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DETECTION OF FAR-INFRARED [O I] AND [O III] EMISSION FROM THE GALAXY M82

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ABSTRACT

The fine-structure lines [O I] 63.2 μm and [O III] 88.4 μm have been detected in a 44″ beam toward the nucleus of the galaxy M82. Each line has a total flux of 2×10^{-17} W cm^{-2}. The [O III] 88.4 μm line is centered at $v_{LSR} = +220$ km s^{-1} and is about 300 km s^{-1} wide (FWHM), consistent with the systemic velocity and rotational broadening seen in other ionic lines in the nucleus of M82. A fractional O^{++} abundance of $O^{++}/O = 0.20$ is derived for the H II regions in the nucleus, indicating that the ionization state is similar to that found in H II regions in the disk of our own Galaxy. Unlike the far-infrared [O III] line, the [O I] 63.2 μm line is centered at $v_{LSR} = +130$ km s^{-1} and is significantly narrower than the instrumental resolution of 180 km s^{-1}. The velocities of the [O I] line and the large density required for the line's excitation seem to rule out association of this emission with the periphery of the central H II region, as would be the conventional interpretation of [O I] 63.2 μm emission. It appears more likely that the far-infrared [O I] line arises in a compact object situated away from the center of M82, or in the dusty intergalactic cloud through which M82 is drifting.

Subject headings: galaxies: nuclei — infrared: spectra — nebulae: H II regions

Dedication.—This work is dedicated to the late George Seiji, machinist and toolmaker at the University of California. The success of the UC Berkeley tandem Fabry-Perot spectrometer is in large part due to the skill with which George carried out its construction. We were deeply saddened by George's untimely death in 1981 June.

I. INTRODUCTION

By virtue of its proximity to Earth and its unusual appearance, the galaxy M82 (NGC 3034) has been studied in great detail for the past three decades. Explosive activity in the nucleus has been postulated to account for the unusual properties of M82 (Lynds and Sandage 1963; Burbidge, Burbidge, and Rubin 1964); however, it currently appears more likely that a burst of massive star formation in its central region (see Rieke *et al.* 1980) and perhaps its interaction with surrounding intergalactic matter (Elvius 1972; Solinger, Morrison, and Markert 1977; Beck *et al.* 1978) are responsible for it's present condition. Indeed, it is apparent from the discrepancy between the color and spectral type of M82 that this galaxy is immersed in a cloud of dust (Morgan and Mayall 1959); this matter is presumed to be part of a "streamer" of neutral material which reaches from M82 all the way to the large spiral galaxy M81, 36′ south of M82 (Roberts 1972; Gottesman and Weliachew 1977), a projected distance of 34 kpc (assuming a distance of 3.25 Mpc to the M81–M82 system; Sandage and Tammann 1975). The nucleus of M82 is masked further by dust within the galaxy. Infrared observations, which suffer very little extinction, are therefore valuable in the study of M82.

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In this *Letter* we report observations in M82 of the lowest lying transitions of neutral and doubly ionized oxygen, [O I] $^3P_1 \rightarrow {}^3P_2$ ($\lambda = 63.2$ μm) and [O III] $^3P_1 \rightarrow {}^3P_0$ ($\lambda = 88.4$ μm), which have wavelengths at which the extinction toward M82 is negligible. Since O^{++} has a fairly high excitation potential (35.1 eV), the [O III] 88.4 μm line traces gas ionized by radiation of relatively high effective temperature. On the other hand, neutral oxygen has an ionization potential nearly identical to that of hydrogen (13.6 eV); thus the [O I] 63.2 μm line is strongest in warm, neutral atomic matter, such as one would find adjacent to H II regions or in shocked neutral atomic gas (Hill and Hollenbach 1978; Shull and McKee 1979). In our own Galaxy, these lines are now well known. The present results represent the first detection of these spectral lines in an extragalactic object.

II. OBSERVATIONS, INSTRUMENT PERFORMANCE, AND CALIBRATION

The instrument used in these observations was the tandem Fabry-Perot spectrometer described by Storey, Watson, and Townes (1980). At 88 μm, the spectrometer's velocity resolution was 125 km s^{-1} (FWHM), while at 63 μm a resolution of 180 km s^{-1} (FWHM) was chosen. The instrumental profile is a Lorentzian. The system noise-equivalent power (NEP) values were 3×10^{-14} W Hz$^{-1/2}$ and 8×10^{-14} W Hz$^{-1/2}$, respectively, at 88 μm and 63 μm, including all spectrometer, telescope, and atmospheric losses. The measurements were carried out in 1982 February with the 91.4 cm telescope of the NASA Kuiper Airborne Observatory. At the observing altitude of 12.5 km, the water vapor column density along the line of sight was typically 15 precipitable microns. The system field of view was 44″ in diameter (FWHM), and the telescope's oscillating secondary mirror was used to provide a 5′, 29 Hz, nearly east-west chop. The standard practice of "nodding" the telescope was used to cancel background emission from the optical path.

Line fluxes in M82 were derived from the observed line-to-continuum ratio and continuum flux densities for the nucleus of M82 of 1150 Jy at 88 μm and 1220 Jy at 63 μm (Telesco and Harper 1980). The absolute accuracy of the resulting [O III] and [O I] line fluxes is estimated to be $\pm 30\%$. The velocity scale was determined by observing fringes of 0.6328 μm He-Ne laser light reflected from the scanning Fabry-Perot interferometer. Wavelength reference points were provided by an H_2O line at 63.324 μm and a D_2O line at 88.526 μm, measured periodically during the observations using the spectrometer's internal gas cell. The rest wavelength of [O III] 88.4 μm line was taken to be 88.355 ± 0.008 μm (Moorwood *et al.* 1980). For the [O I] line, the rest wavelength was taken as 63.18372 ± 0.00003 μm (Evenson 1982).[4]

III. [O III] AND THE EXCITATION OF IONIZED GAS IN M82

Figure 1 shows a profile of the [O III] 88.4 μm line, observed with the beam centered on the nucleus of M82 (1950.0 coordinates: $\alpha = 9^h51^m43^s.9$, $\delta = +69°55'01''$; Rieke *et al.* 1980). Spectra taken at positions 25″ NE and SW of the nucleus indicate that the spectrum in Figure 1 represents the peak of the [O III] distribution, and that the entire H II complex in the nucleus (the dimensions of which are approximately $30'' \times 10''$; Rieke *et al.* 1980) was within our 44″ beam. The velocity of the line center with respect to the local standard of rest ($v_{LSR} = +220$ km s^{-1}), the intrinsic line width (about 300 km s^{-1}, FWHM), and the asymmetry of the profile are all consistent with the intensity distribution and rotation curve seen in [Ne II] 12.8 μm (Beck *et al.* 1978); the large [O III] line width is presumably due to rotational broadening. The [O III] profile also bears a strong resemblance to the CO $J = 1 \rightarrow 0$ profile (Stark 1981). A value for the total [O III] 88.4 μm flux of $(2.0 \pm 0.6) \times 10^{-17}$ W cm^{-2} is obtained from the spectrum shown in Figure 1.

In the following, we use the [O III] 88.4 μm observation to derive the average extinction toward the nuclear H II complex, and the fraction of the oxygen that is present in doubly ionized form. The relatively low electron density of 75 cm^{-3} inferred from H I Brα 4.05 μm observations (Simon, Simon, and Joyce 1979) indicates that the low-density limit is appropriate for all of the lines which are considered here. Under these conditions, the power per unit area, I, in an optically thin, collisionally excited line is

$$I = \frac{hc}{4\pi\lambda}\gamma e^{-\tau_\lambda}\int n_{x^{+i}} n_e \, dl \, d\Omega, \qquad (1)$$

where γ is the collisional excitation rate coefficient, τ_λ is the dust optical depth at wavelength λ, and $n_{x^{+i}}$ and n_e are, respectively, the number densities of the species x^{+i} and electrons, with the integration carried out over the line of sight, l, and the solid angle of the object, Ω. A similar expression may be written for the flux emitted in a recombination line, with γ replaced by the effective recombination rate coefficient α_{eff}. The extinction at $\lambda = 0.5007$ μm may be computed using equation (1) for both the [O III] 88.4 μm and [O III] 0.5007 μm lines and recognizing that the extinction at 88 μm is negligible. The [O III] 0.5007 μm line has been observed with a 10″ beam centered 3″ NE of the nucleus of M82 by Peimbert and Spinrad (1970); the reported flux is 2.4×10^{-19} W cm^{-2}. For comparison to the larger beam far-infrared observations, the optical line flux should be scaled up by a factor between 1 and 3, the higher scale factor corresponding to a [O III] 0.5007 μm distribution similar to the relatively unextinguished H I Brα or [Ne II] distribution. Considering the scale factor to be uncertain within this range, we obtain $A_{5007} = 6.2 \pm 0.7$ mag, which corresponds to $A_V = 5.5 \pm 0.6$ mag (using van de Hulst curve no. 15; Johnson 1968). Here the collisional rate coefficients of Saraph, Seaton, and Shemming (1969) and Eissner and Seaton (1974) have been used, and an electron temperature of 10^4 K has been assumed. The inferred extinction would increase slightly if the electron density were increased, and decrease slightly (0.3 mag per 10^3 K) if the assumed electron temperature were increased.

Ionic abundance ratios may be taken as the ratios of volume emission measures, $\int n_{x^{+i}} n_e \, dl \, d\Omega$, obtained from equation (1). In this case, the O^{++}/O relative abundance is estimated by comparison with H I Brα observations. We assume that oxygen is present in M82 in its cosmic abundance relative to hydrogen, $O/H = 6.6 \times 10^{-4}$ (Allen 1973),[5] and

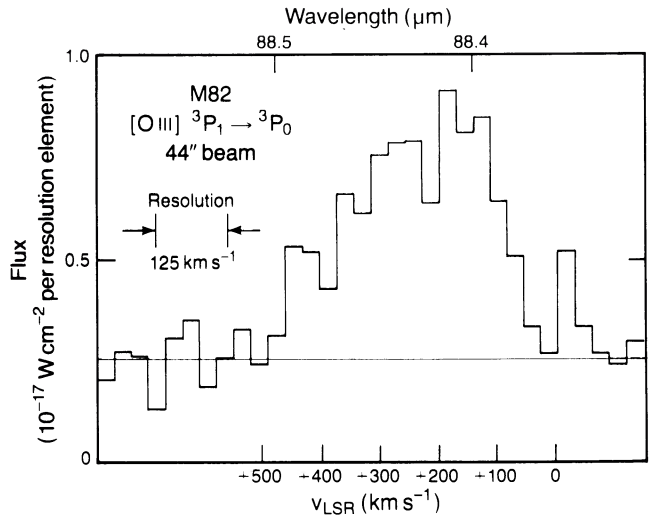

FIG. 1.—The [O III] 88.4 μm line from the nucleus of 82. Accounting for the extra broadening by the finite resolution of the spectrometer, the intrinsic width (FWHM) of the line is about 300 km s^{-1}. The integration time was 40 minutes (75 s per point).

[4]This value supersedes the previously accepted wavelength of 63.17000 μm (Saykally and Evenson 1979). The old value was invalid due to an error in the wavelength of the far-infrared laser line used in the laboratory laser-magnetic resonance measurements on [O I]. The new value is in good agreement with the wavelength of 63.183 ± 0.003 μm determined from our observations of the [O I] 63.2 μm line in the Orion nebula (Werner *et al.* 1982).

[5]Some evidence in support of this assumption is provided by the observations that Ar and Ne are probably present in M82 nearly in their cosmic abundances (Willner *et al.* 1977). Since O, Ne, and Ar are all "primary" nucleosynthesis products, their abundances relative to one another may be constant (see, for example, Talbot and Arnett 1973).

that the intervening grains are similar to those in the direction of the center of our own Galaxy (see Becklin *et al.* 1978). Willner *et al.* (1977) report a total H I Brα flux from the nucleus of M82 of 1.6×10^{-18} W cm^{-2}. The extinction curve by Becklin *et al.* and the average visual extinction derived above lead to an average extinction of 0.24 ± 0.03 mag at the wavelength of the H I Brα line. We thus obtain

$$\frac{\mathrm{O}^{++}}{\mathrm{O}} = \frac{\mathrm{H}}{\mathrm{O}} \frac{\int n_{\mathrm{O}^{++}} n_e \, dl \, d\Omega}{\int n_{\mathrm{H}^+} n_e \, dl \, d\Omega} = 0.20 \pm 0.09,$$

where collision rates at 10^4 K for [O III] have been taken from Saraph, Seaton, and Shemming (1969), and the effective recombination rate coefficient for H I Brα from Giles (1977); this result depends very weakly on electron temperature. The uncertainty given above for the $\mathrm{O}^{++}/\mathrm{O}$ ratio represents the statistical uncertainties in the line fluxes. Systematic errors are also possible, the largest of which would probably be density fluctuations in the source. If the nuclear H II region were sufficiently clumpy that the average electron density would be high enough ($\geq 10^3$ cm^{-3}) to cause appreciable collisional de-excitation in the [O III] 88.4 μm transition, the actual $\mathrm{O}^{++}/\mathrm{O}$ ratio would be higher than the above value.

The ionization state indicated by the derived $\mathrm{O}^{++}/\mathrm{O}$ ratio is rather similar to that for H II regions in our own Galaxy, but it is in apparent disagreement with the low-excitation inferred by Peimbert and Spinrad (1970) from observations of visible lines of O^{++}, O^{+}, and O^{0}. The difference is that Peimbert and Spinrad ascribed the strong [O I] 0.6300 μm line to the same region wherein the [O III] and [O II] lines are produced. If it is assumed instead that the lines of neutral oxygen are not formed in the nuclear H II complex, the visible lines imply the same ionic fractions as derived above. As shown in the following section, the Doppler velocities present in the [O I] 63.2 μm line may indicate that the warm neutral gas producing this radiation is distributed quite differently from the bulk of the ionized gas.

IV. [O I] EMISSION

The [O I] 63.2 μm line from the nucleus of M82 is shown in Figure 2. This spectrum has been corrected for absorption due to the strong telluric $\mathrm{H_2O}$ line at 63.324 μm. The total [O I] flux in the 44″ beam is $(1.9 \pm 0.6) \times 10^{-17}$ W cm^{-2}. Since no mapping was attempted, this may not represent the peak of the [O I] distribution. In contrast to the [O III] 88.4 μm line, the central velocity of the [O I] line is $v_{\mathrm{LSR}} = +130$ km s^{-1}, and no broadening in excess of the instrumental resolution of 180 km s^{-1} is seen. Any [O I] source distributed throughout M82 would produce a very broad line centered at $v_{\mathrm{LSR}} = +220$ km s^{-1}. In particular, if the line were formed in neutral matter at the edges of the H II regions in the nucleus of M82, as would be the most obvious assumption, its profile would resemble that of the [O III] 88.4 μm line. On the other hand, a very compact source in M82 could supply the required narrow line and could be proposed to lie at the proper galactocentric radius to give the observed Doppler shift. Since the [O I] central velocity is also a prominent velocity in the intergalactic

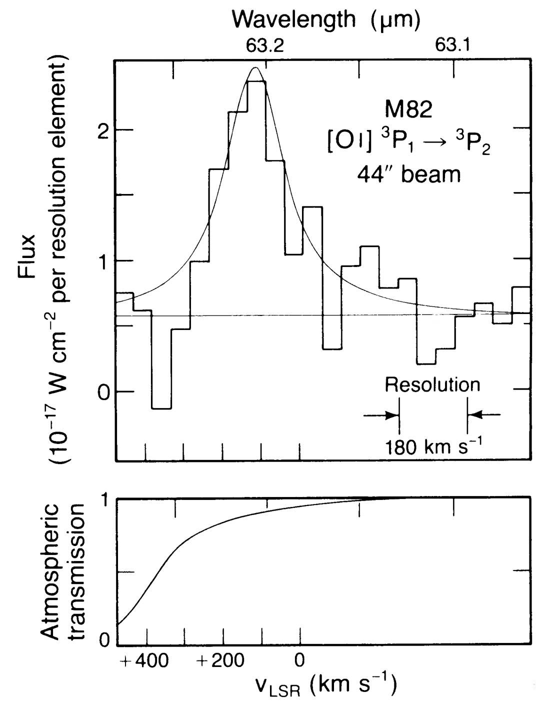

FIG. 2.—The [O I] 63.2 μm emission from the nucleus of M82. The upper panel shows the data (*thick lines*), corrected for telluric absorption, and the instrumental profile (*thin curve*), which has been fitted to the data by a least squares procedure. This spectrum is the result of 58 minutes of integration (2.6 minutes per point). The measured atmospheric transmission, used in the absorption correction, is plotted in the lower panel.

gas in which M82 is immersed (Gottesman and Weliachew 1977), we must also consider this material as a possible source of the line radiation.

Whether the source of the [O I] line is within or external to M82, it is probably an unusual object. Although it is not uncommon for the neutral regions around H II regions in our Galaxy to produce [O I] 63.2 μm lines comparable in brightness to the [O III] 88.4 μm line (see Melnick, Gull, and Harwit 1979; Dain *et al.* 1978), this is unexpected in M82 because of the relatively low densities found for most of the gas in M82 and the high density required to excite the upper level of the [O I] 63.2 μm line. At least 3×10^5 $M_\odot$ of gas with a cosmic abundance of atomic oxygen is required to produce the observed [O I] emission, assuming that the energy levels of O are in thermal equilibrium at $T \gg h\nu/k = 228$ K. However, the atomic hydrogen density required for thermal equilibrium ($\gg 10^5$ cm^{-3}) greatly exceeds any likely density value for the bulk of the gas in M82, so the total neutral mass may be greater than this minimum. Rate coefficients for collisional excitation of the neutral oxygen fine-structure levels by atomic hydrogen have been computed by Launay and Roueff (1977); for temperatures between 300 and 1000 K, the computed values are fitted well by $\gamma \equiv \gamma(^3P_2 \rightarrow {}^3P_1) = (1.85 \times 10^{-13})T$ (T in K, γ in cm^3 s^{-1}). Substitution of this function, the observed line flux, and the cosmic abundance of O into equation (1) gives a mass for the [O I] source of $M = 5.2 \times 10^{13}$ $M_\odot/n_{\mathrm{H}}T$. Unless the gas is almost entirely dissociated, observations of CO rotational lines and the assumption that $\mathrm{CO/H} = 6 \times 10^{-5}$ set an upper limit to M of about 10^7 $M_\odot$, since they indicate that the CO $J = 2 \rightarrow 1$ and $1 \rightarrow 0$ lines are not optically thick (Knapp *et al.* 1980). One possible combination of parameters is $M = 10^7\ M_{\odot}$, $n_H = 5000\ \mathrm{cm}^{-3}$, $T = 1000$ K, and a volume of $6 \times 10^4\ \mathrm{pc}^3$. The CO line optical depths restrict the hydrogen column density to values below about $5 \times 10^{22}\ \mathrm{cm}^{-2}$, so that the emitting gas would be distributed over an area as large as 200 pc in diameter. We discuss below two possible configurations of the warm gas which produces the [O I] line, using these parameters.

A compact object within M82.—A source 200 pc in size or smaller within M82 would produce a narrow enough [O I] line to be consistent with the observations (see the rotation curve derived by Beck *et al.* 1978). It would also be optically thick in the H I 21 cm line and thus may be very prominent on a high-resolution H I 21 cm map. The line center velocity and the rotation curve from Beck *et al.* would place the object about 10″ SW of the nucleus of M82—close to the very compact nonthermal radio source 41.9 + 58. Thus it is conceivable that the [O I] line arises in gas heated in shocks by this object, which has been proposed to be the remnant of an energetic supernova (Kronberg, Biermann, and Schwab 1981).

Dusty intergalactic gas.—Alternatively, the source of the [O I] line could be in the intergalactic cloud in which M82 is immersed, where it is possible for the gas to be more broadly distributed, yet produce narrow lines. For the parameters listed above, the source would fill only a few percent of a 1′ beam, and thus would be in the form of small clumps or slender filaments. Such filaments are known to surround the nucleus of M82 but may belong to the intergalactic cloud (see Solinger, Morrison, and Markert 1977). The central velocity of the [O I] line corresponds roughly to a narrow ($\approx 60\ \mathrm{km\ s}^{-1}$) component in the spectrum of CO $J = 1 \rightarrow 0$ and $J = 2 \rightarrow 1$ (Stark 1981; Knapp *et al.* 1980) and to the asymmetry in the ionic lines. The CO component with this velocity is extended along the minor axis of M82, in the same direction as the filaments, while the other velocity components seem to be confined to the disk (Stark 1981). Heating of the filaments, and hence excitation of the [O I], may be accomplished by soft ultraviolet radiation from the central star cluster.

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