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SUBMILLIMETER AND FAR-INFRARED SPECTROSCOPY OF M17 AND S106: UV-HEATED, QUIESCENT MOLECULAR GAS?

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ABSTRACT

We report measurements of 372 μm $J = 7 \rightarrow 6$ and 186 μm $J = 14 \rightarrow 13$ CO line emission toward the interface between the molecular cloud and the H II region in M17, and toward the center of the bipolar nebula S106. The submillimeter $J = 7 \rightarrow 6$ emission is bright: T_B(Planck) $\approx$ 100 K. The ratio of $14 \rightarrow 13/7 \rightarrow 6$ lines indicates gas temperatures between 200 and 500 K, and hydrogen densities $\geq 10^4$ cm^{-3}. Compared to previously investigated sources of submillimeter and far-infrared CO emission, the $7 \rightarrow 6$ lines are remarkably narrow, with widths of $\Delta v_{FWHM} \approx$ 5–10 km s^{-1}, identical to those of the cool quiescent molecular cloud cores. The unresolved far-IR $14 \rightarrow 13$ line profiles also indicate intrinsic widths less than 20 km s^{-1}.

The warm quiescent molecular gas is in the interface between the exciting OB stars and the surrounding molecular cloud. The molecular hydrogen column densities of the warm component are at least 10^{22} cm^{-2}, representing $\geq$ 5% of the total molecular mass in the cloud cores. Comparison of the submillimeter, far-IR, and millimeter CO line intensities and profiles suggests a model in which clumps of relatively cool gas ($T \approx$ 50 K) have warm surfaces or are embeded in a warm surrounding medium. Possible heating mechanisms of the warm CO gas are slow shocks and heating by protoelectrons in UV-illuminated, photodissociation regions. The present observations favor photoelectric heating.

Subject headings: interstellar: matter — interstellar: molecules — nebulae: individual (M17, S106) — stars: formation

I. INTRODUCTION AND OBSERVATIONS

The M17 SW molecular cloud, at distance $\approx$ 2.4 kpc (Lada 1976; Elmegreen and Lada 1976; Thronson and Lada 1983), forms a sharp interface with the H II region around the luminous M17 OB stellar cluster ($L \approx 6 \times 10^6$ $L_\odot$; Beetz *et al.* 1976, Harper *et al.* 1976). Dense molecular gas in this edge on interface is heated by ultraviolet (UV) radiation from this external OB cluster (Elmegreen and Lada 1976; Gatley *et al.* 1979). The bipolar nebula S106, at distance 0.6 kpc (Staude *et al.* 1982), is commonly interpreted as a remnant cloud around a young, late O or early B star (IRS 4) with luminosity 2×10^4 $L_\odot$ (Gehrz *et al.* 1982) which is associated with bipolar mass outflow of ionized gas (Hippelein and Münch 1981). The exciting star is embedded in a dense disk of diameter ~ 0.15 pc (Mezger *et al.* 1987).

We observed the 806.6517 GHz (372 μm) CO $J = 7 \rightarrow 6$ line with the UCB/MPE Cassegrain Heterodyne Spectrometer (Harris *et al.* 1987) on the NASA Infrared Telescope Facility (IRTF; 32″ beam, 6′ E–W chop throw) in 1986 May and on the United Kingdom Infrared Telescope (UKIRT; 25″ beam, 3′ E–W chop) in 1986 June. The single-sideband system temperature was 9000 K. The backend was a 1024 channel Acousto-optical Spectrometer covering 220 km s^{-1}. We calibrated the zenith sky transmission, which ranged between 15% and 25%, by observing the atmospheric emission temperature at a variety of zenith angles, and assuming a sec(z) emission temperature dependence and a physical sky temperature of 273 K. Absolute temperature scales, calibrated against hot and ambient temperature blackbody loads, are accurate within ±30%. The main beam efficiencies (0.5 on IRTF, 0.35 on UKIRT) were determined by observing Jupiter.

We observed the 185.9994 μm CO $J = 14 \rightarrow 13$ line with the U.C. Berkeley Mark II Tandem Scanning Fabry-Perot spectrometer (Crawford *et al.* 1986; Lugten 1987) in flights from Christchurch, New Zealand (1986 May) and from Moffett Field, California (1986 July) on the NASA Kuiper Airborne Observatory. The system noise equivalent power

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(NEP) was $\sim 4 \times 10^{-15}$ W $\mathrm{Hz}^{-1/2}$, and the velocity resolution chosen was 54 km s^{-1} FWHM in M17 and 39 km s^{-1} in S106 (Lorentzian profile). The beam size was about 55″ FWHM with a chop throw of 4′. Absolute fluxes in the 186 μm lines were calibrated against the continuum fluxes of Mars and Jupiter within $\pm 30\%$.

Position offsets are referred to (0, 0) positions $18^{\mathrm{h}}17^{\mathrm{m}}34\overset{\mathrm{s}}{.}5$, $-16°13'24''$ in M17, and $20^{\mathrm{h}}25^{\mathrm{m}}33\overset{\mathrm{s}}{.}8$, $37°12'50''$ in S106.

II. RESULTS

Figure 1 shows the $7 \rightarrow 6$ and $14 \rightarrow 13$ spectra toward M17 and S106. Figure 2 shows integrated CO line intensities as a function of rotational quantum number J_{upper}. Figure 3 is a 25″ resolution map of CO $7 \rightarrow 6$ emission in S106, superposed on the 22 GHz map of Felli *et al.* (1984).

The submillimeter and far-infrared CO emission in both M17 and S106 comes from warm ($T \geq 200$ K) and relatively dense gas. The main beam brightness temperature of the $7 \rightarrow 6$ line is high: $T_{\mathrm{mb}} \approx 55$–$85$ K. The corresponding Planck brightness temperatures are near 100 K, after correcting the S106 brightness temperature for beam dilution by a factor of ~ 1.4. This is a strict lower limit to the gas kinetic temperature, appropriate if the gas density is high [$n(\mathrm{H_2}) \gg 10^4$ cm^{-3}], the line is optically thick, and if the emission uniformly

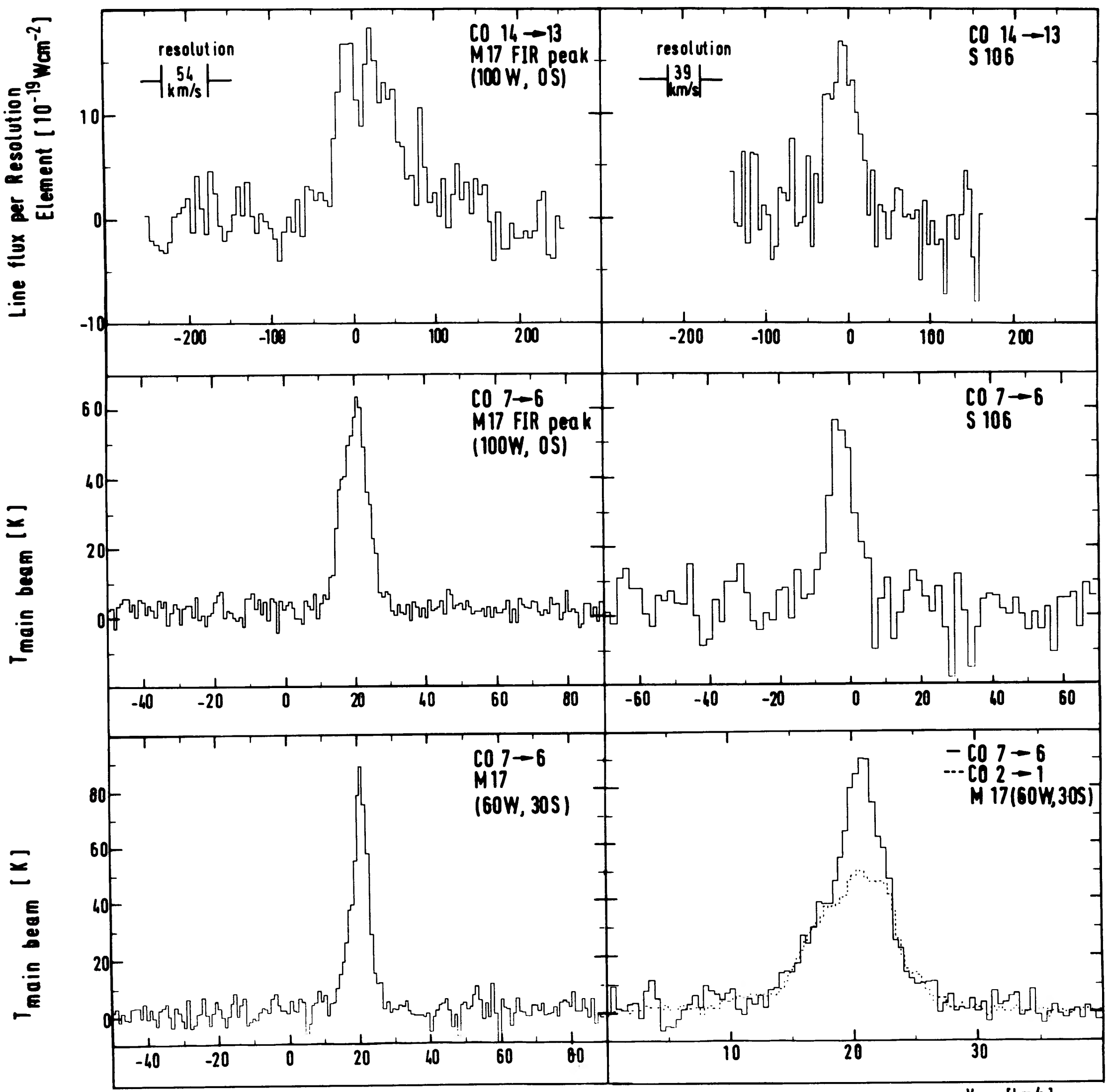

FIG. 1.—$J = 7 \rightarrow 6$ (372 μm) and $14 \rightarrow 13$ (186 μm) CO spectra toward M17 and S106 (no baseline correction to any of the data). Note the changes in velocity and intensity scales. (*top*) $14 \rightarrow 13$ spectra (beam size 55″ toward the far-infrared peak of M17) (*left*; [0, 0] reference at R.A. = $18^{\mathrm{h}}17^{\mathrm{m}}34\overset{\mathrm{s}}{.}5$, decl. = $-16°13'24''$ [1950]), and S106 IRS 4 (*right*; R.A. = $20^{\mathrm{h}}25^{\mathrm{m}}33\overset{\mathrm{s}}{.}8$, decl. = $37°12'50''$). (*middle*) $7 \rightarrow 6$ spectra toward the same positions in M17 (*left*, 32″ beam) and S106 (*right*, 25″ beam). Given are main beam brightness temperatures. (*bottom*) $7 \rightarrow 6$ spectrum toward R.A. = $18^{\mathrm{h}}17^{\mathrm{m}}30\overset{\mathrm{s}}{.}3$, decl. = $-16°13'54''$ (*left*), and the same $7 \rightarrow 6$ spectrum superposed on a CO $2 \rightarrow 1$ spectrum observed with the MWO (N. J. Evans, private communication).

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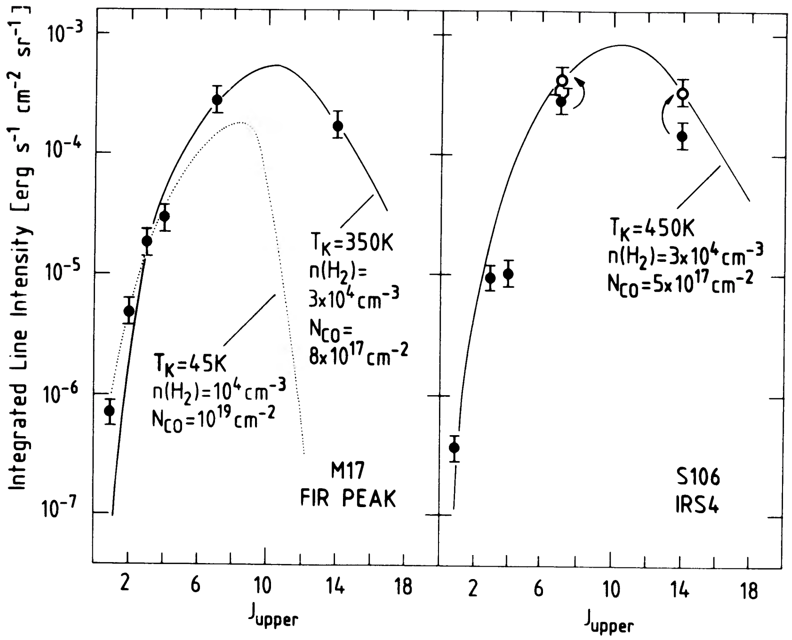

FIG. 2.—Integrated CO intensities as a function of J for the M17 FIR peak (*left*) and S106 IRS 4 (*right*). The $7 \rightarrow 6$ and $14 \rightarrow 13$ data are from this *Letter*. In the case of S106, the open circles are the measured integrated intensities (*filled circles*) corrected for beam dilution. Representative cooling curves for the minimum column densities in the warm gas (see text) are shown with the parameters indicated on the figure. The lower-J data for M17 are taken from Thronson and Lada (1983; $1 \rightarrow 0$), C. J. Lada (private communication; $2 \rightarrow 1$), Rainey *et al.* (1987; $3 \rightarrow 2$), and Schulz and Krügel (1987; $4 \rightarrow 3$). The density and column density of the 45 K component are sufficient to thermalize the gas in the lower-J lines, but have no further significance. Data for S106 are taken from Bally and Scoville (1982; $1 \rightarrow 0$), and White *et al.* (1986; $3 \rightarrow 2$ and $4 \rightarrow 3$).

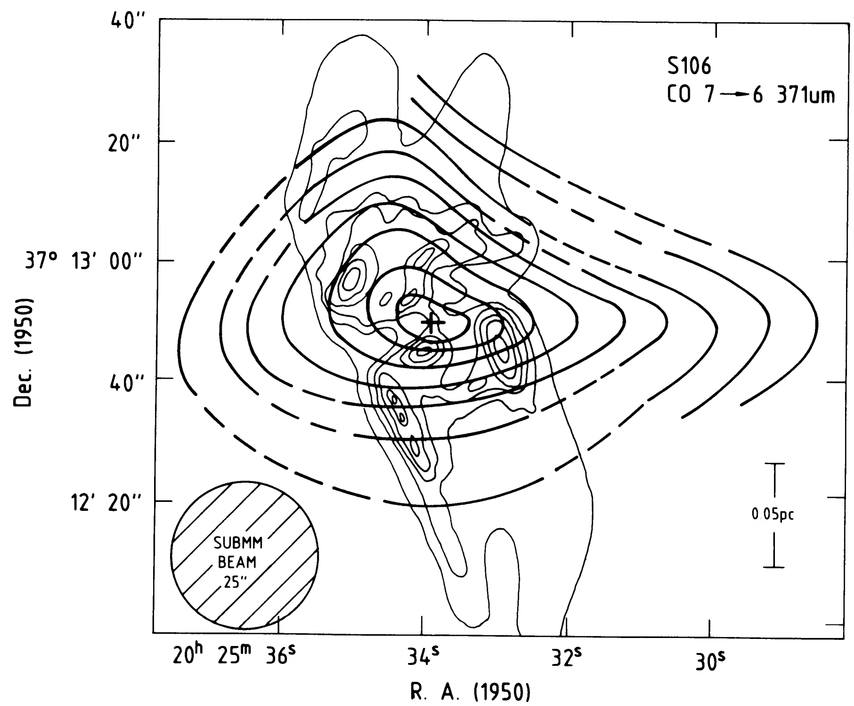

FIG. 3.—Map of $7 \rightarrow 6$ integrated line emission based on spectra taken at 15 positions (UKIRT: beam 25″ FWHM), superposed on a schematic of the radio continuum emission (cf. Felli *et al.* 1984, 2″ beam resolution). The contours are in units of 50 K km s^{-1} (main beam brightness temperature), starting with the lowest contour at 100 K km s^{-1}. The cross marks the position of the exciting star IRS 4.

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fills the beam. The detection of the $J = 14 \rightarrow 13$ line at only slightly lower intensity than the $7 \rightarrow 6$ line immediately shows that a substantial amount of gas is even warmer than 100 K, since the overall CO cooling curve peaks at $J \approx 10$, with an energy above the ground state of about 300 K.

More precise constraints on the physical parameters of the emitting medium can be derived if the $7 \rightarrow 6$ and $14 \rightarrow 13$ lines come from the same gas. We computed level populations of the lowest 25 levels of CO as a function of density, temperature, and column density in an escape probability, radiative transfer formalism. We assumed statistical equilibrium, a CO abundance of 8×10^{-5}, and used cross sections from Schinke *et al.* (1985) and Flower and Launay (1985).

To account for the $7 \rightarrow 6$ brightness temperature in both sources in a medium of density $n(H_2) \leq 10^6$ cm^{-3} and temperature $T_{kin} \leq 1000$ K, the beam-averaged column density of warm CO must be at least 6×10^{17} cm^{-2}. At that column density, where $\tau(7 \rightarrow 6) \approx 1$, the ratio of $14 \rightarrow 13$ to $7 \rightarrow 6$ lines indicates a gas pressure $\geq 10^7$ K cm^{-3}. Hydrogen density/temperature combinations ranging from 1.5×10^5 cm^{-3} at 200 K to 1.6×10^4 cm^{-3} at 700 K give acceptable fits to the line ratio (see representative curves in Fig. 2). There is no reasonable solution at $T_{kin} \leq 150$ K. At higher column densities, trapping decreases the required excitation. At a CO column density of 6×10^{18} cm^{-2}, the required pressure is about 4×10^6 K cm^{-3}, again with similar ranges of possible density/temperature combinations. The most likely kinetic temperature of the warm CO gas in both sources is between 200 and 500 K.

Mapping of the $7 \rightarrow 6$ line in M17 (which will be discussed in detail in Stutzki *et al.* 1987) indicates that the emission originates in a narrow (width $\approx 120'' \equiv 1.4$ pc) ridge at the interface between the H II region and the M17SW molecular cloud. The two positions at which the M17 spectra shown in Figure 1 were taken are directions of maximum $7 \rightarrow 6$ intensity. The $7 \rightarrow 6$ CO emission in S106 is elongated E–W, coming from a compact source with diameter $\approx 50'' \equiv 0.15$ pc centered on IRS 4. The distribution and extent of the submillimeter line emission closely resemble the gas and dust disk (Bieging 1984; Mezger *et al.* 1987) perpendicular to the bipolar ionized flow.

Integrated over the $2' \times 4'$ H II/M17SW interface region (component M17a in Wilson *et al.* 1979), the total mass of warm gas is greater than 500 $M_\odot$ and the mean molecular hydrogen density is greater than 1.2×10^3 cm^{-3}. A comparison to a likely value for the local hydrogen volume density then suggests that the gas is clumped with a volume filling factor of ≈ 0.1. The total ^{12}CO column density at the M17 $7 \rightarrow 6$ peak is about 1–2 $\times 10^{19}$ cm^{-2} [$N(H_2) \approx$ 1–2 $\times 10^{23}$ cm^{-2}], as estimated from the ^{13}CO $J = 1 \rightarrow 0$ intensity (Thronson and Lada 1983) and the 50 μm dust opacity (Gatley *et al.* 1979). Hence, at least 5% of the molecular gas in the M17 interface region is at $T_{kin} \geq 150$ K.

The luminosity of the $7 \rightarrow 6$ line at each of the two positions in M17 (Fig. 1) is about 1 $L_\odot$. Integrated over the interface region, the $7 \rightarrow 6$ luminosity is about 38 $L_\odot$, and the total CO cooling from all rotational lines is 10 times larger. Thus, the CO line emission in M17 contains about 4×10^{-4} of the several 10^6 $L_\odot$ total luminosity in M17a (Harper *et al.* 1976), and about 10^{-2} of the $\lambda \leq 10$ μm luminosity, 3.6×10^4 $L_\odot$ (Harper *et al.* 1976).

In S106, by comparison, the total mass and luminosity of warm gas are about 2 orders of magnitude smaller than in M17 (≥ 0.7 $M_\odot$, 1 $L_\odot$), scaling approximately as the ratio of the UV luminosities of the two star forming regions.

Further constraints on the physical parameters of the molecular gas can be derived from comparison with additional CO lines. In M17, information on ^{12}CO and ^{13}CO line emission is available from a large body of observations of the $1 \rightarrow 0$ up to $4 \rightarrow 3$ transitions (references in Fig. 2). The CO emission from states up to at least $J = 3$ does not appear to come from the same component of gas emitting in transitions with $J \geq 7$. The ^{12}CO brightness temperature does not change much with rotational quantum number up to $J = 4$. This is characteristic of an optically thick, isothermal cloud of temperature ~ 45 K (see model in Fig. 2). At the $(-60'', -30'')$ position, the ^{12}CO brightness temperatures of the lower-J transitions are significantly weaker than the $7 \rightarrow 6$ line. Line shape comparisons also indicate the presence of at least two gas components. The line widths increase from about 8 km s^{-1} for the $1 \rightarrow 0$ line to about 9.6 km s^{-1} for the $3 \rightarrow 2$ line with apparently increased line wings. The discrepancy with the $7 \rightarrow 6$ line brightness is apparent from Figure 1 (*bottom*) which shows a comparison to the $2 \rightarrow 1$ line profile (N. J. Evans, private communication). This comparison also emphasizes that the line profiles in the wings are in good agreement, but that an upper part of the $2 \rightarrow 1$ line appears to be missing. These facts suggest that the changes in line brightness and profile between the $1 \rightarrow 0$ and $7 \rightarrow 6$ lines are caused by radiative transport in gas with at least two different temperature regimes. Multicomponent model computations will be discussed in Stutzki *et al.* (1987).

The situation in S106 is again similar to that in M17 in these points. The lack of a peak in emission from the IRS 4 dust disk in low-excitation 1–0 and 2–1 millimeter molecular lines of ^{12}CO, C^{18}O (cf. Mezger *et al.* 1987) may be partly a result of the increase of gas temperature toward IRS 4.

III. DISCUSSION

The most important finding of our submillimeter and far-infrared observations is the detection of a significant amount of warm quiescent molecular gas. Compared with other sources with equally high kinetic temperatures, the line widths of the submillimeter and far-infrared CO lines in both sources are remarkably narrow. One important observation is that in both sources the velocity dispersion of the warm gas is about the same as that of cooler CO gas further away from the heating sources and deeper into the "undisturbed" molecular cloud. The FWHM of the $7 \rightarrow 6$ line at the far-infrared peak at $(-100'', 0'')$ is 8.5 km s^{-1}, and is 4.7 km s^{-1} at the position $(-60'', -30'')$. In S106, the width of the $7 \rightarrow 6$ line is 9 km s^{-1}, and there are no significant line wings indicative of high-velocity emission. The far-infrared line profiles are unresolved, implying a line width no larger than about 20 km s^{-1} (FWHM). In many sources (e.g., Orion-KL, W51, W49, Sgr A), the $7 \rightarrow 6$ and far-infrared line emission typically extends over a range of at least 30 km s^{-1}.

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a) *Heating Mechanisms of the Warm Quiescent Gas*

Since the gas is warmer than the majority of the dust, heating by collisions of molecules with the dust grains emitting at $\lambda \geq 30\ \mu$m, commonly assumed to be the major source of gas heating in molecular clouds, is not likely to be important. Collisional heating of the gas by dust grains with $T \approx 100$–200 K, emitting strongly in the mid-infrared, is also improbable. Extended $\lambda \leq 10\ \mu$m continuum emission with a luminosity 2 orders of magnitude greater than the CO luminosity has been detected in M17 and S106 (Harper *et al.* 1976; Gehrz *et al.* 1982), but almost certainly comes from dust grains within the H II region, and not from dust mixed with the molecular material. Two attractive heating mechanisms are shocks and photoelectric heating.

i) *Shock Heating*

In many sources MHD shocks (Draine 1980) from supersonic mass flows or cloud-cloud collisions appear to excite high-*J* molecular levels. In M17, Gatley *et al.* (1987) find widespread 2 μm quadrupole line emission from vibrationally excited molecular hydrogen, presumably excited by shocks. In S106, Longmore, Robson, and Jameson (1986) find H_2 emission along the ionized bipolar flow, perpendicular to and more extended than the warm $7 \rightarrow 6$ emission region.

The narrow $7 \rightarrow 6$ lines in M17 and in S106 constrain the shock velocities to less than 10 km s^{-1}. In the models of Draine and Roberge (1984), the $7 \rightarrow 6$ intensity of a 7 km s^{-1} face on, plane parallel shock at a preshock hydrogen density of 10^4–10^5 cm^{-3} and a magnetic field of 100 μG is only about 6 to 25×10^{-6} ergs s^{-1} cm^{-2} sr^{-1} (assumed CO abundance 7×10^{-5}). Hence, the observed $7 \rightarrow 6$ intensities of $\sim 2.5 \times 10^{-4}$ ergs s^{-1} cm^{-2} sr^{-1} require the equivalent of 40 to 10 "stacked-up" fronts within the beam. Such a large number of shocks along any line of sight appears somewhat improbable, but not impossible. For comparison, Martin, Sanders, and Hills (1984) find in their "clumpy cloud" model of M17 that the mean number of fragments at all velocities on a line of sight is about 7 for a best fit to the lower-*J* CO data.

The main arguments against excitation of the submillimeter and far-infrared CO lines by slow shocks are that energy in turbulence would be rapidly dissipated by shocks, and that the warm CO gas near the central energy sources has the same narrow line width as the cooler gas deeper in the molecular cloud. Low-velocity shocks could be produced by clump-clump collisions (turbulence), or by the propagation of the ionization front into the molecular cloud. The total kinetic energy in turbulent clump motions in M17a is $\sim 10^{49}$ ergs. Therefore, the time scale for dissipation of clump-clump velocity differences by shocks is 3×10^4 yr if 20% of the thermal energy liberated in the shock emerges in CO lines. This time scale is quite small, and it would be necessary for turbulent energy to be continuously replenished.

If shock heating were important in the interfaces of M17 and S106, then excitation by shocks from cloud-cloud collisions caused by local velocity dispersion should generate high-*J* CO emission throughout the cloud, which is not observed. An additional shock at the interface of the cloud with the H II region could heat the gas in M17 with the special geometry of shock propagation perpendicular to the line of sight. That scenario, however, is highly unlikely to hold for all sources with narrow submillimeter CO emission: M17, S106, DR21, and G34.3+0.1 (Jaffe, Harris, and Genzel 1987; Jaffe *et al.* 1987).

ii) *Photoelectric Heating*

A second excitation mechanism is gas heating by photoelectrons. The warm molecular gas in M17 and S106 originates in interface regions at the edges of molecular clouds which are exposed to high far-ultraviolet fluxes. The far-UV energy density at the surface of the M17 cloud is about 1.5–2×10^{-8} ergs cm^{-3}, equivalent to 3×10^4 times the UV energy density of the local interstellar radiation field. The UV energy density in S106 is about the same as in M17, due to the difference in sizes. Warm atomic gas ($0°, C^+$) from photodissociation regions at the same positions as the warm CO emission has been found in M17 by Stutzki *et al.* (1987). Tielens and Hollenbach (1985) showed that photoelectrons ejected from dust grains heat the atomic gas in the "photodissociation" region at $A_v \leq 3$ from the cloud surface to $T_{\rm gas} \geq 300\ {\rm K} > T_{\rm dust}$. If prevented from dissociation by self-shielding, molecular material would also be heated by the photoelectric effect. Photoelectric heating of CO is further supported by the coexistence of warm atomic and molecular gas in both M17 and Sgr A with about the same physical parameters (Stutzki *et al.* 1987; Harris *et al.* 1985), and the narrow-line CO $7 \rightarrow 6$ emission which tracks the distribution of ionized gas in W51 (Jaffe *et al.* 1987). Furthermore, the amount of warm CO gas and the size of the emitting regions in M17 and S106 scale linearly with the UV luminosities.

b) *Summary*

Heating of the warm, dense, quiescent molecular gas by collisions with dust grains can clearly be excluded. Slow shocks or heating by photoelectrons are both possible. The most promising mechanism is photoelectric heating. The existence of a substantial amount of warm, quiescent molecular gas in UV-illuminated regions may be of importance locally in most OB star formation regions and globally in external galaxies with large rates of star formation.

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