HII REGIONS AND STAR FORMATION IN THE GALACTIC CENTER

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The centimeter wavelength continuum radiation seen toward the Galactic center (Figure 1) is a mixture of thermal (free-free) and nonthermal (synchrotron) radiation which originates in the nucleus and along the line-of-sight. In this review we discuss only the thermal emission (also see Mezger 1974 and Oort 1977). High-frequency radio continuum and recombination line observations show that the thermal radiation comes from extend, low-density (ELD) HII, and a number of giant "radio HII regions" (see Mezger 1978 for definitions). The approximate half-power contour of the ELD HII (labelled EI in Fig. 1), probably represents a superposition

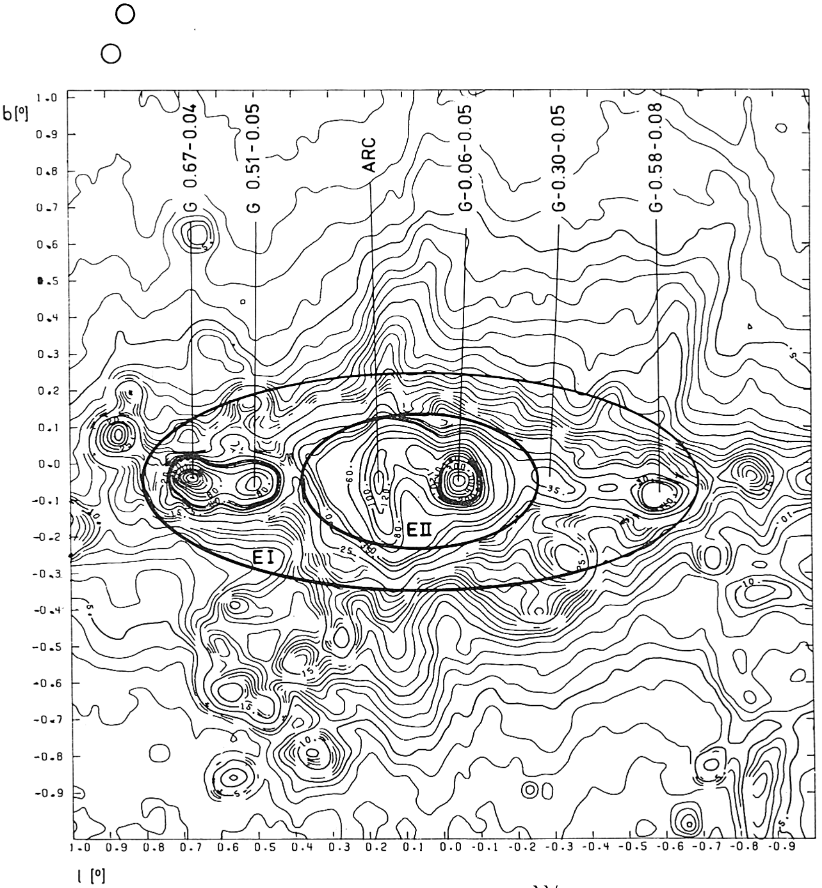

Figure 1: Section of the 5 GHz galactic plane survey by Altenhoff et al. (1978; 100-m telescope, HPBW= 2.6'). EI and EII approximate the half power contours of ELD HII regions.

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of evolved and expanded HII regions. Thermal radiation outside EI comes predominantly from along the line-of-sight (see Pauls and Mezger 1975).

In the Galactic center, as in the spiral arms, HII regions, IR emission from dust, and molecular clouds are closely associated. These three quantities are plotted in Figure 2 for $b = 0^o$ and $|\ell|<5^o$. We see that the free-free and far infrared (FIR) emission correlate well, but the CO is stronger for $\ell>0^o$ and is larger in extent. The latitude distribution is reversed, with the neutral gas forming a thin layer (HPW $\sim$40 pc (CO), $\sim$80 pc (HI)) and the FIR and free-free emission more extended (HPW $\sim$120 pc). This suggests that the ELD HII may be ionization bounded along the galactic plane, but density bounded perpendicular to it.

The Extended, Low Density Ionized Gas. Schmidt (1978a, 1978b) has used continuum observations with the 100-m telescope at 1.7 GHz (HPBW = 7.6'), 2.7 GHz (4.4') and 4.9 GHz (2.6') to separate the thermal and nonthermal radiation in the Galactic center. Assuming S_ν (thermal + nonthermal) $\propto \nu^{-0.1+\alpha}$, Schmidt finds, at 5 GHz, S_5 (thermal) $\sim S_5$ (nonthermal) $\sim$950 Jy, and α(nonthermal) = -0.9 ± 0.15. Then, from a map of just thermal radiation, Schmidt represents the ELD HII by two spheroidal, constant density components (shown in Fig. 1), whose properties are listed in the Table 1.

The electron temperatures in Table 1 were obtained by comparing (Schmidt 1978b) the thermal continuum with the H166α observations of Kesteven and Pedlar (1977). For ($|b|>0^o$, $\ell = 0^o$) and ($b = 0^o, \ell<0^o$) Schmidt (1978b) finds that T_e = 5000 K gives a satisfactory fit to both line and continuum data; but for $\ell>0^o$ the data require T_e = 7500 K. However, since all giant HII regions are at positive longitudes and have T_e $\sim$6000 - 9000 K, we expect the beam-smoothed electron temperature for $\ell>0^o$ to be higher.

Radio recombination line emission attributed to the ELD ionized gas has been reported by Mezger et al. (1974; 5 GHz), Pauls and Mezger (1975; 5 GHz) and Kesteven and Pedlar (1977; 1.4 GHz). 5 GHz observations at positions away from

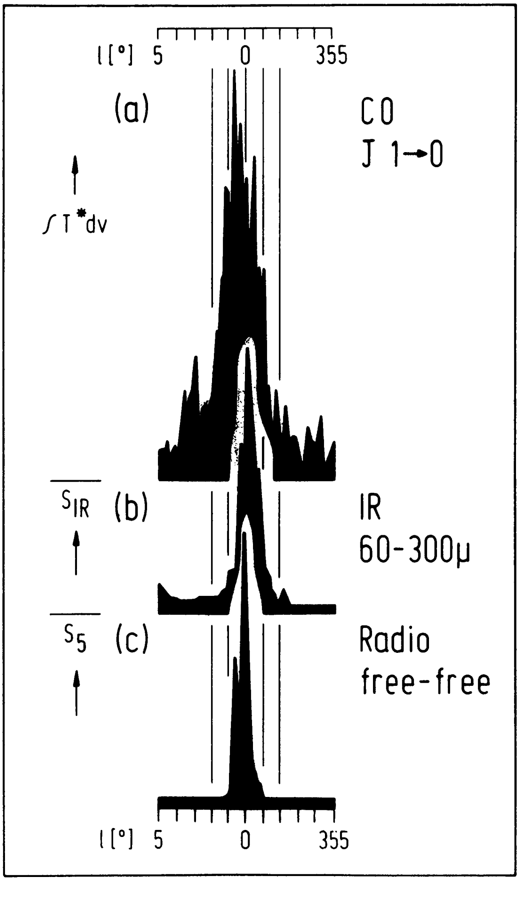

Figure 2: Distribution in the galactic plane of a) integrated CO J=1-0 line profiles (Bania, 1977; HPBW = 1'); b) FIR flux density observed with a 15' beam by Low et al. (1977); c) thermal radio flux density, smoothed to a HPBW of 12' (Schmidt 1978b).

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Table 1

	HPW	Diameter of equivalent spheroid	S_5 Jy	T_e K	N_c' s^{-1}	EM cm^{-6} pc	n_e cm^{-3}	M_{HII} $M_\odot$
EI	90'x36'	300 pc x 120 pc	300*	5000	3.6×10^{51}	1.4×10^4	7	1.4×10^6
EII	38'x22'	130 pc x 80 pc	180	5000	2.2×10^{51}	3.1×10^4	16	3.7×10^5

* corrected for line-of-sight contribution = ∿150 Jy.

the individual sources yield line widths (FWHM) Δv = 50→100 km s^{-1}, and the systematic longitude variation shown in Figure 3. Also shown in Fig. 3 is the observed rotation curve of the HI nuclear disk (extrapolated to positive longitude). We see that the majority of the ionized gas rotates at a lower velocity than that required for dynamical equilibrium with the gravitational field of the stars near the nucleus. However, the ionized gas at ∿-135 km s^{-1} may be associated with the nuclear disk (see also, Kesteven and Pedlar 1977). For $\ell > 0^\circ$ the ionized gas lies in the same region of the ℓ-v diagram as the molecular ridge running between Sgr A and Sgr B2 (see Bania 1977, Scoville 1972). This suggests that the extended HII may be simply a collection of evolved HII regions with associated molecular clouds. The large line-widths of the recombination lines, also present in CO and H_2CO, may be a result of rotation and the large path-length over which the emission is observed. Finally, we note that the diffuse ionized gas appears to lie completely inside the "molecular ring" seen in OH, H_2CO and CO (Bania 1977).

The Giant HII Regions shown in Fig. 1 have a total flux density of ∿320 Jy. All compact HII regions are located at positive longitudes and, with the exception of the Arc feature, are similar to giant HII regions observed in spiral arms. The abundance of ionized He in the Galactic center HII regions is very low, typically 1-2% integrated over the source, implying selective absorption of Lyc-photons by dust. This is consistent with an increase of metal abundance and dust-to-gas ratio towards the center of the Galaxy (Churchwell et al. 1978), but the high LTE electron temperatures and nominal infrared excesses (Gatley et al. 1978) do not fit this picture. Apart from the Arc feature, radial velocities of the giant and ELD HII regions correlate well, suggesting a generic relationship as found in the spiral arm region.

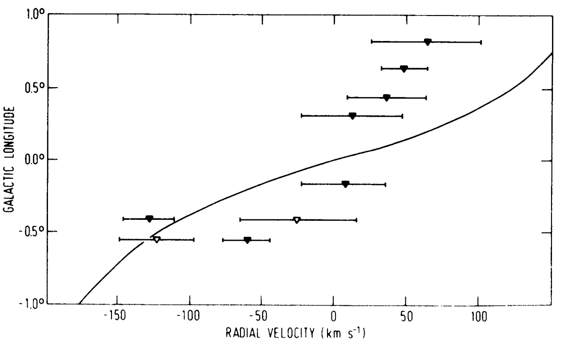

Figure 3: Longitude-velocity diagram of recombination line observations of the ELD HII (filled (dominant component) and open (weaker component) triangles; Mezger et al. (1974, Pauls and Mezger 1975)) and the rotation curve of the HI nuclear disk (extrapolated to positive longitudes; Sanders et al. 1977).

GO.67-0.04 (Sgr B2), GO.51-0.05 and G-0.58-0.08 (Sgr C). These sources are symmetrically located about Sgr A at a projected distance of ∿120 pc. Sgr B2 and GO.51-0.05 are giant HII regions with LTE electron temperatures of 8000 K and 6500 K, respectively. The measured He^+/H^+ ratio in Sgr B2 increases with decreasing beam size (cf. Thum et al. 1978), suggesting different sizes for He^+ and H^+ Strömgren spheres. Sgr C may be a supernova remnant (Downes 1974) since it has a nonthermal spectrum and shows no recombination line emission intrinsic to the source, only lines from the extended HII (Pauls and Mezger 1975). However, Sgr C is a strong far infrared source (Jenning 1975, Low et al. 1977).

The Arc. For $0^o \leq \ell \leq 10'$, there is a complex of radio sources which form an arc-like structure near $b = 0^o$. Radio continuum and recombination line emission from this region have been studied by Pauls et al. (1976), Gardner and Whiteoak (1977) and Pauls and Mezger (1978). The continuum observations of Schmidt (1978a) show an extended region of emission not centered on Sgr A (EII in Fig. 1), while at high frequency (ν>10 GHz) and high resolution (HPBW ∿1') the entire region break ups into discrete sources. One of these, GO.07+0.04, is a strong FIR source (second only in intensity to Sgr A at 69μm) and Gatley et al. (1978) argue that it may be a site of current star formation. Using the 100-m telescope at 5 GHz (HPBW = 2.6'), we have unsuccessfully searched for He^+ in GO.07+ 0.04 (He^+/H^+ <0.01). This result is consistent with the large infrared excess of the source. At 5 GHz, T_e (LTE) = 8000 K.

The ionized gas emits primarily at V_{LSR} = -40±20 km s^{-1} and most of this emission arises north of $b = 0^o$. Observations of HCN indicate that the molecule clouds are anti-correlated in velocity and position with the ionized gas. The maximum HCN emission is in the range $+15 \leq V_{LSR} \leq$ +80 km s^{-1} and lies south of $b = 0^o$ (Fukui et al. 1978).

Sgr A. The radio source Sgr A, associated with the Galactic nucleus, consists of a thermal component (Sgr A West), a nonthermal component (Sgr A East), a halo (diameter ∿6') of thermal + nonthermal emission (see Pauls et al. 1976), and a point-like source (cf. Ekers et al. 1975). Some of the halo emission is thermal because: (1) radio recombination lines are seen within a radius of ∿3' of Sgr A; (2) the low-frequency turnover in the continuum spectrum of Sgr A requires ionized gas with an emission measure of ∿4×10^4 cm^{-6} pc. The sources EI and EII can only provide about 50-60% of this emission measure, suggesting that the remainder comes from HII near Sgr A.

The recombination line emission from Sgr A has recently been summarized by Pedlar et al. (1978). These authors show that there

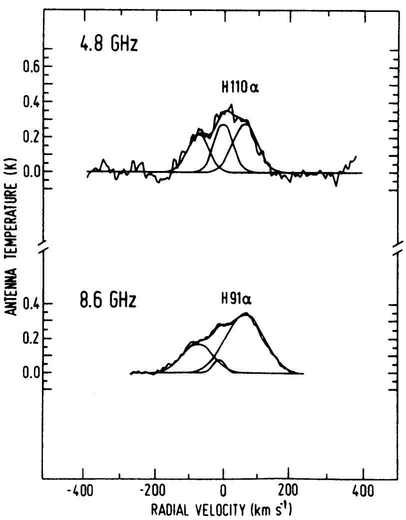

Figure 4: Radio recombination line spectra toward Sgr A West. HPBW (H110α) = 2.6'; HPBW (H91α) = 1.5'.

is weak masering of the line emission which sets in at $\nu \sim 1.4$ GHz and increases as ν decreases (see also Casse and Shaver 1977). Above 5 GHz, Sgr A West emits very broad recombination lines (Pauls et al. 1974). H110α and H91α spectra (Figure 4) show three components with LSR velocities near 0 km s^{-1} and $\sim \pm 75$ km s^{-1}. The line near 0 km s^{-1} probably arises in HII in the halo around Sgr A West and Sgr A East; then, the increased intensity at H110α may be explained by stimulated emission from Sgr A West. The observed line-widths are larger than those from any other HII region in the Galaxy. Similar velocities and velocity dispersions are found from observations of NeII (Wollman et al. 1976, 1977).

Infrared observations show that the inner $\sim 30''$ of Sgr A West contains a number of compact sources plus more extended emission (Becklin et al. 1978a, b; Willner 1978; Neugebauer et al. 1978; Rieke 1978). Some of the compact sources appear to be O stars or star clusters. The extended emission seen in the middle to FIR seems likely to be dust heated by hot stars. These facts suggest that star formation is currently taking place within the inner parsec of the Galaxy.

The Origin of the FIR Radiation from the nuclear region is generally accepted to be due to dust grains heated by stellar radiation. However, it is still not clear if these dust grains are mainly located in dense molecular clouds or in ionized gas.

Figure 5 shows on overlay of the main contours of a FIR map (40-350μm) by Alvarez et al. (1974) on the 5 GHz map of the thermal radiation constructed by Schmidt (1978a). This map confirms the close correlation already seen in Fig. 2. We have integrated radio and IR maps in circles of radius R centered on Sgr A West; for $\lesssim 8'$ we used the high resolution observations by Ekers et al. (1975), Pauls et al. (1976) and Harvey et al. (1976).

In Fig. 6 we plot, as function of radius R, (1) the IR luminosity L_{IR}; (2) the total luminosity of PopII stars from eq. (5) of Sanders and Lowinger (1972); (3) the total luminosity of PopI stars, estimated by converting S_5 into N_c', the number of Lyc-photons absorbed by gas, and subsequently into $N_c = \{f_{net}(1-f)\}^{-1} N_c'$, the number of Lyc-photons emitted by all O stars contained in a cylinder of radius R. We used $f_{net}(1-f) = 0.33$ (see following section). Then $5.75\, N_c h\nu_\alpha$ is the total luminosity of stars of all masses which have been

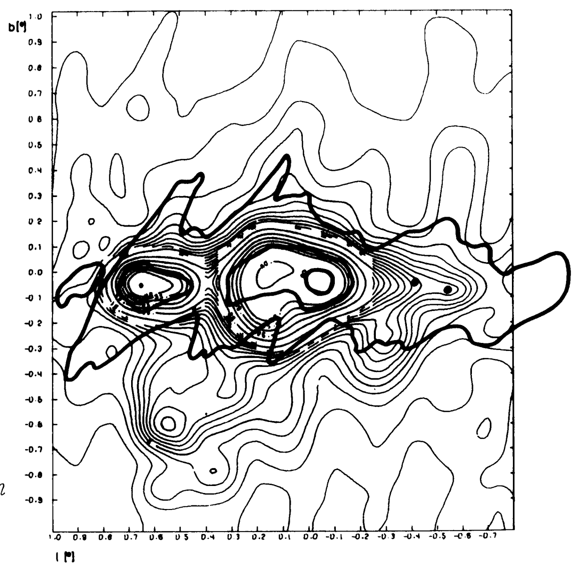

Figure 5: Overlay of the IR map of the galactic center region obtained by Alvarez et al. (1974; 40-350μm; HPBW = 5.6') on the map of thermal radio emission constructed by Schmidt (1978a; HPBW = 7.6').

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formed together with the O stars, *if* Salpeter's original luminosity function holds.

Figure 6a shows that both PopI and PopII stars provide enough energy to account for the observed FIR radiation. However, (1) the correlation between thermal radio and IR emission (Figs. 2 and 5); (2) the fact that for well mixed PopI and II stars the effective (Planck mean) absorption optical depths for PopI radiation is larger; and (3) the fact that 3-color photometry by Gatley et al.(1977) shows molecular clouds in the nucleus as "cold" and ionized gas as "hot" regions, indicates that the contribution of PopI stars to the heating of dust is stronger than in the spiral arms. In the spiral arms Mezger (1978) has estimated that old and young stars contribute equally to the heating. Within $R \lesssim 150$ pc we estimate that PopI stars contribute 2/3 of the energy which heats the dust.

The infrared excess, (IRE) = $L_{IR}/N_c' h\nu_\alpha$, is related to the fraction of Lyc-photons absorbed directly by dust. This quantity is shown in Fig. 6b. The low values for $R \lesssim 5'$ show that the ionized gas may be dust depleted beyond Sgr A West (Mezger 1974; Gatley et al. 1977).

<u>The Star Formation Rate.</u> The number of Lyc-photons absorbed per sec by gas, N_c' is related to the Lyc-photon production rate N_c of the ionizing O stars by $N_c' = f_{net} N_c$ for ionization bounded HII regions, and by $N_c' = f_{net}(1-f)N_c$ for density-bounded HII regions. Here $(1-f_{net})$ is the fraction of Lyc-photons absorbed by dust and f is the fraction of Lyc-photons which escape the density bounded HII region.

HII Regions	ΣS_5/Jy	T_e/K	$\Sigma N_c'/s^{-1}$	f_{net}	(1-f)	$\Sigma N_c/s^{-1}$
giant	320	8000	3.1×10^{51}	0.3	1.0	1.0×10^{52}
ELD	480	5000	5.8×10^{51}	0.61	0.57	1.7×10^{52}

The table above gives N_c' for compact and ELD HII regions based on the values S_5 and T_e listed. For the compact HII regions we estimate $f_{net} = 0.3$; an average value derived from IR luminosity, He^+-abundance and the assumptions used by Smith et al. (1978). For the ELD HII region we estimated the values f_{net} and (1-f) given in the table above from an analysis similar to that used by Mezger (1978) for the spiral arm ELD HII region.

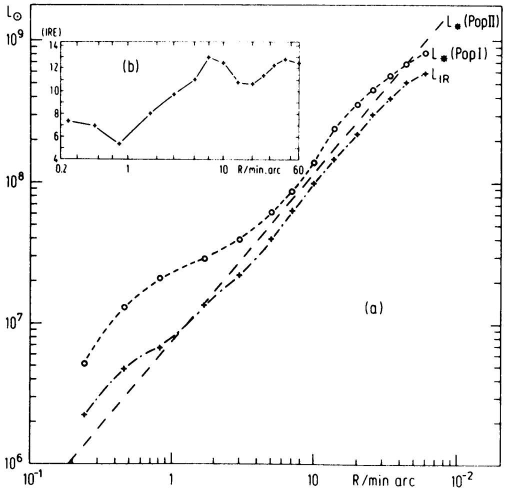

Figure 6: 6a: Luminosities, integrated within cylinders of radius R, of i) the IR emission L_{IR}; ii) the radiation of old (PopII) stars L_* (PopII); iii) the radiation from O star clusters L_* (PopI). 6b: The IR excess, (IRE) = $L_{IR}/N_c' h\nu_\alpha$.

The total Lyc-photon production rate in the nuclear region ΣN_c (giant + ELD HII) = 2.7×10^{52} s^{-1}, or $\sim$8% of the total Lyc-photon production rate in the Galaxy, $(30+2.7)10^{52}$ s^{-1} (Mezger 1978). If the stellar birth rate function is constant within the Galaxy, a similar ratio must hold for the star formation rates. The Arc feature may not be ionized by O stars; in this case the nuclear star formation rate would be $\sim$7%.

Mezger (1974) has shown that the Lyc-photon production rate by nuclei of planetary nebulae is negligible.

Finally, although the estimates of L_{IR} and N_c are not quite independent, it is of interest to compare the integrated luminosity from the map by Alvarez et al., 6×10^8 $L_\odot$, with the IR luminosity of the spiral arm region estimated by Mezger (1978) on the basis of observations by Low et al. (1977), $\sim 6 \times 10^9$ $L_\odot$. The corresponding ratio, $\sim$9%, is also a roug estimate of the star formation rate in the nuclear and spiral arm regions

Summary. Ionized gas extends from the center of the Galaxy out to a radius R $\sim$150 pc, while the molecular clouds extend to R $\lesssim$300 pc. Within this radius, the total stellar mass is $\sim 1.5 \times 10^9$ $M_\odot$, the total gas mass is $\sim 1.2 \times 10^7$ $M_\odot$ of which $\sim 2 \times 10^6$ $M_\odot$ is ionized. Most of the neutral gas is in molecular clouds which probably occupy less than 5% of the interstellar space.

With the possible exception of the Arc feature, the giant HII regions indicate recent, large-scale star formation. The extended, low-density HII appears to be evolved HII regions whose Strömgren spheres have merged. Between 25% (Arc feature not included) and 37% (Arc feature included) of the O stars are contained in compact HII regions; in spiral arms the corresponding ratio is 18%. This may indicate that the present star formation rate is somewhat higher than the star formation rate averaged over the past 5×10^6 yr. O stars appear to contribute most to the heating of dust grains which emit in the FIR.

The nucleus of the Galaxy consists of the compact HII region Sgr A West, which contains a cluster of O stars, surrounded by more extended HII of lower density (halo). Within a radius of $\sim$10 pc the gas appears to be depleted of dust. Sgr A West as well as the thermal halo emit very broad recombination lines; the mechanism for the broadening of the lines is not understood.

The He^+-abundance in nuclear giant HII regions is extremely low. This could be due to an increased metal abundance, which would effect the Lyc-photon radiation field through 1) increased stellar opacities, 2) and/or increased dust-to-gas ratio, and/or 3) selective absorption by dust grains. However, LTE electron temperatures of nuclear giant HII regions are higher than those in spiral arm HII regions; this argues against an increased metal abundance in the center of the Galaxy.

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DISCUSSION

Terzian: Although O-type stars may be present in the galactic nucleus which may contribute a large fraction of the ionizing radiation, we should also include the important contribution of ionizing radiation from the central stars of planetary nebulae, because the number density of planetary nebulae in the galactic central region is very high.

Mezger: We considered this using your own estimates of the characteristics of PN: these contribute less than 10% of the Lyc-photon production rate in the nuclear region.

Sanders: From your recombination line observations, you can isolate, kinematically, those components of the thermal continuum emission which arise in the inner part of the Galaxy. If you do this, can you say whether or not the HII seems to be distributed in a tilted disk?

Mezger: The distribution of the ELD ionized gas shows in the inner part a remarkable spherical symmetry, whose center, however, does not coincide with Sgr A West but is somewhat shifted towards $\ell > 0°$. Further out, the ELD ionized gas is elongated parallel to the galactic plane but its plane of symmetry lies at $b < 0°$.

Puget: In the far-infrared data which you mentioned, there is evidence for variation in the dust temperature which might be relevant to the question of the region of origin of this radiation: in HII regions or in molecular clouds. Except for the central peak the evidence suggests that most of the far-infrared emitted within 300 pc of the galactic center comes from molecular clouds.

Mezger: I do not agree. All the observational evidence which I have presented indicates that the main contribution to the FIR emission at wavelengths $\lambda < 300\mu$ comes from dust particles embedded in ionized gas which are heated by radiation from O stars.

Schmidt-Kaler: In the last passages of your talk you compared the nuclear region with the whole Galaxy. I have three questions: (1) What were the initial mass functions you used? (2) What is the gas turn-over rate ($M_\odot$/year) as a consequence of the stellar evolution (and formation) processes which you described? (3) What is the ensuing chemical enrichment in the nuclear region compared to the whole Galaxy?

Mezger: (1) I derived Lyc-photon production rates. If these are to be converted into star formation rates one needs an IMF. (2) If I assume that the IMF is constant throughout the Galaxy and similar to Salpeter's IMF the star formation rate would be about 0.3 $M_\odot$/year in the nuclear region and the instantaneous return rate would be about 0.08 $M_\odot$/year. (3) At the moment I can only make the qualitative statement that Z(nuclear region) > $Z_\odot$, but I cannot say it is three or six times larger.

Sinha: Dr. F. J. Kerr, Dr. R. W. Hobbs, and I have mapped a 5'x5' area around Sgr A at 90 GHz. In the map shown in the adjacent figure, the Sgr A East component can be separated from the Sgr A West source. The ratio of the flux of the two components is equal to the ratio expected from the 6-GHz map of Ekers et al. (A.&A. 43, 159) after proper corrections for the different beam sizes are made. The Sgr A East component does not appear to have a non-thermal spectrum between 6 and 90 GHz.