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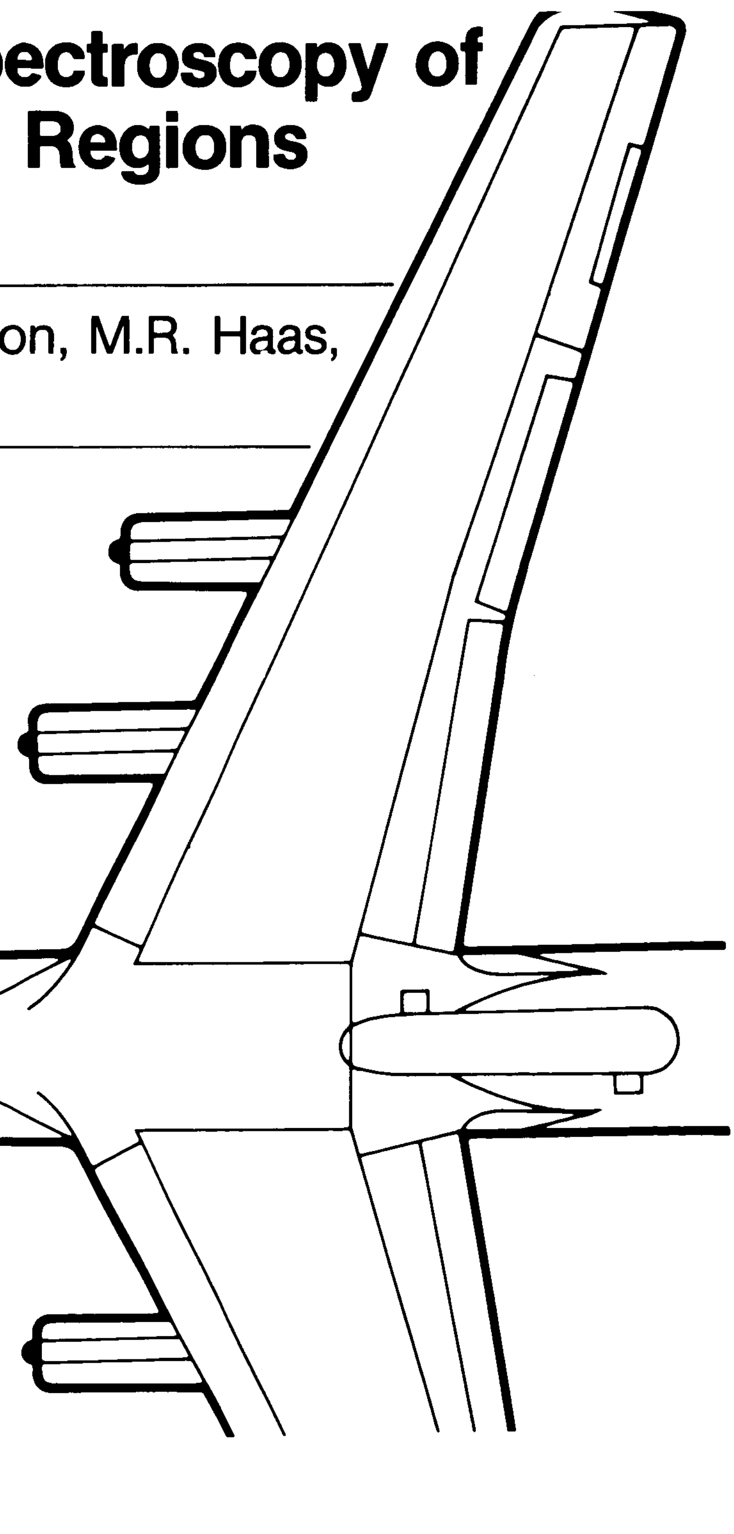
October 1986



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Space Administration

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# Far Infrared Spectroscopy of Star Formation Regions in M82

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## Abstract

Emission lines of [O III] at 52 μm and 88 μm and of [N III] at 57μm in the nucleus of the galaxy M82 have been observed from the Kuiper Airborne Observatory with the facility's cooled grating spectrometer. The [N III] line has not been previously detected in any extragalactic source. The fluxes in the lines indicate ~$4 \cdot 10^7$ M⊙ of ionized gas and a large population of massive stars (equivalent to $5 \cdot 10^5$ O8.5 stars), sufficient to power the infrared luminosity of the nucleus. We use the 52 to 88 μm line intensity ratio to find an average electron density of 210 ± 75 in the nucleus; this is 10 to 100 times lower than values typically observed in individual compact HII regions in our Galaxy. The relative line strengths of the [O III] and [N III] lines imply an $N^{++}/O^{++}$ ratio of .45 ± .1, significantly lower than is measured by the same method in individual HII regions at similar galactocentric distances (≲400 pc) in our Galaxy. This lower $N^{++}/O^{++}$ ratio may be due to a lower N/O ratio, higher stellar temperatures, or both, in M82. At spectral resolutions of ~90 km/s, all three line profiles are similarly asymmetric. They can be well fitted by two Gaussian distributions with widths of ~150 km/s and central velocities of ~110 and ~295 km/s, bracketing the systemic velocity of the nucleus of ~210 km/s. Within uncertainties, both the $N^{++}/O^{++}$ ratio and the electron density are the same for both Gaussian components; this indicates no major large-scale gradient in either quantity within the nucleus.

## I. Introduction

The nucleus of the irregular galaxy M82 is thought to be an active site of recent star formation. Models based on previous observations predict a greater proportion of early-type stars there than in our own Galaxy (Rieke et al. 1980; Kronberg, Biermann, and Schwab 1985). Since the far infrared [O III] and [N III] lines we have observed are emitted primarily in regions ionized by early-type stars, and since these lines suffer only minimal obscuration, their fluxes are a sensitive probe of the presence of early-type stars throughout the nucleus. In addition, the ratios of these line intensities allow the electron density and $N^{++}/O^{++}$ ratio in the interstellar medium of M82 to be determined and compared to those in our Galaxy.

Several previous measurements of M82 show similar, highly asymmetric line profiles. The CO 1→0 line measured with a 50" beam (Young and Scoville 1984), and the Hα (Heckathorn 1972) and [Ne II] 12.8 μm (Beck et al. 1978) lines in synthesized 1' beams all have widths of ~300 km/s (FWHM), mean velocities roughly equal to the systemic velocity of the galaxy (~210 km/s), and peak intensities at substantially lower velocities (~110 km/s). Previous far IR measurements of the 52 and 88 μm [O III] lines (Duffy et al. 1984; Watson et al. 1984; Lugten et al. 1985), the 158 μm [C II] line (Crawford et al. 1985), and the [O I] 63 μm line (Watson et al. 1984) may be consistent with the CO, Hα, and [Ne II] lines but have poorer signal-to-noise.

In section II, we present new measurements of the [O III] lines at higher spectral resolution and improved signal-to-noise which show similar profiles to the CO, Hα, and [Ne II] lines. We also report the first measurement in an extragalactic source of the [N III] line, which has a similar line profile. From these measurements we derive the electron density and $N^{++}/O^{++}$ ratio in the nucleus. In section III we discuss these results, estimate the number and temperature of the exciting stars in the nucleus, and discuss physical interpretations of the asymmetric [O III] and [N III] line shapes. Our conclusions are given in section IV.

## II. Observations and Results

M82 was observed with the facility cooled grating spectrometer (CGS) on the 91.4 cm telescope of NASA's Kuiper Airborne Observatory. The CGS has a liquid helium cooled echelle grating 45 cm in length which disperses light onto a detector array. For these observations, 6 discrete Ge:Ga photoconducting detectors were used to measure intensities at adjacent wavelengths. Different wavelengths are observed by changing the angle of the echelle. Resolving power $\lambda/\Delta\lambda$ varies from ~1700 to ~6000 depending on echelle order and aperture size. The CGS is described in detail by Erickson et al. (1984, 1985).

The 51.815 μm and 88.356 μm transitions of [O III] were observed on the night of 6 February 1985; the 57.330 μm [N III] line was measured 4 February 1985. The infrared beam was centered at $\alpha_{1950} = 9^h\ 51^m\ 42.8^s$; $\delta_{1950} = 69°54'59''$ using a nearby guide star. This position is nearly half way between the two 10 μm continuum peaks of Rieke et al. (1980). Estimated pointing error was ± 5 arcsec. The chopping secondary mirror was driven perpendicular to the major axis of the galaxy, with an amplitude of 4'. Our effective beam diameter of 48" included the roughly 30" by 15" region of ionized gas in the nucleus (Beck et al. 1978).

M82 was observed at spectral resolving powers of 2900 (88 μm), 2600 (57 μm), and 3300 (52 μm). At these resolving powers, the widths of the Doppler-broadened spectral lines exceed the total bandpass of the spectrometer's 6 detectors. Therefore, 3 or 4 different echelle positions were used to provide contiguous wavelength coverage over each line and its nearby continuum.

Raw spectra were corrected for absorption by atmospheric water vapor and instrument response by dividing them by calibration spectra of the Kleinmann-Low (KL) nebula taken the same night at the same or a nearby wavelength. The absolute flux calibration was then obtained by multiplying these ratios by the KL flux as measured by Erickson et al. (1981). The continuum of KL was observed at only one of the echelle positions at which each line in M82 was observed. Calibration spectra at the other (nearby) wavelengths were generated by correcting the measured KL spectrum for changes in the wavelength-dependence of the atmospheric transmission and the instrument response. The water vapor correction was calculated assuming 7 precipitable microns of water in the line of sight as inferred from fitting a narrow unresolved atmospheric water line measured on each flight with the CGS. Errors introduced by uncertainties in this correction are less than a few percent. The relative instrument response at different wavelengths was measured on the ground immediately after each flight using a blackbody calibration source. These corrections are 15% or less at 88 and 57 μm, but as large as a factor of 1.75 at 52 μm due to variations in the transmission of the instrument caused by interference effects in the CGS long-pass filter. Calculated diffraction losses are less than 10% and somewhat uncertain, so we did not correct for them. The final spectra are shown in figures 1 - 3.

Both [O III] lines and the [N III] line have asymmetric profiles which are qualitatively quite similar. To obtain flux estimates, we fitted each spectrum with a curve consisting of a constant continuum plus two superposed Gaussians. The free parameters in each fitted curve were the continuum flux density and the intensity, half-width and peak wavelength of each Gaussian. The fits are good for all three lines ($\chi^2$ per degree of freedom $\leq 1$) and are also shown in figures 1 - 3.

In table 1 we list velocities and fluxes for each line as a whole and separately for each Gaussian component in each line; we refer to the two components as A and B. Radial velocities were calculated from the centroid of each Gaussian, using rest wavelengths from Moorwood et al. (1980). Quoted velocity uncertainties are largely due to systematic uncertainties (estimated at ±25 km/s) in the wavelength calibration, which is based on laboratory observations of water lines and in-flight observations of the Trapezium. For the 57 μm line, the uncertainty in the rest wavelength is also significant (±17 km/s). These systematic uncertainties do not affect the velocity separation of components A and B, which is ~185 km/s in all three lines (table 1). Quoted uncertainties in the line component widths represent the statistical uncertainty in fitting the curves to the data.

Flux uncertainties in table 1 are statistical only; systematic uncertainties are estimated at an additional ± 20% of the fluxes. The ratio of fluxes in components A and B, which is relatively unaffected by systematic uncertainties, also does not differ significantly from line to line. Absolute line fluxes have been corrected for foreground extinction in M82 by extrapolating the value of $\tau$ = .30 at 33 μm (Houck et al. 1984) using a $1/\lambda$ wavelength dependence. These corrections are 21, 19, and 12% at 52, 57, and 88 μm respectively; the line flux ratios are thus not strongly affected by extinction corrections.

Our observed continuum flux densities are 20% to 40% greater than the broad-band photometric measurements of Telesco and Harper (1980), who used a 50" beam. Our 52 μm and 88 μm line fluxes differ by 15% and 35% respectively from our previous measurements made with a 37" beam (Duffy et al. 1984). These differences are all within estimated combined uncertainties. However, our 88 μm line flux is roughly half the value reported by Watson et al. (1984) with a 44" beam. This discrepancy is not understood.

The relative line strengths of the 52 μm and 88 μm lines can be used to determine the average electron density in the emitting gas ($O^{++}$ regions). We assume the transitions are excited by collisions with electrons and are optically thin. Using a 5-level model $O^{++}$ atom (Rubin 1984) with atomic constants from Mendoza (1983), we find $n_e$ = 210 ± 75 in the nucleus. Assuming that some of the systematic flux uncertainties (e.g. that due to error in the assumed flux of the calibration source) cancel when taking line flux ratios, we used the statistical plus half the systematic uncertainty as the total uncertainty when calculating the density. Since the spectra can no doubt be well fitted by mathematical functions other than the two Gaussians we have used, we do not claim that these Gaussians represent physical sources. However, because the relative flux in the two components is indistinguishable for the two [O III] lines, our spectra show no evidence for a large-scale gradient in electron density within the nucleus.

At the low density seen in M82, the [O III] line ratio is more density sensitive (Saraph and Seaton 1970) than the [S III] 33.4 μm/18.7 μm line ratio measured by Houck et al. (1984). They measured an average electron density in $S^{++}$ regions of $120^{+280}_{-120}$ $cm^{-3}$, which is lower than but consistent with our value. Their observations do not have sufficient spectral resolution to detect asymmetries in the line profiles.

We calculate $N^{++}/O^{++}$ abundance ratios from the relative strengths of the [N III] and two [O III] lines and the atomic models of Rubin (1984). We find a ratio of .45 ± .1 for the whole nucleus, again including estimated systematic errors as discussed above. Like the electron density, the $N^{++}/O^{++}$ ratio does not show large variations across the nucleus.

## III. Discussion

### 1. Properties of Exciting Stars

Models of M82 based on a wide range of observed properties indicate that it has a large population of early-type stars (Rieke et al. 1980; Kronberg, Biermann, and Schwab 1985). We use observed infrared line fluxes and H II region models to independently estimate the average effective temperature, number, and total bolometric luminosity of these stars.

The H II region models of Rubin (1985) show that the luminosity in the [O III] 52 μm line relative to that in Brα depends strongly on the effective temperature of the exciting stars but only weakly on the interstellar electron density or the number of ionizing photons. Using the observed Brα flux of the nucleus Willner et al. (1977) and our 52 μm line flux, Rubin's models imply a stellar temperature of 35500 ± 300 K (spectral type O8.5) for uniform density H II regions having O/H ratios within a factor of 2 of solar ($6.76 \cdot 10^{-4}$).

Our observed [O III] line luminosities and those predicted for model H II regions having this stellar temperature imply that the [O III] lines are excited by the equivalent of $5 \cdot 10^5$ O8.5 stars in the nucleus of M82. By comparison, Mezger (1982) estimates that O stars in the entire Milky Way produce $3 \cdot 10^{53}$ Lyman continuum photons per second, equivalent to only $2 \cdot 10^5$ O8.5 stars (Panagia 1973).

The early-type stars needed to produce the observed [O III] lines also account for the observed bolometric luminosity ($4 \cdot 10^{10}$ $L_\odot$; Telesco and Harper 1980) of the nucleus. At $5.4 \cdot 10^4$ $L_\odot$ each, the $5 \cdot 10^5$ O8.5 stars required to produce the [O III] lines have a total bolometric luminosity of

$2.5 \cdot 10^{10}$ L⊙, nearly the observed value. Most of this luminosity appears in the far IR because the short wavelength starlight is absorbed and reradiated by dust.

## 2. Electron Densities

The average electron density we measure in M82 (210 ± 75 $cm^{-3}$) is much less than densities measured in individual Galactic H II regions by the same method; those values are typically in the range 1,000 to 20,000 $cm^{-3}$ (Lester et al. 1983). However, the higher densities found in our Galaxy may result primarily from an observational selection effect. Radio observations (Mezger and Smith 1975; Smith, Biermann, and Mezger 1978) indicate that only 10 - 20% of the O stars in our Galaxy are surrounded by compact ($n_e$>~$10^3$ $cm^{-3}$) H II regions; the remaining 80 - 90% have "extended low density" (ELD) H II regions with typical densities of ~10 $cm^{-3}$ (Mezger 1978). The Galactic H II regions most often observed, those with high surface brightnesses and large densities, are thus atypical; large-beam observations of our Galaxy would measure a lower electron density than is seen in individual compact H II regions.

Houck et al. (1984) present a simple model of the interstellar medium in M82 which corrects for this selection effect and accounts for the observed electron density. They conclude that there is proportionately less high density ionized gas in M82. Our observed electron density for M82, which agrees with that of Houck et al., supports this conclusion. This lack of high density gas may be a result of the high supernova rate (0.2 per year) in M82 (Kronberg and Sramek 1985); winds from these supernovae may blow significant amounts of interstellar gas out of the nucleus of M82 and thus reduce the gas density (Chevalier and Clegg 1985; Wyse and Silk 1985).

## 3. Mass of Ionized Gas

Our measurement of the electron density in M82 allows us to improve the estimate of Willner et al. (1977) of the mass of ionized gas implied by their Brα line flux. To first order, the Brα flux per unit mass of ionized gas $L_{Br\alpha}/M_{HII}$ in H II regions is proportional to the interstellar electron density and independent of the effective temperature of the exciting star(s). For an average electron density of 210 $cm^{-3}$, Rubin's H II region models and the observed dereddened Brα luminosity ($8.5 \cdot 10^6$ L⊙; Willner et al.) give an ionized gas mass of $4 \cdot 10^7$ M⊙ in the inner 30" of M82. This is half Willner's value of $7 \cdot 10^7$ M⊙, which was obtained assuming a volume filling factor for ionized gas $f = (n_e^{ave}/n_e^{rms})^{1/2} = 1$.

## 4. N/O Ratio in M82

The average $N^{++}/O^{++}$ ratio (.45 ± .1) we measure in M82 can be compared to those obtained by the same method for individual Galactic H II regions by Dinerstein et al. 1984. They find values from 0.2 to 1.2 with a tendency to increase towards the Galactic center. Our $N^{++}/O^{++}$ ratio pertains to the central 400 pc of M82; the two measured H II regions within this distance from the center of our Galaxy, Sgr A and G0.5-.1, have higher

$N^{++}/O^{++}$ ratios ($0.7^{+.6}_{-.2}$ and 1.1 ± .2, respectively). These Galactic values would be even higher (by ~50%) if derived using the up to date Rubin model atom used here.

The lower $N^{++}/O^{++}$ ratio in M82 may reflect a lower N/O ratio. Low N/O in M82 is expected from the models of Rieke et al. (1980) and Kronberg, Biermann, and Schwab (1985) which indicate a large population of high-mass ($M/M_\odot > 20$), hot ($T > 35000$ K) stars and an extreme shortage of stars below 5 - 10 $M_\odot$. Numerous high-mass stars imply a large oxygen abundance, since supernovae from these stars are the principal source of oxygen in the interstellar medium (Weaver et al. 1978). Few lower-mass stars may additionally imply a lower nitrogen abundance, since the main source of this element is stars of 5 - 10 $M_\odot$ (Wyse and Silk 1985).

However, another effect can influence the observed $N^{++}/O^{++}$ ratio. The models of Rubin (1985) indicate that although O and N are both almost completely doubly-ionized in H II regions excited by very hot stars, a larger fraction of N than of O is doubly-ionized by cooler stars (figure 4). This means that the $N^{++}/O^{++}$ ratio approaches the actual N/O ratio in H II regions excited by hot stars, but is significantly greater in lower-excitation regions. The size of this effect is largely independent of density and clumping of the ionized gas, and depends weakly on the interstellar O/H ratio (figure 4). Thus the lower $N^{++}/O^{++}$ ratio in M82, while suggestive of a lower N/O ratio, may instead be completely due to a predominance of stars hotter than those exciting Sgr A or G0.5-.1.

Because $N^{++}/O^{++}$ ratios depend very strongly on stellar temperature, and because these temperatures are not well known in either M82 or the Galactic center, our $N^{++}/O^{++}$ ratios and those of Dinerstein et al. are only upper limits to the corresponding N/O ratios. These limits are consistent with each other and with the N/O ratio of 0.2 found for the Orion region from models based on IR line measurements (Simpson et al. 1986).

## 5. Sources of Line Emission in M82

It is clear from the measured line profiles that neither $O^{++}$ nor $N^{++}$ emission is uniformly distributed throughout the nucleus. Two possible explanations are (1) the stars which ionize this gas (those having effective temperatures above ~30000 K) may be nonuniformly distributed, for example in a ring in the galactic plane (which we see edge-on) or (2) the gas and dust densities are nonuniform and peak away from the center of the nucleus, perhaps because of strong stellar winds flowing out from the center. Either possibility can account for the two maxima in the 10 μm emission (Rieke et al. 1980) by producing two maxima in the temperature or the column density, respectively, of the emitting dust. The location of the 10μm peaks and the Beck et al. (1978) rotation curve give velocities for these peaks of 130 and 250 km/s, which would be consistent with those of the Gaussians fitted to the [O III] and [N III] lines (about 110 and 295 km/s) if the coordinate scale of the 10 μm map were shifted 1 - 2" relative to that of the rotation curve. This agreement suggests that the two components fitted to the observed line profiles could correspond to the two 10 μm emission peaks.

## IV. Conclusions

1) Fluxes in the [O III] 52 and 88 μm lines indicate excitation of the interstellar medium in the nucleus of M82 by the equivalent of $5 \cdot 10^5$ 08.5 stars. The bolometric luminosity of these stars roughly equals that of the nucleus, suggesting that they are its primary energy source. This is consistent with the picture of M82 as an active site of recent star formation.

2) The electron density of 210 $cm^{-3}$ derived from the 52 to 88 μm line ratio is consistent with the value obtained by Houck et al. (1984) from lower resolution measurements of the [SIII] 33.4 and 18.7 μm lines. These densities are much lower than those measured by the same method in individual H II regions in our Galaxy. We support the conclusion of Houck et al. that there is proportionately less high-density gas in M82 than in our Galaxy.

3) Our determination of the electron density in M82 allows us to recalculate the mass of ionized gas in the nucleus implied by the Brα flux of Willner et al. (1977). We find $4 \cdot 10^7$ M☉ of ionized gas, roughly half Willner's estimate.

4) The $N^{++}/O^{++}$ ratio derived for the nuclear gas from our ionized line fluxes is less than those derived in the same way for two H II regions at comparable galactocentric radii in our Galaxy. This may result from (1) a lower N/O ratio in M82, possibly due to an overabundance of oxygen caused by frequent supernovae and/or an underabundance of nitrogen due to a lack of

low mass stars, (2) a higher average stellar temperature in M82 than in the Galactic H II regions, or some combination of (1) and (2). Either mechanism points to the nucleus of M82 as an active site of massive star formation.

5) Both [O III] lines and the [N III] line have asymmetric profiles which are indistiguishable within the uncertainties. Our data thus show no evidence for large-scale variations in the $N^{++}/O^{++}$ ratio or electron density within the nucleus.

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Table 1: Line Flux Measurements and Velocities in M82

| Species | Rest Wavelength (microns) | | $V_{LSR}$ (km/s) | FWHM (km/s) | Flux ($10^{-18}$ W/cm²) |
|---|---|---|---|---|---|
| [O III] | 51.815 | A | 81 ± 25 | 120 ± 30 | 6.3 ± 0.4 |
| | | B | 272 ± 25 | 141 ± 25 | 3.9 ± 0.4 |
| | | Total Flux | --- | --- | 10.4 ± 0.6 |
| | | Velocity Difference | 191 | --- | --- |
| [N III] | 57.330 | A | 126 ± 30 | 190 ± 20 | 3.0 ± 0.2 |
| | | B | 314 ± 30 | 135 ± 20 | 1.3 ± 0.2 |
| | | Total Flux | --- | --- | 4.3 ± 0.3 |
| | | Velocity Difference | 188 | --- | --- |
| [O III] | 88.356 | A | 122 ± 25 | 150 ± 10 | 5.8 ± 0.2 |
| | | B | 299 ± 25 | 150 ± 10 | 3.4 ± 0.3 |
| | | Total Flux | --- | --- | 9.2 ± 0.3 |
| | | Velocity Difference | 177 | --- | --- |

Figure Captions

Figure 1: Observed line profile of the 51.815 μm $^3P_2 \rightarrow ^3P_1$ transition of [O III] in the nucleus of M82. Data were taken 6 February 1985 with a 48" beam in three observations totalling 36 minutes. The horizontal axis shows velocity with respect to the Local Standard of Rest. Error bars represent ± 1 standard deviation of the mean. The solid line is a two-Gaussian fit to the data.

Figure 2: The 57.330 μm $^2P_{3/2} \rightarrow ^2P_{1/2}$ transition of [N III] measured in 4 observations totalling 31 minutes on the night of 4 February 1985. The solid line is again a two-Gaussian fit to the data.

Figure 3: The 88.356 μm $^3P_1 \rightarrow ^3P_0$ transition of [O III] observed for a total of 10 minutes on 6 February 1985. The solid line is again a two-Gaussian fit to the data.

Figure 4 (bottom): Plot of $N^{++}/O^{++}$ ionic abundance ratio divided by overall N/O ratio in model H II regions as a function of effective temperature of exciting star, as calculated by Rubin (1985). The different curves are for different interstellar O/H ratios (labelled). The top plot shows the dependence of $N^{++}/O^{++} \div N/O$ on the O/H ratio for several temperatures.

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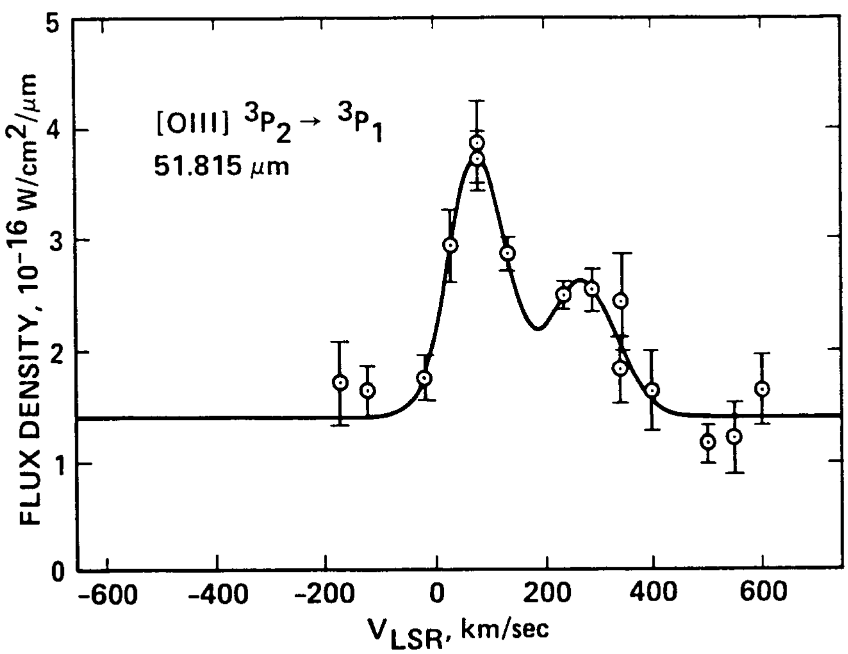

[OIII] $^3P_2 \rightarrow {}^3P_1$
51.815 μm
FLUX DENSITY, $10^{-16}$ W/cm$^2$/μm
$V_{LSR}$, km/sec
0
1
2
3
4
5
-600
-400
-200
0
200
400
600

figure 1

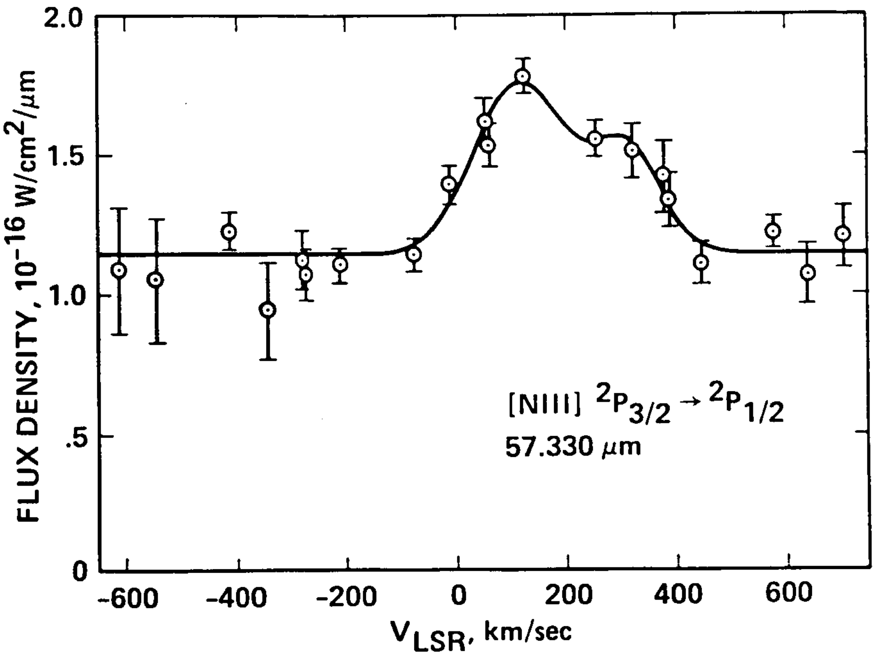

2.0
1.5
1.0
.5
0
FLUX DENSITY, 10⁻¹⁶ W/cm²/μm
-600
-400
-200
0
200
400
600
V_LSR, km/sec
[NIII] ²P3/2 → ²P1/2
57.330 μm

figure 2

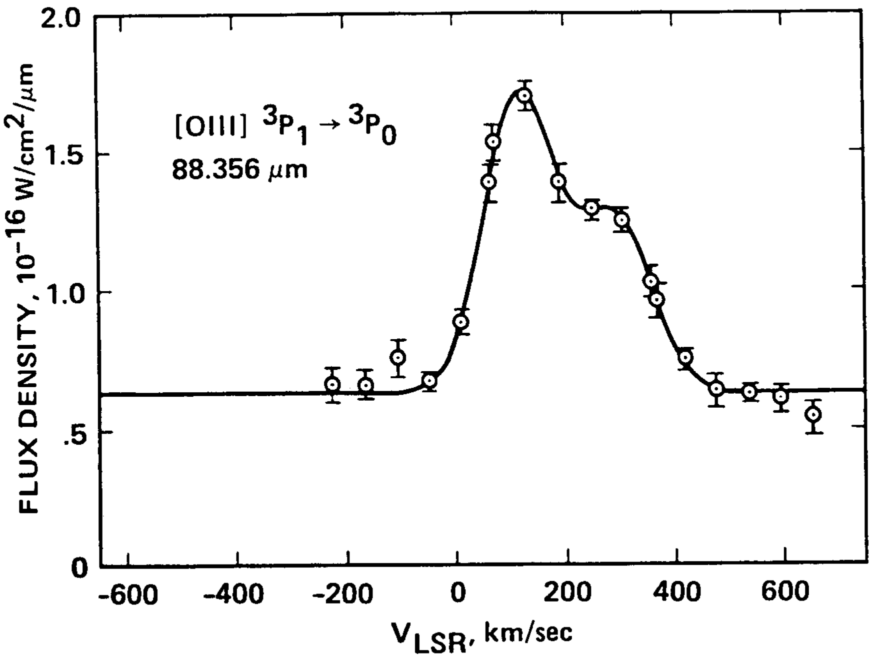
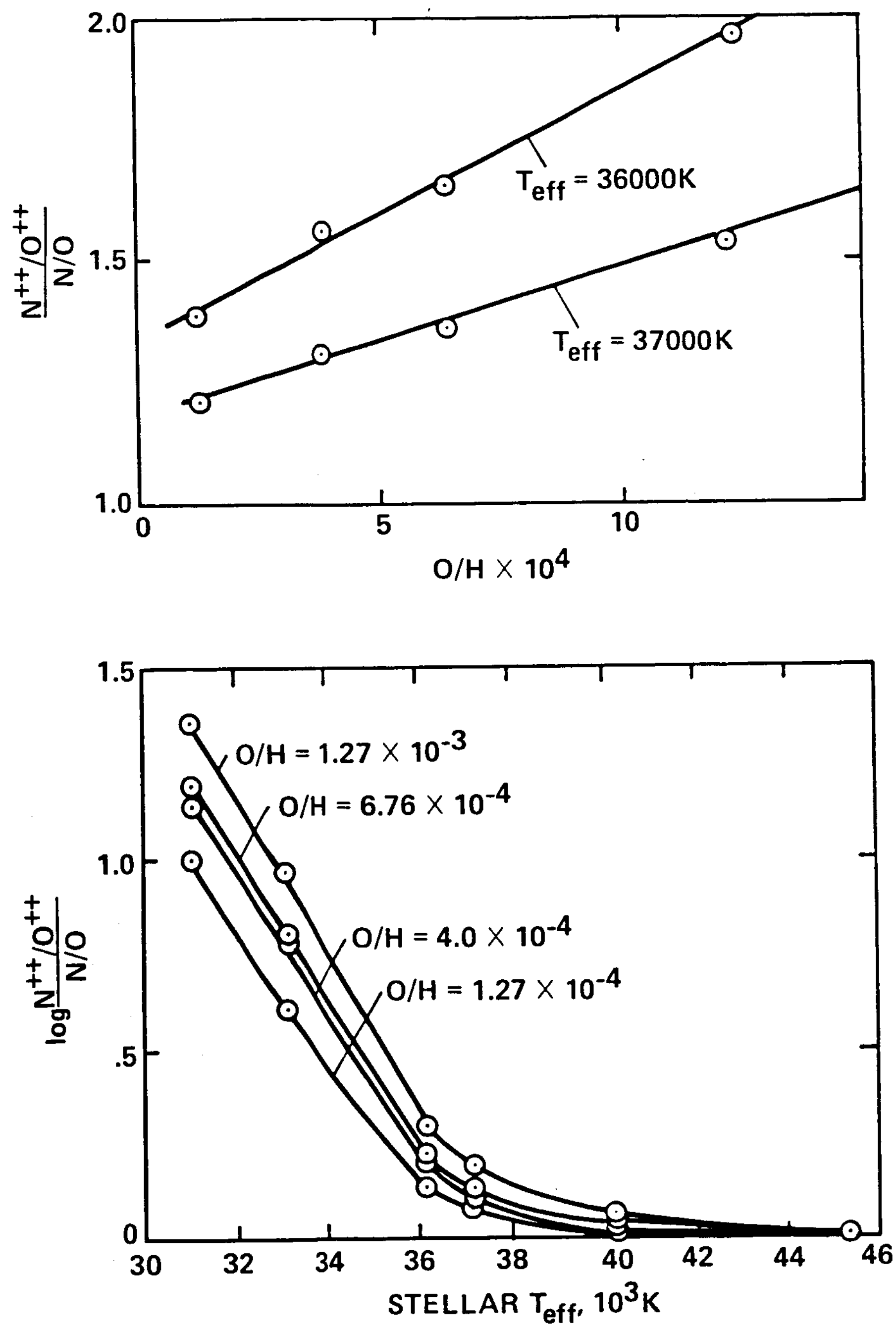

FLUX DENSITY, 10⁻¹⁶ W/cm²/μm
[OIII] ³P₁ → ³P₀
88.356 μm
2.0
1.5
1.0
.5
0
-600
-400
-200
0
200
400
600
V_LSR, km/sec

figure 3



2.0
1.5
1.0
0
5
10
$\frac{N^{++}/O^{++}}{N/O}$
O/H × 10^4
T_eff = 36000K
T_eff = 37000K
1.5
1.0
.5
0
30
32
34
36
38
40
42
44
46
$\log \frac{N^{++}/O^{++}}{N/O}$
STELLAR T_eff, 10^3K
O/H = 1.27 × 10^-3
O/H = 6.76 × 10^-4
O/H = 4.0 × 10^-4
O/H = 1.27 × 10^-4


figure 4

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**16. Abstract**

Emission lines of [O III] at 52 μm and 88 μm and of [N III] at 57 μm in the nucleus of the galaxy M82 have been observed from the Kuiper Airborne Observatory with the facility's cooled grating spectrometer. The [N III] line has not been previously detected in any extragalactic source. The fluxes in the lines indicate $\sim 4 \cdot 10^7$ M of ionized gas and a large population of massive stars (equivalent to $5 \cdot 10^5$ O8.5 stars), sufficient to power the infrared luminosity of the nucleus. We use the 52 to 88 μm line intensity ratio to find an average electron density of 210 ±75 in the nucleus; this is 10 to 100 times lower than values typically observed in individual compact HII regions in our Galaxy. The relative line strengths of the [O III] and [N III] lines imply an $N^{++}/O^{++}$ ratio of 0.45 ±0.1, significantly lower than is measured by the same method in individual HII regions at similar galactocentric distances ($\lesssim$400 pc) in our Galaxy. This lower $N^{++}/O^{++}$ ratio may be due to a lower N/O ratio, higher stellar temperatures, or both, in M82. At spectral resolutions of ~90 km/s, all three line profiles are similarly asymmetric. They can be well fitted by two Gaussian distributions with widths of ~150 km/s and central velocities of ~110 and ~295 km/s, bracketing the systemic velocity of the nucleus of ~210 km/s. Within uncertainties, both the $N^{++}/O^{++}$ ratio and the electron density are the same for both Gaussian components; this indicates no major large-scale gradient in either quantity within the nucleus.

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