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AFGL 5376: A STRONG, LARGE-SCALE SHOCK NEAR THE GALACTIC CENTER

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ABSTRACT

We present observations of ^{12}CO $J = 2$–1 emission in a 15′ × 15′ region around AFGL 5376 ($l = 359°.5$, $b = 0°.43$), an unusually warm ($T_c = 100$ K) and extended *IRAS* source located near the Galactic center. The new spatial maps made with the Caltech Submillimeter Observatory (CSO) confirm that (1) there is a clear association of high-velocity CO emission with the infrared source—the CO emission nearly completely surrounds the infrared peak at a radius of about 4′, and (2) AFGL 5376 defines the most prominent portion of a strong (∼50 km s^{-1}), large-scale (90 pc) shock front. Contour maps produced from the Bell Labs ^{12}CO $J = 1$–0 Galactic center datbase are also presented; they show that the forbidden velocity emission surrounding AFGL 5376 forms a well-defined tongue of gas that extends perpendicularly from the Galactic plane out to $b \cong 0°.9$. The shape and location of the CO tongue lead us to suggest that it is the molecular counterpart of the western limb of a prominent radio continuum feature, the Galactic center lobe (GCL). Its total H_2 mass is $\sim 10^6\ M_\odot$. The distributions of relatively low velocity (50–115 km s^{-1}) and high velocity (115–160 km s^{-1}) gas are separated across a remarkably well defined and narrow rift which extends latitudinally through the CO tongue for about 0°.6 (about 90 pc, assuming $d_{gc} = 8.5$ kpc), making it perhaps the largest continuous shock observed near the Galactic center.

We hypothesize that the rift bisecting the western edge of the GCL marks the location where a system of gas in noncircular motion about the Galactic center is colliding with ambient material above the Galactic plane. The absence of CO emission directly toward the peak of AFGL 5376 and along other portions of the shock front is attributed to the shock-induced dissociation or heating of CO; only the shock-heated dust grains have survived to manifest themselves as the infrared source AFGL 5376. The western edge of the radio continuum GCL is evidence of shock ionization along a line parallel to the dissociation front.

The noncircular gas motions characterizing the gas associated with AFGL 5376 are linked to the large-scale kinematical feature known as the expanding molecular ring (EMR). The observations presented here are used to contrast competing theories for the EMR: an explosion-induced ring of expanding gas versus the reaction or orbiting gas to a bar potential.

Subject headings: Galaxy: center — ISM: individual (AFGL 5376) — ISM: kinematics and dynamics — ISM: molecules — shock waves

1. INTRODUCTION

AFGL 5376 is an extended (6′ radius) and approximately circularly symmetric infrared source located near the Galactic center ($l, b = 359°.5, 0°.43$) (Cox & Laureijs 1989; Uchida & Morris 1989; Uchida, Morris, & Serabyn 1990, hereafter Paper I). In both *IRAS* images and the Air Force rocket surveys of the Galactic center (Little & Price 1985), AFGL 5376 appears prominently at wavelengths near 25 μm; however, it only marginally stands out against the background in the other *IRAS* bands. AFGL 5376 is thus comprised of unusually warm dust grains. Its dust color temperature, based on ratios of excess *IRAS* fluxes (3.0 MJy sr^{-1} at 12 μm, 121.5 MJy sr^{-1} at 25 μm, and 360.6 MJy sr^{-1} at 60 μm), is approximately 100 K (for an emissivity proportional to frequency, the dust temperature is 94 K from the [25 μm/12 μm] ratio, and 73 K from the [60 μm/25 μm] ratio; Uchida 1993; Uchida & Morris 1994). AFGL 5376 is unique by virtue of this fact; the only other extended infrared source within a degree of the Galactic center that shares this characteristic is AFGL 5382, a known foreground H II region. However, AFGL 5376 is not observed in Galactic center radio continuum surveys (Altenhoff et al. 1978; Sofue et al. 1984) and can therefore be ruled out as an H II region. There is no evidence for a supernova remnant within its vicinity nor is there any indication in the infrared of a concentration of nearby evolved stars. Thus, the heating of the dust in AFGL 5376 does not appear to originate from a stellar source.

Another intriguing aspect of AFGL 5376 is its proximity to the western side of the Galactic center lobe (GCL), a hypothesized large-scale radio continuum shell straddling the Galactic center (Sofue & Handa 1984; Sofue 1985). The GCL is defined by two arc-shaped spurs, located at $l = 0°.2$ (the eastern spur: GCL-E) and 359°.4 (the western spur: GCL-W), both of which extend from the Galactic plane out to about $b = 0°.9$. The morphology of the GCL, and its location with respect to the Galactic center, have led some to speculate that it is either the result of a tremendous energy release from the Galactic center and the subsequent channeling of material out of the plane by poloidal field lines (Sofue 1984; Umemura et al. 1988) or the result

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of the extrusion of gas along magnetic field lines twisted by Galactic rotation (Uchida, Shibata, & Sofue 1985; Shibata & Uchida 1987).

In Paper I we presented ^{12}CO $J = 2$–1 observations taken along several strips across AFGL 5376 and nearby portions of GCL-W. These observations revealed high forbidden velocity ($V = 60$–160 km s^{-1}) spectral lines with large line widths ($\Delta V = 23$–33 km s^{-1}) toward these features. Association of this gas with AFGL 5376 was implied: both the latitude and the longitude strips crossing AFGL 5376 show peaks in CO emission 4′ to either side of the infrared maximum, suggesting that AFGL 5376 is surrounded by a ring of molecular material. The high velocities and large line widths, characteristic of the Galactic center gas population (Bally et al. 1987, 1988), locate AFGL 5376 near the Galactic center. At a few locations, the velocity field jumps discontinuously; abrupt shifts in velocities of ≥ 20 km s^{-1} occur over one or two beam spacings. If all of this emission does indeed arise from the same region and not from a line-of-sight superposition of unassociated molecular features, then the velocity jumps probably indicate that AFGL 5376 and GCL-W are the sites of strong shocks.

Based on these data, we speculated that GCL-W is a direct result of the ejection or extrusion of non–circularly moving gas from the Galactic plane, and that AFGL 5376 is a molecular cloud participating in this gas flow. The high dust temperature in AFGL 5376, and the abrupt velocity jumps observed nearby, would then be indications of shock activity resulting from the collision process.

While the CSO data of Paper I provided interesting clues into the nature of AFGL 5376 and its potential association with GCL-W, they were sparse. A more complete sampling of the region around AFGL 5376 was warranted to better (1) investigate the putative association between AFGL and the surrounding CO emission, (2) detail the correspondence of the out-of-plane CO emission with GCL-W, (3) resolve the regions over which the velocity jumps occur, and (4) determine if these velocity jumps represent continuous shock fronts, and if so, determine the spatial extent of the shock region.

In this paper we present a new set of ^{12}CO $J = 2$–1 observations, taken at the Caltech Submillimeter Observatory, comprising a complete 15′ × 15′ grid centered on AFGL 5376. Also presented are ^{12}CO $J = 1$–0 maps produced from the AT&T Bell Laboratories Galactic center database (Bally et al. 1994) which detail the larger scale gas distribution (1$^\circ\!\!.$5 × 2$^\circ\!\!.$0) around AFGL 5376 and the GCL. The maps confirm that AFGL 5376 is almost completely surrounded by high "forbidden" velocity CO gas and that, on a large scale, this gas feature is tongue-shaped, extending perpendicular to the Galactic plane. Furthermore, it is nearly coincident with the GCL and is longitudinally bisected by what is perhaps the largest continuous shock front in the Galactic center region.

2. OBSERVATIONS

2.1. *Equipment and Technique*

The ^{12}CO $J = 2$–1 transition was observed during the week of 1990 August 5 with the 10.4 m antenna of the Caltech Submillimeter Observatory (CSO), located near the summit of Mauna Kea, Hawaii. The HPBW of the telescope at the transition frequency of 230.538 GHz was 32″. A pointing uncertainty of approximately ±3″ was achieved by centering the antenna on the peak signal from Saturn. The receiver front end

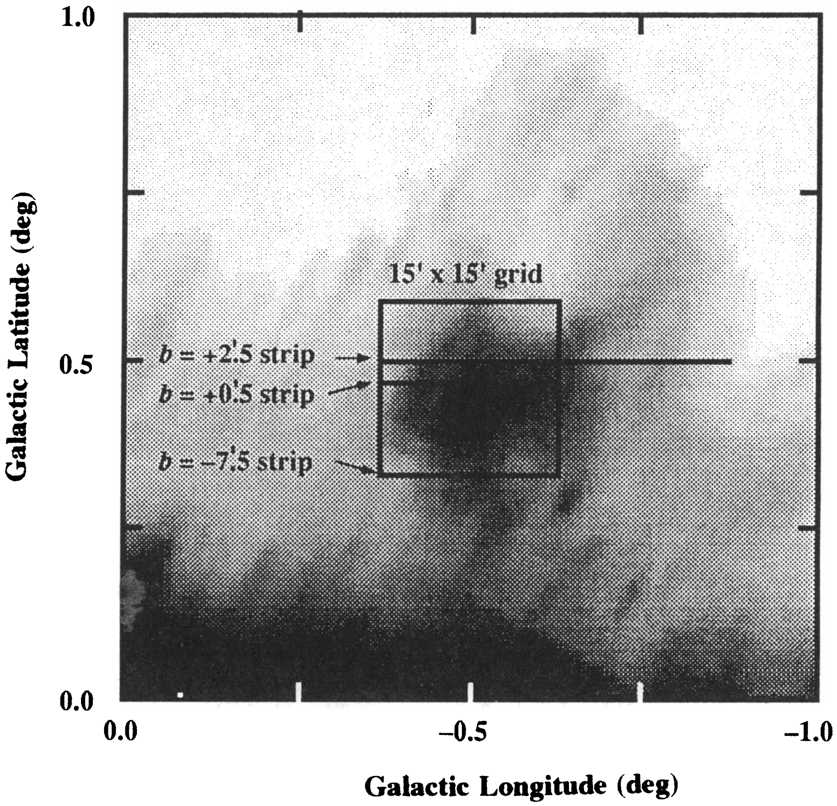

FIG. 1.—A 25 μm inverse gray-scale *IRAS* image of AFGL 5376 and the Galactic center lobe. The box outlines the grid of ^{12}CO $J = 2$–1 observations done with the 10.4 m antenna (32″ beam) of the CSO. The horizontal lines mark the locations of the 30″ sampled strips across AFGL 5376.

was a waveguide-mounted SIS receiver (Ellison & Miller 1987). An acousto-optical spectrometer with 1024 channels and a frequency range of 500 MHz comprised the back end. The total velocity coverage was 325 km s^{-1}, centered on 0 km s^{-1}, and the velocity resolution was about 1.3 km s^{-1}.

Sky subtraction was done by positional chopping; the off position was located at ($l, b = 0^{\circ}.5, -1^{\circ}.5$), a location relatively far from the Galactic plane and devoid of CO emission. The average double-sideband temperature during the observations was approximately 1100 K. A total of 60 s was spent on source to achieve a typical rms noise level of about 0.2 K.

The observations from the CSO were analyzed with CLASS, the Grenoble spectral line reduction program. Baseline offsets and nonlinearities were removed with polynomial fits of order 4 or less to portions of the spectra deemed to be free of line emission. The spatial maps generated from the AT&T Bell Labs Galactic center ^{12}CO database were made with COMB, a spectral line reduction program developed at the same institution.

2.2. *The Directions Observed*

The observed positions are shown in Figure 1 superposed over a 25 μm *IRAS* image of the region. A total of 331 positions was observed, most being distributed on a 1′ spaced, 15′ × 15′ grid centered on the infrared peak of AFGL 5376 at $l = 359^{\circ}.50$, $b = 0^{\circ}.433$. The positional offsets ($\Delta l, \Delta b$) quoted in this paper are with respect to this central position. At several selected latitudes ($\Delta b = -7'.5, +0'.5$ and $+2'.5$), strips crossing AFGL 5376 were measured with 30″ spacings between spectra. Additionally, at $\Delta b = +2'.5$, the strip was extended by about 15′ toward negative longitudes.

3. RESULTS

3.1. *Channel Maps and Position-Velocity Diagrams*

Figure 2*a* presents a contour map/gray-scale image of emission integrated between the velocities of 50 and 160 km s^{-1}. All the gas within this frame, as indicated by its high velocities and large line width, is probably located at the distance to the Galactic center. Furthermore, the sign of the velocity is against the sense of Galactic rotation on this side of the Galactic center, a situation characteristic of a small percentage of Galactic center gas clouds. The ^{12}CO emission around AFGL 5376 is present in all directions except to the northwest (in the Galactic coordinate frame; $l = -33'$, $b = 29'$), where a break in the emission is seen. Note in Figure 1 that this is also the direction in which an elongated ridge of infrared emission extends from AFGL 5376. Figure 2*b*, a superposition of the ^{12}CO data (in gray scale) with the 25 μm infrared emission from the *IRAS* maps (contours), details a striking anticorrelation between the high positive velocity ^{12}CO gas and the infrared emission of AFGL 5376. This figure clearly illustrates what was alluded to by the strip scans presented in Paper I, that the molecular gas surrounds, and so appears to be associated with, the IR feature.

Figure 3 is a contour map of high positive velocity CO emission from a $1^{\circ}.5 \times 2^{\circ}$ region containing AFGL 5376, produced from the ^{12}CO $J = 1$–0 Galactic center database of AT&T Bell labs (Bally et al. 1994). The expanded subimage shows the placement of the higher resolution $J = 2$–1 CSO data. The large-scale map shows that the high velocity emission surrounding AFGL 5376 is part of a large-scale structure extending perpendicularly from the gas in the plane out to at least $b = 0^{\circ}.9$ ($z = 140$ pc). The integrated CO emission bifurcates near the location of AFGL 5376, and maxima in the CO emission intensity are seen directly to either side of the infrared source. The radio continuum spur, GCL-W, corresponds to the westernmost portion of the CO emission "tongue" projecting vertically from the Galactic plane at $l \cong 359^{\circ}.5$. It is noteworthy that no high-velocity CO feature of this type is observed at the location of GCL-E ($l = +0^{\circ}.2$) (Bally et al. 1994).

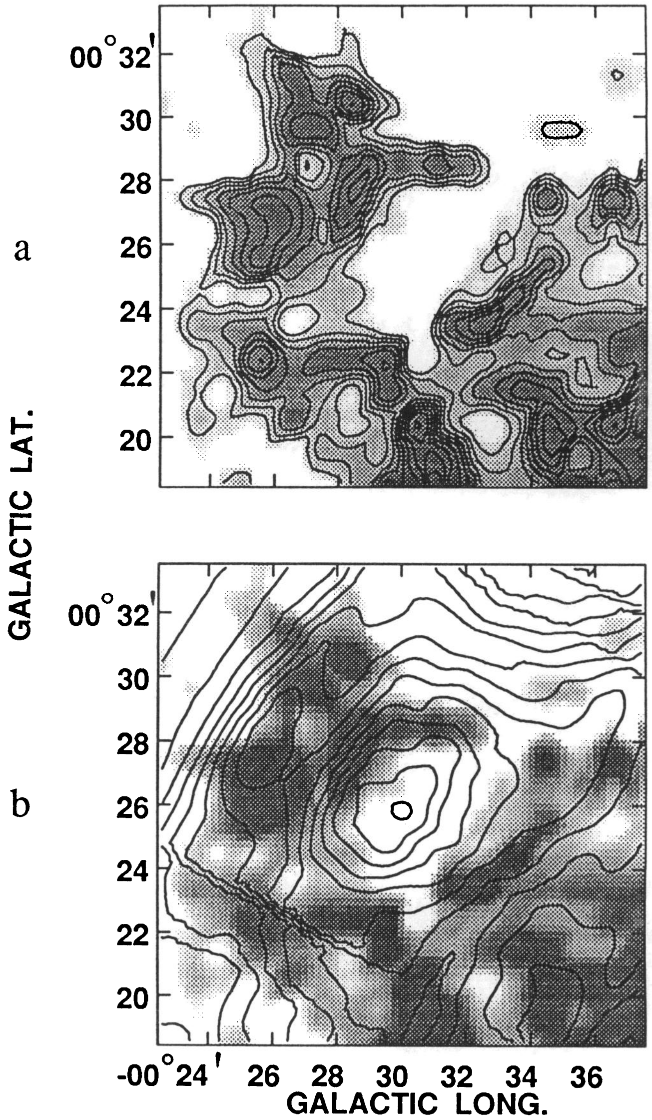

FIG. 2.—*Top*: Spatial map of ^{12}CO $J = 2$–1 emission (integrated between 50 and 160 km s^{-1}) of a 15′ × 15′ region centered on AFGL 5376. The contour levels start at 60 K km s^{-1} and continue in increments of 12 K km s^{-1}. *Bottom*: Superposed on the ^{12}CO $J = 2$–1 gray-scale image is a contour map of the 25 μm emission observed with *IRAS*. Note the precise alignment of the infrared peak with the "hole" in the CO emission. The gray-scale flux range is between 50 and 100 K km s^{-1}. The contour levels start at 2.77×10^7 Jy sr^{-1} and continue in increments of 1.28×10^7 Jy sr^{-1}. Absolute flux = contour value + map bias, where map bias = 1.1×10^7 Jy sr^{-1}.

Figures 4*a*–4*d* are longitude-velocity diagrams which cross AFGL 5376 at $\Delta b = +2'.5, +0'.5, -3'.5$, and $-7'.5$, respectively; they illustrate the steep velocity gradient across this region. A remarkable velocity jump of 60 km s^{-1}, which occurs

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EMR may be facilitated by strong poloidal magnetic field lines hypothesized to pervade the Galactic center region (Morris 1990).

Figure 8, an *l*-*v* diagram at $b = 0\overset{\circ}{.}333$ covering an extended range in longitude, illustrates the consistency in the kinematics of material crossing the shocks in AFGL 5376 (indicated by arrows) with that of the larger scale EMR. The sweeping arc feature evident at nearly all longitudes in this figure is part of the overall elliptical trace which can be attributed to the expanding ring.

The EMR shock model for GCL-W leaves the following question unanswered: if GCL-W is indeed due to the encounter between a radially expanding ring of molecular material with the normally rotating ambient ISM, why is the out-of-plane spur and its associated shocks at the location of GCL-W unique, or nearly so? Should not an azimuthally symmetric ring running into a uniform disk yield effects which are azimuthally symmetric, and so equally observable over the full extent of the EMR? Clumping may provide an explanation. The molecular concentration containing AFGL 5376 corresponds to a pronounced maximum in the *l*-*v* diagrams of CO emission (Fig. 8 and Binney et al. 1991, Fig. 2), indicating that it is perhaps an unusually massive concentration of gas within the EMR. As a result, the shock at this location may be more conspicuous than elsewhere around the EMR. However, the EMR model predicts that less prominent shocks should be present at other locations around the EMR, so a careful search should be made for their manifestations.

While the idea of the EMR has long been an appealing one since it accounts, in a dynamically straightforward manner, for much of the observed noncircular gas motion in the region, the existence of the EMR is still a subject of debate due to the difficulties that remain in explaining a few of its characteristics. The most serious of these is its large energy requirement: about 10^{54} ergs is needed to initiate its expansion if it had originated within 50 pc of the Galactic center. If the efficiency of the transfer of explosive or luminous energy into kinetic energy of the EMR is properly taken into consideration, the energy requirement is even higher still, between 10^{55} and 10^{58} ergs. Indeed, by most accounts, the lower end of this range approximates the energy output of a galactic starburst, and the upper limit approaches that of a Seyfert galaxy ($\sim 10^{59-60}$ ergs). Indications of such a massive centralized cluster of stars or supernovae are weak at best. Sgr B2 (at $l \approx 0\overset{\circ}{.}7$) and Sgr C (at $l \approx -0\overset{\circ}{.}5$), the most prominent star-forming regions currently within the Galactic center region, are in no way associable with the EMR (as its central energy source)—both are strongly displaced from the center of this feature. Even if they had been centered within the EMR, these star-forming regions are far from being extensive enough to account for its expansion. The Sgr B region, the largest of the two H II complexes, is thought to contain only a few dozen O-type stars.

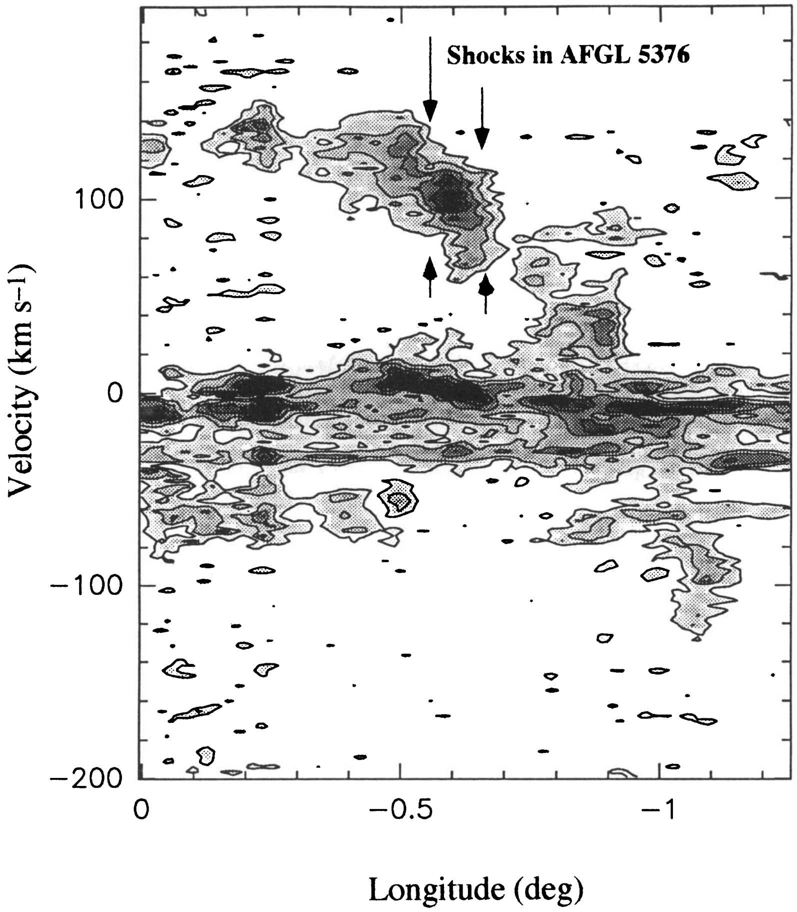

FIG. 8.—Contours of ^{12}CO $J = 1$–0 emission across AFGL 5376 in the longitude-velocity diagram at $b = +0\overset{\circ}{.}333$, from the Bell Labs Galactic center survey. Contour levels begin at 1 K and increase in increments of 1 K. The locations of the hypothesized shocks in AFGL 5376 are indicated by the arrows.

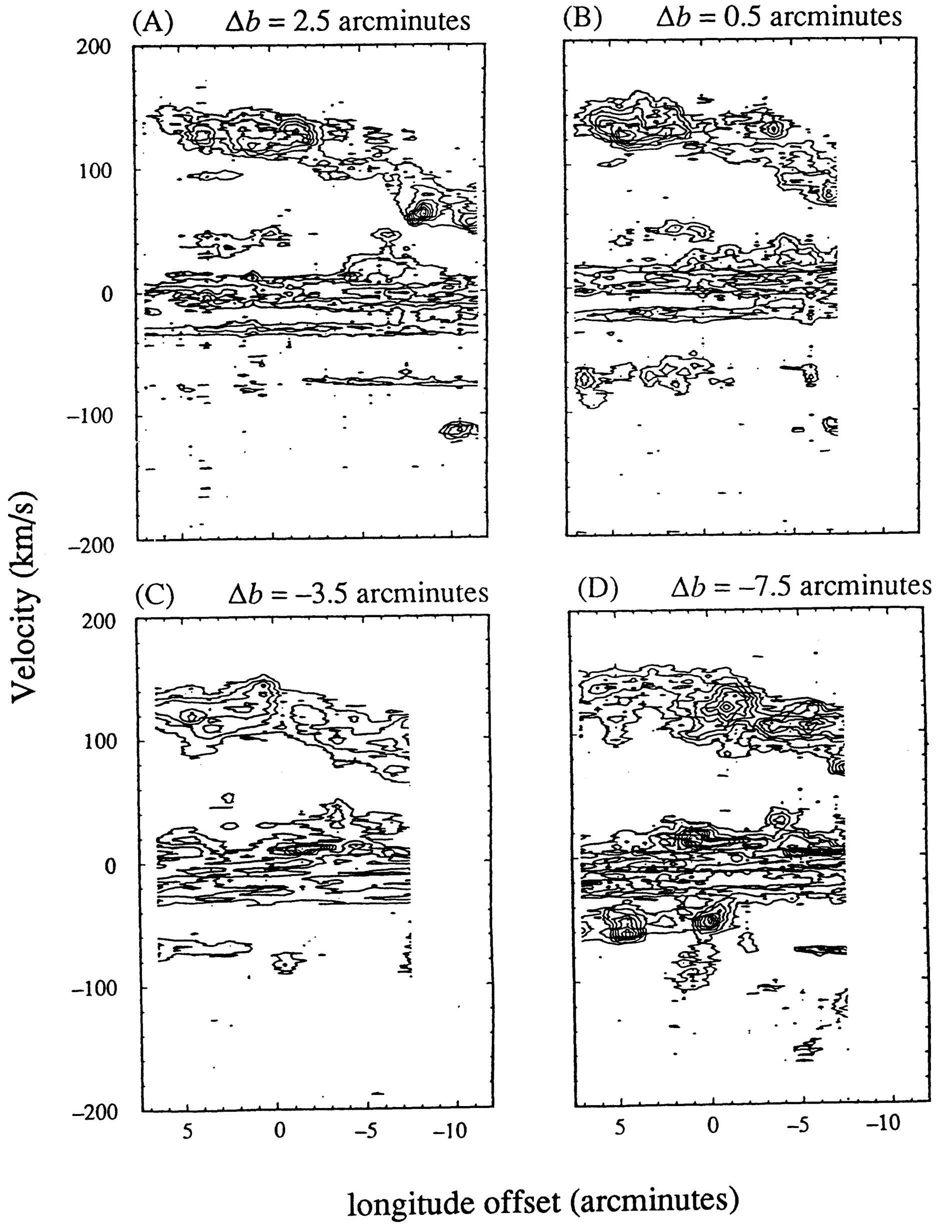

FIG. 4.—Longitude-velocity diagrams of ^{12}CO, $J = 2\text{–}1$ emission measured across AFGL 5376 with the CSO at (panel *a*) $\Delta b = +150''$, (panel *b*) $\Delta b = +30''$, (panel *c*) $\Delta b = 210''$, and (panel *d*) $\Delta b = -450''$. The emission from the AFGL region is seen between 50 and 150 km s^{-1}. The contour levels are as follows: panel *a* (0.75–6.0 by 0.75 K), panel *b* (0.75–4.75 by 0.6 K), panel *c* (0.7–6.0 by 0.75 K), and panel *d* (0.55–12.0 by 0.55 K). The sampling interval is 30″ for all but panel *c*, where it is 60″.

3.2. *The Mass of AFGL 5376 and the GCL*

An averaged spectrum was produced from all $J = 1\text{–}0$ CO spectra within an 18′ × 18′ region centered on AFGL 5376 (359°.5, 0°.43), and containing almost all of the flux in the Bell Labs maps at $b > 0°.25$. A Gaussian was then fitted to the spectral component associated with AFGL 5376 and the GCL; it has an average central velocity of 122 km s^{-1} and FWHM of 39 km s^{-1}. Using the empirically determined relation between ^{12}CO luminosity and H_2 column density in the disk of our Galaxy, $N_{H_2}/W_{CO} = 2.8 \times 10^{20}$ cm^{-2} (K km s^{-1})$^{-1}$ (Bloemen et al. 1986), we determine an average H_2 column density of $N_{H_2} = 2.8 \times 10^{22}$ cm^{-2}. By assuming that this column density applies to the entire tongue of molecular gas evident in the Bell Labs maps, we estimate the total H_2 mass of the out-of-plane portion of GCL-*W* ($b > 0°.25$) to be 1×10^6 $M_\odot$. The AFGL 5376/GCL region is not evident in the ^{13}CO and CS maps reported by Bally et al. (1987), indicating that the gas density in this region is somewhat less than that of average Galactic center molecular clouds found along the plane.

The mass of hot dust within 4′ of the peak of AFGL 5376 is estimated at only 10^{-2} $M_\odot$ (Uchida 1993), and even for a gas-to-dust ratio of 1000 (allowing for some evaporation of dust in the shock), the associated gas mass, presumably in the form of dissociated or hot gas, is far less than the total molecular mass in AFGL 5376. If the average radial velocity of CO near AFGL 5376 (122 km s^{-1}) is taken as the minimum shock velocity for the molecular gas associated with the GCL, then the minimum total kinetic energy of this feature in the Galactic rest frame, not ascribable to Galactic rotation, is $\sim 10^{53}$ ergs.

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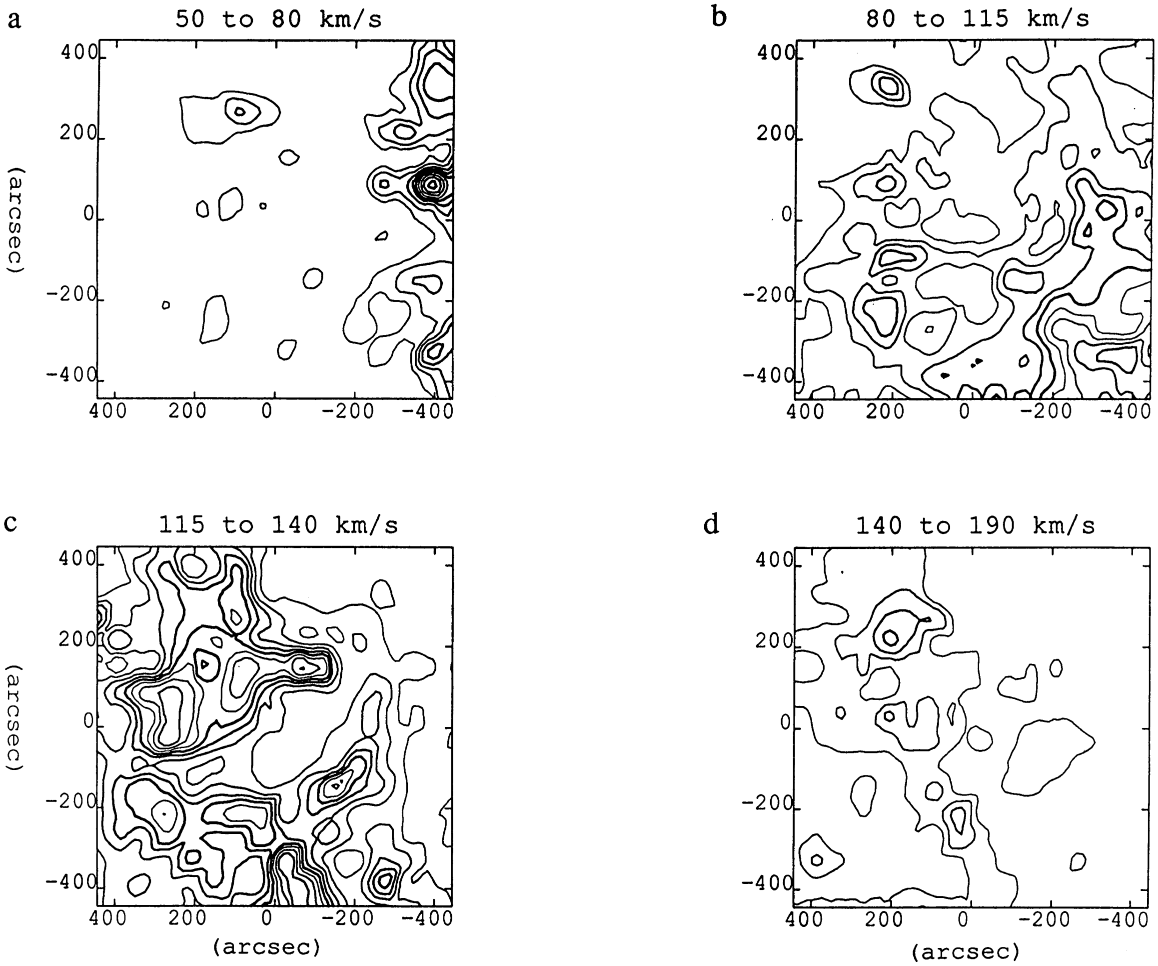

FIG. 5.—AFGL 5376: a high-resolution map of ^{12}CO, $J = 2$–1 emission integrated between 50 and 80 km s^{-1} (panel *a*), 80 and 115 km s^{-1} (panel *b*), 115 and 140 km s^{-1} (panel *c*), and 140 and 190 km s^{-1} (panel *d*). The contour levels in all four panel are in increments of 10 K km s^{-1}.

4. DISCUSSION

4.1. *The Association of Molecular Gas with AFGL 5376 and the GCL*

The observations presented here clearly show that high-velocity, large line width ^{12}CO emission is associated with AFGL 5376. The striking anticorrelation between the 25 μm IR emission and the surrounding ^{12}CO $J = 2$–1 line emission suggests that the process responsible for heating the emitting dust grains is also the process which has rendered CO undetectable, either by considerably raising its rotational temperature, or by dissociating it in a powerful shock (§ 4.2). The evidence for a shock is strong, and the velocity jumps across the shock are large enough to be consistent with the shock dissociation hypothesis.

The alternative possibility is that CO molecules in AFGL 5376 have been rotationally heated so much that the intensity of the lower lines ($J = 2$–1 and $J = 1$–0) is small owing to the dilution of population among all accessible rotational states. At high temperatures, the partition function for a linear molecule varies as the effective rotational temperature, $T_{\rm rot}$. Taking ΔE as the energy difference between the rotational states involved in a transition, it can be shown that the Rayleigh-Jeans brightness temperature of a line originating in a level having rotational energy less than $kT_{\rm rot}$ is proportional to $T_{\rm rot}^{-1} \exp(-\Delta E/kT_{\rm rot}) \approx T_{\rm rot}^{-1}$. Consequently, a rotational temperature of several hundred degrees can account for the pronounced minimum in the CO intensity on the infrared peak. This alternative is viable only if the density is high enough to keep higher lying rotational states populated. It could be assessed with sensitive observations of higher lying levels such as $J = 4 \rightarrow 3$ or $7 \rightarrow 6$. The absence of CS emission already indicates that the density probably does not exceed $\sim 10^5$ cm^{-3}.

The ^{12}CO emission surrounding AFGL 5376 begins near the Galactic plane and extends out to $b = 0\overset{\circ}{.}9$, forming a tongue of gas that corresponds to the radio continuum and infrared feature GCL-W. These observations strengthen our prior assertions that AFGL 5376 is located at the Galactic center and is associated with GCL-W. Together they comprise one of the most prominent known extensions of gas from the Galactic plane.

4.2. *A Model of the AFGL 5376/GCL-W Shock Region*

The fully sampled observations confirm that the CO gas in this region exhibits large velocity jumps (as high as 60 km s^{-1}) over spatial scales of less than a few parsecs. The spatial maps detail the remarkable structure of the jump region; high- and low-velocity CO emission are separated over a well-defined rift

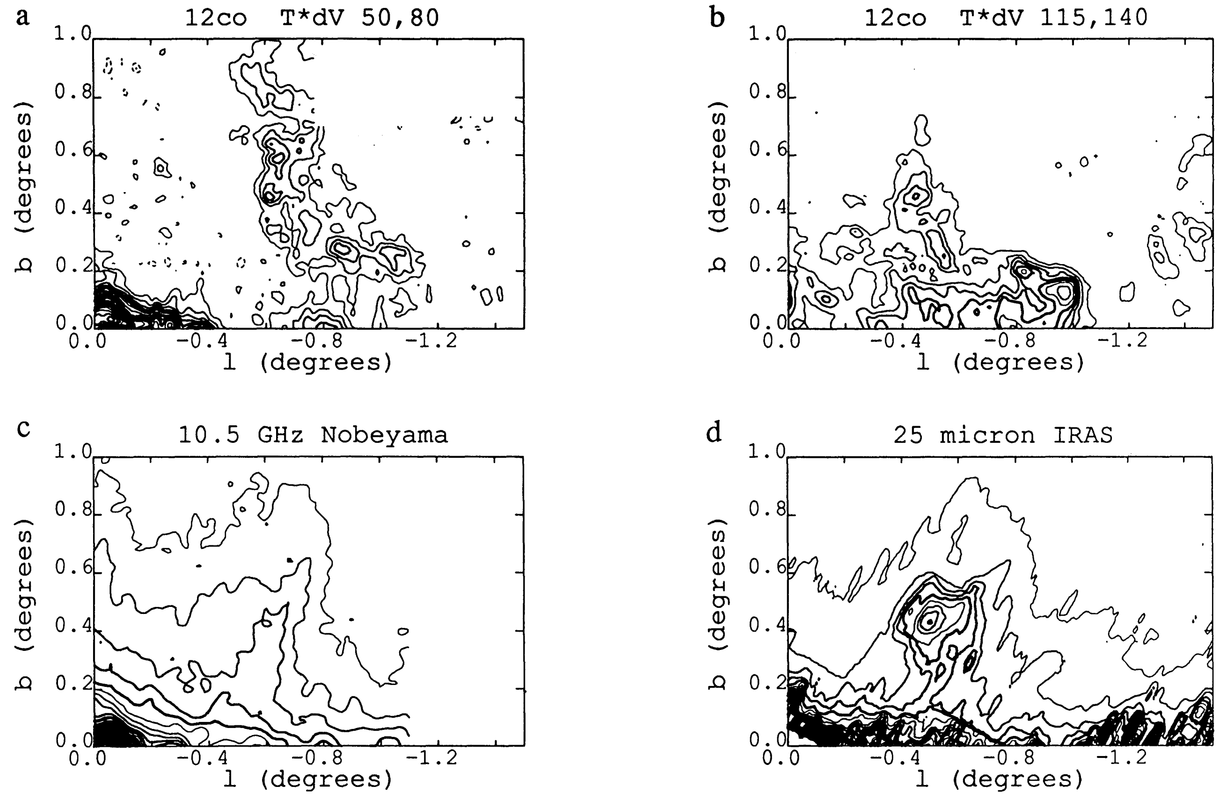

FIG. 6.—GCL: contour map of ^{12}CO $J = 1$–0 emission integrated between 50 and 80 km s^{-1} (panel *a*) and between 115 and 140 km s^{-1} (panel *b*). The contour levels are in increments of 20 and 25 K km s^{-1} respectively. Panel *c*: 10.5 GHz radio continuum map (from the Nobeyama survey) of GCL-W. Contour levels are in increments of 9.0×10^{-2} K. Panel *d*: contour map of 25 μm emission from AFGL 5376. Contour levels are in increments of 2×10^7 Jy sr^{-1}. Absolute flux = contour value + map bias, where map bias = 1.1×10^8 Jy sr^{-1}.

extending 0°6 in latitude (90 pc) through the CO tongue. The combination of the placement of these features and the observed velocity jumps provides strong evidence that the vertical ridge is undergoing a strong shock as a result of bulk gas motions in the region.

Figure 7 is a schematic superposition of the shock probes onto the 25 μm *IRAS* contour map of AFGL 5376 and the GCL. The ionization implied by the presumably thermal 10.5 GHz continuum is spatially associated primarily with the 50–80 km s^{-1} CO emission, suggesting that this system of gas is the leading edge of a strong ionizing shock (Front 1) with a westward transverse velocity component. The "rift" dividing the high- and low-velocity CO emission (Front 2) is displaced eastward from the most intense ridge of continuum emission, indicating less ionization at this location. However, the absence of detectable CO emission along some portions of the rift, especially toward the peak of AFGL 5376, implies molecular dissociation (or strong heating), so this location likely indicates the presence of a second front, which may primarily be a dissociation front. The extent of the 25 μm infrared emission indicates the presence of shock heated dust throughout the entire GCL-W region; the peak emission is located along the bisecting "rift" (Front 2).

We suggest that the radio continuum ridge and the "rift" bisecting the CO tongue to the east mark two separate, but probably related, parallel shocks. The strong ionizing shock (Front 1) is hypothesized to be the leading edge of an encounter between dense noncircularly-moving gas ($V_r >$ 50–80 km s^{-1}, where V_r is the velocity along a radius vector from the Galactic center) which is moving away from the Galactic center, and diffuse ambient gas that is moving in more-or-less normal orbits about the Galactic center. The relative velocity between the two systems of gas is large, over 100 km s^{-1}, well exceeding the minimum velocity required for CO dissociation ($\sim$25 km s^{-1}) and for production of an H-ionizing, *J*-type shock front ($\sim$50 km s^{-1}). The presumably dissociative shock (Front 2), coincident with AFGL 5376, could then be regarded as the reverse shock, where noncircularly moving preshock gas at velocities of 115–140 km s^{-1} encounters the slower moving (50–80 km s^{-1}) postshock material preceding it. The relative line-of-sight velocity between the two components observed in CO is about 60 km s^{-1}, sufficient to produce a *J*-type shock, molecular dissociation, and some H ionization. Based on the observed radio continuum emission, the degree of ionization along this interface is less than that at Front 1, consistent with the shock velocity being smaller at this location (Front 2). The extended component of 25 μm emission indicates dust heating across both fronts. The peak IR emission from AFGL 5376 marks a region of either enhanced dust column density (such as a molecular cloud) belonging to the noncircularly moving gas systems, or a region of unusually high temperature. The reverse shock also has a high enough velocity to dissociate CO within AFGL 5376, resulting in the apparent molecular "hole" toward the peak; in this case, only the shock-heated dust grains have survived.

Note that, in this model, the postshock gas should be swept along with the interstellar medium rotating about the Galactic center. Thus, for redshifted gas at negative longitude, the rota-

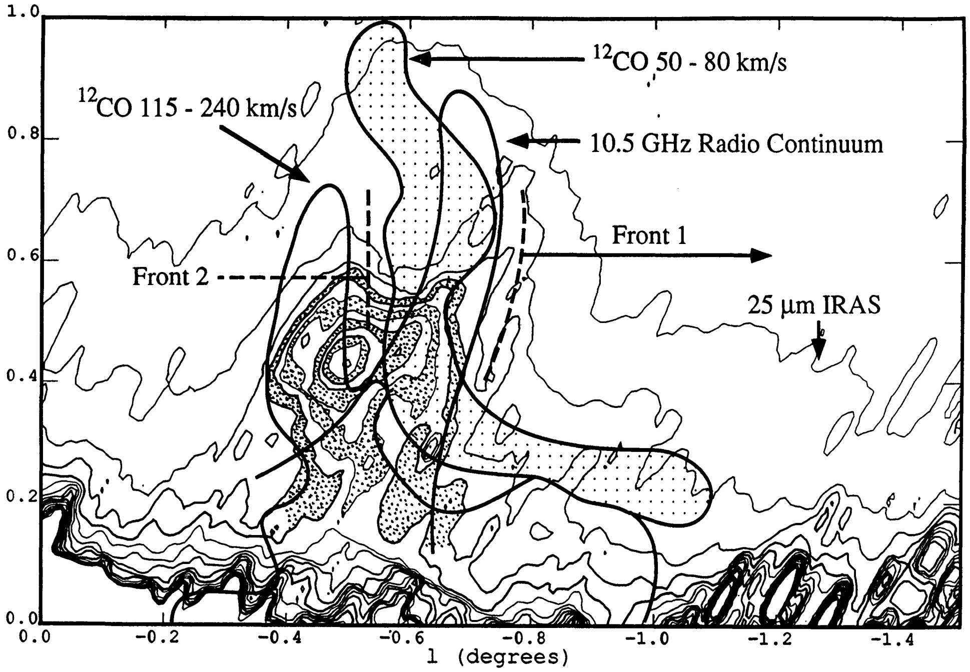

FIG. 7.—25 μm *IRAS* contour map of AFGL 5376/GCL region with superposed line tracings of the 10.5 GHz radio continuum, 50–80 km s^{-1} and 115–140 km s^{-1} CO emission. The outlines are based approximately on the midlevel contours in each emission map. The two potential shock fronts are labeled and their hypothesized transverse component of motion is shown by the arrows.

tion of the Galaxy should sweep the postshock gas (50–80 km s^{-1}) to more negative longitude than the preshock gas (>115 km s^{-1}), as is observed.

4.3. *The Out-of-Plane Molecular Feature and the GCL*

A number of theories have been formulated to explain the apparent shell morphology of the radio continuum emission comprising the GCL. Sofue (1984, 1985) has modeled the GCL in terms of a point explosion occurring in a spheroidal nucleus surrounded by a diffuse halo. Umemura et al. (1988) have expanded on this idea by including magnetic fields perpendicular to the Galactic plane in their simulations. An explosion of 10^{54} ergs in energy and collimated by a 30 μG magnetic field reproduces the geometrical attributes of the GCL remarkably well. The typical velocity of material channeled out of the plane in these models is on the order of 200 km s^{-1}.

Uchida et al. (1985) proposed an alternative scenario in which the GCL is extruded from the Galactic plane as a result of the twisting and pinching of poloidal magnetic field lines by Galactic rotation and the infall of matter from the H I disk. In the latest refinement of this model (Shibata & Uchida 1987) a central gravitational potential that produces a flat rotation curve beyond a galactocentric radius of 20 pc is used; the resulting outflow from the plane has velocities on the order of 100 km s^{-1}. They argue that, in contrast to the central explosion scenario, their model is able to account for the asymmetry of the GCL with respect to the Galactic center. Since the collimation by magnetic field lines is closely linked to the inward migration of material from the gaseous disk, which shows a pronounced asymmetry, gas ejection from the plane is not necessarily expected to occur at positions symmetrically placed about the Galactic center.

Heyvaerts, Norman, & Pudritz (1988) have presented a model which attributes the origin of many Galactic center features, including the GCL, the Galactic center radio arc, and Sgr A, to magnetic activity in the center. They propose that magnetic loops are being generated in a disk near the central mass concentration which is sheared by Galactic rotation. The dissipation of the magnetic energy produces winds which have cleared out and are maintaining an ionized region of 30–50 pc radius centered on the Galactic center. The exterior of this region is bordered by molecular clouds formed from swept-up atomic material. In their model, GCL-E and GCL-W mark the locations where detached magnetic loops are colliding with the molecular interface, resulting in heating, particle acceleration, and subsequent production of nonthermal emission. The projected positions of the spurs are independent of each other and may be located anywhere within the inner ~50 pc of the Galactic center, since magnetic loop contact can occur at any point along the perimeter of the molecular interface. Hereafter, we refer to this model as the magnetic loop model.

While some of the above models for the GCL are based on the assumption that it is a complete shell structure, and that the eastern (GCL-E) and western (GCL-W) spurs of the GCL are manifestations of a single phenomenon (Sofue 1985; Reich, Sofue, & Fürst 1987), we (Paper I) and Tsuboi et al. (1986) have noted a number of apparent physical differences between them and have argued that GCL-E and GCL-W are two unrelated, out-of-plane features that are arbitrarily placed with respect to each other. Our new observations support this assertion, by providing yet another physical difference between the two spurs. High forbidden velocity CO emission (60–160 km s^{-1}) is closely correlated with GCL-W, but no comparable CO component (at any velocity) is observed toward GCL-E ($l = 0^\circ.2$), (Bally et al. 1994).

The other known out-of-plane molecular feature, previously observed in the ^{13}CO survey by Bally et al. (1987, 1988), is known as the "$l = 1^\circ.5$ complex"; it extends between $b \cong \pm 0^\circ.75$ and displays radial velocities between 20 and 120 km s^{-1} (somewhat smaller in magnitude than those observed toward AFGL 5376 and having a permitted sign). While this feature is similar in morphology to the vertical tongue of molecular gas associated with AFGL 5376 (and GCL-W), it is definitely not associated with GCL-E, located at $l = 0^\circ.2$, nearly $1^\circ.3$ away. The $l = 1^\circ.5$ complex is in fact close (in projection) to the eastern edge of the expanding molecular ring (EMR: § 4.4), and we suggest that it and AFGL 5376 mark locations where the latitudinal extent of the EMR material is broadened by interaction with ambient gas. Sofue (1990) argues that the $l = 1^\circ.5$ complex (he places it at $1^\circ.4$) marks a cylindrical wall defining the vertically extended EMR; he interprets a tongue of gas extending to negative latitudes at $l = -1^\circ.2$ as the opposite counterpart, inasmuch as that longitude coincides with the opposite extremity of the EMR. According to that interpretation, these features are the limb-brightened extremities of the cylindrical EMR. However, the $l = -1^\circ.2$ feature has been attributed to a localized expanding shell of molecular gas surrounding the supernova remnant, or superbubble, G359.1$-$0.5 (Uchida et al. 1992). Therefore, we pursue the interpretation that AFGL 5376, and perhaps the $l = 1^\circ.5$ complex as well, represent localized extrusions of gas from the Galactic plane, though not necessarily located at the longitudinal extremities of the EMR.

The magnetic twist model might be able to account for the positional asymmetries of the radio continuum spurs, but it cannot easily explain the complete absence of molecular gas at latitudes greater than $b = 0^\circ.4$ in GCL-E. Similar difficulties are faced by the magnetic loop model, since interaction with a molecular interface is needed in order for an expanding magnetic loop to produce an observed radio continuum spur.

One piece of evidence which has been used to associate GCL-E and GCL-W as opposite parts of a single, large-scale structure is an apparent connection between GCL-W and G359.54+0.18. G359.54+0.18 is a set of linear, nonthermal radio filaments observed toward the base of GCL-W (Bally, Yusef-Zadeh, & Hollis 1989). To date, seven such filamentary structures have been found and all are positioned within 1° of the Galactic center (Yusef-Zadeh 1989); they are thought to be the manifestations of a strong poloidal magnetic field which is hypothesized to exist in the Galactic center region (Yusef-Zadeh et al. 1984; Sofue & Fujimoto 1987; Bally et al. 1988; Benford 1988; Morris & Yusef-Zadeh 1989; Morris 1990). The most prominent set of filamentary structures, the Galactic center radio arc, is associated with GCL-E (Yusef-Zadeh et al. 1984; Tsuboi et al. 1985; Seiradakis et al. 1985, 1989; Yusef-Zadeh & Morris 1988). The potential association between G359.54+0.18 and GCL-W has thus been used to argue that GCL-E and GCL-W are similar structures. However, observations by Bally et al. (1989) indicate that G359.54+0.18 is probably associated with a molecular cloud having a velocity of -140 km s^{-1}, far different from the observed velocity of molecular gas in GCL-W (about $+120$ km s^{-1}). Consequently, it is highly unlikely that G359.54+0.18 is associated with GCL-W, and therefore no parallel can be drawn between GCL-E and GCL-W based on the Galactic center filaments.

Perhaps the strongest evidence against the interpretation of the GCL in terms of the magnetic loop model, and against those models which attempt to explain the GCL as a complete cylindrical shell, is the observed forbidden velocity of CO emission associated with GCL-W and the large velocity jumps seen in the region. A consequence of both the magnetic twist and magnetic loop models would be that the GCL rotate roughly in accord with Galactic rotation. The sign of the observed CO velocity from GCL-W is, however, opposite to that given by Galactic rotation! Moreover, in the context of the magnetic loop scenario, it is not clear whether strong shock production will take place when a magnetic loop collides with the molecular interface. If a shock does arise, it will probably be weak; the Alfvén velocity at the molecular interface (180 km s^{-1}; Heyvaerts et al. 1988), probably exceeds the estimated loop expansion velocity ($\sim$50–100 km s^{-1}). Therefore, it appears that this scenario cannot readily account for the bulk gas motions nor the apparent CO dissociation (or CO heating) observed toward AFGL 5376.

4.4. *The Origin of Noncircular Motions in the Galactic Center*

4.4.1. *An Expanding Molecular Ring?*

In the longitude-velocity diagrams crossing the Galactic center Bally et al. 1988, Fig. 4) three major components of emission are apparent: (1) line-of-sight foreground emission, with radial velocities satisfying $|V| < 30$ km s^{-1}, extending over all longitudes; (2) emission from Galactic center disk clouds, which appear as a diagonal line crossing the origin at $l, v = (0, 0)$, the slope of which is determined by the inner rotation curve of the Galaxy; and (3) a trapezoidal or approximately elliptical pattern which surrounds the Galactic center and extends between $l \cong 1^\circ.7$ and $-1^\circ.0$ and $v \cong -200$ and $+200$ km s^{-1} (Robinson & McGee 1970; Sanders & Wrixon 1974). Hereafter, we refer to this trapezoidal/elliptical shaped feature as the "*l-v* emission envelope" or "emission envelope." The shape of the *l-v* emission envelope (whether a trapezoid or ellipse) is a matter of interpretation, depending on whether one considers the sharp vertices at $l, v = (-1^\circ.1, -210$ km s^{-1}) and $+1^\circ.7, +200$ km s^{-1}) to be part of this feature, or to instead belong to the disk population described in point (2). Regardless, this envelope is comprised of emission at velocities which are forbidden with respect to the sense of Galactic rotation in two of the four quadrants of the *l-v* diagram ($+l$, $-b$ and $-l$, $+b$). In fact, much of the forbidden velocity emission observed, including radial motions observed directly toward the Galactic center, falls within this trace.

This emission ellipse may be attributed to an expanding ring of molecular clouds surrounding the Galactic center—the EMR (Scoville 1972; Kaifu, Kato, & Iguchi 1972; Bania 1977; Güsten & Downes 1980). The EMR is hypothesized to be a 160 pc radius ring of molecular clouds surrounding the Galactic center and expanding radially at a velocity of about 150 km s^{-1} (Bania 1977, corrected for a Galactic center distance of 8.5 kpc). The projected major axis of the EMR appears to be tilted with respect to the Galactic plane by about 10°–20° (to $+b$ at negative longitudes), and inclined toward the observer by about the same angle. It has been proposed to be the result of a highly energetic event occurring near the Galactic center (Scoville 1972; Kaifu et al. 1972).

In Paper I, we adopted the EMR as the source of the noncircular gas motions observed toward AFGL 5376. The orientation of the EMR is such that the receding portion of its western edge presumably has a velocity component away from the Galactic plane near the location of AFGL 5376 and GCL-W (Paper I, Fig. 10). The existence of two parallel shock fronts can be accommodated by noting that a reverse shock would naturally result from the strong encounter of the EMR, identified here with the 115–160 km s^{-1} molecular material, with gas in roughly circular galactic orbits. The production of an extended linear shock front across the leading edge of the

EMR may be facilitated by strong poloidal magnetic field lines hypothesized to pervade the Galactic center region (Morris 1990).

Figure 8, an *l*-*v* diagram at $b = 0.^{\circ}333$ covering an extended range in longitude, illustrates the consistency in the kinematics of material crossing the shocks in AFGL 5376 (indicated by arrows) with that of the larger scale EMR. The sweeping arc feature evident at nearly all longitudes in this figure is part of the overall elliptical trace which can be attributed to the expanding ring.

The EMR shock model for GCL-W leaves the following question unanswered: if GCL-W is indeed due to the encounter between a radially expanding ring of molecular material with the normally rotating ambient ISM, why is the out-of-plane spur and its associated shocks at the location of GCL-W unique, or nearly so? Should not an azimuthally symmetric ring running into a uniform disk yield effects which are azimuthally symmetric, and so equally observable over the full extent of the EMR? Clumping may provide an explanation. The molecular concentration containing AFGL 5376 corresponds to a pronounced maximum in the *l*-*v* diagrams of CO emission (Fig. 8 and Binney et al. 1991, Fig. 2), indicating that it is perhaps an unusually massive concentration of gas within the EMR. As a result, the shock at this location may be more conspicuous than elsewhere around the EMR. However, the EMR model predicts that less prominent shocks should be present at other locations around the EMR, so a careful search should be made for their manifestations.

While the idea of the EMR has long been an appealing one since it accounts, in a dynamically straightforward manner, for much of the observed noncircular gas motion in the region, the existence of the EMR is still a subject of debate due to the difficulties that remain in explaining a few of its characteristics. The most serious of these is its large energy requirement: about 10^{54} ergs is needed to initiate its expansion if it had originated within 50 pc of the Galactic center. If the efficiency of the transfer of explosive or luminous energy into kinetic energy of the EMR is properly taken into consideration, the energy requirement is even higher still, between 10^{55} and 10^{58} ergs. Indeed, by most accounts, the lower end of this range approximates the energy output of a galactic starburst, and the upper limit approaches that of a Seyfert galaxy ($\sim 10^{59-60}$ ergs). Indications of such a massive centralized cluster of stars or supernovae are weak at best. Sgr B2 (at $l \approx 0.^{\circ}7$) and Sgr C (at $l \approx -0.^{\circ}5$), the most prominent star-forming regions currently within the Galactic center region, are in no way associable with the EMR (as its central energy source)—both are strongly displaced from the center of this feature. Even if they had been centered within the EMR, these star-forming regions are far from being extensive enough to account for its expansion. The Sgr B region, the largest of the two H II complexes, is thought to contain only a few dozen O-type stars.

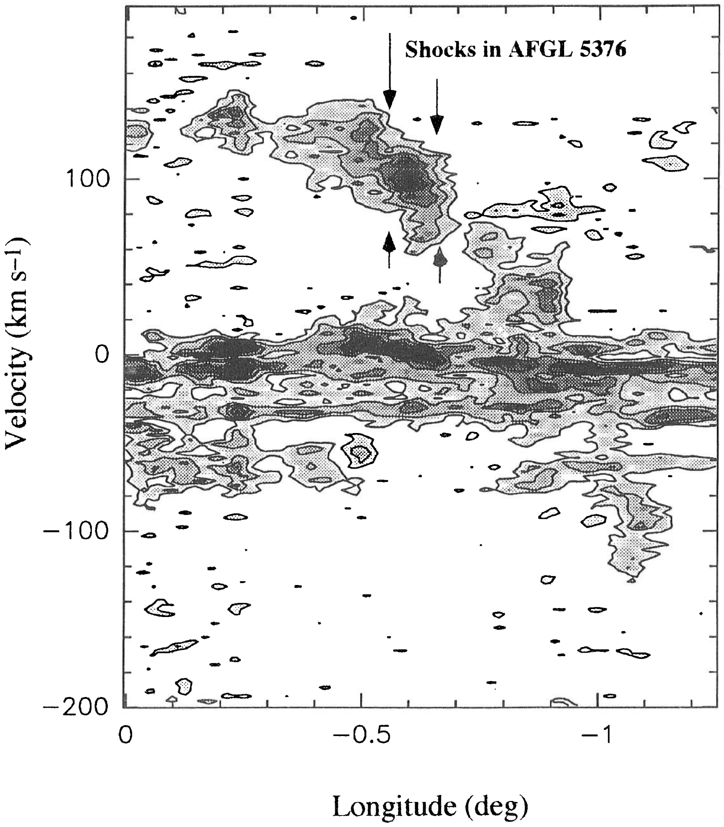

FIG. 8.—Contours of ^{12}CO $J = 1$–0 emission across AFGL 5376 in the longitude-velocity diagram at $b = +0.^{\circ}333$, from the Bell Labs Galactic center survey. Contour levels begin at 1 K and increase in increments of 1 K. The locations of the hypothesized shocks in AFGL 5376 are indicated by the arrows.

The central Sgr A complex is a more likely source of energy. Indeed, the presence of a population of luminous blue objects within the central parsec (Allen, Hyland, & Hillier 1990) might be most conservatively explained by a recent, major star formation event (Rieke & Lebofsky 1982). On the other hand, there may be problems with a hypothesis involving a starburst this close to the Galactic center (Morris 1993), so one might instead appeal to an episode of accretion activity within the central parsec to obtain the requisite energy.

Evidence for a major explosive event in the Galactic nucleus may be present in the form of the ultrahot (10^8 K), X-ray–emitting gas that has been observed there (Skinner et al. 1987; Koyama et al. 1989; Yamauchi et al. 1990). A link between this gas and the EMR may be drawn by noting that they have comparable physical extents; the hot gas is observed to have an elliptical distribution with a major axis of about 270 pc along the plane, only slightly smaller than the apparent diameter of the EMR. A surprisingly large supernova rate is required to maintain this bubble of hot gas in the face of cooling and expansion. Ozernoy, Titarchuk, & Ramaty (1993) consider the properties of an explosion (or the ensemble of almost simultaneous supernova explosions in close proximity) needed to account for the bubble, assuming that it is a transient feature. They deduce a characteristic energy release of 10^{54} ergs, which is comparable to the current kinetic energy of the EMR, but which is substantially less than needed to account for this kinetic energy, given a realistic efficiency for the conversion of explosion energy to cloud kinetic energy. Perhaps the hot gas can be equally well modeled with an older, but more energetic explosion.

4.4.2. *The Alternative Mechanism for Organized, Noncircular Motions: The Central Bar Scenario and its Problems*

The alternative to having the EMR as a source of noncircular gas motions is to have molecular gas follow highly elliptical orbits or streamlines within a nonaxisymmetric or barred potential (e.g., Peters 1975). Binney et al. (1991) demonstrate that orbits in a barred potential, if properly oriented with respect to the observer, can reproduce the apparent trapezoidal shape of the *l-v* emission. The linear band of emission crossing the *l-v* origin, and located interior to the emission trapezoid, is explained by gas within the innermost Galactic orbits (Fig. 3 of Binney et al. 1991).

While the central bar scenario avoids some of the problems inherent to the EMR model, such as the high energies required for the originating event, it is not entirely free of its own difficulties. The shortcomings of the bar model are described at length by Uchida (1993)—in summary, they are as follows:

1. In the bar orbit model, there is no shock foreseen across the top of the parallelogram, *except* at its corners, which correspond to the extrema of the limiting, cusped orbits (Binney et al. 1991, Fig. 3). If the shock in AFGL 5376 is therefore to be identified with the cusp, then the preshock velocity of $\sim +140$ km s^{-1} is far too high relative to that in the model (≤ 25 km s^{-1}), *and*, as can clearly be seen in Figure 8, the postshock gas remains at positive velocities and decelerates only slowly through zero at increasingly negative longitude, rather than reversing sign abruptly and accelerating toward the observer at approximately constant longitude, as is required in the model.

2. The observed emission parallelogram is not symmetric about the Galactic center. Its longitudinal "edges" are located at $l = +1\overset{\circ}{.}7$ and $-1°$ respectively; its center of symmetry is at $l = 0\overset{\circ}{.}35$. While the bar model does produce some such asymmetry in its *l-v* trace owing to viewing and projection effects, the predicted offset is considerably less than that observed (Binney et al. 1991).

3. The orbital model sheds little light on the out-of-plane molecular spurs toward AFGL 5376 and at $l = +1\overset{\circ}{.}5$. As noted above, the existence of a large-scale shock toward AFGL 5376 is consistent with the EMR scenario. The $l = 1\overset{\circ}{.}5$ complex, although not well studied, does share a few characteristics with the AFGL 5376 molecular spur which make it another candidate for association with the EMR. While shocks are found along certain orbits within a central bar, given the locations at which the shocks should occur, it is not evident how they might lead to spurs perpendicular to the Galactic plane. A large-scale poloidal magnetic field might help collimate gas extruded by a shock taking place near the plane, but it does not offer any clues about the velocity structure along the length of GCL-W.

4. Finally, the shape of the *l-v* emission envelope, or parallelogram, transforms into an ellipse at high Galactic latitudes $|b| > 0\overset{\circ}{.}15$, something that is not foreseen by the existing bar model, in which the orbits are in the Galactic plane. The high-latitude emission trace is more consistent with the EMR scenario which predicts an elliptical emission trace in the *l-v* diagrams. However, three-dimensional orbits in a tilted gas layer in the presence of a bar might also produce elliptical traces at high latitudes, so this shortcoming may not be insurmountable.

5. CONCLUSIONS

^{12}CO $J = 2$–1 observations of a $15' \times 15'$ region around AFGL 5376, an unusually warm and extended *IRAS* source located 65 pc out of the Galactic plane near the Galactic center, have revealed the following:

1. There is a striking anti correlation between the infrared source AFGL 5376 and the surrounding ^{12}CO emission. AFGL 5376 thus appears to be associated with this high-velocity, large–line width molecular gas and is located at the distance to the Galactic center.

2. The high forbidden velocity gas in this region is coincident with, and morphologically similar to, the western lobe of the radio continuum GCL. AFGL 5376, the vertical tongue of molecular gas, and the GCL are apparently associated.

3. An abrupt, linear velocity jump in the CO velocity field near AFGL 5376 implies that a strong, large-scale shock extends ~ 100 pc perpendicular to the Galactic plane.

4. The linear extension of molecular gas out of the Galactic plane, coincident with GCL-W, appears to be the result of an out-of-plane collision between a system of noncircularly moving gas and ambient material (in normal orbits about the Galactic center) located above the Galactic plane. The radio continuum feature, GCL-W, is attributed to the forward shock, which is strong enough to account for its ionization. The extended velocity discontinuity in the molecular gas, which is parallel to GCL-W, but displaced from it by about 30 pc, is interpreted as the associated reverse shock. AFGL 5376, which lies on the reverse shock, corresponds to a location where the CO is either dissociated or greatly heated. This unusual far-infrared source is apparently the direct manifestation of dust grains heated by the shock.

5. AFGL 5376 lies on the trace of the so-called Expanding Molecular Ring in the longitude-velocity diagrams of the

Galactic center, and it thereby offers clues to the nature of this large-scale kinematical feature. We find that the presence of shocks at this location supports the original expanding ring hypothesis, rather than the more recent hypothesis that the EMR is the reaction of orbiting gas to a bar potential. However, serious problems remain with both models.

An improved understanding of the cause and the structure of the large-scale shock in AFGL 5376 will be possible when observational shock diagnostics are brought to bear on it.

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