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THE ELECTRON DENSITY IN M82 FROM THE S III MID-INFRARED LINE RATIO

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ABSTRACT

Strong detections have been made of both the 18.7 μm and 33.4 μm lines of S III in the irregular galaxy M82. This represents the first detection of the 33.4 μm line in an extragalactic object. These measurements sample the ionized gas component which dominates the observed infrared forbidden line and infrared hydrogen recombination line emission. From the ratio of the line fluxes an electron density of 120 (+280, − 120) cm^{-3} is deduced. This result is in agreement with previous estimates of the density derived from high-frequency radio continuum measurements and an assumed emitting volume. They impose further constraints on possible starburst models.

Subject headings: galaxies: individual — infrared: spectra

I. INTRODUCTION

Infrared and radio measurements of M82 have revealed large amounts of heavily obscured ionized gas in M82 which is not seen optically (Willner *et al.* 1977; Beck *et al.* 1978; Simon, Simon, and Joyce 1979; Rodriguez and Chaisson 1980). This *Letter* reports the strong ($> 7\ \sigma$) detection of the [S III] 33.47 μm line, the first such detection in an extragalactic object, and a complementary measurement of the [S III] 18.71 μm line in the well-studied irregular galaxy M82. These observations sample the optically invisible ionized gas and provide a means of directly estimating the average electron density.

In the past, optical doublets such as [O II] λ3729/λ3726 and [S II] λ6717/λ6731 were the only direct means of measuring electron densities in H II regions (cf. Osterbrock 1974, and references therein). Although the ratio of the intensities of these lines is relatively insensitive to temperature fluctuations and extinction variations, the absolute intensities are quite temperature and extinction dependent. As a result, optical measurements of the electron density are weighted toward regions along the line of sight of higher temperature and lower extinction. In addition, heavily obscured H II regions cannot be studied at all using these ratios. Recently, however, Herter *et al.* (1982*a*, *b*) have used the 18.71 μm and 33.47 μm line pair of S III for determining densities in a number of galactic H II regions. These lines have the advantage over optical lines of little intrinsic temperature dependence in line strengths and less sensitivity to the effects of extinction.

II. OBSERVATIONS

The observations reported here were made using the 91 cm telescope of the Kuiper Airborne Observatory (KAO). Flight altitude was in excess of 12.5 km with 10 μm or less of precipitable water vapor in the line of sight for both the sources and calibrators. A dual-grating, liquid-helium-cooled spectrometer (Houck and Gull 1982), containing a three-element Si:Sb detector array and a three-element Ge:Be detector array was used for the 18.7 μm and 33.4 μm measurements, respectively. The two grating-detector combinations were used on a single flight in 1984 January 19–20. The in-flight NEP per detector was 3×10^{-14} W $\mathrm{Hz}^{-1/2}$ for the Si:Sb system and 5×10^{-14} W $\mathrm{Hz}^{-1/2}$ for the Ge:Be system. The resolution of the spectrometer (FWHM) is approximately 0.03 μm at 18.7 μm and 0.06 μm at 33.4 μm. The beam size was approximately 25″ in diameter on the sky. A chopper throw of 2′ roughly perpendicular to the long axis of the optical image was used. The Moon and α Ori were used as calibrators with the Moon being the primary one. The overall flux calibration is estimated to be accurate to ±15%. Spectra taken at 18.71 μm and 33.47 and 33.47 μm are shown in Figure 1, and the line fluxes are given in Table 1. The 18.71 μm line flux is in agreement with that measured by Houck, Forrest, and McCarthy (1980).

The observing position was centered approximately midway between the strongest 10 μm peak which is roughly coincident with the 6 cm nonthermal peak and a somewhat weaker 10 μm peak ~ 15″ to the east. The signal was maximized by measuring several locations along the long axis of the galaxy. Pointing accuracy is better than 5″.

In order to use the observed line ratio to estimate electron density, the fluxes must be corrected for extinction along the line of sight. Since a large fraction of the ionized gas in M82 is not seen optically but only in the radio and infrared (cf. Willner *et al.* 1977), extinction estimates based on visual measurements are inappropriate for correcting the [S III] line fluxes. Although not optimum because of beam size and wavelength differences, the Brackett line ratio Brα/Brγ observed by Simon, Simon, and Joyce (1979) with an 11″ beam at a position included within our beam area is used. The deduced visual extinction was $A_v = 14 \pm 5$ mag assuming $A_v = 20E_{(\gamma-\alpha)}$. Using their observed line ratio, the intrinsic line ratio of 2.83 for 10,000 K (Brocklehurst 1971; Giles 1977), $\tau_{\mathrm{Br}\alpha}/\tau_{\mathrm{Br}\gamma} = 0.53$, and $\tau_{18.7} = 1.13\tau_{\mathrm{Br}\alpha}$ (Herter *et al.* 1981), we find $\tau_{18.7} = 0.8 \pm 0.3$. The corresponding extinction at 33.47 μm is given by $\tau_{33.47} = 0.35\tau_{18.7} = 0.3 \pm 0.1$. These reddening corrections have been used in Table 1 to derive the dereddened line flux. On this basis we find a line ratio $F_{33.5}/F_{18.7} =$

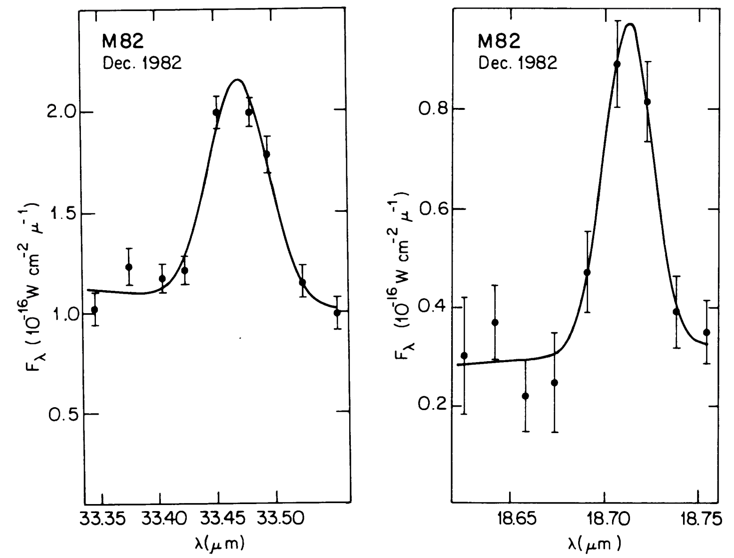

FIG. 1.—Spectra of M82 centered approximately midway between the strongest 10 μm peak which is roughly coincident with the 6 cm nonthermal peak and the somewhat weaker 10 μm peak ~ 15″ to the east. The beam size was 25″. The resolutions at the [S III] 33.47 μm and 18.71 μm lines were approximately 0.06 μm and 0.03 μm, respectively.

TABLE 1

S III LINE FLUXES IN M82

λ (μm)	Transition	Observed Line Flux (W cm^{-2})	Dereddened Flux (W cm^{-2})
18.71	$^3P_1$–$^3P_2$	$4.26 \pm 0.5 \times 10^{-18}$	$9.50 \pm 3.1 \times 10^{-18}$
33.47	$^3P_0$–$^3P_1$	$1.16 \pm 0.16 \times 10^{-17}$	$1.57 \pm .19 \times 10^{-17}$

1.65 ± 0.6. The error in this ratio due to the uncertainty of the extrapolation of the extinction curve from Brackett-α to longer wavelengths is difficult to estimate. Because only the relative difference between 18.7 and 33.5 μm is important, this error is probably negligible compared to the error in the derived extinction due to the uncertainty in the measured Brackett lines.

III. ELECTRON DENSITY

The ratio of the 33.47 μm line flux to the 18.71 μm line flux is sensitive to changes in the electron density for $100 \le n_e \le 10^4$ cm^{-3}. This dependence is shown in Figure 2. The curves were derived using the transition probabilities and collision strengths tabulated by Mendoza (1983). The dereddened line flux ratio yields an electron density of 120 (+500, − 120) cm^{-3} for an assumed electron temperature of 7500 K.

Willner *et al.* (1977) derive an rms electron density of 30 cm^{-3} on the basis of their Brα line flux measurement. Rodriguez and Chaisson (1980) find an rms density of 60 cm^{-3} in an analysis of the thermal component of the radio continuum emission. These latter authors estimate the density by comparing the observed hydrogen recombination line emission over a number of frequencies with a detailed model fit. They find an electron density of 300 cm^{-3} best fits the data, indicating a filling factor of 0.04.

Within the combined errors our average density estimate is in agreement with all of the above results. Because the rms and average densities are in close agreement, limits can be set on the degree of clumping within the ionized gas. This will be discussed in more detail below. Two effects combine to increase the uncertainty in the S III result. First, the large uncertainty in the extinction results in a substantial uncertainty in the dereddened line ratio and hence the electron density estimate. Second, the maximum sensitivity of the [S III] 33.47 μm–18.71 μm line pair is at ~ 1000 cm^{-3} (see Fig. 2). The sensitivity of this line ratio to changes in the electron density diminishes considerably at densities of 100 cm^{-3} and below. A more sensitive indicator of the density in the low-density regime is the [O III] 88.4 μm–51.8 μm line pair. This pair has its peak sensitivity at $n_e \approx 200$ cm^{-3}. [O III] line measurements have been made recently (Duffy, Haas, and Erickson 1984).

The preceding estimate of the electron density from the [S III] 33.47 to 18.71 μm line ratio is based on a simple model

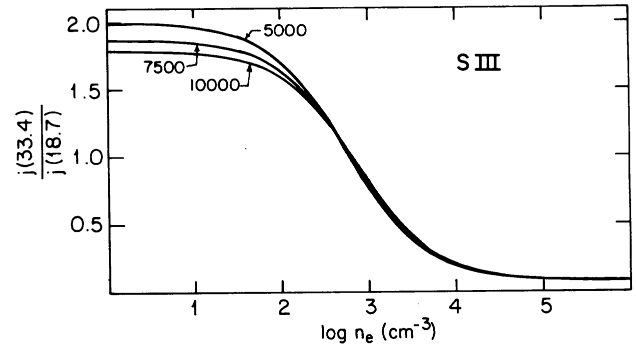

FIG. 2.—Predicted [S III] 33.47 μm to 18.71 μm ratio vs. density. The labeled curves are for different assumed electron temperatures (K). The atomic parameters used in the computations are taken from the compilation of Mendoza (1983).

1984ApJ...287L..11H

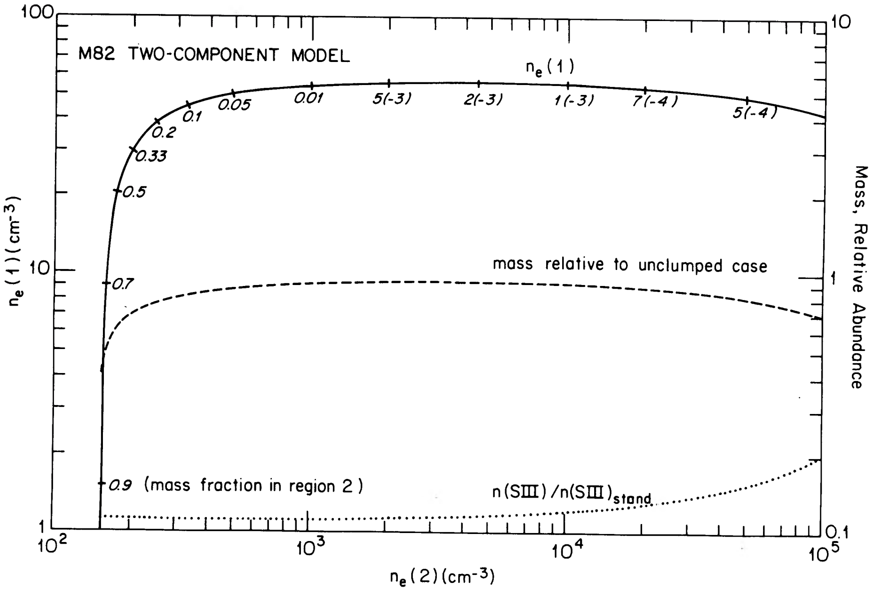

FIG. 3.—Acceptable range of densities for a two-component model which fit the observed line ratio of 1.6 and an rms density of 60 cm^{-3} (*solid line*). The mass fraction occupied by the high-density component is also indicated along the curve. The dashed line represents the total mass of the ionized gas relative to that expected if no clumping occurs. The dotted line is the estimated S III abundance relative to standard (S/H = 1.6 × 10^{-5}).

which assumes the observed emission originates from clumps of uniform density gas contained within a vacuum. In reality, however, there is likely to be a distribution of densities contributing to the observed line and radio emissions. Some insight into the nature of the emission region may be gained by a simple multiple component model, that is, a model in which only several density components are considered. The simplest of these would be a two-component model consisting of higher density clumps surrounded by lower density material.

This two-component model must produce the observed line ratio as well as the rms density derived from hydrogen recombination observations. Even in this simple case, however, the densities of the two components are not uniquely determined. Figure 3 shows the allowed range of densities for the two components which reproduces the observed [S III] 33.47 to 18.71 μm line ratio of 1.6 and the rms density of 60 cm^{-3}. The low- and high-density components are taken to be regions 1 and 2, respectively. Note that as the density of the low-density region goes to zero, the density of the high-density component is a minimum and as expected achieves the same value found using the simple filling factor arguments in the previous section. Marked along the curve is the fraction of the mass of the gas occupied by the high-density component. The total mass of the gas is only a weak function of the actual density and is given also in Figure 3 relative to the amount expected for an unclumped gas.

Our current measurement shows that probably less than 1% of the ionized gas is at densities of 1000 cm^{-3} or greater. The absence of significant high-density ionized gas places restrictions on the range of possible starburst models, by limiting the rate at which star formation has occurred in the recent past. The absence of a high-density component implies that the low-density line emissivity coefficients usually used in making abundance estimates for M82 are indeed appropriate (Willner *et al.* 1977; Houck, Forrest, and McCarthy 1980).

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