θ^1C region, the value quoted is accurate to within 30%, limited by the statistical accuracy of T_A* for the ^{13}C II line. Our C II column density of 1×10^{19} cm^{-2} for θ^1C is about a factor of 3 higher than that obtained by Tielens and Hollenbach (1985) from simple physical considerations. In their calculation, photodissociation of CO and ionization of C to C$^+$ within the cloud proceed only to the UV penetration depth ($A_v \approx 4$), which is limited primarily by absorption by dust. For a standard H I column density of 1.9×10^{21} cm^{-2} per magnitude of extinction, and an assumed carbon fractional abundance of 4×10^{-4}, their calculated C II column density is 3×10^{18} cm^{-2}. This value can be increased by changing the extinction properties of the dust or the dust-to-gas ratio. Also, the C II column density derived from observations will generally be higher, since the line of sight into a plane-parallel region will not necessarily be in the direction to the ionizing star, as assumed in the calculation.

d) *Spatial and Velocity Structure*

Our observations at four locations within the Orion complex are too few to provide much information on the spatial structure, other than to confirm the known fact that C II emission is extended over more than 4′. Our high spectral resolution does give new data on the C II velocity structure, however. The spectra show evidence for four velocity components: 2.5, 5.8, 8.3, and 10.8 km s^{-1}. Our three strongest velocity components in C II are clearly seen in C$^+$ recombination lines at 6.1, 8.4, and 10.8 km s^{-1}, with widths of 4–5 km s^{-1}, comparable to those in the ^{12}C II line (Jaffe and Pankonin 1978). The much larger beamsize of 2′.6 for the recombination line work, however, precludes making detailed lineshape or spatial comparisons. Nevertheless, the general agreement in component velocities supports the expectation that the recombination lines and the C II radiation arise from similar regions.

Another point of significance is that the spectrum of C II emission from BN–KL at $V_{LSR} = 8$ km s^{-1} shows evidence for a broad component with a linewidth of ~ 7.5 km s^{-1} in addition to the narrow 3.0 km s^{-1} linewidth component. This broad emission does not arise from the "hot core" component seen in NH_3 (Morris, Palmer, and Zuckerman 1980), although the linewidth is comparable, because the V_{LSR} of the ammonia emission is 5.2 km s^{-1}. Nor is it likely to arise from the shocked gas which is thought to produce the CO plateau emission and the broad (30–40 km s^{-1}) component of lines such as O I, since this C-type shock is nonionizing. Also, the profiles of lines produced by the shock generally show a blue asymmetry, while the present data show no asymmetry and only moderate wings. Nevertheless, the spectrum of BN–KL shows a different character than the other spectra obtained, and it would be informative to observe the emission from the wings of the C II line in more detail, and in particular to examine variations with position near BN–KL.

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A. L. BETZ, R. T. BOREIKO, and J. ZMUIDZINAS: Space Sciences Laboratory, University of California, Berkeley, CA 94720