NASA TM-84307

NASA Technical Memorandum 84307

Airborne Astronomy Program
Medium Altitude Missions Branch
Preprint Series 002

NASA-TM-84307 19830005761

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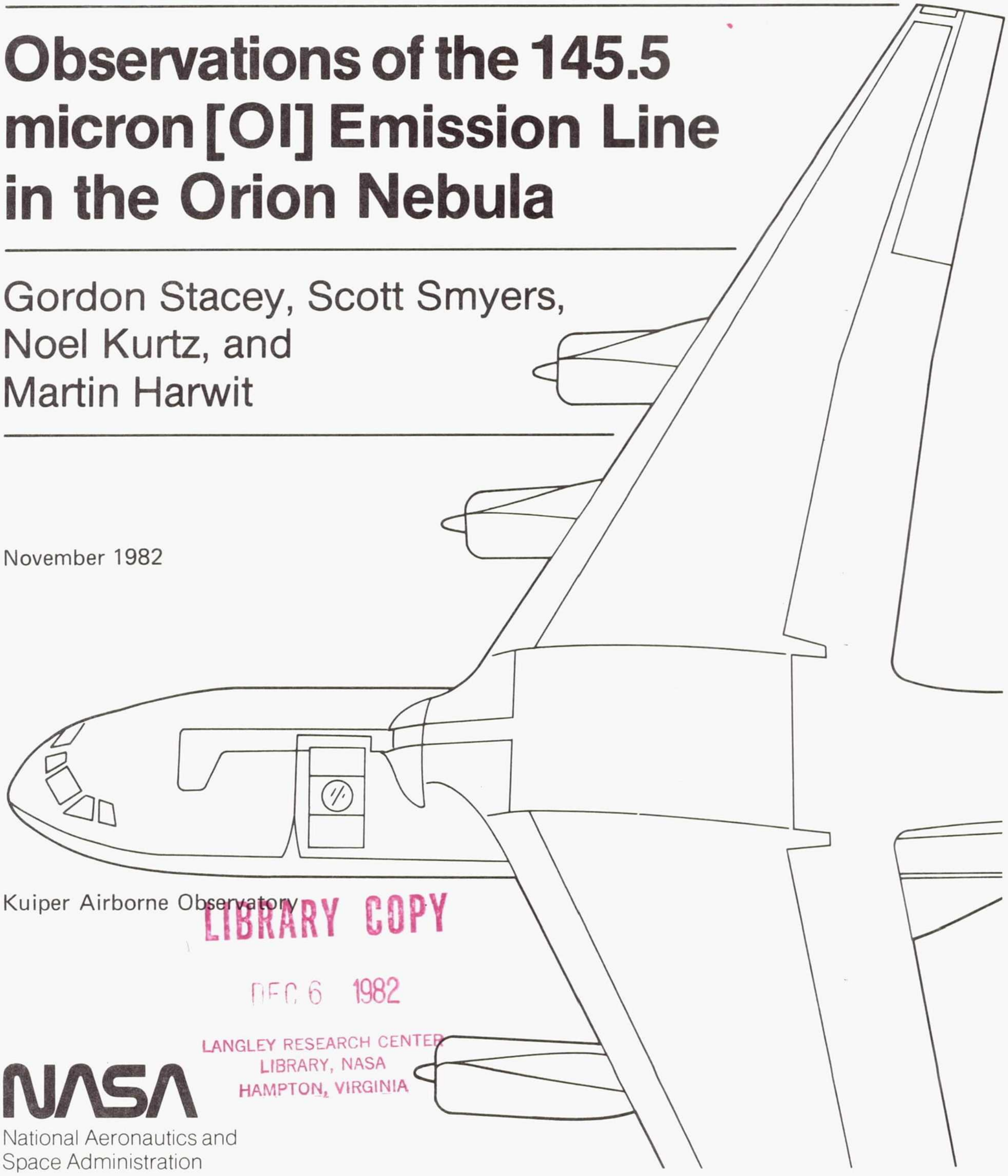
November 1982



Kuiper Airborne Observatory

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Gordon Stacey
Scott Smyers
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Martin Harwit, Center for Radiophysics and Space Research, Cornell University, Ithaca, New York

NASA
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Ames Research Center
Moffett Field, California 94035

N83-14032 #

OBSERVATIONS OF THE 145.5 MICRON [OI]
EMISSION LINE IN THE ORION NEBULA

Gordon Stacey, Scott Smyers, Noel Kurtz and

Martin Harwit

Center for Radiophysics and Space Research
Cornell University
Ithaca, New York 14853

Subject Headings: Interstellar medium — shocks, cooling; fine-structure transitions; submillimeter astronomical spectroscopy.

Accepted by: The Astrophysical Journal Letters, September 1982

ABSTRACT

We have obtained a first set of observations of the [OI] $^3P_0 - {}^3P_1$ (145.5 μ) transition. We observed the line both in a $1' \times 1'$ beam centered on the Trapezium, and in a $7' \times 7'$ beam encompassing most of the Orion Nebula. We also have constructed a wide beam ($7' \times 7'$) map of the region which shows that most of the emission is confined to the central regions of the nebula. These observations may be compared with reported measurement of the $^3P_1 - {}^3P_2$ (63.2 μ) transition in Orion and are consistent with optically thin emission in the 145.5 μ line and self-absorbed 63.2 μ emission lines. We discuss mechanisms for the excitation of neutral oxygen and conclude that much of the observed emission originates in the thin, radio-recombination-line-emitting CII/HI envelope bordering on the HII region.

I. INTRODUCTION

In recent years the study of far-infrared fine-structure lines has provided a wealth of information concerning ionic abundances, densities, and temperatures in gaseous nebula. The $^3P_1 - {}^3P_2$ (63.2μ) and $^3P_0 - {}^3P_1$ (145.5μ)* inverted triplet transitions of neutral oxygen are of particular interest as their excitation temperatures of 228° and 327°K, respectively, imply that these lines can be strongly emitted in intermediate temperature regimes associated with low-velocity shocks, ionization fronts, or generally warm neutral regions.

The 63.2μ line was first detected astronomically by Melnick et al. (1979) in the Orion Nebula. More recently, it has been mapped in Orion (Furniss et al. 1982, Werner et al. 1982) and is found to be fairly uniform over a broad region extending roughly 6' in declination and 4.5' in right ascension, centered on the Kleimann-Low (KL) region.

Here, we report the first detection of the 145.5μ line emission, both in a 1' × 1' beam centered on the Trapezium and in a 7' × 7' beam encompassing most of the nebula. Comparisons of the 63.2μ data with 145μ observations allow us to conclude that the emission largely comes from the warm neutral regions surrounding the ionized gas.

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*Davies et al. (1978) have recently measured the wavelength of the $^3P_0 - {}^3P_1$ transition to great precision in the laboratory and find the wavelength to be $145.52548 \pm 9 \times 10^{-5}$μ.

II. INSTRUMENTATION

A. Kuiper Airborne Observatory

On the mornings of January 14 and 15, 1982, we observed the Trapezium region of the Orion Nebula from NASA's Kuiper Airborne Observatory flying at an altitude of 12.5 km. The instrument used has been described elsewhere (Harwit et al. 1981; Stacey et al. 1982). The rectangular field of view, as measured in flight, was approximately $1^{\prime}$ square and our resolving power was approximately 1000. At zero pathlength in the interferometer, we measured an in-flight system noise-equivalent-power, NEP, of $2.9 \times 10^{-13} W - Hz^{-1/2}$, determined through observations of the Kleinmann-Low continuum.

B. Learjet

Following our KAO series, we conducted a series of observations of the Orion Nebula with the 30-cm telescope aboard NASA's Learjet during February 1982. The instrument used has been described by Houck and Ward (1979). Observations of Jupiter suggest an in-flight system — NEP of $2.6 \times 10^{-13} W\ HZ^{-1/2}$. The full-width, half-power beam size was determined as $7^{\prime} \times 7^{\prime}$ square through observations of Jupiter. The amplitude of our 35 Hz chopper throw was $14^{\prime}$ in a S.E.-N.W. direction. Our instrumental profile is gaussian-shaped and has a full-width, half-maximum, corresponding to a resolving power of $\lambda/\Delta\lambda = 110$.

III. OBSERVATIONS

Two Learjet flights were dedicated to determining the 145μ flux in the central $\hat{7'} \times \hat{7'}$ of the nebula. Figure 1 is the average of the 15 spectra taken on these flights, each of which shows the feature at 145.5μ. Two flights were also dedicated to determining the spectrum of Jupiter, our Learjet calibration source in the 145μ region. Unfortunately, it was not possible to take spectra of both M42 and Jupiter on the same flight, so we used the Jupiter spectra whose telluric water vapor features most nearly matched those of M42 to calibrate our final spectrum. Our best estimate for the line flux of the central regions is $4.7 \pm 0.9 \times 10^{-16}$ W cm^{-2}.

We also spent a Learjet flight mapping the entire M42 region. Our beam size is so large that a five-point map covers most of the region of interest. No flux was detected outside the central region at a level above 10^{-16} Watt cm^{-2}, with the possible exception of a region South and East of the Trapezium where a somewhat higher flux might be present.

The 145.5μ transition was also observed from the KAO in a $\hat{1'} \times \hat{1'}$ beam centered on the Trapezium. The final spectrum, Fig. 2, represents the average of six spectra taken on two different nights with two different detectors. Of the six, all but one show the feature at 145.5 μ which we identify as the OI line. The line flux was calibrated against continuum flux measurements on the KL Nebula* and on Mars, and has a value of $4.8 \pm 1.4 \times 10^{-17}$W-cm^{-2}.

C. <u>63μ Observations</u>

The first observations of the 63μ emission from M42 indicated a flux of 8×10^{-15}W cm^{-2} in a $4' \times 6'$ beam (Melnick et al. 1979). More recently, the region has been mapped at 63μ by Furniss et al. (1982) and Werner et al. (1982). Their observations agree to within quoted errors with those of Melnick et al. From the contour map of Furniss et al., we estimate the total 63μ flux in a $7' \times 7'$ beam as 7.3×10^{-15}W cm^{-2}. This corresponds to an average 63μ intensity of 1.8×10^{-9} W cm^{-2} sr^{-1}, the value we compare with our broadbeam ($7' \times 7'$) 145μ observations.

For the Trapezium region, Furniss et al. have observed an intensity of 3.8×10^{-9} W cm^{-2}sr^{-1} in a 1.35' diameter beam, while Werner et al. measured 6.2×10^{-9} W cm^{-2} sr^{-1} in a .75' diameter beam. For our models of the Trapezium region, we approximate the 63μ intensity in a $1' \times 1'$ beam as 5.0×10^{-9}W cm^{-2} sr^{-1}.

Table 1 summarizes these data.

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* Werner et al. (1976) find that the emission within a 1' beam at KL may be modeled as a 70°K blackbody if the emissivity falls as 20/λ, where the wavelength is measured in microns.

IV. DISCUSSION

OI is neutral, and may be excited by electron and proton impact as well as the impact of neutral species. Since the ionization potential of oxygen, 13.618eV, is so close to that of hydrogen, 13.589eV, we may expect to find almost no OI in the HII region itself. It may exist, however, in the ionization front separating an HII region and an HI region as well as in HI, or molecular hydrogen regions.

A. Ionization Front

The primary excitation mechanism for neutral oxygen in the ionization front is the impact of electrons, with a lesser contribution from proton impacts. Melnick (1981) has calculated the emissivities of the 63μ and 145μ lines for electron impact as a function of density and temperature. We note that the thickness of the ionization front is of the order of a mean free path for a hydrogen ionizing photon, $\sim 10^{17}/n_H$cm, and assume pressure equilibrium between a D-type ionization front and the compact HII region ($n_e \sim 2200$ cm^{-3}, $T_e \sim 7000$°K, Schraml and Mezger, 1969). For 50% ionization and an electron temperature of 3000°K a simple argument then shows that the line intensity expected from the ionization front is four orders of magnitude smaller than the measured intensity. We conclude that the 63μ and 145μ emission does not come from such a front. Here, and in the estimates given below, we assume oxygen atoms to be present in cosmic abundance, $n_O/n_H = 6.8 \times 10^{-4}$.

B. Shocked Neutral Regions

Collision cross sections for oxygen atoms excited through neutral hydrogen impacts have been calculated by Launay and Roueff (1977). We use these to calculate the emissivity of the 63μ and 145μ lines as a function of density and temperature. Following Melnick (1981) we use the ratio of the 63μ to 145μ intensities to determine the number density of hydrogen atoms in the emitting region.

The broadbeam 63μ and 145μ intensities are in a ratio of 16:1. If the gas were optically thin, this line ratio would indicate that the temperature of the emitting regions was $\sim 2000^{\circ}$K with a number density of hydrogen atoms $\sim 1.2 \times 10^{4} \mathrm{cm}^{-3}$. The observed intensity over the entire nebula, then, corresponds to a radiating mass $\sim 30\ M_{\odot}$ of hot, neutral hydrogen. In that case a 157μ [CII] flux comparable to the observed value would be emitted as well (Russell et al. 1980). However, measurements of highly excited rotational transitions of CO by Storey et al. (1981) and Stacey et al. (1982) indicate $\sim 1.5\ M_{\odot}$ of hot ($T \gtrsim 750^{\circ}$K) neutral hydrogen in the Orion nebula confined to the KL - BN region. Furthermore, Beckwith et al. (1982) estimate $\sim .05\ M_{\odot}$ of hot ($T \gtrsim 1500^{\circ}$K) molecular hydrogen through observations of rotational transitions of molecular hydrogen. We conclude that the temperature of the [OI] emitting regions is unlikely to be as high as 2000°K.

C. Warm Neutral Regions

[OI] transitions may also be excited through collisions with neutral hydrogen in warm HI regions just beyond the ionization front. Photons incapable of ionizing hydrogen but capable of ionizing carbon , $912\ \mathring{A} \leq \lambda \leq 1101\ \mathring{A}$, will penetrate the ionization front to the neutral regions. The photons will then ionize the neutral carbon, heating the gas, producing a warm-ionized-carbon/neutral-hydrogen envelope about the HII region. This ionizing flux has been shown (Werner 1970 and Walmsley 1975) to be largely attenuated by dust absorption, with optical depth unity at a distance $L \sim 5 \times 10^{20}\ n_{HI}^{-1}$cm. In the models which follow, we use the constraint that the column density of neutral hydrogen in the CII region is $\tau \sim 6$ or $N_{HI} \sim 3 \times 10^{21}$ cm^{-2}.

The 157μ CII fine-structure line observation of Russell et al. (1980) and the C109α radio recombination line observations of Jaffe and Pankonin (1978) indicate that a reasonable temperature for the CII region immediately surrounding the ionized gas is $T \sim 200 - 300^{\circ}$K. However, for these temperatures, the [OI] line ratio is more likely to be of the order 30 , which means the 63μ emission must be self-absorbed.
If we take $T \sim 300^{\circ}$K, then the minimum column density of neutral oxygen for the observed Trapezium emission is $N_{OI} \sim 4 \times 10^{18}$cm^{-2}, for which we calculate a line center optical depth of the 63μ line

$$\tau = \sqrt{\varepsilon}\ \frac{n(2)}{n(OI)}\ \frac{N_{OI}\ \lambda^3\ A_{12}}{8\pi^{3/2}\ \Delta V_D} \sim 2.2$$

where ε is the probability per absorption that the atom then is collisionally de-excited ($\sim .20$ for $T \sim 300^{\circ}$K,

$n_H \sim 10^5$ cm^{-3}). $\frac{n(2)}{n(OI)}$ is the ratio of the number density of oxygen atoms in the ground (J = 2) state to the total number density of oxygen atoms, and ΔV_D is the Doppler width of the line, taken as the width of the C109α radio-recombination-line, $\Delta V_D \sim 4$ km sec^{-1}.

We construct models for both the broadbeam ($7\hat{'} \times 7\hat{'}$) observations and the Trapezium ($1\hat{'} \times 1\hat{'}$) observations with self-absorption of 63μ line radiation in mind. Our broadbeam 145μ observations indicate an average intensity of 1.1×10^{-10} W $cm^{-2} sr^{-1}$ in our $7\hat{'} \times 7\hat{'}$ beam. Jaffe and Pankonin (1978) find the C109α radio-recombination-line to be extended over a region ∿10' square. They model their observed emission as emanating from two thin ionized-carbon/neutral-hydrogen regions, one on either side of the HII region. Using this model, assuming a column density of neutral hydrogen in the emitting region of $3 \times 10^{21} cm^{-2}$, and assuming pressure equilibrium with the compact HII region, the observed 145μ flux is consistent with optically thin emission from the two fronts for a kinetic temperature $T \sim 220$ K^{O} and $n_H \sim 1.4 \times 10^5$ cm^{-3}. The optically thick 63μ intensity would also arise from these sheets provided local, line-of-sight velocities were as low as 0.66 km sec^{-1}. These are smaller than the observed velocity spread of the carbon recombination lines. But those lines are distributed over broad emitting regions, each region possibly having a rather narrower velocity spread locally, than the ∿4 km sec^{-1} observed over the entire surface of the layers. Table 2 summarizes these characteristics.

To model the emission from the Trapezium region, we must first subtract the intensity contribution of the broad-beam model. This leaves a 63μ intensity of 3.2×10^{-9} W $cm^{-2} sr^{-1}$ and a 145μ intensity of 4.5×10^{-10} W cm^{-2} sr^{-1}. We present two models which will produce this intensity.

Model I assumes that the Trapezium emission originates in one sheet of column density $N_{HI} \sim 3 \times 10^{21} cm^{-2}$. Assuming optically thick 63μ emission with a thermal linewidth, we derive a brightness temperature of 580^{o}K. The 145μ emission is then also optically thick, with an intensity $I = 3.1 \times 10^{-10}$ W cm^{-2} sr^{-1}. This is somewhat lower than the observed value, but still within the quoted errors.

Model 2 is based on the optical Na-D line work of Isobe (1980). Isobe models the Na-D emission from the Trapezium as emanating from globules, i.e., clumps of cold neutral gas embedded in the HII region. To explain the observed 63μ and 145μ emission, we require an average of three globules along the line of sight in the Trapezium. In projection, each globule then contributes two CII/HI, [OI] emitting fronts.

If we assume a reasonable temperatue $T = 310^{o}$K for the CII fronts, then pressure equilibrium requires that $n_{HI} \sim 10^{5} cm^{-3}$. The 63μ emission will be optically thick in each front and will arrive from only the front nearest the observer. The optically thin 145μ emission, however, will arrive from a total of six fronts. These six fronts would then give rise to enhanced C109α emission in the Trapezium region which is also observed (Jaffe and Pankonin 1978).

ACKNOWLEDGEMENTS

We thank the flight and ground crews of both the Kuiper Airborne Observatory and the Learjet at the NASA-Ames Research Center for their excellent support. We also thank our colleague, Jim Houck, for loaning us his excellent offset guiding stage. We would especially like to thank Roger Emery and Michael Werner for making their respective 63μ data available to us prior to publication, and Dan Watson, who provided constructive criticism as a referee. This work was supported by NASA Grants NSG-2347 and NGR 33-010-146.

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TABLE 1

Observations

Region	Wavelength (microns)	Flux ($W\ cm^{-2}$)	Intensity ($W\ cm^{-2} sr^{-1}$)	Comments
Broad beam				
$7' \times 7'$ beam	145.5μ	$4.7 \pm 0.9 \times 10^{-16}$	1.1×10^{-10}	This work.
	63.2μ	7.5×10^{-15}	1.8×10^{-9}	Estimate from contour map of Furniss et al., (1982).
Trapezium				
($1' \times 1'$ beam)	145.5μ	$4.8 \pm 1.4 \times 10^{-17}$	5.7×10^{-10}	This work.
	63.2μ	4.6×10^{-16}	3.8×10^{-9} ($1.35'$ disk)	Furniss et al., (1982).
		2.3×10^{-16}	6.2×10^{-9} ($0.75'$ disk)	Werner et al., (1982).
		4.2×10^{-16}	5.0×10^{-9} ($1' \times 1'$ beam)	Adopted value This work.

TABLE 2

Models

Region	N_{OI} (cm^{-2})	n_{HI} (cm^{-3})	I ^oK	ΔV_D ($km\ s^{-1}$)	I_{63} $W\ cm^{-2} sr^{-1}$	I_{145} $W\ cm^{-2} sr^{-1}$	τ_{63}	τ_{145}
Entire Nebula								
(7' $\times$ 7' beam)	4×10^{18}	1.4×10^5	220	0.66 (calc.)	1.8×10^{-9}	1.1×10^{-10}	6.4	0.92
Two Layer								
Trapezium								
(1' $\times$ 1' beam)								
Model 1								
One Layer	4×10^{18}	5.3×10^4	580 (calc.)	0.64	3.2×10^{-9}	3.1×10^{-10}	5.6	1.6
Model 2								
Globules	1×10^{19}	1.0×10^5	310	1.4 (calc.)	3.2×10^{-9}	4.5×10^{-10}	3.2	0.53

Note: Models assume pressure equilibrium between CII region and the compact HII region, ($T_e \sim 7000^oK$, $n_e \sim 2200\ cm^{-3}$) and that the column density of neutral hydrogen in the CII region is $3 \times 10^{21}\ cm^{-2}$.

FIGURE CAPTIONS

Figure 1 - 145.5μ flux as measured in $7' \times 7'$ beam of the Learjet centered on the Trapezium. The continuum has been fitted by a least squares method ignoring the spectral points in the water vapor band and in the emission feature. The emission line has been fitted by a least squares Gaussian which accurately mimics our instrumental profile. Error bars indicate one standard deviation from the mean. Not shown is the region of a weaker atmospheric H_2O band at 144.5μ.

Figure 2 - Fourier transform spectrum of the 145.5μ emission for a $1' \times 1'$ beam centered on the Trapezium. The band pass of our interferometer-grating-spectrometer-combination is triangular in profile, with approximately one micron between half-power points. It is centered on 145.5μ. Below 144.7μ and above 146.1μ we expect no signal contribution, and these wavelength regions may be used for an estimate of the noise. The feature at 146μ is probably part of the noise. All spectral components are positive because our Fourier transform takes the square root of the sum of the squares of the cosine and sine transforms. The chopper throw was $7.2'$ in a SE to NW direction.

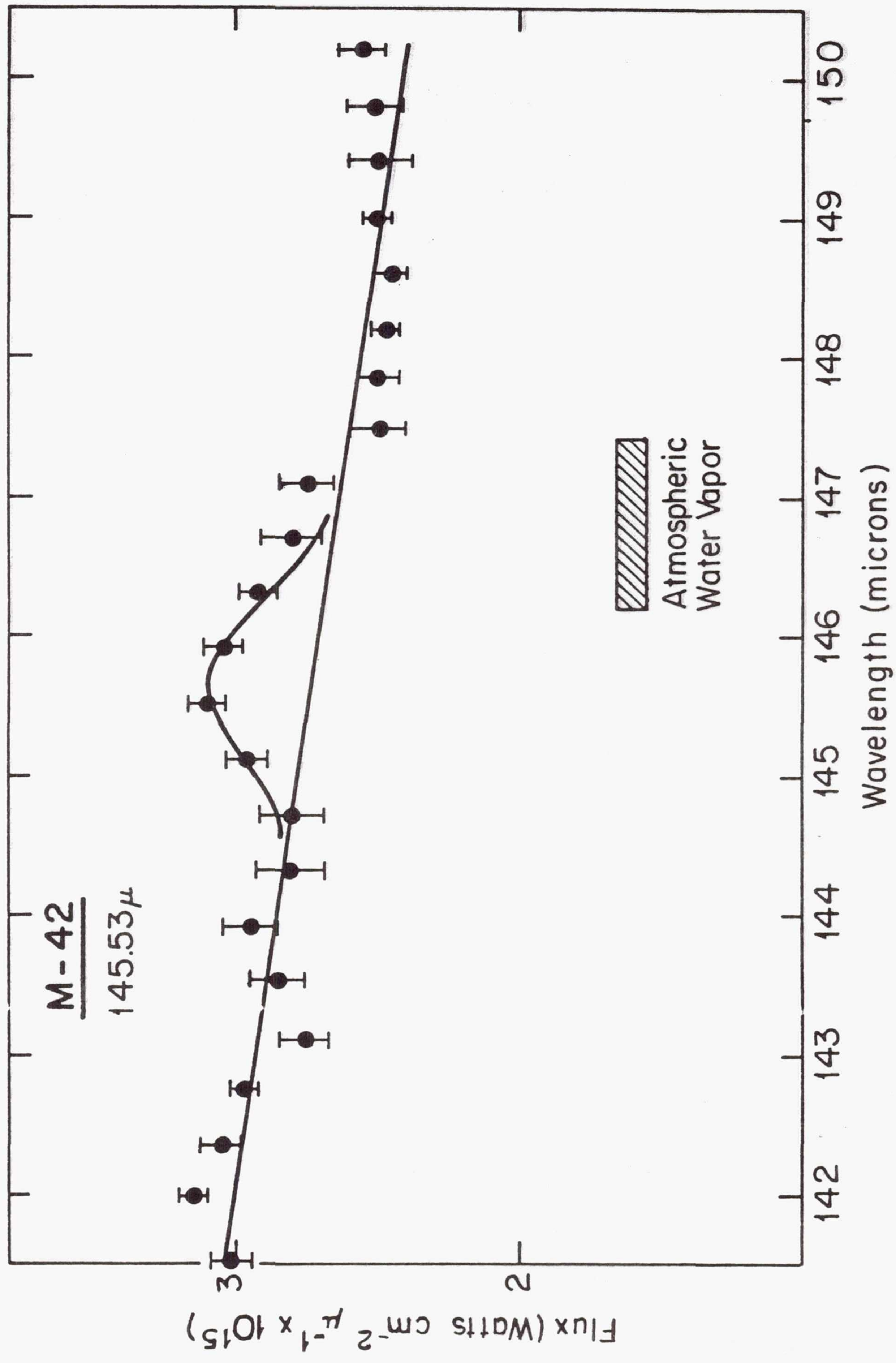
M-42
145.53μ
Atmospheric Water Vapor
Wavelength (microns)
142
143
144
145
146
147
148
149
150
Flux (Watts cm-2 μ-1 x 10 15)
3
2

Figure 1

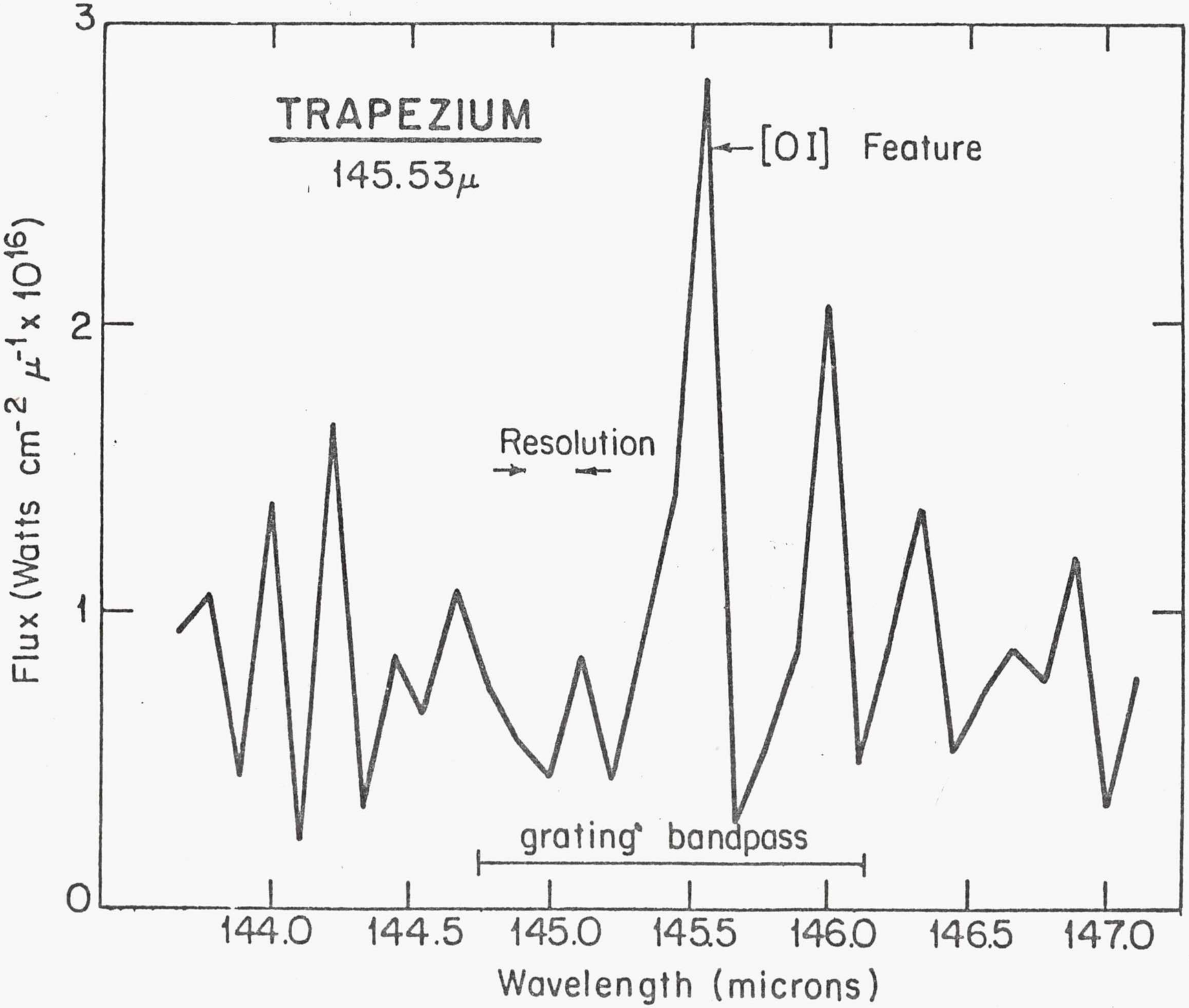
TRAPEZIUM
145.53μ
[OI] Feature
Resolution
grating bandpass
Flux (Watts cm-2 μ-1 x 1016)
Wavelength (microns)
0
1
2
3
144.0
144.5
145.0
145.5
146.0
146.5
147.0

Figure 2

1. Report No. NASA TM-84307	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle OBSERVATIONS OF THE 145.5 MICRON (OI) EMISSION LINE IN THE ORION NEBULA		5. Report Date November 1982 6. Performing Organization Code A-9155
7. Author(s) Gordon Stacey, Scott Smyers, Noel Kurtz and Martin Harwit		8. Performing Organization Report No. A-9155
9. Performing Organization Name and Address Center for Radiophysics and Space Research, Cornell University, Ithaca, New York		10. Work Unit No. 352-02-03 11. Contract or Grant No. NSG-2347 NGR 33-010-146
12. Sponsoring Agency Name and Address National Aeronautics and Space Administration Washington, D.C. 20546		13. Type of Report and Period Covered Technical Memorandum 14. Sponsoring Agency Code

15. Supplementary Notes

Preprint Series #2. Supported by NASA grants. Point of Contact: L. C. Haughney, Ames Research Center, Moffett Field, Calif. 94035, M/S 211-12, (415) 965-5339, FTS 488-5339

16. Abstract

We have obtained a first set of observations of the (OI) $^3P_0$ - $^3P_1$ (145.5 μ) transition. We observed the line both in a 1' × 1' beam centered on the Trapezium, and in a 7' × 7' beam encompassing most of the Orion Nebula. We also have constructed a wide beam (7' × 7') map of the region which shows that most of the emission is confined to the central regions of the nebula. These observations may be compared with reported measurement of the $^3P_1$ - $^3P_2$ (63.2 μ) transition in Orion and are consistent with optically thin emission in the 145.5 μ line and self-absorbed 63.2 μ emission lines. We discuss mechanisms for the excitation of neutral oxygen and conclude that much of the observed emission originates in the thin, radio-recombination-line-emitting CII/HI envelope bordering on the HII region.

17. Key Words (Suggested by Author(s))	18. Distribution Statement
Interstellar medium-shock cooling Fine structure transition Submillimeter astronomical spectroscopy	Unlimited STAR Category - 89

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

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