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THE INTERSTELLAR MEDIUM IN THE CENTRAL 1 KILOPARSEC OF M82

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ABSTRACT

We have observed the far-infrared fine-structure lines of [O I], [O III], and [C II] toward the center of the galaxy M82. Within 500 pc of the nucleus, the far-infrared emission lines contain $\sim 2 \times 10^8\ L_\odot$, or about 0.5% of the bolometric luminosity. The C^+ emission shows a strong peak at the nucleus, and its spatial extent along the minor axis of M82 is a few hundred pc. The absolute and relative intensities of the lines show that the neutral gas in the inner disk of M82 is in dense ($n_H \approx 10^4$ cm^{-3}), relatively small clouds (0.1–1 pc), thin filaments, or sheets of very low volume filling factor, associated with a lower density ionized medium ($n_e \approx 100$ cm^{-3}) of moderately high filling factor (~ 0.1). Within 500 pc of the nucleus, we estimate that $\sim 3 \times 10^7\ M_\odot$ ($\sim 15\%$ of the total mass of interstellar gas) is contained in H II regions and $3 \times 10^7\ M_\odot$ in photodissociation regions. Each is about one to two orders of magnitude more than in our own Galaxy. This high fraction of ionized gas, the unusual clumpy cloud structure, and large scale height of the neutral gas along the minor axis probably are direct consequences of the high UV energy density and rate of star formation at the center of M82.

The spectra and maps indicate that there is a component of ionized and neutral gas near LSR ≈ 150 km s^{-1} centered near the compact radio source 41.9+58 and elongated along the minor axis of M82. The gas is especially dense in this region ($n_e \approx 6 \times 10^2$, $n_H \approx 4 \times 10^4$ cm^{-3}, gas pressure $\approx 10^7$ K cm^{-3}) and appears to be associated with X-ray emission and the inner Hα filaments.

Subject headings: galaxies: individual — galaxies: nuclei — infrared: spectra

I. INTRODUCTION

M82 is the prototype of an "infrared active" galaxy. Its total far-infrared luminosity is $\sim 4 \times 10^{10}\ L_\odot$ (Telesco and Harper 1980; D. A. Harper, private communication), about 4 times greater than its visible and near-infrared luminosity. It contains a large number of compact nonthermal radio continuum sources which may be the remnants of supernovae exploding at a rate of ~ 0.1 yr^{-1} (Kronberg and Wilkinson 1975; Kronberg, Biermann, and Schwab 1981). Rieke *et al.* (1980) have proposed that the infrared and radio activity is the result of a massive star burst in the nucleus which has converted over the past 10^7 yr approximately $10^8\ M_\odot$ of interstellar gas into newly formed stars of mass between a few and a few tens of solar masses.

We have previously detected the 63 μm and 88 μm fine-structure line emission from [O I] and [O III] toward the center of M82 (Watson *et al.* 1984). In the present *Letter*, we discuss the spatial distribution of the 158 μm [C II] emission (most spectra first presented by Crawford *et al.* 1985). We also report the detection of the other two fine-structure lines of [O I] and [O III] at 146 and 52 μm, and some mapping of the 63 μm [O I] line. The relative strengths, line profiles, and spatial distributions of these lines give new information on the interstellar medium of M82.

II. OBSERVATIONS

The data were taken in 1983, 1984, and 1985 with the NASA Kuiper Airborne Observatory. The spectrometer was the UC Berkeley tandem Fabry-Perot described by Storey, Watson, and Townes (1980), Watson (1983), and Lugten, Crawford, and Genzel (1987). The system NEP including all instrumental and atmospheric losses was 5×10^{-14} W Hz$^{-1/2}$ at 52 and 63 μm and 6–8 $\times 10^{-15}$ W Hz$^{-1/2}$ at 146 and 158 μm. The FWHM beam sizes and velocity resolutions (Lorentzian instrumental response) used at the different wavelengths, together with the derived line fluxes, are given in Table 1. We also use for our analysis the data of the [O III] 88 μm line reported by Watson *et al.* (1984) and the (C II] 158 μm line reported by Crawford *et al.* (1985; see Table 1). We chopped the telescope's secondary by 4′ and nodded the telescope (beam-switched) between spectral scans.

Absolute calibration of the line fluxes reported in Table 1 comes from the line-to-continuum ratios in M82 and the continuum in Orion-KL. The fluxes used for calibration are listed in Table 1. The M82 fluxes are from D. A. Harper (private communication) who also gives an empirical curve for conversion of fluxes at different apertures. The Orion-KL fluxes are from Werner (1982). Absolute line fluxes are uncertain by about $\pm 30\%$. Relative line fluxes are accurate to $\pm 20\%$ and velocities to ± 10 to ± 20 km s^{-1}, depending on the resolution and signal-to-noise ratio. To convert LSR velocities to heliocentric velocities, subtract 6 km s^{-1}. The center position of our measurements was at the 2 μm peak: R.A. = $09^h51^m43^s.9$, decl. = 69°55′01″.0 (1950) (Rieke *et al.* 1980).

To compute line intensity ratios from measurements made with different beam sizes, we use the curve of growth given by Harper. This gives intensities that increase slightly slower than linearly with beam diameter between 30″ and 55″ (as one might expect for a nearly edge-on galaxy). The uncertain-

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TABLE 1
FAR-INFRARED LINE FLUXES IN M82

Line: Species and Transition	Line: Wavelength (μm)	Size: Beam Size (arcsec)	Size: Solid Angle (sr $\times 10^8$)	FWHM Velocity Resolution (km s^{-1})	Integrated Line Flux (W cm^{-2})	Absolute Calibration[a,b] (Jy)
[O III] $^3P_2 \rightarrow {}^3P_1$	51.815	30	2.7	125	8.2×10^{-18}	900 (M82)
[O I] $^3P_1 \rightarrow {}^3P_2^c$	63.1837 ...	45	5.5	125	1.9×10^{-17}	...
		30	2.7	125	1.8×10^{-17}	1040 (M82)
[O III] $^3P_1 \rightarrow {}^3P_0^c$	88.356	45	5.5	125	1.1×10^{-17}	1500 (M82)
[O I] $^3P_0 \rightarrow {}^3P_1$	145.526	55	8	125	8.1×10^{-19}	1040 (M82); 47000 (Orion; 50″)
[C II] $^2P_{3/2} \rightarrow {}^2P_{1/2}$	157.7408 ...	55	8	95	1.4×10^{-17}	940 (M82); 40000 (Orion; 50″)
				50	1.3×10^{-17}	940 (M82); 40000 (Orion; 50″)

[a] M82 continuum flux using aperture curve of growth (referred to 50″ flux) from D. A. Harper (private communication).
[b] Orion continuum flux from Werner 1982.
[c] See also Watson *et al.* 1984.

ties in densities and temperatures quoted below, reflect an uncertainty of $\pm 30\%$ to $\pm 50\%$ in line ratios, depending on the signal-to-noise ratio.

III. RESULTS

Figure 1 shows the spectra of the five far-infrared fine-structure lines toward the center of M82. Table 1 is a list of the line fluxes. Figure 2 shows maps of the 158 μm continuum and [C II] line emission derived from spectra taken at 10 positions (most of these spectra are displayed in Crawford *et al.* 1985).

a) Line Luminosities

As reported by Watson *et al.* (1984) and by Crawford *et al.* (1985), the atomic and ionic far-infrared emission lines toward M82 are very bright. The luminosity of all five lines is $\sim 2 \times 10^8$ $L_\odot$ in a $\sim 60''$ beam centered on the nucleus, that is, about 0.5% of the bolometric luminosity. Most remarkable is the high relative and absolute brightness of the 63 μm [O I] line which requires high densities and temperatures for excitation. As reported by Watson *et al.* (1984), the absolute intensities of the [O III] lines are consistent with the ionizing flux and effective temperature estimated from radio and infrared data ($N_{\rm Lyc} = 6 \times 10^{53}$ photons s^{-1}) and with the 5007 Å [O III] line if the average visual extinction toward the nucleus of M82 is ~ 6 mag and $O^{++}/O \approx 0.2$, similar to the disk of our Galaxy.

b) Line Profiles

The line profiles toward the nucleus shown in Figure 1 can be characterized by a superposition of two components. One component has an observed width of FWHM ≈ 350 km s^{-1} centered at LSR velocity ~ 220 km s^{-1}. A second component at LSR ≈ 100–170 km s^{-1} of observed width FWHM ~ 100–150 km s^{-1} (intrinsic width ≈ 80 km s^{-1}) appears prominent in the high-excitation lines (the [O I] 63 μm line and the [O III] 52 μm line), and is apparent as a blue hump or asymmetry in the [O III] 88 μm and [C II] lines (see also Duffy *et al.* 1987). We will refer to this feature as the "150 km s^{-1}" component. The apparent overall blueshift of the 63 μm line (velocity centroid ~ 130 km s^{-1} LSR) is due in part to the telluric H_2O absorption feature at ~ 660 km s^{-1} LSR. However, the 63 μm line appears only marginally consistent with the other line profiles. The far-infrared line profile of the [C II] 158 μm line is very similar to the profiles of the CO $1 \rightarrow 0$ and $2 \rightarrow 1$ lines, although the blue feature appears to be centered at higher velocity (~ 170 km s^{-1}) in the CO profiles (Olofsson and Rydbeck 1984; Rickard *et al.* 1977; Sutton, Masson, and Phillips 1983; Young and Scoville 1984). The two components also appear in the radio recombination lines observed by Seaquist, Bell, and Bignell (1985).

c) Spatial Distribution and Kinematics

Maps of the [C II] integrated intensity and the 158 μm continuum emission are presented in Figures 2*e* and 2*f*, respectively. The maps are derived from high signal-to-noise ratio spectra similar to Figure 1 (*middle*); the differences between the various maps are significant. Both the [C II] integrated emission and the continuum emission are peaked at the nucleus but are extended along the major and minor axes of the galaxy. The continuum emission is more extended along the major axis of the galaxy than along the minor axis, similar to the mid-infrared and far-infrared continuum maps by Rieke *et al.* (1980). In contrast, the integrated line emission shows similar extent along the minor axis but rather small extent along the major axis. This may be evidence for significant [C II] emission several hundred pc above and below the plane of M82 in regions of bright Hα filaments.

The individual velocity maps shown in Figures 2*a*–2*d* are consistent with the rotation pattern of M82 (e.g., Olofsson and Rydbeck 1984; Young and Scoville 1984), clearly indicating that much of the far-infrared line emission originates in the inner rotating disk or ring. The "150 km s^{-1}" excess emission is centered within 10″ of the center, and also within 10″ of the bright radio point source 41.9+58. Recombination line measurements indicate that the ionized gas near that source has an LSR velocity ~ 150 km s^{-1}. It is likely, therefore, that the 150 km s^{-1} component in the far-infrared lines originates in a region near the radio point source. There

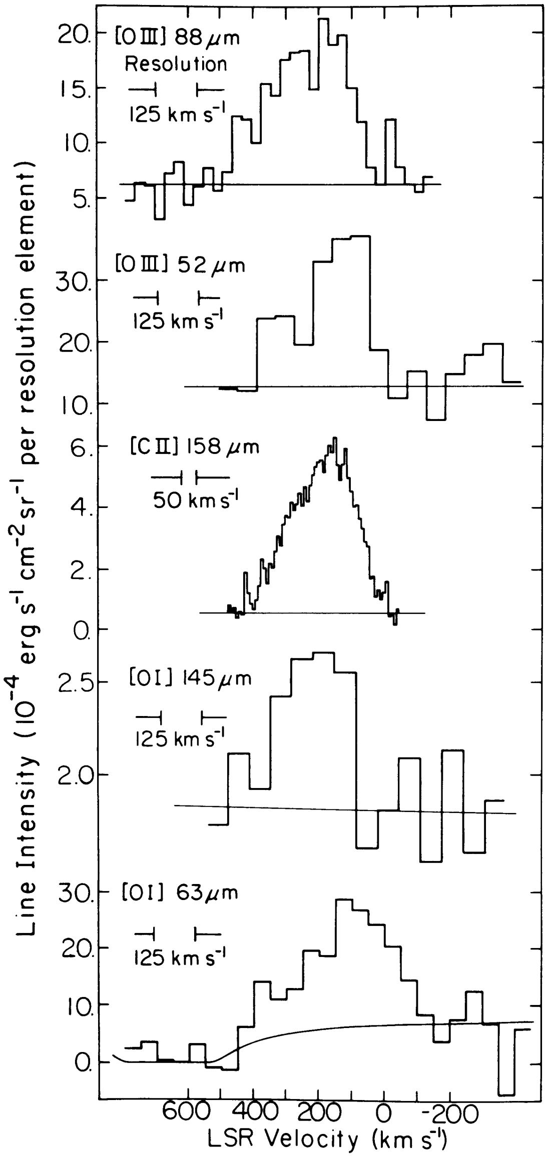

FIG. 1.—The [O III] 88 μm, 52 μm, [C II] 158 μm, and [O I] 145 μm, 63 μm line emission from the nucleus of M82 (*top to bottom*). Beam sizes were 45″, 30″, 55″, 55″, and 30″, respectively. The velocity resolution, fluxes, and flux calibration for each line are given in Table 1. In addition to the [C II] spectrum shown (*middle*), we have 10 more high signal-to-noise ratio spectra from which the maps of Fig. 2 were made (see Crawford *et al.* 1985). The shape and apparent velocity centroid of the [O I] 63 μm line are affected by a strong telluric H_2O absorption feature at $V_{LSR} \approx 660$ km s^{-1}. The effect of the feature on the continuum is shown by the light line. The atmospheric transmission has been taken into account in calculating the integrated flux shown in Table 1.

also is limited additional spatial information on the other lines. The 63 μm [O I] emission (observed with a 30″ beam) appears to be concentrated near the nucleus as well, and the observed [O I] source size is $\leq 60''$, consistent with the same size as the [C II] emission. As reported by Watson *et al.* (1984), the size and location of the 88 μm [O III] emission is consistent with an origin in the central H II region complex (Rieke *et al.* 1980).

d) *State of the Ionized Gas*

Since the far-infrared lines are collisionally excited, the relative intensities can be used to determine electron densities in the ionized gas from the [O III] 52/88 μm ratio (weak temperature dependence since $h\nu_{\rm FIR}/k \ll 10^4$ K). For the ionized gas, we use the calculations by Lester *et al.* (1986) which give the [O III] line ratio as function of density and temperature derived from the cross sections by Mendoza (1983) and Aggarwal (1983). In a single-component model and for an electron temperature between 5 and 10×10^3 K, the resulting electron density is $n_e = 120^{+120}_{-80}$ cm^{-3}. If the emission is decomposed into the 150 km s^{-1} and wide components, the resulting electron density in the 150 km s^{-1} gas is $n_e = 600^{+1000}_{-350}$ cm^{-3} and $n_e = 60^{+140}_{-60}$ cm^{-3} for the gas in the wide component. If the radio flux at 90 GHz (0.5 Jy in a 65″ beam; Jura, Hobbs, and Maran 1978) is interpreted as free-free emission, an rms electron density of ~ 7 cm^{-3} is inferred. Hence, the ionized mass in the wide component is 1×10^7 $(60 \text{ cm}^{-3}/n_e) M_\odot$ and the volume filling factor of the gas is $\phi_v^{\rm wide} = 0.1(60/n_e)$ (Seaquist, Bell, and Bignell 1985).

e) *State of the Neutral Gas*

An estimate of the hydrogen density and gas temperature in the neutral atomic gas can be obtained from the ratios of the [O I] 63 μm/[O I] 146 μm and [O I] 63 μm/[C II] 158 μm lines. This requires that the [O I] and [C II] emission regions be coextensive and that the line emission be optically thin. There is good observational support for both assumptions (cf. Crawford *et al.* 1985; Crawford *et al.* 1986; Stacey 1985; Genzel and Stacey 1985). We take the atomic hydrogen collisional excitation rate coefficients calculated by Launay and Roueff (1977*a*, *b*), and make the assumption that the O°/C^+ abundance ratio is 2.2, the same as the O/C ratio in the solar neighborhood. The results are not very sensitive to the precise value taken for the O°/C^+ ratio. From the integrated line ratios we find an atomic hydrogen density of $10^{4.3 \pm 0.5}$ cm^{-3} and a gas temperature of 200^{+180}_{-60} K. A decomposition of the line profiles indicates somewhat higher densities in the 150 km s^{-1} component than in the broad component (4×10^4 cm^{-3} compared to 1.5×10^4 cm^{-3}).

The gas pressure in the two components of the neutral atomic medium of M82 is between about 2 and 6×10^6 K cm^{-3}. The neutral atomic interstellar medium thus is at approximately the same pressure as the 10^4 K ionized gas (0.6 to 6×10^6 K cm^{-3}). If the extended X-ray emission in M82 is interpreted as coronal gas of temperature $\sim 10^7$ K, its inferred pressure is approximately 2×10^6 K cm^{-3} (Watson *et al.* 1985).

The volume filling factor of neutral gas in M82 is very small, and the emission probably comes from a large number of small clouds or thin sheets. A lower limit of the total mass of gas in C^+ regions in the central 1 kpc of M82 is 3×10^7 $M_\odot$ which is derived from the [C II] flux with the assumption that the C^+ to hydrogen ratio is 3×10^{-4}. Hence, the average hydrogen density is ~ 10 cm^{-3} and the *volume* filling factor of C^+ regions is a few $\times 10^{-4}$ to 10^{-3}. A lower limit of the *beam area* filling factor, on the other hand, comes from the brightness of the C^+ and O° lines. The Planck

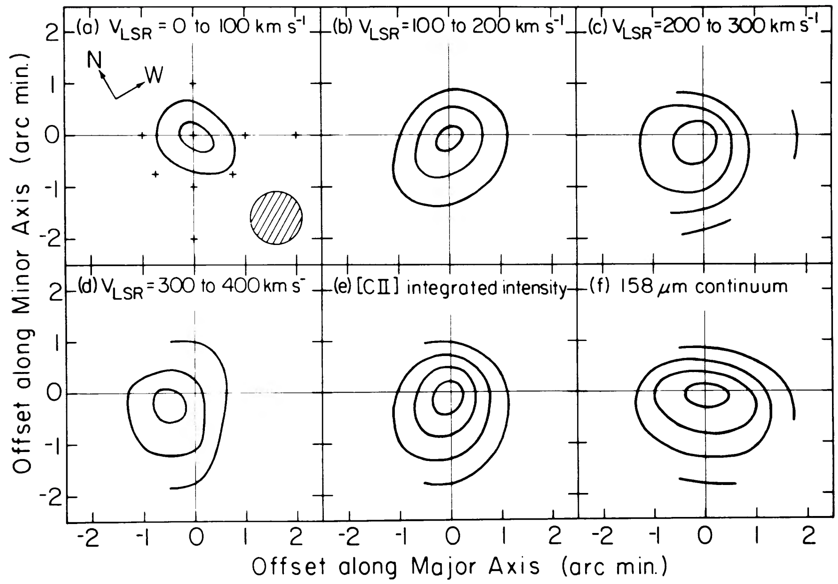

FIG. 2.—The spatial distribution of [C II] 158 μm emission, taken with a 55″ beam (shown in panel *a*) and 95 km s^{-1} velocity resolution. Spectra for the nine beam positions indicated by crosses in panel *a* are given by Crawford *et al.* 1985. A tenth spectrum was also taken at a position offset 2′ to the NW along the minor axis. Contour levels are linear with each level representing 2×10^{-4} ergs s^{-1} cm^{-2} sr^{-1} per resolution element in panels *a* and *b*; 1×10^{-4} ergs s^{-1} cm^{-2} sr^{-1} per resolution element in panels *c* and *d*; 4×10^{-4} ergs s^{-1} cm^{-2} sr^{-1} per resolution element in panel *e*; and 250 Jy in panel *f*.

brightness temperature of the C^+ line is ~ 20 K. The C^+ line is about 20 times weaker than optically thick emission at $T \approx 200$ K (the gas and excitation temperature) completely filling the beam. The optical depth of the C^+ line probably is not large even in the brightest star formation regions (Crawford *et al.* 1985; Crawford *et al.* 1986; Lugten, Stacey, and Genzel 1987), and a conservative lower limit of the area filling factor of C^+ regions at a given velocity is $\sim 10^{-1}$. The overall area filling factor of C^+ clouds irrespective of velocity may easily approach or exceed unity, since the total velocity width of the C^+ line ($\Delta v_{FWHM} \approx 260$ km s^{-1}) is significantly larger than the velocity width of a single cloud.

The large ratio ($> 10^2$) of area to volume filling factor indicates that the gas is arranged in clouds, filaments, or sheets with a large ratio of surface area to volume. In the framework of spherical clouds, the ratio of area to volume filling factor is a measure of cloud sizes and we infer (Genzel *et al.* 1985)

$$R_{\rm source}/R_{\rm cloud} \approx \phi_A/\phi_V > 10^2. \tag{1}$$

With a source radius of a few hundred pc, individual clouds must be smaller than a few pc. If the area filling factor of all clouds were unity, the implied cloud sizes are 0.1 to 1 pc. The mass of each cloud would be 10–10^4 $M_\odot$ and the total number of clouds would be 10^3–10^6. For the case of randomly oriented thin sheets, the sheet thickness replaces $R_{\rm cloud}$ in equation (1), and the sheets would be thinner than a few pc.

There is evidence that the *molecular* emission in M82 also comes from a similar distribution of gas. The ratios of $2 \rightarrow 1$ to $1 \rightarrow 0$ ^{12}CO intensities and $1 \rightarrow 0$ ^{12}CO to ^{13}CO and ^{12}CO to C^{18}O intensities suggests that the CO emission is optically thin (Knapp *et al.* 1980; Stark and Carlson 1984; Sutton, Masson, and Phillips 1983). Lo *et al.* (1985) find peak CO 1–0 brightness temperatures of 16 K on a scale size of 110 pc (7″), more than 3 times higher than typical giant molecular clouds in our own Galaxy when averaged over the same scale. This implies intrinsic ^{12}CO brightness temperatures of at least several tens of K. The requirements of low optical depth and relatively high brightness temperature then suggest small (0.1 to 1 pc), dense cloudlets (Knapp *et al.* 1980).

IV. CONCLUDING REMARKS

Table 2 contains a comparison of the characteristics of the central 1 kpc of M82 and our own Galaxy. It is striking that M82 is quite comparable to our Galaxy in its stellar and gaseous (H_2 + H I) mass, but is exceptional in its infrared luminosity which is almost two orders of magnitude larger than in our Galaxy. This fact is, of course, a cornerstone of the starburst hypothesis (Rieke *et al.* 1980). The large infrared luminosity probably indicates that the OB star formation rate and the energy density of the UV radiation field (ε_{UV} in Table 2) are two orders of magnitude larger than in our Galaxy. The data presented in this *Letter*, by Lo *et al.* (1985), and by Seaquist, Bell, and Bignell (1985) are in very good agreement with the starburst hypothesis and now clearly demonstrate the effects of high star formation rate on the interstellar medium. In M82 we find the following:

1. About 30% of the interstellar gas mass is directly affected by photoionization and UV heating and is present in H II and C^+ regions (Table 2). The corresponding number in our galaxy is 1%–2%.

2. The large energy density in the radiation field and in cloud motions and cosmic rays due to stellar winds and

TABLE 2

COMPARISON OF THE INTERSTELLAR MEDIA IN THE CENTRAL 1 KILOPARSEC OF M82 AND OUR OWN GALAXY

Parameter	M82	Galaxy
Far-IR luminosity ($L_\odot$)	4×10^{10} [a]	5×10^{8} [b]
Near-IR + visible luminosity	$1\text{–}2 \times 10^{10}$ [c]	$2\text{–}5 \times 10^{9}$ [b]
ϵ_{UV} (6×10^{-13} ergs cm^{-3})	$1\text{–}3 \times 10^{3}$ [d]	10–100 [d]
Total stellar and gaseous mass	$5\text{–}10 \times 10^{8}\ M_\odot$ [c]	$10^{10}\ M_\odot$ [c]
Mass in molecular hydrogen	$8 \rightarrow 40 \times 10^{7}$ [f, g, h]	$5 \rightarrow 40 \times 10^{7}$ [j, k]
Mass in atomic hydrogen	1×10^{7} [m]	4×10^{6} [n]
Mass in C^+ regions	3×10^{7} [p]	5×10^{6} [n]
Mass in H II regions	3×10^{7} [q]	4×10^{6} [n, r]
Pressure of the interstellar medium (K cm^{-3})	$10^{6}\text{–}10^{7}$ [p]	3×10^{4} [p]

[a] D. A. Harper private communication.
[b] Mezger 1984.
[c] Rieke *et al.* 1980.
[d] Calculated from total far-IR luminosity using $\epsilon_{UV} = L_{IR}/\pi c R^2$, where c is the speed of light, and R is the radius of the source; Crawford *et al.* 1985.
[e] Oort 1977.
[f] Jaffe, Becklin, and Hildebrand 1984.
[g] Sutton, Masson, and Phillips 1983.
[h] Young and Scoville 1984.
[j] Blitz *et al.* 1985.
[k] Sanders, Solomon, and Scoville 1984.
[m] Weliachew, Fomalont, and Greisen 1984.
[n] Stacey 1985.
[p] This *Letter*.
[q] Seaquist, Bell, and Bignell 1985.
[r] Mezger 1978.

supernovae explosions has heated the overall neutral interstellar medium to 50 to 200 K (Olofsson and Rydbeck 1984; Lo *et al.* 1985), compared to about 10 K in the disk of our Galaxy.

3. The large energy input due to OB star formation has created a high pressure in H II regions and in the neutral gas. The neutral interstellar gas is compressed to densities about an order of magnitude higher than in our own Galaxy, and there is a coronal medium which extends to large scale heights. The high gas pressure may also be responsible for large cloud motions which drives the molecular (Lo *et al.* 1985; Stark and Carlson 1984) and warm atomic gas to a few hundred pc above the plane.

One might speculate what consequences on present and future star formation the unusual state of the interstellar medium in M82 should have. First, the high temperatures and densities probably favor the formation of massive stars (Larson 1985), as was inferred by Rieke *et al.* (1980). Second, the neutral interstellar clouds may eventually be dispersed and completely disrupted, thus preventing further star formation and bringing the starburst to an end.

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