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[O I] 63 MICRON ABSORPTION IN NGC 6334

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ABSTRACT

The [O I] 63 μm transition has been imaged around five far-infrared (FIR) and radio continuum sources in the southern massive star formation region NGC 6334. The [O I] 63 μm line is found in absorption toward the FIR continuum source NGC 6334V. This is only the second case in which the [O I] 63 μm line has been seen in absorption against a continuum source. From the depth of the absorption line, the minimum column density of oxygen is calculated to be $N(O^0) \gtrsim 5 \times 10^{18}$ cm^{-2}. This amount of oxygen is consistent with [O I] 63 μm absorption due to atomic gas in the foreground molecular cloud.

The [O I] 63 μm line is found in emission toward the other four sources observed: NGC 6334, sources A, C, D, and E. Single-component photodissociation region (PDR) models suggest densities of $n \sim 10^4$ cm^{-3} for these sources, based on previously observed [O I] 145 μm and [C II] 158 μm intensities. However, unphysically large far-ultraviolet (FUV) fields are implied for three of the sources, particularly for NGC 6334A. Neither one- nor two-component photodissociation region models can explain the anomalously low [O I] 63 μm intensity toward NGC 6334A nor the absorption toward NGC 6334V. We suggest that self-absorption of the [O I] 63 μm line, such as has been suggested toward DR 21, is suppressing the observed [O I] 63 μm intensity. This underestimate leads to an overestimate of the derived FUV field strengths throughout NGC 6334. The discovery of several more star-forming sites in which the [O I] 63 μm is in absorption or is self-absorbed implies that this line is not always a reliable PDR diagnostic because the PDR models do not treat the radiative transfer through the molecular cloud.

Subject headings: infrared: ISM: continuum — H II regions — ISM: individual (NGC 6334) — stars: formation

1. INTRODUCTION

Atomic oxygen is one of the principal coolants of the interstellar medium via its fine-structure lines in the far-infrared (FIR). In particular, the [O I] 63 μm line emission dominates the cooling at FUV fluxes of $10^3 \lesssim G_0 \lesssim 10^6$ (G_0 is the FUV field in units of Habings or 1.6×10^{-3} ergs cm^{-2} s^{-1}; Habing 1968) and hydrogen densities of 10^3 cm$^{-3} \lesssim n_0 \lesssim 10^6$ cm^{-3} (Tielens & Hollenbach 1985a). These are the densities and fluxes expected in the photodissociation regions (PDRs) that surround the H II regions of massive young stars. Current models of PDRs (e.g., Tielens & Hollenbach 1985a; Wolfire, Tielens, & Hollenbach 1990; Burton, Hollenbach, & Tielens 1990; Meixner & Tielens 1993, 1995) use the [O I] 63 μm intensity as a key parameter for deducing the FUV field and the density in PDRs. This should make observations of the [O I] 63 μm transition a vital tool for probing the physical conditions of PDRs around massive young stars, such as those found in NGC 6334. However, recent observations suggest that the [O I] 63 μm line is self-absorbed toward DR 21 (Poglitsch et al. 1996). In light of this discovery, careful scrutiny of the [O I] 63 μm line as a PDR diagnostic for the current PDR models is necessary.

In this paper, we describe new [O I] 63 μm observations toward NGC 6334. NGC 6334 is a nearby (1.7 kpc; Neckel 1978) star-forming cloud with at least seven distinct sites of massive star formation. The inferred spectral types range from B0 to O7 (Loughran et al. 1986; Rodríguez, Cantó, & Moran 1982). Because multiple sites exist in the same cloud, global effects, such as elemental abundances or global magnetic fields, will not contribute to the differences among the stars. Only local effects such as age, mass, and UV field vary from site to site. This allows a cleaner comparison of the young stars and their effects on the surrounding gas than if they were forming in different clouds. Because NGC 6334 is relatively nearby ($1' = 0.5$ pc) and has multiple, well-separated sites of massive star formation, it is an ideal laboratory in which to study the differences in the PDR gas properties due to local conditions.

We have observed the [O I] 63 μm transition ($^3P_1 \rightarrow {}^3P_2$) toward five of the radio and FIR continuum sources in NGC 6334.[1] We find the [O I] 63 μm line in absorption against the southernmost FIR continuum source, NGC 6334V (McBreen et al. 1979). This is the first time the [O I] 63 μm line has been seen in absorption against a continuum source. Toward the other sources, NGC 6334 sources A, C, D, and E (Rodríguez et al. 1982), the intensity peaks are slightly offset from the positions of the H II regions. The intensity of the emission line toward NGC 6334A is surprisingly weak relative to the intensities of the [O I] 145 μm and [C II] 158 μm emission lines. NGC 6334A may be the second site toward which the [O I] 63 μm line has been seen in self-absorption (the other is DR 21; Poglitsch et al. 1996).

[1] Source designations follow the nomenclature of Rodríguez et al. (1982) for radio continuum sources NGC 6334, sources A, C, D, and E, and the notation of McBreen et al. (1979) for the FIR continuum source NGC 6334V. The change in notation is necessary because of the fact that source NGC 6334E is not an FIR continuum source and source NGC 6334V is not a radio continuum source.

2. OBSERVATIONS

The [O I] 63 μm line was observed with the Far-infrared Imaging Fabry-Perot Interferometer (FIFI) (Poglitsch et al. 1991; Stacey et al. 1992) on the NASA Kuiper Airborne Observatory (KAO) in 1992 August. FIFI has a 5×5 focal plane array, with detectors spaced by 20″ at 63 μm. At 63 μm, the FWHM angular resolution is 22″ and the noise-equivalent flux density (NEFD) is 2.0×10^{-18} W cm^{-2} Hz$^{-1/2}$. For these observations, the scan width was 350 km s^{-1} and one spectral resolution element was $\Delta v_{\rm FWHM} = 50$ km s^{-1}. This gave a sensitivity of 670 Jy per resolution element for each 1 minute scan. Between 4 and 12 one minute scans were averaged together at each sky position. In addition to the pointings toward five of the continuum sources (Table 1), small maps were made around two of the sources that showed strong [O I] 63 μm emission, NGC 6334 sources C and D. The observations were chopped and nodded against reference positions 7′.5 away (P.A. $= -67°$) in order to eliminate atmospheric and background effects. A gas cell filled with NH_3 was observed for wavelength calibration at the beginning and at the end of the run. The intensities were calibrated by observing an internal blackbody during the run. Using the SPEC-PC program of N. Geis, Lorentzians were fitted to the spectra, which yielded the continuum level, peak intensity, integrated intensity, and line center position, with the line width held constant at $\Delta v = 50$ km s^{-1} (this assumes that the lines are spectrally unresolved). Only signals greater than 2 σ above the noise were considered valid detections, where σ is the noise-equivalent power (NEP) of FIFI at 63 μm weighted by the appropriate integration time; if the line center fit was not within 3 σ (56 km s^{-1}) of the known velocity of the cloud, the fit was rejected.

3. [O I] 63 μm ABSORPTION

We find the [O I] 63 μm line in absorption against the FIR continuum toward NGC 6334V (Fig. 1). The best-fit Lorentzian is shown for the (0, 0) position. Although the fit assumes that the line is unresolved, the fact that the line is nearly black at the line center indicates that the line is not greatly unresolved at the resolution of $\Delta v = 50$ km s^{-1}. This is in contrast to the line width of $\Delta v = 14$ km s^{-1} for the [C II] 158 μm emission reported by Boreiko & Betz (1995). The true line width is likely to be between these two values, which can be considered limits to the line width. Two methods are examined to find the optical depth of the absorption line. The first follows a curve-of-growth analysis, while the second follows a simpler method to find the minimum optical depth of the line. In each method, the optical depth for the limiting line widths ($\Delta v = 14$ and 50 km s^{-1}) is calculated. The minimum oxygen column density, and hence minimum hydrogen column density, is then calculated and compared with the hydrogen column density determined by other methods.

3.1. *Curve-of-Growth Analysis*

For an unresolved optically thick absorption line, the equivalent width W_v, which is the ratio of the integrated intensity of the absorption line $I_{\rm int}$ (integrated over the best-fit Lorentzian) to the continuum level I_c, can be used to estimate the minimum optical depth of the line (Spitzer 1978):

$$I_{\rm int} = \int I_{\rm line}\, dv\,, \tag{1}$$

$$W_v = \frac{I_{\rm int}}{I_c}\,, \tag{2}$$

$$\tau_0^{\rm min} = \exp\left(\frac{W_v\sqrt{\ln 2}}{\Delta v}\right)^2\,, \tag{3}$$

where $I_{\rm line}$ is the intensity of the absorption line and Δv is the line width. Equation (2) assumes that the line is saturated in the "flat" part of the curve-of-growth, before the damping wings become important. At NGC 6334V the integrated intensity is $I_{\rm int} = 3.7 \pm 0.4 \times 10^5$ Jy km s^{-1}, $I_c = 5100 \pm 800$ Jy, which gives an equivalent width of $W_v = 73 \pm 14$ km s^{-1}. By assuming Δv ([O I] 63 μm) $\approx \Delta v$ ([C II] 158 μm) $= 14$ km s^{-1} (Boreiko & Betz 1995), the minimum optical depth is $\tau_0^{\rm min} \approx 1.5 \times 10^{8+4(11)}_{-2(5)}$. On the other hand, with $\Delta v = 50$ km s^{-1}, the minimum optical depth is $\tau_0^{\rm min} \approx 4.4^{+8.2}_{-2.6}$.

If, instead of using the intensity integrated over the Lorentzian, only the central channels are integrated directly, the integrated intensity becomes $I_{\rm int} = 2.0 \pm 0.4 \times 10^5$ Jy

TABLE 1

OBSERVATIONAL PARAMETERS

SOURCE	LOCATION[a] (α, δ) (B1950)	INTENSITIES (10^{-3} ergs^{-1} cm^{-2} ster^{-1})[b] [O I] 63 μm	[O I] 145 μm	[C II] 158 μm	CONTINUUM 63 μm (Jy)
V	17 16 36, −35 54 23	-5.3 ± 1.44	<0.056	0.57 ± 0.074	>5100
A	17 16 57.8, −35 51 45	1.8 ± 0.66	0.73 ± 0.124	0.94 ± 0.074	1900 ± 250
C	17 17 10, −35 48 49	7.4 ± 1.04	0.49 ± 0.056	1.73 ± 0.074	<800
D	17 17 21, −35 46 27	7.0 ± 1.14	0.45 ± 0.056	2.30 ± 0.074	<800
E	17 17 29.8, −35 43 08	3.0 ± 1.04	0.10 ± 0.056	1.20 ± 0.074	<800
F	17 17 32.3, −35 44 04	...	0.13 ± 0.056	1.25 ± 0.074	>4600

NOTE.—Units of right ascension are hours, minutes, and seconds, and units of declination are degrees, arcminutes, and arcseconds.

[a] Positions of the array centers are as follows: A, E, and F are 6 cm radio positions (Rodríguez et al. 1982); C, D, and V are 70 μm positions (Loughran et al. 1986). Note that the 70 μm position for source V reported by Loughran et al. (1986) is approximately 30″ north of the correct emission peak.

[b] Intensities are at the position of the radio peak, except for NGC 6334V, which has no radio continuum emission and is taken at the 63 μm continuum peak. [C II] 158 μm and [O I] 145 μm taken from Kraemer 1997. Quoted uncertainties are 2 σ, where σ is the instrumental NEP weighted by the appropriate integration time; upper limits are 2 σ upper limits.

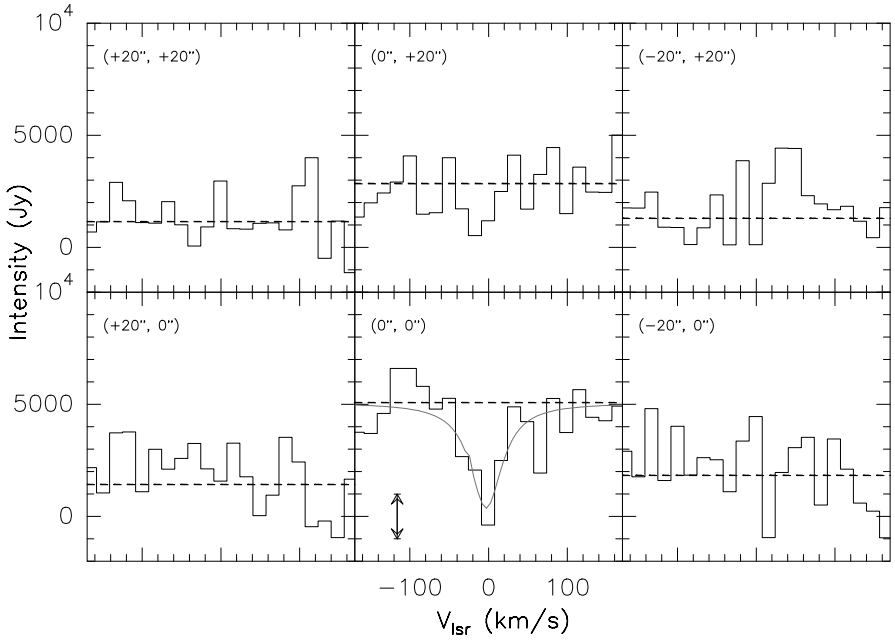


FIG. 1.—[O I] 63 μm spectra toward NGC 6334V. The 63 μm continuum level at each position is shown by the dashed line. Note that the [O I] 63 μm absorption spectrum coincides with the peak of the 63 μm continuum emission. Positional offsets are with respect to NGC 6334V. The position of the absorption spectrum is $\alpha = 17^h16^m36^s$, $\delta = -35°55'04''$. The best-fit Lorentzian is superposed on the absorption spectrum at NGC 6334V. Parameters for the fit are as follows: offset (continuum level) = 5100 Jy; peak = −4700 Jy; center = 0 km s^{-1}; width (fixed) = 50 km s^{-1}.

km s^{-1}. This implies an equivalent width of $W_v = 40 \pm 10$ km s^{-1} and $\tau_0^{\min} \approx 300^{+7000}_{-24}$ for $\Delta v = 14$ km s^{-1} and $\tau_0^{\min} \approx 1.6^{+2.0}_{-1.3}$ for $\Delta v = 50$ km s^{-1}.

3.2. *Optically Thin Method*

As an alternative to the curve-of-growth analysis, the optical depth is calculated by comparing the depth of the center of the absorption feature to the continuum level. While this method is strictly applicable only if the line is optically thin, it will give the *minimum* optical depth for the optically thick case. In this approximation, the optical depth is given by

$$e^{-\tau_0} \approx \frac{I_{\rm cont} - I_{\rm abs}}{I_{\rm cont}}, \tag{4}$$

$$\approx \frac{5100 - 4700}{5100}. \tag{5}$$

At the line center, the depth of the Lorentzian is $I_{\rm abs} = -4700 \pm 1900$ Jy, relative to the continuum level, $I_{\rm cont} = 5100 \pm 800$ Jy. This suggests that the minimum optical depth at the line center is $\tau_0^{\min} \approx 2.5 \pm 0.4$.

3.3. *Minimum Column Density*

The minimum optical depth of the absorption line can be used to derive the minimum column density of the atomic oxygen. The $^3P_1$ state, the upper level of the [O I] 63 μm transition, is 228 K above the ground state and the critical density is $n_{\rm crit} = 4.7 \times 10^5$ cm^{-3} (Tielens & Hollenbach 1985a). Because of this, all the oxygen atoms are assumed to be in the ground state (a reasonable assumption if the absorption is from cooler or less dense foreground material). The column density of oxygen, $N(O^0)$, is then given by

$$N(O^0) = \frac{g_l}{g_u} \frac{8\pi}{\lambda^3 A_{ul}} \int \tau_v \, dv, \tag{6}$$

where g_i is the statistical weight of level i, $A_{ul} = 8.46 \times 10^{-5}$ s^{-1} (Baluja & Zeippen 1988) is the Einstein A-coefficient, and $\lambda = 63$ μm. τ_v is the optical depth as a function of velocity:

$$\tau_v = \tau_0 \exp\left[-\left(\frac{v - v_\tau}{\sigma}\right)^2\right], \tag{7}$$

$$= \tau_0 \exp\left\{-\left[\frac{1.665(v - v_\tau)}{\Delta v}\right]^2\right\}. \tag{8}$$

This gives for the oxygen column density

$$N(O^0) = \frac{g_l}{g_u} \frac{8\pi}{\lambda^3 A_{ul}} \tau_0 \sqrt{\pi} \frac{\Delta v}{2.354}, \tag{9}$$

$$= 3.48 \times 10^{12} \tau_0 \Delta v(\text{cm}^{-2}), \tag{10}$$

where Δv is in units of cm s^{-1}. The oxygen abundance is assumed to be the solar abundance, $[O]/[H] = 8.5 \times 10^{-4}$ (Anders & Grevesse 1989). For a Galactocentric distance of 6.8 kpc for NGC 6334, this value is consistent with the Galactic oxygen abundance gradient recently derived by Smartt & Rolleston (1997). A smaller oxygen abundance of $[O]/[H] = 5 \times 10^{-4}$ is assumed in the PDR models (§ 5.1), which is consistent with the distance of NGC 6334 with the Galactic oxygen abundance gradient of Afflerbach, Churchwell, & Werner (1997). Use of the smaller value for the oxygen abundance would increase the derived hydrogen column densities by approximately 50% but would not affect the following discussion or conclusions regarding the line widths.

Because only the minimum optical depth can be calculated, only lower limits on the column density have been derived. Table 2 summarizes the minimum column density results for each combination of derivation method and Δv. The results for a narrow line width ($\Delta v = 14$ km s^{-1}) in the curve-of-growth analysis are inconsistent with the results of the optically thin analysis, which does not depend on the line width. Furthermore, at $N(\mathrm{H})^{\min} \sim 10^{29}$ cm^{-2} or even 10^{24} cm^{-2}, a narrow line implies densities clearly incompatible with the *molecular* hydrogen column density derived from a variety of methods, including extinction estimates [$N(\mathrm{H_2}) \approx 5.5 \times 10^{22}$ cm^{-2}, $\theta = 1'.9$, where θ is the FWHM of the telescope beam; Phillips, de Vries, & de Graauw 1986; $\theta = 25''$; Straw & Hyland 1989], the CO 1–0 integrated intensity [$N(\mathrm{H_2}) \approx 8.9 \times 10^{22}$ cm^{-2}, $\theta = 45''$; Kraemer 1997; Kraemer & Jackson 1998; using a conversion factor of 2.3×10^{20} cm^2 K^{-1} km^{-1} s; Strong et al. 1988], and CO excitation models [$N(\mathrm{H_2}) \approx 1.3 \times 10^{23}$ cm^{-2}, $\theta = 45''$; Kraemer 1997; Kraemer & Jackson 1998].

On the other hand, for the other limiting case ($\Delta v = 50$ km s^{-1}), the minimum hydrogen column density is a few times 10^{22} cm^{-2}. Unlike two of the three methods with $\Delta v = 14$ km s^{-1}, this result is consistent both among the derivation methods and with the results from previous observations. The large line width of the absorption line suggests that the absorbing gas may be in a shocked region. There is a strong molecular outflow in the region (e.g., Fischer et al. 1982; Phillips & Mampaso 1991), as well as shock-excited H_2 emission (Straw & Hyland 1989) and NH_3 masers (Kraemer & Jackson 1995). The line widths of shocked lines are expected to be of order the shock velocity, as opposed to PDR lines, which should be much narrower (e.g., Hollenbach & McKee 1989). Thus, a possible explanation for the discrepancy between the line widths of the [C II] 158 μm emission line and the [O I] 63 μm absorption line is that while the [C II] 158 μm line arises from photodissociated gas, the [O I] 63 μm absorption arises from shocked gas.

Although these methods give only lower limits for the optical depth, and hence hydrogen column density, they agree to within a factor of a few with the measures of molecular hydrogen. This close agreement between the total hydrogen column density measured by the oxygen absorption and molecular column density determined by other methods indicates that both are measuring the same gas. That is, the absorbing atomic oxygen is in predominantly molecular material. We suggest, therefore, that like the results of Poglitsch et al. (1996), the [O I] 63 μm absorption toward NGC 6334V is due to an atomic component within a *molecular* cloud.

4. [O I] 63 μm LINE EMISSION

The [O I] 63 μm line was detected in emission around four of the five continuum sources observed in NGC 6334 (Table 1). In each case, the emission is offset from the position of the H II region by $\approx 20''$ (= 0.2 pc) (Fig. 2). Toward NGC 6334 sources C and D, the [O I] 63 μm emission peaks occur to the east and northeast, respectively, of the radio continuum positions. The emission peak near NGC 6334E is south of the H II region. Toward NGC 6334A, the [O I] 63 μm emission occurs at the western and southern edges of the H II region, avoiding the radio continuum peak completely. Such positional offsets between [O I] 63 μm emission and the radio continuum source have also been seen in DR 21 (Lane et al. 1990) and Orion (Furniss et al. 1983; Werner et al. 1984).

The intensity of the [O I] 63 μm emission could be suppressed through absorption by cold foreground material. This, however, should not preferentially suppress emission in the line of sight toward the H II region, since the absorption we suggest is self-absorption, not absorption against the continuum as was seen in NGC 6334V (§ 3). Limb brightening of the edges of a spherical PDR centered on the H II region should also not be a factor, since the [O I] 63 μm line in PDRs is generally assumed to be optically thick (Tielens & Hollenbach 1985a).

A possible explanation for the displacement of the [O I] 63 μm emission peaks from the H II regions is that the massive young star is embedded in a clumpy medium. Only the edges of the dense clumps toward the star will become PDRs. If the clump lies between the star and the observer, the colder, backside of the clump can absorb the [O I] 63 μm line emission, thus suppressing the emergent intensities. If the clump is observed at an angle, that is, edge-on, the emission will not be self-absorbed. However, if the clumps are distributed uniformly, this would produce a ring of emission, not only on one side as is observed.

Alternatively, there might be structure in the gas density in the cloud. If the [O I] 63 μm line is subthermally excited, the intensity will be greatest where the density is highest. The critical density of the 63 μm line is $n_{\mathrm{crit}} = 4.7 \times 10^5$ cm^{-3}, so the line might be subthermal even in the moderately dense gas ($n \sim 10^4$–10^5 cm^{-3}) typically found in PDRs. Comparison of the [O I] 63 μm emission with CS ($7 \rightarrow 6$) emission shows that the [O I] 63 μm tends to occur along the edge of the CS ($7 \rightarrow 6$) emission, which traces

TABLE 2

DERIVED OPTICAL DEPTHS AND COLUMN DENSITIES

	$\Delta v = 14$ km s^{-1}			$\Delta v = 50$ km s^{-1}		
	Curve of Growth[a]			Curve of Growth		
Parameter	Lorentzian	Central Channels	Absorption Depth	Lorentzian	Central Channels	Absorption Depth
$\tau_0^{\min}$	$1.5(8)^{+4(11)}_{-2.2(5)}$ [b]	$3(2)^{+7(3)}_{-24}$	2.5 ± 0.4	$4.4^{+8.2}_{-2.6}$	$1.6^{+2.0}_{-1.3}$	2.5 ± 0.4
$N(\mathrm{O}^0)^{\min}$	$4.5(26)^{+1.2(30)}_{-7(23)}$	$8(20)^{+2(22)}_{-7(19)}$	7.8 ± 1.2 (18)	$4.6(19)^{+8.6(19)}_{-2.7(19)}$	$1.6(19)^{+2.1(19)}_{-1.4(19)}$	2.6 ± 0.5(19)
$N(\mathrm{H})^{\min}$	$5.3(29)^{+1.4(33)}_{-8.6(26)}$	$9.9(23)^{+2.4(25)}_{-8.3(22)}$	8.6 ± 1.5(21)	$5.4(22)^{+1.0(23)}_{-3.2(22)}$	$1.9(22)^{+2.5(22)}_{-1.6(22)}$	3.1 ± 0.5 (22)

[a] As described in the text, the curve-of-growth analysis is reported for the integrated intensity of the best-fit Lorentzian and for that of the central channels.

[b] $a(b) = a \times 10^b$.

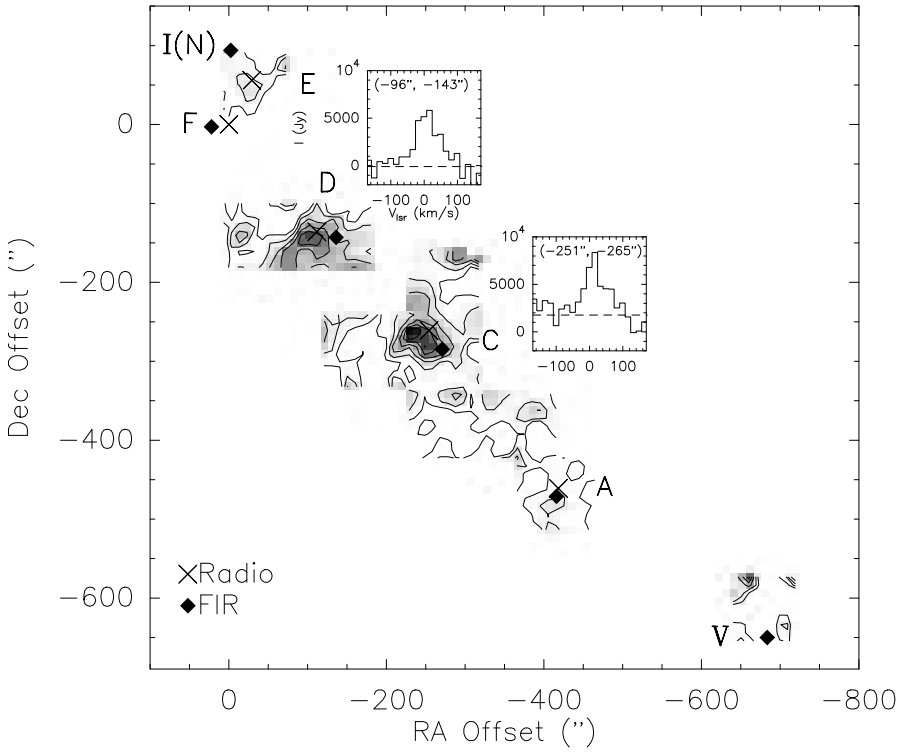


FIG. 2.—[O I] 63 μm emission from NGC 6334. The peak integrated intensity is near source C, $7.4 \pm 1.0 \times 10^{-3}$ ergs^{-1} cm^{-2} ster^{-1}. Contour levels are at 15% intervals of the integrated intensity peak. Positional offsets are with respect to NGC 6334F at $\alpha = 17^h17^m32^s$, $\delta = -35°44'04''$. Radio sources are marked with crosses, and FIR sources are marked with solid diamonds (except where the solid diamond marks the position of the millimeter source NGC 6334I[N]). The emission spectra show the emission peaks near NGC 6334, sources D and C.

dense gas ($n_{crit} = 1.7 \times 10^7$ cm^{-3}) and is even further offset from the continuum positions. That is, the [O I] 63 μm emission is brightest at the edges of denser regions of the surrounding molecular cloud. This coincidence between the [O I] 63 μm emission and the edge of the CS ($7 \rightarrow 6$) emission best supports the scenario that the offsets in the [O I] 63 μm emission from the continuum sources are due to density structure intrinsic to the cloud. In other words, the PDRs are not created in a uniform medium.

5. DISCUSSION

5.1. *PDR Models*

The current models of PDRs describe the heating and cooling processes in the PDR and include gas chemistry, thermal balance, and radiative transfer of the cooling lines (Tielens & Hollenbach 1985a; Wolfire et al. 1990; Burton et al. 1990; Meixner & Tielens 1993). The photoelectric effect via electrons ejected from dust grains is the dominant heating mechanism. The dominant coolants at low extinction ($A_v \lesssim 2$) are the [O I] 63 μm and [C II] 158 μm fine-structure lines, while the rotational lines of CO become the dominant coolants at higher optical depths. The [O I] 63 μm line is generally optically thick. By comparing the observed FIR flux, the [C II] 158 μm/[O I] 63 μm and [O I] 63 μm/[O I] 145 μm intensity ratios[2] with the PDR models, the gas density [$10^2 < n$ (cm^{-3}) $< 10^6$] and incident UV field ($10 < G_0 < 10^6$) should, in principle, be constrained. The different PDR models can be divided into those that consider a single, homogeneous component (e.g., Tielens & Hollenbach 1985a; Wolfire et al. 1990) and those that include clumping (e.g., Burton et al. 1990; Meixner & Tielens 1993, 1995). The two-component models treat the clumps as homogeneous spheres of uniform density embedded in a less dense, homogeneous medium. The single-component models are applied first to the observations, and only if the simple models fail are the two-component models applied.

5.2. *Comparison of Observations with the Models*

The observed line intensity ratios are compared with the single-component PDR models of Wolfire et al. (1990) in order to determine the gas density and FUV field strength at NGC 6334 sources A, C, D and E. Because of the absorption in the [O I] 63 μm emission seen toward NGC 6334V (§ 3), the models are not applied to this position. (The [C II] 158 μm and [O I] 145 μm observations are presented by Kraemer et al. 1994 and Kraemer 1997 and will be discussed more fully in a future paper.) Table 3 summarizes the observed line ratios and model predictions at the sources. The single-component models suggest reasonable values for the density and FUV field strength at NGC 6334E: $n \sim 10^{3.8}$ cm^{-3} and $G_0 \sim 10^{3.7}$ Habings. These values are comparable to those found in other massive star-forming regions in the Galaxy from the models of Wolfire et al. (1990) (see Table 3).

However, the single-component models do not fit the observed intensity ratios at NGC 6334 sources A, C, or D. The models suggest reasonable densities of $n \sim 10^4$ cm^{-3}

[2] Hereafter, the intensity ratios will be abbreviated as R_{145}^{63}, R_{63}^{158}, and R_{158}^{145}.

TABLE 3

FIR Line Ratios and Single-Component Model Fits[a]

Source	[C II] 158 μm/[O I] 63 μm	[O I] 63 μm/[O I] 145 μm	log n (cm^{-3})	log G_0 (Habing)	Reference
		NGC 6334			
A	0.53 ± 0.12	2.42 ± 0.54	3.8	>6	1
C	0.341 ± 0.032	10.37 ± 1.46	4.0	5.3	1
D	0.507 ± 0.054	10.02 ± 1.60	3.8	5.8	1
E.....	0.649 ± 0.152	18.7 ± 11.4	3.8	3.7	1
		Galactic			
Center.....	0.21 ± 0.06	14 ± 4	5.0	4.9	2
M82	0.14 ± 0.04	23 ± 7	4.7	3.9	2
Orion	$0.11^{+0.6}_{-0.4}$	11^{+9}_{-4}	4.8	4.2	2
DR 21.....	0.20 ± 0.03	...	4.3	4.8	3

[a] [O I] 63 μm intensities were convolved to 55″, the resolution of the [C II] 158 μm and [O I] 145 μm data. For NGC 6334, uncertainties in the ratios (2 σ) reflect the uncertainties in the data from Table 1 and incorporate the convolution of the 63 μm data. For the other sources, uncertainties are taken from the literature, where available (reference 2: 30% of line ratio; reference 3: ≈2 σ). Density (n) and FUV field strength (G_0) are the best fits to the single-component PDR models of Wolfire et al. 1990 and are accurate to roughly ±0.5 dex.

References.—1. This work; 2. Wolfire et al. 1990; 3. Lane et al. 1990, using the alternative method outlined in Wolfire et al. 1990.

but unphysically high FUV fields (Table 3). The implied densities are consistent with molecular hydrogen densities from excitation models of CO observations, which give $n_{H_2} \sim 10^{3.5}$ cm^{-3} (Kraemer et al. 1997; Kraemer & Jackson 1998). The predicted FUV field, on the other hand, is significantly higher than for other Galactic star-forming regions, such as Orion (log $G_0 \approx 4.2$; Tielens & Hollenbach 1985b; Wolfire et al. 1990), DR 21 (log $G_0 \approx 4.8$; Lane et al. 1990), or the Galactic center (log $G_0 \sim 4.9$, inside 5 pc; Wolfire et al. 1990) or for the nuclei of starburst galaxies (e.g., M82: log $G_0 \sim 3.9$, inside 330 pc; Wolfire et al. 1990). Furthermore, the expected FUV field strength in a 55″ beam (the beam size of the long wavelength observations) can be calculated from the known spectral types of the three sources (Rodríguez et al. 1982). This gives FUV field strengths of log $G_0 \sim 4$, more than an order of magnitude less than those implied by the PDR models.

We therefore turn to the two-component models of Burton et al. (1990) and Meixner & Tielens (1993, 1995). Again, like the single-component models, these models do not fit the observed ratios. They cannot produce strong enough [O I] 145 μm and [C II] 158 μm emission without also producing too much [O I] 63 μm emission. For source A in particular, the observed R_{145}^{63} is significantly smaller than the models predict for the entire range of densities and FUV fields that the models explore. This could be due to excess [O I] 145 μm emission or suppressed [O I] 63 μm emission or a combination of both. The intensity ratio R_{158}^{145} toward NGC 6334A ($R_{158}^{145} \approx 0.7$) is comparable to what is seen in other massive star formation regions such as M17 ($R_{158}^{145} = 0.7$; Meixner et al. 1992) and Orion ($R_{158}^{145} = 0.8$; Stacey et al. 1993). On the other hand, both R_{145}^{63} and R_{158}^{63} are smaller than in other regions. R_{145}^{63} ranges from ≈13 in Orion (θ^1C; Stacey et al. 1993), and M17 (Meixner et al. 1992) ranges to ≈30 in the Galactic center (Genzel et al. 1985). In NGC 6334A, R_{158}^{145} is comparable to that in other high-mass star-forming regions in the Galaxy, but both ratios involving [O I] 63 μm are lower. We conclude, therefore, that the [O I] 63 μm intensity is anomalously faint toward NGC 6334A.

The [O I] 63 μm emission may also be suppressed toward sources C and D as well as toward sources A and V, although our velocity resolution is too coarse to detect self-absorption. The actual FUV fields would thus be smaller than those inferred in this analysis and more consistent with the fields expected from the known spectral types. The [C II] 158 μm line profiles (Boreiko & Betz 1995) show evidence for self-absorption toward most observed positions in NGC 6334, even though this transition is usually assumed to be optically thin. Opacity effects will be even more significant in the optically thick [O I] 63 μm transition. While the PDR models assume that the [O I] 63 μm line is optically thick, they do not treat the radiative transfer through the molecular cloud. Instead, they assume an edge-on or face-on viewing geometry. Even the models that include clumps assume that the clumps and the interclump medium are radiatively decoupled and thus neglect the potential effects of absorption.

Several sources have now been found in which the [O I] 63 μm line is seen in absorption, both in self-absorption (DR 21; Poglitsch et al. 1996) and against a continuum source (NGC 6334V; this work), or the line is anomalously faint relative to other FIR fine-structure lines (M17SW: Meixner et al. 1992; Meixner & Tielens 1993; NGC 6334A: this work). The existence of these sources in which the [O I] 63 μm behavior cannot be adequately described by either single-component or clumpy models suggests that the [O I] 63 μm line may not be a reliable diagnostic for the physical conditions of PDRs. Theoretical models that include radiative transfer through the cooler gas in the outer regions of the PDR and through the cold molecular cloud are needed to test whether self-absorption can explain the growing number of sources with anomalously faint [O I] 63 μm emission.

6. CONCLUSIONS

1. We have detected the [O I] 63 μm transition in absorption toward the FIR continuum source NGC 6334V. This is only the second detection of [O I] 63 μm absorption against a continuum source. The minimum derived column

density of atomic oxygen is $N(O^0) \gtrsim 5.2 \times 10^{19}$ cm^{-2}. Thus, the [O I] 63 μm absorption observed toward NGC 6334V is due to less excited (cooler or less dense) gas in the foreground molecular cloud.

2. The [O I] 63 μm line is in emission toward four additional continuum sources in the star-forming complex: NGC 6334, sources A, C, D, and E. In each source, the emission is offset from the radio continuum position. The positional offset may be due to density structure of the cloud in which the PDRs are embedded.

3. Single-component models of PDRs suggest gas densities for NGC 6334, sources A, C, D, and E, of $n \sim 10^4$ cm^{-3} but give unphysically large FUV field strengths for three of these sources, particularly for source A. Two-component models also do not fit the observed line ratios of NGC 6334A. Specifically, the intensity of the [O I] 63 μm emission is lower than expected relative to the [O I] 145 μm and [C II] 158 μm intensities. We suggest that until the PDR models treat radiative transfer through the molecular cloud, which could have a significant column density of atomic oxygen, the [O I] 63 μm line may not be a reliable PDR diagnostic.

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