NASA-TM-84321

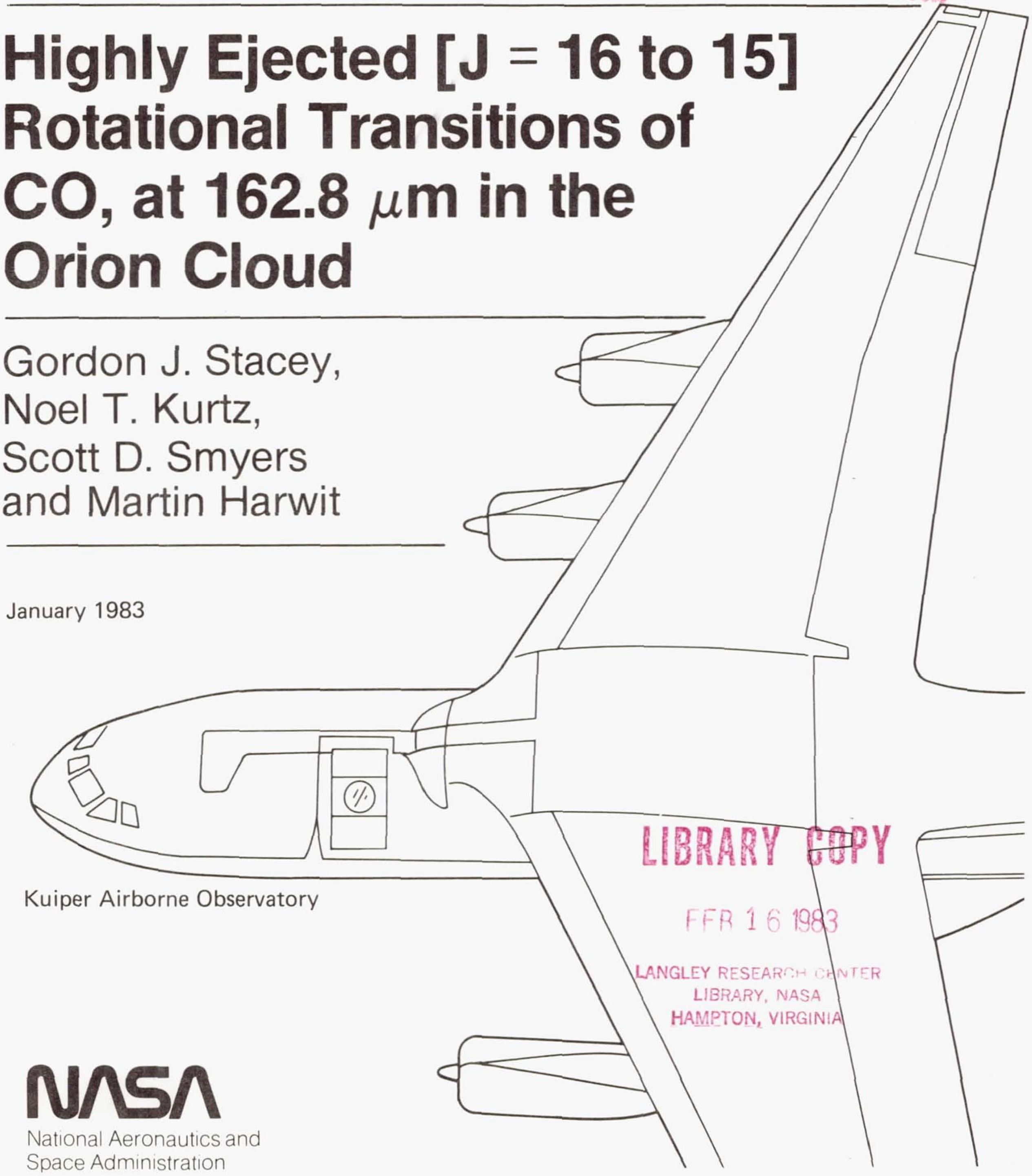
NASA Technical Memorandum 84321

Airborne Astronomy Program
Medium Altitude Missions Branch
Preprint Series 004

Highly Ejected [J = 16 to 15] Rotational Transitions of CO, at 162.8 μm in the Orion Cloud

Gordon J. Stacey,
Noel T. Kurtz,
Scott D. Smyers
and Martin Harwit

January 1983



Kuiper Airborne Observatory

NASA
National Aeronautics and
Space Administration

NASA Technical Memorandum 84321

Airborne Astronomy Program
Medium Altitude Missions Branch
Preprint Series 004

Highly Ejected [J = 16 to 15] Rotational Transitions of CO, at 162.8 μm in the Orion Cloud

Gordon J. Stacey
Noel T. Kurtz
Scott D. Smyers
Martin Harwit, Center for Radiophysics and Space Research, Cornell University, Ithaca, New York

NASA
National Aeronautics and
Space Administration

Ames Research Center
Moffett Field, California 94035

N83-19660#

HIGHLY EXCITED (J = 16 to 15) ROTATIONAL TRANSITIONS OF CO, AT 162.8μm, IN THE ORION CLOUD

Gordon J. Stacey, Noel T. Kurtz, Scott D. Smyers
and Martin Harwit

Astronomy Department
Center for Radiophysics and Space Research
Cornell University
Ithaca, New York, 14853-0352

Subject Headings: Interstellar medium-shocks, cooling; CO transitions; submillimeter astronomical spectroscopy

Accepted by: Monthly Notices of the Royal Astronomical Society as a Short Communication.

Received 1982 September 16.

ABSTRACT

We present the first observations of the $J = 16$ to $J = 15$, 162.8μ transition of CO from an astronomical source. These measurements were carried out on the Kleinmann-Low Nebula. The intensity observed is in good agreement with predictions from previous spectroscopic work carried out in the far infrared by the University of California, Berkeley group, and by our group at Cornell. The observation strengthens our previous claim that $\approx 1.5\ M_{\odot}$ of molecular hydrogen is heated to a temperature above 750 K within the shocked region in the Nebula. We present upper limits to the OH intensity in the $F_2(^2\Pi_{1/2})$ transitions $J = 3/2$ to $J = 1/2$ which fall into two groups centered respectively at 163.12 and 163.40μ.

I. INTRODUCTION

Two years ago Watson et al., 1980, discovered radiation from highly excited CO molecules in the Kleinmann-Low Nebula. Rotational transitions from upper levels in the range J = 21 to J = 30 were studied. This radiation is believed to emanate from shocked molecular hydrogen regions and gases left in the wake of shocks. The lines observed lie in the 87- to 124-micron wavelength range.

By observing at longer wavelengths, our group has recently also observed the J = 17 to J = 16 transition at 153μ (Stacey et al. 1982). Here we report new observations obtained in January 1982 in which we also observed the J = 16 to J = 15 line at 162.8μ (Fig. 1). The interesting feature of both transitions is the virtual independence of their strengths from temperature and density conditions over a wide range of temperatures above 750 K and molecular hydrogen densities above 10^6 cm^{-3} (McKee et al. 1982, Stacey et al. 1982). This enables one to define the mass of CO in the Kleinmann-Low Nebula at temperatures above 750 K, at least within a factor of two, to be 8 x 10^{30}g, corresponding to our observed intensity of 6.4 x 10^{-17} Watt cm^{-2} in the line. By assuming cosmic abundance, and one-quarter of the carbon to be present in the form of CO, as justified by Storey et al. 1981, we then find that about 1.5 $M_{\odot}$ of molecular hydrogen have been heated to these temperatures within the nebula.

Since direct observations of the hydrogen are complicated by enormous near-infrared opacities -- opacities believed to play a negligible role at 163μ -- this indirect estimate of the total mass of material involved in shocks is significant.

II. OBSERVATIONS AND RESULTS

On the morning of January 14 and 15, 1982, we observed the Kleinmann-Low (KL)/Becklin-Neugebauer (BN) region of the Orion Nebula while flying aboard the Kuiper Airborne Observatory (KAO) at an altitude of 12.5 km. The instrument used on the 90-cm telescope was our interferometer-grating-spectrometer described elsewhere (Harwit et al. 1981). The resolving power of this instrument is roughly $\lambda/\Delta\lambda \approx 1000$, corresponding to a line-of-sight velocity spread ≈300 km sec^{-1}. The bandpass of our instrument is roughly one micron between half-power points, and the separation between independent spectral line is 0.13μ at 162.8μ. Our beam is approximately 1' square, and we measure an in-flight system-noise-equivalent-power (NEP) of 2.9×10^{-13} W $Hz^{-1/2}$, as judged through observations of the KL-BN continuum spectrum. Two stressed gallium-doped germanium detectors are housed in our instrument. The portions of the spectrum observed are separated by 0.7μ. While one detector observed a range around 162.5μ, the other was centered at 163.2μ.

Two sets of observations were undertaken: First, we sought the intensity of the 162.8μ transition from a field of view centered on the Becklin-Neugebauer object, but including the Kleinmann-Low Nebula. These data were obtained on January 14. The following night we attempted to map the region, at 153.3μ, in order to assess the size of the emitting region we had observed the previous September. Five fields of view were observed, the peak emission region and four others, respectively displaced by approximately half an arc minute to the north, south, east and west. Time limitations precluded our taking more than one spectrum per region. Within our noise values, which were of the order of half the signal strength, we observed no definite signal outside our main beam, although there was a hint of extension toward the northwest. This suggests that the dimensions of the region emitting at 153μ are not appreciably extended on a scale of one arc minute, a result consistent with observations of Phillips et al. 1979 and Storey et al. 1981, respectively, in the $J = 3 \rightarrow 2$ and $J = 21 \rightarrow 20$ transitions.

Figure 1 shows the spectrum observed at 162μ. The flux observed from the 162.8μ line was calibrated against the known continuum emission from the Nebula or which we assumed a flux modeled by Werner et al. (1976) as that from a 70 K blackbody whose emissivity beyond wavelength $\lambda = 20\mu$ drops as $20/\lambda$. The flux in the line is then calculated to be $6.4 \pm 1 \times 10^{-17}$ W cm^{-2}. This may be compared to our previously cited 153μ flux of 7×10^{-17} W cm^{-2} (Stacey et al. 1982).

III. DISCUSSION

It is also worth comparing our result to intensities seen in other transitions observed from the same field of view. These are exhibited in Fig. 2. The line intensities observed at high J values are well fitted with a curve constructed by McKee et al. (1982) based on a shock model which reaches a peak temperature of $\approx 3 \times 10^3$ K, in the neutral gas.

At low J-values a magnetohydrodynamic shock model due to Draine and Roberge (1982) gives a somewhat better fit, since it includes a range of preshock, shock, and post-shock temperatures. The low J-values refer to cool gas that exhibits a wide velocity range in the "pedestal" spectrum. Evidently there is more cool gas than accounted for in the simple models. The results obtained are consistent with our previous (Stacey et al. 1982) claim that the total number of molecules in our beam, in a gas component at temperature above 750 K and $n_{H_2} > 10^6$ cm^{-3}, is 10^{53} CO molecules. As previously concluded this corresponds to about 1.5 $M_\odot$ of hydrogen in such a heated cloud.

As a side product of our CO observations, we also observed the part of the spectrum in which OH radicals emit around 163.1 and 163.4μ. At the longer of these two wavelengths, our second detector was used. For OH, the $F_2(^2\Pi_{1/2})$ transitions $J = 3/2$ to $J = 1/2$, exhibit sets of three closely spaced lines clustered respectively around 163.12 and 163.40μ (Brown et al. 1982). Our spectral resolution suffices only to resolve these six lines into two distinct groups. Storey et al. (1981a) previously observed companion transitions $F_1(^2\Pi_{3/2})$ $J = 5/2$ to $J = 3/2$, where six closely spaced lines again break into two clearly separated sets of three, respectively, at 119.23 and 119.44μ. While the Berkeley group clearly observed these lines in absorption against the Galactic Center, they placed less confidence in an apparent emission they saw from the BN region, where each of the two small features seen appeared displaced from the expected line position by 1/20 micron. At any rate, if correct, the line intensity of both these features corresponds to 1.6×10^{-17} W cm^{-2}.

Our own observations of the 163μ lines place upper limits of 1.5×10^{-17} W cm^{-2}-- one standard deviation from the mean--on each of these features. For a hydrogen density $n_{H_2} = 10^6 cm^{-3}$, Flower et al.

(1982) calculate a cooling rate for OH, through all transitions, of $\approx 5 \times 10^{-18}$ erg sec^{-1} per OH molecule. In order to observe OH emission from BN at the level of sensitivity cited by either the Berkeley group or given by our upper limits, one would require a column density $\approx 3.6 \times 10^{15}$ cm^{-2} as noted by the Berkeley group. This must be compared to a column density $N_{CO} \approx 9 \times 10^{17}$ cm^{-2} obtained by averaging the total number of CO molecules observed over the area of our beam. If one-quarter of the carbon is in the form of CO, and cosmic abundance of carbon is assumed, we have $n_{CO}/n_{H_2} \approx 1.7 \times 10^{-4}$. In that case the mean OH density along the line of sight would give $n_{OH}/n_{H_2} \leq 7 \times 10^{-7}$ for the shocked region.

This is important for the following reason. The oxygen abundance should be roughly twice the carbon abundance if normal cosmic abundances hold in the nebula. As summarized by Stacey et al., however, observations by a variety of different workers and techniques have shown that there is little oxygen in atomic form, or in the form of H_2O, in the Kleinmann-Low Nebula. Since the OH abundance also appears to be low, oxygen, if as abundant as expected, would have to be in the form of O_2. That would be consistent with models for cool dense molecular clouds produced by

Iglesias (1977) but less readily reconciled with the shock models of Iglesias and Silk (1978) which suggest that much of the molecular oxygen is destroyed in hot shocks. It is interesting, nevertheless, that observations of this kind are able to lead us to a juncture where chemical reaction schemes in interstellar space can now be subjected to detailed analysis.

ACKNOWLEDGEMENTS

The work reported here was supported through NASA Grant NSG-2347. We thank the staff of the KAO for their whole-hearted support throughout our observing run. Bruce Draine kindly sent us a preprint of his article with Wayne Roberge, prior to publication. Dan Watson very kindly discussed some of the Berkeley group's results with us before publication, and permitted us to cite them. Jim Houck gave us the use of his excellent offset guider for the observations we report.

REFERENCES

Brown, J. M., Schubert, J. E., Evenson, K. M. and Radford, H. E., 1982, Astrophys. J. 258, 899.

Draine, B. T. and Roberge, W., 1982, Astrophys. J., 259, L91.

Flower, D. R., Guilloteau, S. and Hartquist, T. W., 1982, Mon. Not. R. astr. Soc., 200, 55P.

Goldsmith, P., Erickson, N. R., Fetterman, H. R. Clifton, B. J., Peck, D. D., Tannenwald, P. E., Koepf, G. A., Buhl, D. and McAvoy, N., 1981 Astrophys. J., 243, L79.

Harwit, M., Kurtz, N. T., Russell, R. W. and Smyers, S. D., 1981, Appl. Optics, 20, 7792.

Iglesias, E. 1977, Ap. J., 218, 697.

Iglesias, E. and Silk, J., 1978, Ap. J., 226, 851.

McKee, C. F., Storey, J. W. V. and Watson, D. M., 1982, Ap. J., 259, 647.

Phillips, T. G., Huggins, P. J., Neugebauer, G. and Werner, M. W., 1977, Astrophys. J., 217, L161.

Stacey, G, Kurtz, N, Smyers, S., Harwit, M., Russell, R, and Melnick, G., 1982, Astrophys. J., 257, L37.

Storey, J. W.. V., Watson, D. M., Townes, C. H., Haller, E. E., and Hansen, W. L., 1981, Astrophys. J., 247, 136.

Storey, J. W. V., Watson, D. M. and Townes, C. H., 1981a, Astrophys. J., 244, L27.

Watson, D. M., Storey J. W. V., Townes, C. H., Haller, E. E. and Hansen, W. L., 1980, Astrophys. J., 239, L129.

Watson, D., 1982, private communication.

Werner, M. W., Gatley, I., Harper, D. A., Becklin, E. E., Lowevnstein, R. F., Telesco, C. M., and Thronson, H. A., 1976, Ap. J., 204, 420.

FIGURE CAPTIONS

Figure 1 - The spectrum of the Kleinmann-Low Nebula at 162.5μ. Our instrumental profile predicts a triangular spectral response for the continuum emission from the Nebula--dashed lines. Below 162.1μ and above 163.1μ we expect to observe no signal. The noise in these portions of the spectrum is a measure of our overall uncertainty. The Fourier transformed spectrum is a power spectrum so that all values shown are positive. Error bars are one standard deviation from the mean for the three spectral runs represented here. A triangular apodization was used in the Fourier reduction. The CO line is not resolved with our instrument.

Figure 2 - Intensities in the CO transitions J to J-1 observed by different groups for an aproximately 40" to 1' beam centered on the Kleinmann-Low Nebula. Symbols have the following meanings:

▲Phillips et al. 1977, ▼Goldsmith et al. 1981, △Stacey et al. 1982, ▽Storey et al. 1981, Watson et al. 1980, Watson 1982; □results presented in this paper.

Filled symbols ground-based; open symbols airborne observations. The solid curve is drawn for a 10^3K gas with density n_{H_2} = 10^6 cm^{-3} as given by McKee et al. (1982). The dashed curve, at low J-values was obtained by Draine and Roberge (1982) for a comprehensive magnetohydrodynamic shock model.

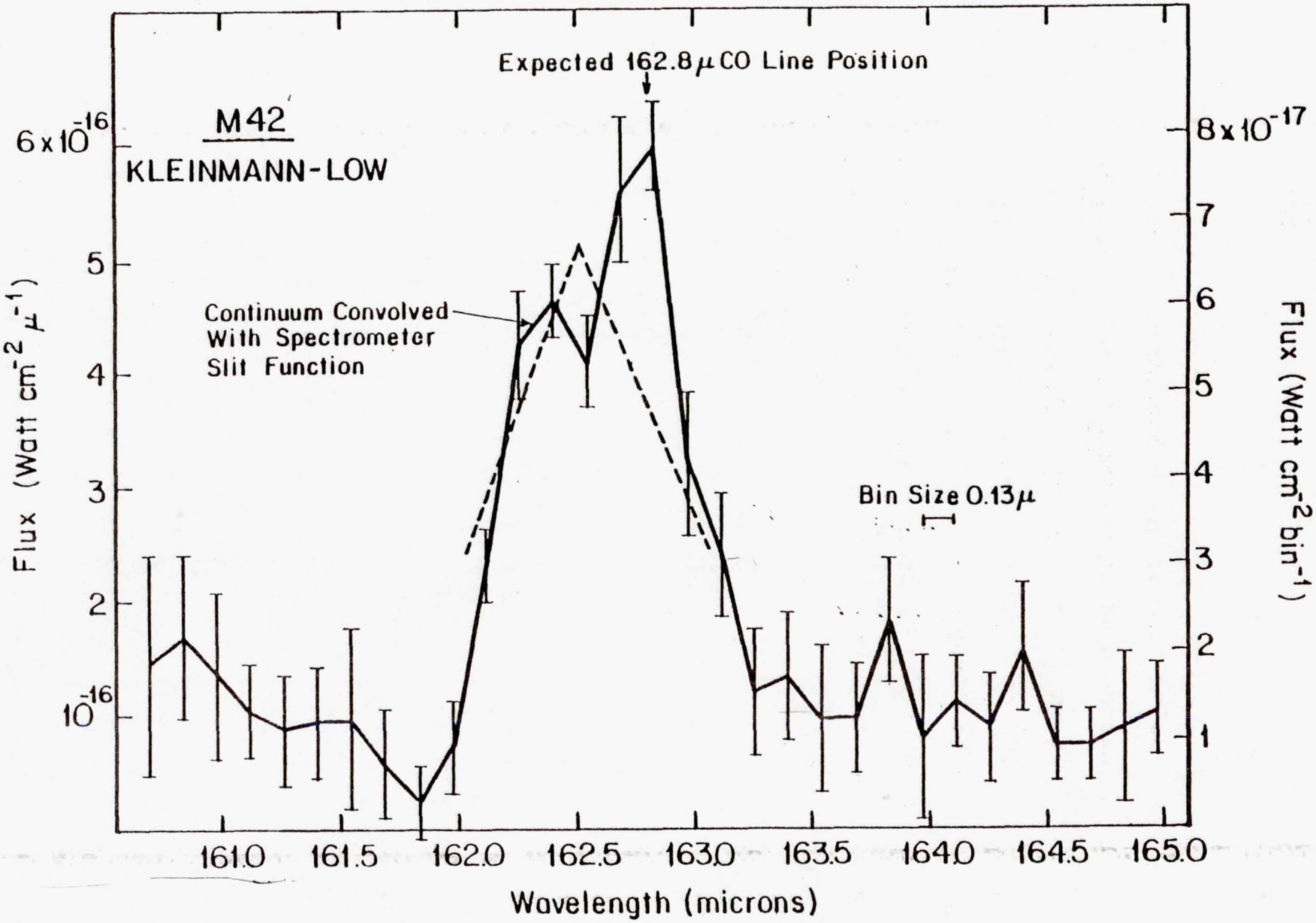
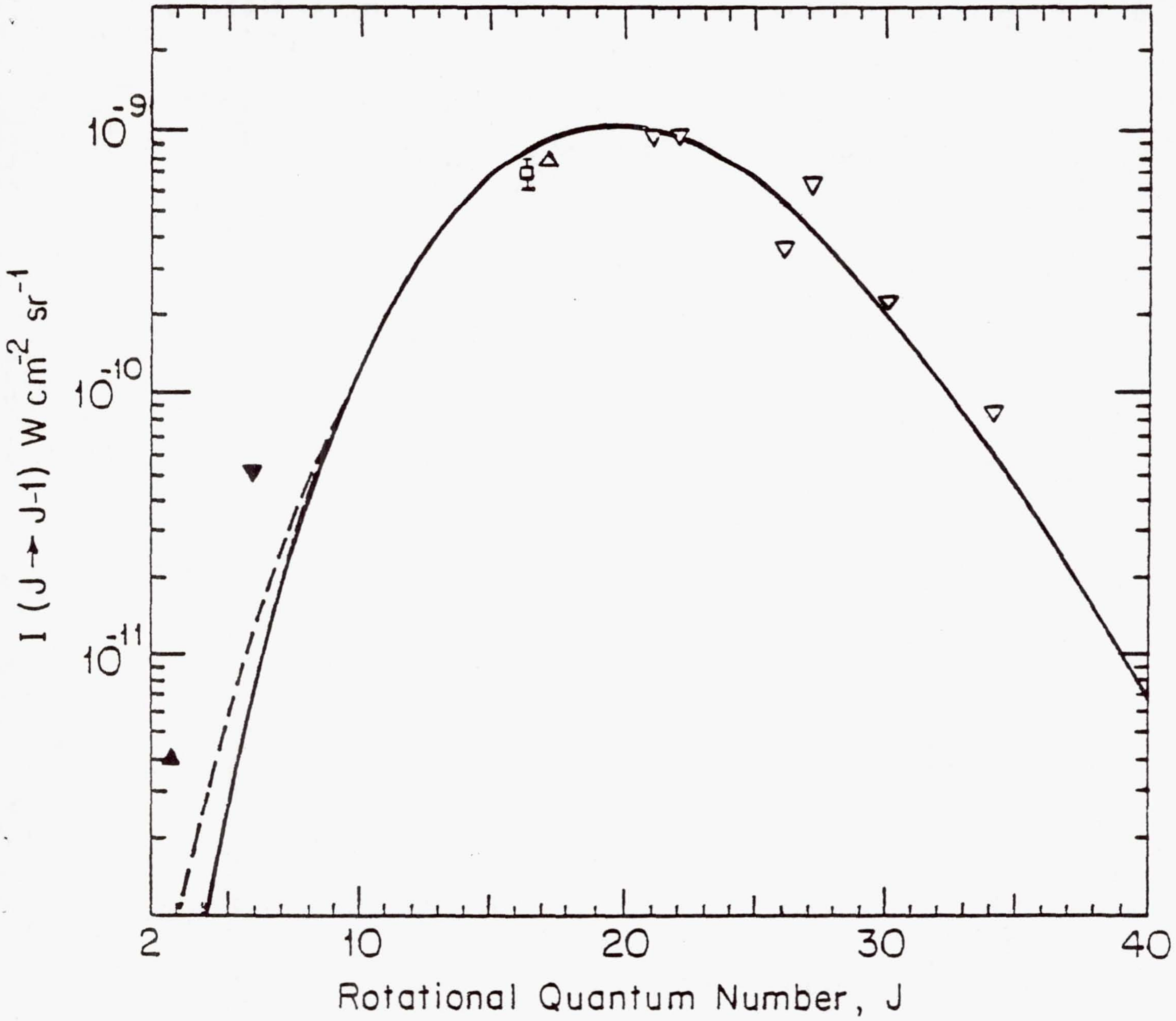

Expected 162.8μ CO Line Position
M42
KLEINMANN-LOW
Continuum Convolved With Spectrometer Slit Function
Bin Size 0.13μ
Flux (Watt cm^{-2} μ^{-1})
6 x 10^{-16}
5
4
3
2
10^{-16}
Flux (Watt cm^{-2} bin^{-1})
8 x 10^{-17}
7
6
5
4
3
2
1
161.0
161.5
162.0
162.5
163.0
163.5
164.0
164.5
165.0
Wavelength (microns)

Figure 1



I (J→J-1) W cm^{-2} sr^{-1}
10^{-9}
10^{-10}
10^{-11}
2
10
20
30
40
Rotational Quantum Number, J

Figure 2

1. Report No. NASA TM-84321	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle HIGHLY EXCITED (J = 16 TO 15) ROTATIONAL TRANSITIONS OF CO, AT 162.8 μm, IN THE ORION CLOUD		5. Report Date January 1983 6. Performing Organization Code
7. Author(s) Gordon J. Stacey, Noel T. Kurtz, Scott D. Smyers, and Martin Harwit		8. Performing Organization Report No. A-9214 10. Work Unit No. 352-02-03
9. Performing Organization Name and Address Center for Radiophysics and Space Research Cornell University, Ithaca, New York		11. Contract or Grant No. 13. Type of Report and Period Covered Technical Memorandum
12. Sponsoring Agency Name and Address National Aeronautics and Space Administration Washington, D.C. 20546		14. Sponsoring Agency Code

15. Supplementary Notes Preprint Series 004 - Supported by NASA grants. Point of Contact: L. C. Haughney, Ames Research Center, M/S 211-12, Moffett Field, Calif. 94035, (415) 965-5339, FTS 448-5339.

16. Abstract

We present the first observations of the J = 16 to J = 15, 162.8 μ transition of CO from an astronomical source. These measurements were carried out on the Kleinmann-Low Nebula. The intensity observed is in good agreement with predictions from previous spectroscopic work carried out in the far infrared by the University of California, Berkeley group, and by our group at Cornell. The observation strengthens our previous claim that $\approx 1.5\ M_\odot$ of molecular hydrogen is heated to a temperature above 750 K within the shocked region in the Nebula. We present upper limits to the OH intensity in the $F_2(^2\pi_{1/2})$ transitions J = 3/2 to J = 1/2 which fall into two groups centered respectively at 163.12 and 163.40 μ.

17. Key Words (Suggested by Author(s)) Astronomy Interstellar medium shocks CO transitions Submillimeter astronomical spectroscopy	18. Distribution Statement Unlimited STAR Category - 89

19. Security Classif. (of this report) Unclassified	20. Security Classif. (of this page) Unclassified	21. No. of Pages 17	22. Price* A02

*For sale by the National Technical Information Service, Springfield, Virginia 22161