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HETERODYNE SPECTROSCOPY OF THE $J = 17–16$ CO LINE IN ORION

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

AND

J. ZMUIDZINAS
Department of Astronomy, University of Illinois
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ABSTRACT

We have obtained high-resolution spectra of the 153 μm $J = 17–16$ CO line in the BN–KL region of Orion using a laser heterodyne spectrometer. The line shows broad wings (30 km s^{-1} FWHM at BN) characteristic of the plateau emission as well as a narrower component probably associated with the quiescent gas in the molecular ridge. From an analysis of the plateau emission together with that observed in lower J CO transitions, we derive an excitation temperature of 180 ± 50 K and minimum column density of 1×10^{18} cm^{-2} for CO in this component, which constitutes 80% of the total integrated intensity of the $J = 17–16$ line near BN. The peak intensity of the narrower component observed at 0.8 km s^{-1} resolution increases relative to that of the plateau component toward θ^1C and away from BN, while the width decreases from 10 to 4 km s^{-1} (FWHM).

Subject headings: interstellar: molecules — nebulae: internal motions — nebulae: Orion Nebula

I. INTRODUCTION

The core of the Orion molecular cloud has been extensively studied in many molecular transitions, and the data have been interpreted to show the existence of three main components in this region. The ambient molecular cloud (ridge) is spatially extended, and produces relatively narrow lines (FWHM 3–7 km s^{-1}) at a V_{LSR} near 9 km s^{-1}. The outflow source or plateau emission region is characterized by broad lines (~ 30 km s^{-1} FWHM) with V_{LSR} of 7–9 km s^{-1}. Part of the plateau emission originates from a somewhat compact region (25″–40″ in low-excitation lines), but there is some indication that this size increases with excitation. Finally, the "hot core" component is a hot ($T > 200$ K) and dense ($n_H > 10^6$ cm^{-3}) region which is spatially compact ($\sim 10''$) and gives rise to lines of $\sim 8–15$ km s^{-1} width, with a V_{LSR} of ~ 5 km s^{-1}.

High-excitation molecular emission from the BN-KL region has been attributed to the interaction of the high-velocity outflow material with the ambient molecular cloud, thereby producing a shock which heats the gas (Draine and Roberge 1982; Chernoff, Hollenbach, and McKee 1982). The observed vibrational emission from H_2 (Beckwith *et al.* 1978; Nadeau, Geballe, and Neugebauer 1982; Scoville *et al.* 1982; Geballe *et al.* 1986) has been interpreted as originating from shock-excited gas at temperatures near 2000 K, although some contribution from ultraviolet-excited H_2 cannot be excluded (Hayashi *et al.* 1985). However, detailed modeling on the basis of these data is hampered by the uncertain, but probably significant, effect of extinction. Observations in transitions of the next most abundant molecule, CO, reveal evidence of disturbed gas originating from the plateau source. The low-J ($J < 4$) transitions show very extended wing emission (Plambeck, Snell, and Loren 1983; Richardson *et al.* 1985), but the bulk of the intensity arises from relatively cool ($T < 100$ K) quiescent gas from the ridge. High-J ($J > 10$) transitions, on the other hand, should be sensitive primarily to much hotter gas, originating in either the "plateau" gas or the "hot core," with less confusion from emission by the quiescent cloud. These components can in most cases be distinguished by their differing V_{LSR}, spatial characteristics, and line widths. The BN-KL region has been observed in several higher J CO lines (Crawford *et al.* 1986; Storey *et al.* 1981; Watson *et al.* 1980, 1985), but unfortunately the instrumental resolution was insufficient to measure line profiles. While integrated intensities provide significant information for interpreting conditions in the high-excitation gas, accurate line profiles and velocities provide greater constraints for the hot gas kinematics.

The work presented here describes the first high-resolution observations of the 153 μm $^{12}C^{16}O$ $J = 17–16$ line obtained with a heterodyne spectrometer. The results from five positions near BN show that the emission originates primarily from the "plateau" gas, with no discernible contribution from the "hot core," but that a narrower emission component which is more identifiable with warm quiescent ridge gas also exists.

II. INSTRUMENTATION AND CALIBRATION

The far-infrared heterodyne receiver used for these observations is described in detail by Betz and Zmuidzinas (1984). The local oscillator is an optically pumped $^{15}NH_3$ laser, and the mixer is a cooled GaAs Schottky diode in a corner-reflector mount. The system noise temperature was measured during the observations to be 21,000 K (SSB). The "back end" consists of two filterbanks in parallel, one consisting of 64 channels of 20 MHz (3 km s^{-1}) resolution, and the other of 40 channels of 5 MHz (0.8 km s^{-1}) resolution. For a wide line such as that expected from the high-velocity plateau region, the wide bandwidth filterbank is essential to determine the shape of the wings, while the higher resolution filterbank gives a more detailed look at the shape near line center, where asymmetries may be most prominent.

Observations in the 100–200 μm range need to be made at aircraft altitudes or higher, since water vapor in Earth's atmosphere renders this band essentially opaque from the ground. The spectrometer was flown aboard the Kuiper Airborne Observatory at an altitude of 12.5 km, where the atmospheric transmission at the source-corrected CO frequency is approximately 0.97. The CO $J = 17$–16 line at 1956.0181 ± 0.0001 GHz (Nolt *et al.* 1987) falls less than 50 MHz from a weak H_2O line in Earth's atmosphere. Fortunately, the Doppler shift of Orion at the time of these observations was approximately 36 km s^{-1} and that, along with the intrinsic source V_{LSR} of ∼9 km s^{-1}, shifted the frequency of the observed CO line 250 MHz (36 km s^{-1}) from the atmospheric H_2O line, and even further from the atmospheric CO line. Scans of the lunar limb were used to measure the beam size to be ∼43″ (FWHM), and the coupling efficiency ∼0.5. Pointing accuracy is estimated to be better than 15″. The data were obtained with the chopping secondary of the telescope operated at 2 Hz with a throw of 6.′3 E–W. This throw amplitude should be sufficient to avoid confusion from possible emission in the reference beam because of the relatively compact nature of the plateau source.

Absolute flux calibration was obtained from spectra of the Moon, for which we assume a physical temperature of 394 K and emissivity of 0.98 (Linsky 1973). The single-sideband line intensity was derived from the measurement by using the unequal (but known) transmission of the quartz aircraft pressure window and the atmosphere in the two receiver sidebands. The lunar calibration was maintained throughout the flight by frequent observations of an internal blackbody source used as a secondary standard. The uncertainty in the absolute calibration from all contributions apart from the unknown source coupling is estimated to be no greater than 10%.

The velocity scale accuracy of the data is determined both by the CO line and $^{15}NH_3$ laser frequencies. The former has recently been measured to better than ±0.1 MHz (2 σ) by Nolt *et al.* (1987), but the latter frequency was previously not known with comparable accuracy. Therefore we measured the difference in frequency between the laser and the CO $J = 17$–16 transition by using our heterodyne spectrometer in its flight configuration. Radiation from a blackbody source was passed through a sample cell containing CO at room temperature, and the absorption line was analyzed in the filterbanks. The frequency difference was found to be 6731.0 ± 0.5 MHz, which establishes the $^{15}NH_3$ laser frequency at 1962.7491 ± 0.0005 GHz. The overall 1 σ velocity scale accuracy of our spectra is thus ±0.1 km s^{-1}.

III. OBSERVATIONS

The data were obtained on the night of 1988 January 26 at five locations within the Orion complex: BN, H_2 peak 1, H_2 peak 2, 30″ SE of H_2 peak 2 along the line joining peaks 1 and 2, and at θ^1C. These positions are shown in Figure 1, superposed upon a map of the $v = 1$–0 $S(1)$ H_2 emission (Beckwith *et al.* 1978). As can be seen from this figure, our beam size of 43″ is sufficiently large that several localized sources such as BN, IRc2, and the hot core lie within a single beam. For convenience we refer to this position simply as BN without implying that this specific object is the origin for the observed radiation. Figure 2 shows the spectra obtained at each position, from

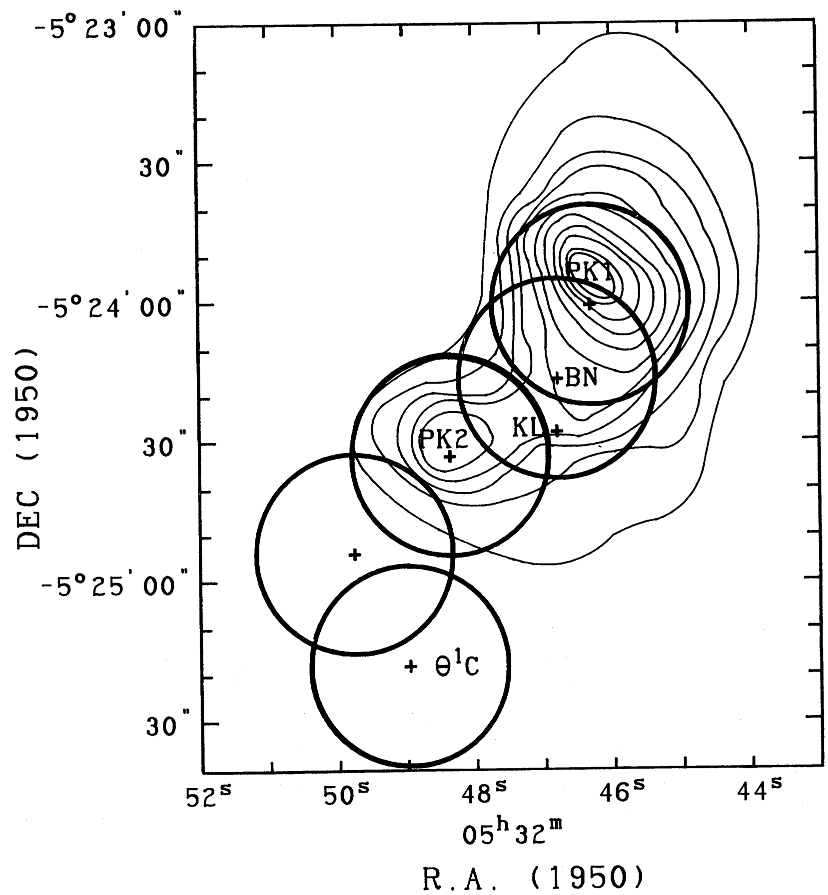

FIG. 1.—Location of the positions observed, superposed upon a map of H_2 vibrational emission from Beckwith *et al.* (1978). The outermost contour represents the limits of the map. The circle size indicates the beam size used for the observations.

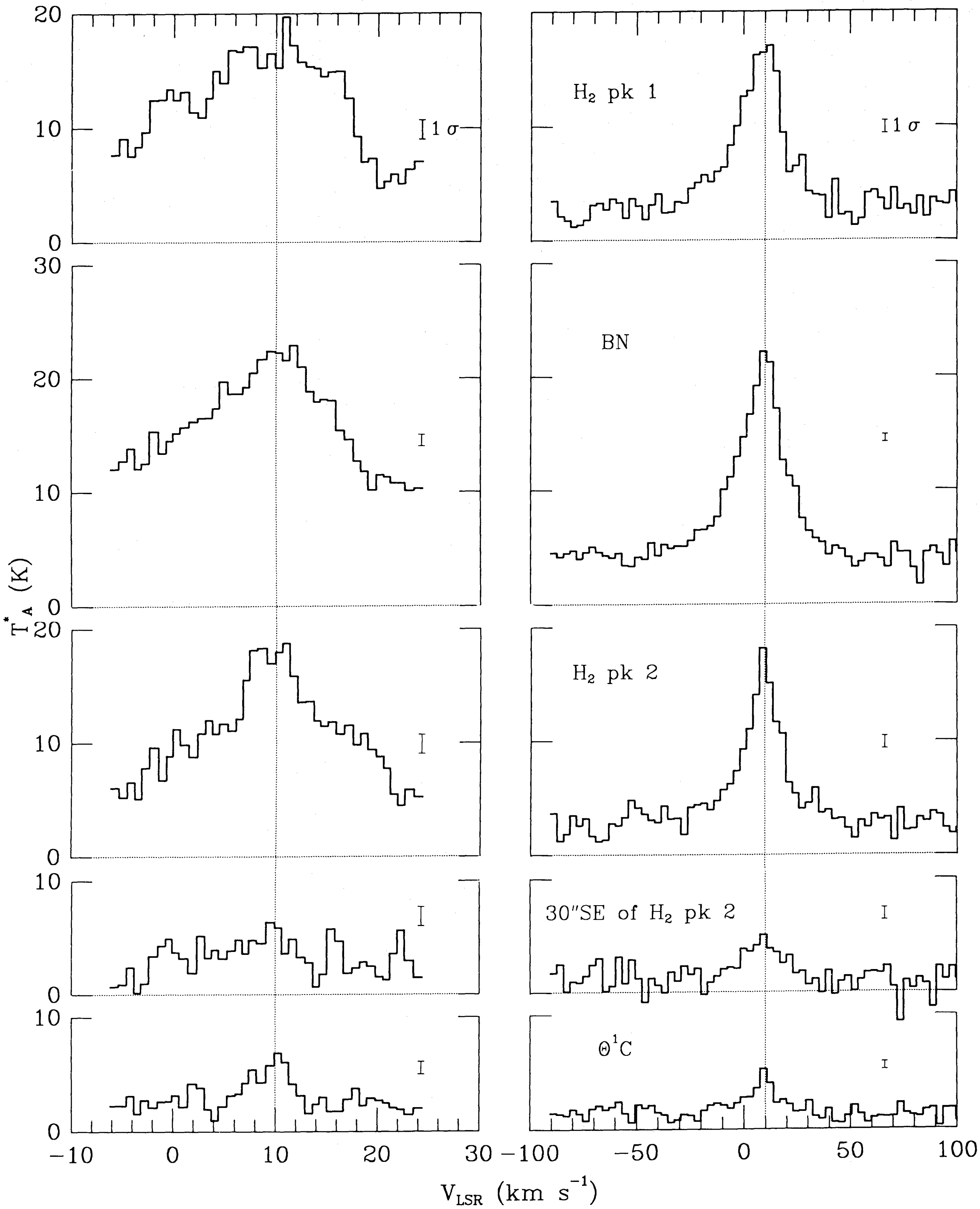

FIG. 2.—Spectra of the $J = 17$–16 line of CO at 0.8 km s^{-1} (*left panel*) and 3.0 km s^{-1} (*right panel*) resolution from five positions in Orion. Integration times are 24 minutes for BN, 20 minutes for θ^1C, and 8 minutes for each of the three remaining positions. The dotted vertical line is at 10 km s^{-1}.

TABLE 1

153 MICRON CO $J = 17 \rightarrow 16$ RESULTS

Source	T_A^*[a] (K)	V_{LSR} (km s^{-1})	Line Width (km s^{-1}, FWHM)	Integrated Intensity (ergs s^{-1} cm^{-2} sr^{-1})	Continuum[b] (K)
H_2 peak 1	9.1 (1.1)	4.6 (1.4)	26.4 (2.0)	$2.81 (0.16) \times 10^{-3}$	1.74 (0.10)
	6.8 (1.3)	11.4 (0.5)	10.7 (1.7)		
BN	12.0 (0.4)	6.8 (0.4)	31.2 (1.1)	$3.53 (0.09) \times 10^{-3}$	2.49 (0.06)
	6.6 (0.5)	10.6 (0.2)	8.3 (0.7)		
H_2 peak 2	10.0 (0.6)	9.4 (0.3)	22.2 (1.2)	$2.26 (0.16) \times 10^{-3}$	1.74 (0.09)
	5.8 (0.7)	9.6 (0.2)	4.4 (0.7)		
30″ SE of H_2 peak 2	3.3 (0.3)	8.9 (0.9)	20.8 (2.7)	$5.21 (0.16) \times 10^{-4}$	0.65 (0.09)
θ^1C	1.4 (0.2)	6.9 (1.8)	30.8 (6.3)	$3.60 (0.10) \times 10^{-4}$	0.80 (0.10)
	3.5 (0.4)	9.7 (0.2)	3.8 (0.5)		
Average BN, peak 1, peak 2	10.3 (0.4)	6.6 (0.4)	30.8 (0.6)	$3.23 (0.05) \times 10^{-3}$	2.18 (0.05)
	6.7 (0.4)	10.6 (0.2)	9.3 (0.6)		

NOTE.—Quantities in parentheses are 1 σ statistical uncertainties.

[a] T_A^* is corrected for the continuum.

[b] The continuum temperatures are single-sideband values.

both the 40 × 5 MHz filterbank (*left panel*) and 64 × 20 MHz filterbank (*right panel*). The positions are approximately uniformly spaced in a NE–SW direction. No continuum or slope has been subtracted from the data, and no smoothing has been applied. Table 1 summarizes various parameters deduced from the spectra.

All of the parameters in Table 1, with the exception of integrated intensity, were obtained from fits of the continuum plus one or two Gaussian profiles to the data. In the fitting procedure, the calculated Gaussian was degraded to the resolution of the individual filterbanks, thus permitting a simultaneous fit to both sets of data. All of the fits were found to be good representations of the data, with residuals consistent with those expected from statistical uncertainty (i.e., system noise). Only one Gaussian profile was fitted to the data 30″ SE of H_2 peak 2 because of the lower signal-to-noise ratio of this spectrum; the existence of two components cannot, however, be ruled out. Figure 3 shows the average of spectra from BN and H_2 peaks 1 and 2 (which have similar characteristics) together with the calculated two-Gaussian profile and the wide component of the fit alone. The quality of the fit, which reproduces the wide wings as well as the asymmetry seen most clearly in the higher resolution data, lends support to the interpretation of the line profile in terms of two distinct components, although this interpretation is not unique. A possible physical basis for the two components is discussed in IV.

The antenna temperature of the continuum obtained from the fit was corrected to a single-sideband value by using the different (but known) transmissions of the pressure window and the atmosphere in the two sidebands. Comparison of these continuum values with those interpolated from the data of Werner *et al.* (1976) indicates that our measurements are about a factor of 1.7 lower. This discrepancy is unlikely to be attributable to pointing errors, since the proportionality between the continuum intensity of Werner *et al.* (1976) and that of the present data remains approximately constant for each location. Nor can it arise from incorrect determination of the pressure window or atmospheric transmission, since these factors are common to the continuum and the calibration, which are both intrinsically double-sideband. Our continuum temperature for BN of 2.49 ± 0.06 K at 153 μm is in good agreement with the 2.40 ± 0.08 K measured at 157 μm by Boreiko, Betz, and Zmuidzinas (1988) using totally independent data and calibration. It should be noted that our continuum measurement does not influence our calibration of the CO line intensity, but is mentioned mainly for comparison with other observations which rely on line-to-continuum estimates for calibration.

The integrated intensity in the $J = 17$–16 line at BN has previously been measured by Stacey *et al.* (1982) to be $8.0 \pm 2.5 \times 10^{-3}$ erg s^{-1} cm^{-2} sr^{-1}. This intensity estimate was calibrated with respect to the continuum measurement of Werner *et al.* (1976). If our lower continuum temperature is adopted, however, the two determinations for the CO $J = 17$–16 integrated intensity agree to within the statistical uncertainties.

The uncertainties associated with the parameters of Table 1 are derived only from statistical fluctuations (1 σ), as determined from the rms noise in spectra of sources for which no CO $J = 17$–16 emission was seen. The noise per channel was found to correspond to that expected from a system noise temperature of 21,000 K (SSB) which was measured as such independently. Furthermore, the effective noise decreased with integration time as expected for a random process, showing that system instabilities or standing wave problems do not contribute significantly to the uncertainties in the results.

IV. ANALYSIS AND CONCLUSIONS

In general, CO line emission could have contributions from several distinct regions such as the quiescent ridge, the plateau, and the hot core. Distinction among these contributions usually requires additional information on the characteristics of each emission component, and the resolution and sensitivity to distinguish between these characteristics. This is certainly true in the case of low-J lines, where the temperature of the quiescent cloud is such that the low-J levels are substantially populated, which leads to optically thick emission that dominates other possible contributions except in the line wings. The shape of the wing profile and its intensity as a function of rotational level provides information on the temperature, optical depth, and velocity structure of the high-velocity gas. However, the range of J of observed lines must be large so that systematic uncertainties in source coupling and calibration do not overwhelm the real dependence of intensity on J. Heretofore, resolved line profiles for CO have been obtained only up to the $J = 7$–6 transition. We choose to exclude profiles

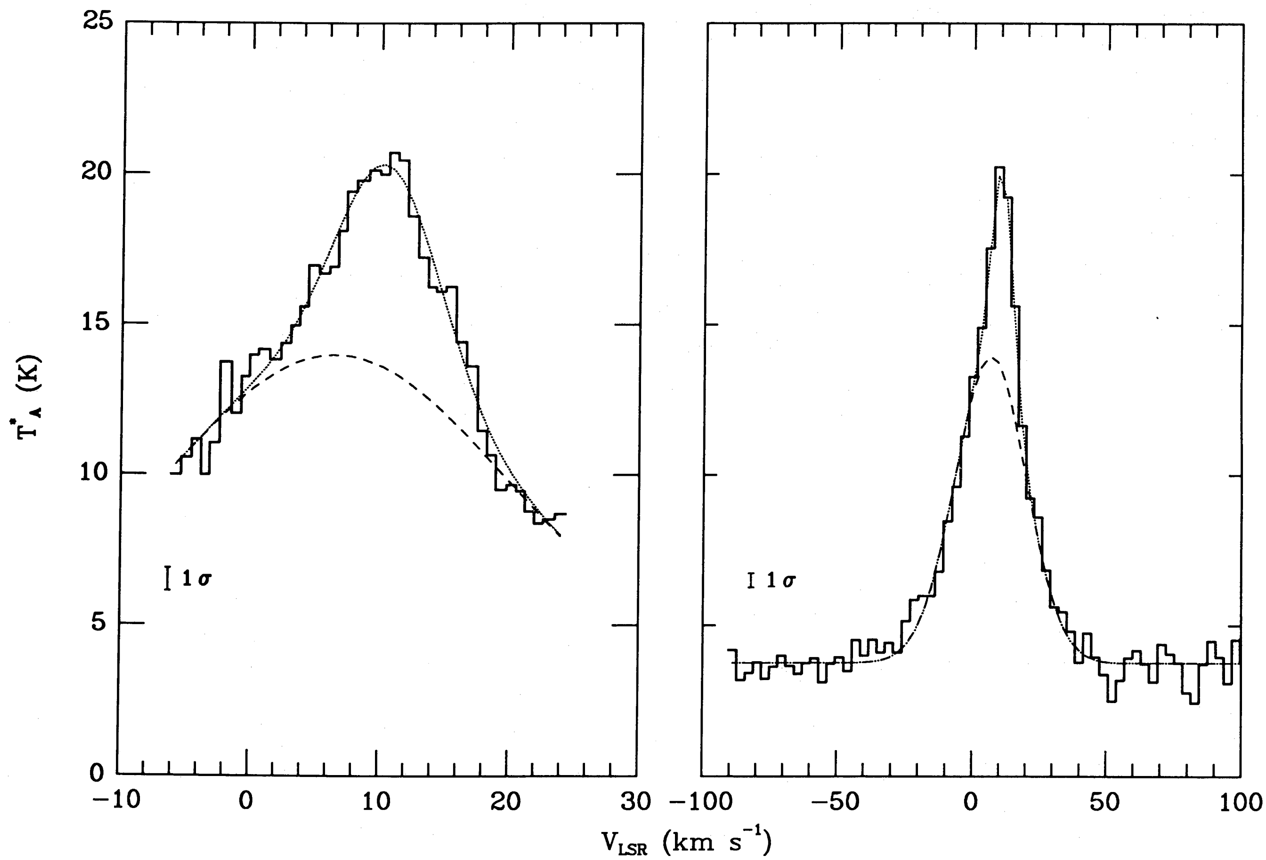

FIG. 3.—The averaged spectrum of the $J = 17–16$ line of CO from the BN, H_2 peak 1, and H_2 peak 2 positions. Total integration time is 40 minutes. The dotted line shows the two-component Gaussian fit to the data, while the dashed line shows only the wide component of the fit.

obtained from deconvolution, since these are more susceptible to systematic uncertainties resulting from incomplete knowledge of the instrumental response. The range of energy levels over which the plateau emission is well resolved is increased by more than a factor of 5 by the $J = 17–16$ data presented here, and consequently the constraints on deduced properties of the high-velocity gas are more stringent.

a) Fitting Procedure—Broad Emission Component

The optical depth at a frequency ν in a CO transition $J + 1 \rightarrow J$, assuming all level populations are thermalized, is given by

$$\tau(\nu) = \frac{8\pi^3}{3h} \frac{\mu^2(J+1)e^{-E_l/kT_x}}{Q_r(T_x)} (1 - e^{-h\nu/kT_x}) \int n\phi(v)ds \,, \quad (1)$$

where μ is the dipole moment (0.112 Debye; Lang 1980), Q_r is the rotational partition function, E_l is the energy of the lower level involved in the transition, n is the number density of CO, $\phi(v)$ is the line profile function (in velocity units) which also includes a beam filling factor due to possible clumpiness, and the integral is performed along the path from the observer through the molecular cloud. For convenience, the integral can be replaced by $N\phi(v)$, where N is an equivalent column density, and $\phi(v)$ is redefined for this relationship to hold. The LVG (large velocity gradient) condition is assumed, so that radiation from all values of J arises in an equivalent manner from different velocity components of the gas. With this assumption, $\phi(v)$ does not depend upon rotational level, and therefore comparisons of intensities in the wings of lines with various J can meaningfully be made at the same absolute velocities. In the limit of small optical depth, equation (1) can be rearranged to show the dependence of intensity on J:

$$\ln\left(\frac{(J+1)h\nu}{kT_A{}^*}\right) = \frac{E_u}{kT_x} + \ln\left(\frac{3hQ_r(T_x)}{8\pi^3\mu^2 N\phi(v)}\right) . \quad (2)$$

Therefore, a least-squares fitting of the quantity on the left-hand side of the equation to E_u, the energy of the upper level involved in the transition, yields a slope of $1/kT_x$ and an intercept related to $N\phi(v)$. Note that this relationship underscores the need to have as large a range of E_u as possible. This fitting procedure was carried out using the line profiles for the BN region for $J = 1–0$ and $J = 2–1$ from Plambeck, Snell, and Loren (1983), $J = 3–2$ from Richardson *et al.* (1985), $J = 6–5$ from Koepf *et al.* (1982), $J = 7–6$ from Schultz *et al.* (1985), and the present data for $J = 17–16$. For each line, a baseline (and for the case of the $J = 6–5$ data also a slope) was determined from a one-component or two-component Gaussian fit, and subtracted from the data. Beam sizes for the $J = 1–0$ through $J = 17–16$ observations were 64″, 75″, 55″, 35″, 35″, and 43″, respectively.

b) Assumptions in the Fitting Procedure

The assumptions implicit in the fitting procedure are that (1) a single temperature characterizes all the transitions, (2) the source coupling correction is similar for all the observations and relatively small, (3) all the levels are in LTE, and (4) the radiation in the wings of all the transitions is optically thin.

The first assumption cannot be addressed by the present limited set of observations. While there is evidence that a range of excitations exists in the plateau region (Blake *et al.* 1987), a single-temperature interpretation will be used as a preliminary approach. The derived temperature will then represent a "level-averaged" temperature for the wing radiation.

The relative constancy of the CO $J = 17–16$ emission at BN and H_2 peaks 1 and 2 suggests that the source is extended over more than 1′, consistent with the value of 1′.5 (FWHM) deduced by Storey *et al.* (1981) from $J = 21–20$ data. If the source distribution is similar in lower J transitions, then the magnitude of individual corrections for source coupling is expected to be small. Interferometric mapping in CO $J = 1–0$ (Masson *et al.* 1987) shows that approximately 25% of the plateau emission originates from a source slightly larger than 25″ in extent, while the remainder is smoothly distributed on a scale of $\sim 1'$ or more. Our data have insufficient spatial resolution to determine whether this small-scale structure exists in the $J = 17–16$ line, and therefore we proceed on the assumption that most of the wing emission comes from an extended region so that individual source coupling values do not greatly affect the data. There is some evidence that the source size is $\leq 40''$ in other low-J CO transitions (e.g., Erickson *et al.* 1982). If the source size increases with excitation and is spatially unresolved in the low-J lines, then there will be a systematic error in our procedure which leads to an estimate of the excitation temperature that is too high and of the column density that is too low. For example, the inclusion of a source coupling correction consisting of the ratio of the solid angle of the beam to that of a 45″ source lowers the estimate of the excitation temperature by about 25% and raises the column density by about a factor of 3. The unknown source distribution produces the greatest uncertainty in our procedure, even though the beam sizes of all the observations are similar.

Densities within the plateau region are known to be fairly high ($n > 10^6$ cm^{-3}) from observations of several transitions of molecules with high dipole moments (e.g., Keene, Blake, and Phillips 1983; Loren and Wootten 1986; Padman *et al.* 1985; Moore, Langer, and Huguenin 1986; White *et al.* 1986; Blake *et al.* 1987). The critical density for a rotational transition in CO increases with J, reaching approximately 2×10^6 cm^{-3} at 180 K for the $J = 17–16$ transition (McKee *et al.* 1982). Thus, available evidence indicates that all the levels used in the present analysis are thermalized, or nearly so. The effect of sub-thermal excitation, which would be seen mainly in the $J = 17–16$ data, would be to lower the measured value of T_A^* compared to its thermal value, which would lead to a temperature estimate that is too low and a column density that is too high. This latter effect is opposite in sense to that produced by a source whose size appears to increase with excitation.

The fourth assumption is the most difficult to address. Plambeck, Snell, and Loren (1983) in their analysis of $J = 2–1$ and 1–0 data suggest that the line wings are moderately optically thick over a large range of velocities, since the ratio of the intensities in the two lines is smaller than that expected for optically thin gas. Richardson *et al.* (1985) subsequently deduced from their observations of the $J = 3–2$ line in concert with available $J = 2–1$ and 1–0 data that the plateau emission was thin in the $J = 1–0$ line but moderately thick in the $J = 3–2$ transition. These various estimates of optical depth depend upon an assumed excitation temperature (usually 70–90 K), source coupling corrections for individual telescopes to an assumed source size (typically $\sim 40''$), proper correction for spike emission, and accurate knowledge of the baseline. Most likely the $J = 1–0$ line wings are optically thin, and the $J = 17–16$ wings almost certainly will also be thin, and therefore our fitting procedure could be followed with just these two sets of data. Should the wings in intermediate-J lines be optically thick, as suggested by the ratios of the $J = 3–2$ and $J = 1–0$ data, the effect would be to saturate the value of T_A^* for these transitions, with adverse effects on the quality of the fit; specifically, the column density would be underestimated. The derived excitation temperature, however, would be relatively unaffected.

c) *Results and Interpretation*

The fitting was performed at velocity intervals of 5 km s^{-1} from -25 to 0 km s^{-1} and 20 to 45 km s^{-1} $V_{\rm LSR}$, with the individual spectra degraded to 5 km s^{-1} resolution. The excitation temperature T_x derived from least-squares fits to equation (2) over these intervals is 180 ± 35 K, with no significant variation in T_x with wing velocity. Including an estimate of possible systematic effects raises the 1 σ uncertainty to ± 50 K. The values of $N\phi(v)$ range from 0.09×10^{16} cm^{-2} (km s^{-1})$^{-1}$ in the far wings to 2.2×10^{16} cm^{-2} (km s^{-1})$^{-1}$ closer to line center, and have uncertainties of 30%.

The fitting procedure depends critically on the existence of the $J = 17–16$ data, which arise from an energy level a factor of 5 higher than those of transitions previously observed with equivalently high spectral resolution. The intensities of wing emission in lower J data ($J \leq 7$) are not mutually consistent with either optically thin or thick emission from a source of any size, to within the reported uncertainties of the individual measurements. These inconsistencies mask any true dependence of wing emission intensity on J over the much smaller range of J sampled by low-J observations alone.

The relative constancy of the derived excitation temperature with velocity is interesting, in that an outflow source might be expected to have a temperature gradient, which would be translated into a dependence of T_x on $V_{\rm LSR}$ by the relationship between distance from the source and velocity. The absence of this effect implies that the outflow is not a smooth one, and suggests the presence of clumps, as pointed out by Plambeck, Snell, and Loren (1983) and Padman *et al.* (1985). Provided that the beam filling factor of the clumps is not so low as to make optical depths within a single clump large, the effect on the derived temperature will be negligible.

The derived parameters are relatively insensitive to the data at any given J because of the range in J available. For example, a 20% change in T_A^* of the $J = 1–0$ line results in a 6% change in $N\phi(v)$, with very little change in T_x, while the equivalent change in the $J = 17–16$ line changes T_x by 5%, with little effect on $N\phi(v)$. Intermediate-J lines have comparable effects on a combination of the two parameters. Therefore, provided that no significant common systematic effects exist in the data, these parameters characterize the gas giving rise to the extended wing emission in CO.

If the assumption is made that the line shape function is a Gaussian, then a fitting procedure can be used to determine the value of $N\phi(v)$ at the peak, and the total value of N. This procedure indicates that $N\phi(v)$ is well-represented by a Gaussian, at least in the wings, centered at $V_{\rm LSR} = 6.5 \pm 0.5$ km s^{-1} with a FWHM of 35.7 ± 1.5 km s^{-1} and amplitude $(2.65 \pm 0.16) \times 10^{16}$ cm^{-2} (km s^{-1})$^{-1}$. Integrating over the fitted line profile then gives a total column density for CO in this component of the gas of $(1.0 \pm 0.1) \times 10^{18}$ cm^{-2}, where the formal error represents solely the uncertainty in the parameters of the fit to the derived $N\phi(v)$ profile. An assumed CO fractional abundance of $[CO]/[H_2] = 1.2 \times 10^{-4}$ (Watson 1982) thus gives $N_{H_2} \sim 8 \times 10^{21}$ cm^{-2}, which is consistent with the limit derived by Blake *et al.* (1987) of $N_{H_2} \leq 1 \times 10^{23}$ cm^{-2}.

The optical depth at line center for the high-velocity component with $T_x = 180$ K peaks at $J = 8$–7 with a value of $0.5/\Omega$, where Ω is the beamfilling factor ($0 < \Omega < 1$). The corresponding optical depth for the $J = 17$–16 CO line at line center is 0.07. This result confirms that our procedure is at least self-consistent, and that the emission in the wings of the $J = 17$–16 line is optically thin for reasonable values of the filling factor.

d) Comparison with Other Observations

Our estimate of 180 ± 50 K for the excitation temperature of CO in the plateau emission source is consistent with values deduced from other emission lines thought to arise in the same region. For example, Masson *et al.* (1984) find a brightness temperature of 160 K for the CO $J = 1$–0 line originating from the compact ($\sim 25''$ FWHM) component of the plateau emission. Schloerb *et al.* (1983) have observed a number of SO_2 transitions of varying excitation, and found that $T_x \sim 150$ K is most consistent with the intensities observed in the higher excitation lines. Blake *et al.* (1987) also show that a range of temperatures up to ~ 200 K characterizes the excitation of many other molecules in the plateau source.

An excitation temperature as low as 180 K is insufficient to produce significant radiation in transitions with $J > 20$. For example, at line center the expected antenna temperature and integrated intensity are about 2 K and 1.1×10^{-3} ergs cm^{-2} s^{-1} sr^{-1} in the $J = 21$–20 transition, with further decrease at higher J. This estimate is inconsistent with the measured integrated intensities of high-J lines which are about an order of magnitude or more larger than the values expected from this 180 K component (Watson *et al.* 1980; Storey *et al.* 1981; Watson *et al.* 1985). However, as discussed by these authors, the radiation at higher J is well described by a single-component model of "warm," postshock gas at $T \sim 750$ K. This single-component model incorporates an earlier measurement of the $J = 17$–16 integrated intensity (Stacey *et al.* 1982), which, as discussed previously, is already somewhat higher than our measured value. Furthermore, if one accepts the similarity of line shape in the wings of the $J = 17$–16 line with that in the lower J lines (see Figs. 4*a* and 4*b*) as evidence that the same component gives rise to the wing radiation in all of these transitions, then the discrepancy with the 750 K model increases, since only approximately 20% of our observed $J = 17$–16 intensity is left unaccounted for by the 180 K gas component.

The two approaches are complementary, in that Storey *et al.* (1981) and Watson *et al.* (1985) make a model based on data from the higher J lines, which should be sensitive predominantly to the higher temperature post shock gas. Their model, however, does not address the origin of the "excess" emission in low-J lines formed in cooler gas. We, on the other hand, attempt to describe the cooler high-velocity gas that is seen in the wings of low-J and intermediate-J lines. At the intermediate-J values, both gas components can be expected to contribute significantly to the line intensity, and neither description alone suffices. The high resolution available in the present observations allows us to separate these contributions to some extent, with the conclusion that up to $J = 17$–16 most of the radiation can be explained as arising from the cooler gas. Reconciling this conclusion with the model of Storey *et al.* (1981) and Watson *et al.* (1985) requires an increase in T_x in their model to decrease the expected contribution from hot gas to the intensities of the $J = 17$–16 and 16–15 lines, and a change in the H_2 density to fit the modified data. It would be informative to observe a high-excitation line ($J > 20$) at resolution similar to that of the present observations to confirm the expected decrease in intensity of the high-velocity, cool component of the line, and to compare a line profile typical of the > 750 K gas with that of the narrower component seen in our $J = 17$–16 data.

There is no similarity of the observed $J = 17$–16 line with that of the H_2 vibrational emission in the central region, as shown in Figure 4*c*. In particular, the marked asymmetry seen in the H_2 profile is absent in the CO data. This is not unexpected, since the vibrational emission is thought to arise from 2000 K gas (Beckwith *et al.* 1978), which is not expected to produce a noticeable contribution to any of the CO rotational lines (Storey *et al.* 1981; Watson *et al.* 1985). However, Scoville *et al.* (1982) conclude from their H_2 vibrational emission data that the asymmetry of the profile results at least partially from the superposition of two distinct emission components, the stronger of which has a V_{LSR} near that of OMC 1 and a FWHM of less than 50 km s^{-1}. If that is indeed the case, then it is possible that the line profiles of the CO and H_2 emission from this component are more similar than indicated by Figure 4*c*.

As evidence that the high-J infrared CO line emission has a common origin with some high-excitation millimeter-wave spectral lines, Figure 4*d* shows a comparison of our CO $J = 17$–16 spectrum with that of the SO 7_8–6_7 transition (Loren and Wootten 1986), which arises from an energy level approximately 65 K above the ground, and is associated with the plateau source. As can be seen, the agreement in line profiles is very good, suggesting strongly that emission seen in both lines arises from the same gas. The SO observations were done with a beam size of $1' \times 1'.2$. Although some CO $J = 17$–16 radiation is expected to arise from the hot core, it is likely optically thin since it was not detected. Any optically thick emission would have been seen, even with the beam dilution expected for this compact source.

e) Narrow Component Emission

The narrower component that we observe does not arise in the "hot core," because its V_{LSR} of 9–11 km s^{-1} is higher than that attributed to hot core emission but typical of the value characteristic of the ridge emission, and in addition it is spatially extended. If our narrow emission represents a contribution that increases with higher J, then it could perhaps be identified with a shock-heated component of the ridge. More observations at good spatial and spectral resolution are needed to clarify this point.

Figure 5*a* shows the spatial behavior of the two components of the CO $J = 17$–16 spectra. As can be seen from this figure, the intensity of the narrower component is strongest at H_2 peak 1 and decreases monotonically fairly steeply to the southeast in a manner consistent with the change in H_2 vibrational emission (see Fig. 1 and Fig. 5*a*), while the wider component is strongest at BN and has approximately equal integrated intensities at H_2 peak 1 and peak 2 positions. It

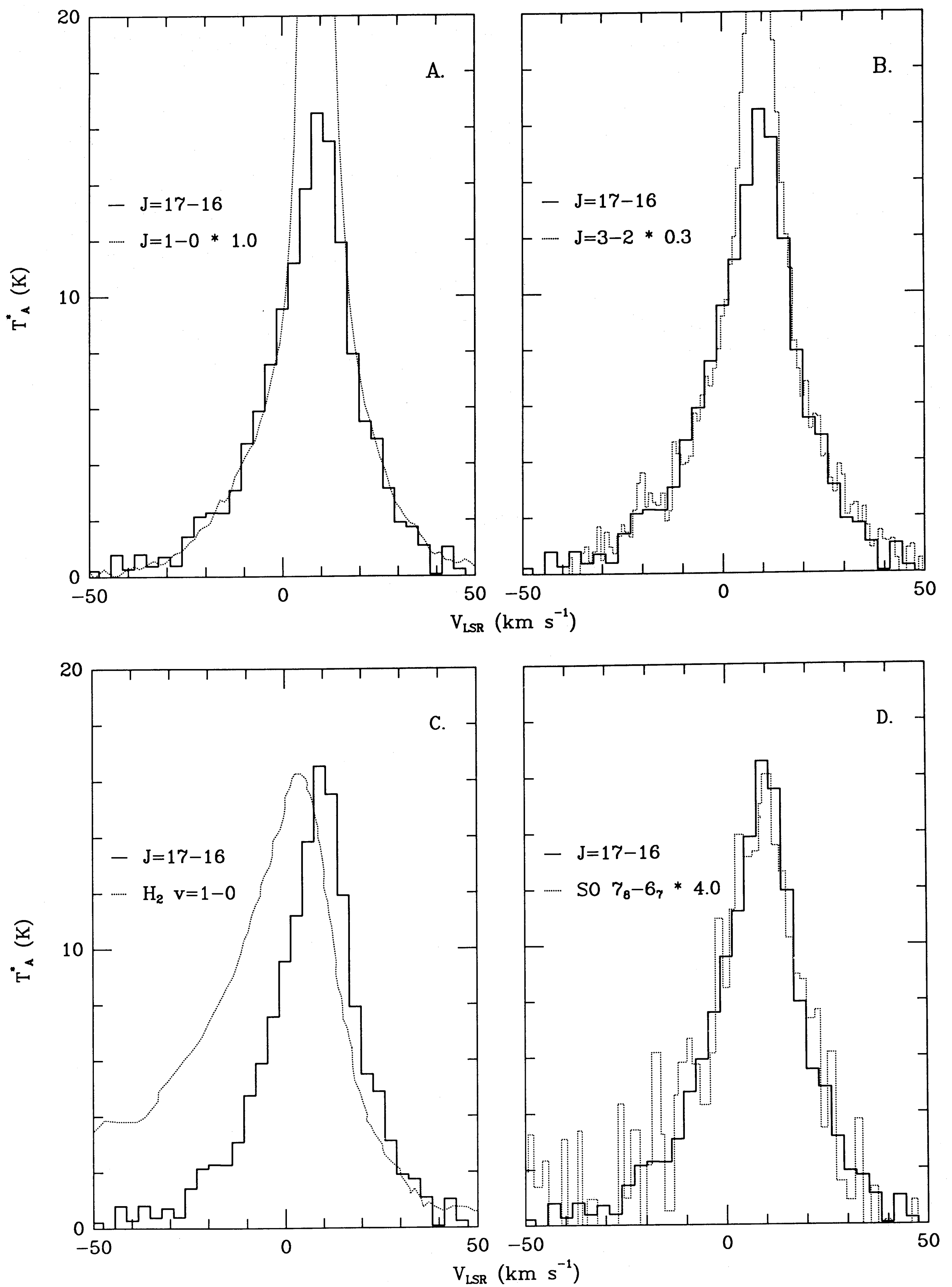

FIG. 4.—The averaged spectrum of the J = 17–16 line of CO (*solid line*), compared with spectra of (*a*) CO J = 1–0 (Plambeck *et al.* 1983); (*b*) CO J = 3–2 (Richardson *et al.* 1985); (*c*) H_2 v = 1–0 $S(1)$ (Nadeau, Geballe, and Neugebauer 1982); and (*d*) SO 7_8–6_7 transition (Loren and Wootten 1986). The continuum has been subtracted from all spectra.

should be noted that this intensity decrease is solely due to a reduction in the component line width. The peak temperatures at the three positions are quite similar. It would be possible by increasing the relative contribution of the narrow component to the line to obtain a spatial distribution similar to that seen in the $J = 21$–20 data of Storey *et al.* (1981), which is also shown in Figure 5*a* for comparison.

The existence of the narrow line component in the $J = 17$–16 line, especially at θ^1C, suggests that phenomena other than shocks may contribute to the excitation of high-J CO lines. It has been shown by Hayashi *et al.* (1985) that some vibrational emission from H_2 is produced from UV-excited gas. Tielens and Hollenbach (1985) state that production of CO at the edges of photodissociation regions is initiated by reactions of vibrationally excited H_2. CO produced in an excited state can lead to high-J rotational emission. If CO is self-shielding, then a substantial amount of CO emission would be expected from UV-heated gas, as is suggested by observations of CO $J = 7$–6 in M17 and S106 (Harris *et al.* 1987). Further evidence for UV-heated CO is provided by the strong, narrow lines of CO $J = 6$–5 emission seen in OMC 1 away from the BN-KL region (Koepf *et al.* 1982). The line width and V_{LSR} of the narrow component in the $J = 17$–16 data are similar to those of other species such as C II known to be produced in the photodissociation region (Boreiko, Betz, and Zmuidzinas 1988). Dual production mechanisms of shocks and ultraviolet photoelectric heating at different spatial locations within the Orion complex are also seen in the O I line at 63 μm (Werner *et al.* 1984). This latter line shows distinct spatial peaks near θ^1C and BN, but with different widths, being unresolved at θ^1C and with FWHM ~50 km s^{-1} near BN. The θ^1C region is an interesting candidate for further high-resolution observations in other high-J CO transitions to investigate the excitation mechanism for this narrow emission.

Finally, it is interesting to note the different spatial dependences of the V_{LSR} of the CO line components deduced from

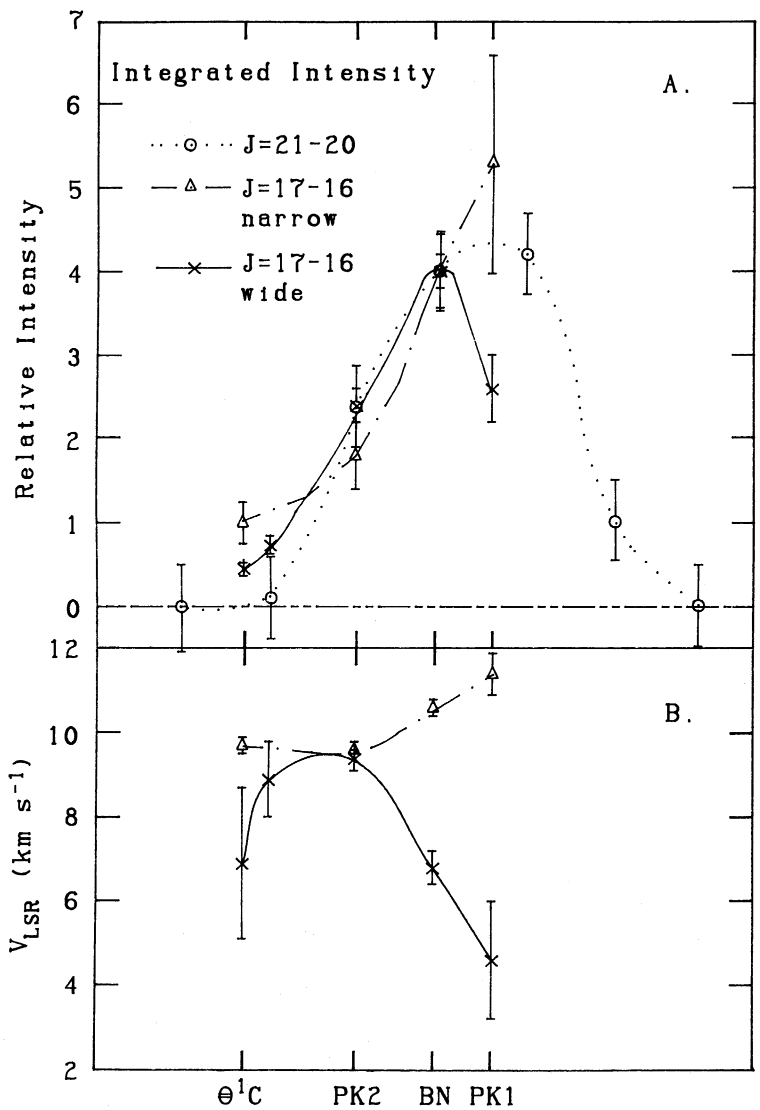

FIG. 5.—Spatial dependence of (*a*) the integrated intensity of the two components of the CO $J = 17$–16 emission compared with that of the $J = 21$–20 line observed by Storey *et al.* (1981), normalized at BN; and (*b*) the V_{LSR} of each of the two components of the $J = 17$–16 emission.

our fits. As shown in Figure 5*b*, the V_{LSR} of the wide component generally decreases from SE to NW, and is always less than that of the narrow component, which increases from SE to NW, although more slowly. This strongly suggests that the narrow component does not originate from the hot core, which is characterized by $V_{LSR} \sim 5.5$ km s^{-1}, but rather from the molecular material in the ridge, which shows a general decrease in V_{LSR} from NE to SW and a V_{LSR} in the range between 8 and 10 km s^{-1} (Bastien *et al.* 1981). The velocity trend in the wide component is similar to that seen in the high-velocity emission in lower J transitions (Snell *et al.* 1984), further confirming the plateau as the source of the wide component of the $J = 17$–16 CO emission.

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A. L. Betz and R. T. Boreiko: Space Sciences Laboratory, University of California, Berkeley, CA 94720

J. Zmuidzinas: Astronomy Department, University of Illinois, 1011 West Springfield Avenue, Urbana, IL 61801