THE LARGE SCALE INFRARED EMISSION IN THE GALACTIC PLANE—OBSERVATIONS

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I. INTRODUCTION

For a long time, the inner region of our Galaxy has been veiled by strong interstellar extinction in visible light. The situation has been greatly improved by recent exploration in the infrared region, where the interstellar extinction becomes practically negligible.

Infrared radiation is deeply involved in a variety of matters and processes in the galaxy. Near infrared radiation is predominantly emitted by late type stars which include the major part of the mass in the Galaxy and hence govern its dynamics. Short wavelength radiation (UV and visible) emitted from early type stars is easily absorbed by dust around the stars themselves or by interstellar dust, and reemitted in middle or far infrared regions. A variety of emission lines, fine structure lines of neutral and ionized heavy elements, as well as many molecular lines are also clustered in the middle and far infrared regions.

Since their line intensities are generally very weak, and, moreover, spectroscopic observations demand relatively difficult techniques in their detection, the surveys so far done have been limited mostly to continuum emission. Here we shall try to compile them and discuss briefly their implications to the structure of our Galaxy in its inner region.

II. SURVEY OF THE INFRARED SURVEYS

During the past decade, numbers of observations were devoted to measurements of the brightness distribution in the galactic plane, mostly either in the near infrared or far infrared regions plus a few in middle infrared. They are listed in Table 1, with their observational parameters.

C. G. Wynn-Williams and D. P. Cruikshank (eds.), Infrared Astronomy, 247–260.

In the near infrared surveys made at balloon altitudes, the observable wavelength is severely restricted within a narrow band centered at 2.4 μm, a unique band gap of the OH airglow emission which was found to show patchy distribution with rapid variation in space and time, in the course of the first trial of near IR survey (Sugiyama et al. 1973). The surveys have been made extensively in the northern sky by various authors (ref. 4, 5, 6, 7, 8, 12, 13, 14). Recently they were extended to the southern sky (ref. 15).

Observations outside the OH-band gap were also tried but were fatally influenced by the irregular change in the OH emission, and the results are restricted to limited regions near the galactic center (ref. 7, 15).

Rocket observations allowed investigators to choose their observing wavelength freely and expand it from near infrared to middle and far infrared regions (ref. 2, 3, 12, 19, 22).

Most of the far infrared surveys were conducted by balloons (ref. 1, 9, 10, 11, 16, 17, 18, 21, 23, 24) and some by airplane (ref. 20). The early works were mostly single band surveys in fragments of galactic longitudes, but the current surveys have widened the longitude range (ref. 9) and developed into two-dimensional mappings (ref. 16, 21, 24). The observing wavelength was also extended to submillimeter range (ref. 17). A complete set of two color longitude profiles was just reported recently (ref. 23).

III. GENERAL FEATURES OF THE RESULTS

1) Near Infrared Distribution

The near infrared mappings in the northern sky made by various authors in different methods and resolutions show excellent agreement with one another. Combining the recent observations in the southern sky with theirs, Hayakawa et al. (1980b) provided a synthesized map of the Milky Way between ℓ = 290° and 70°, which is reproduced in Figure 1. One can easily recognize there a familiar isophoto of an edge-on galaxy; indeed our Galaxy is the nearest and the largest edge-on galaxy!

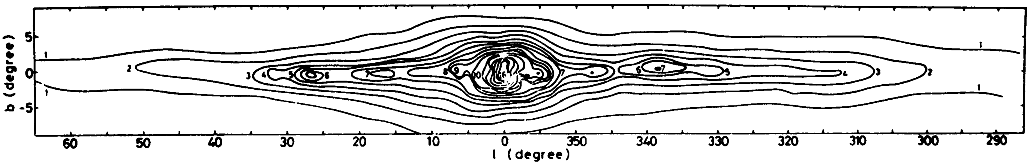

Fig. 1. The synthesized map of 2.4 μm emission in the galactic plane (Hayakawa et al. 1980b).

The central concentration, the so-called bulge, extends ±15° in longitude and ±7.5° in latitude, corresponding to 3 kpc and 1.5 kpc in linear size, if 10 kpc is adopted for the distance of the galactic center.

The brightness distribution in the central region of the bulge is modified by strong interstellar extinction. In fact the effect is more clearly revealed in the detailed mapping with higher resolution (Oda et al. 1979) as shown in Figure 2.

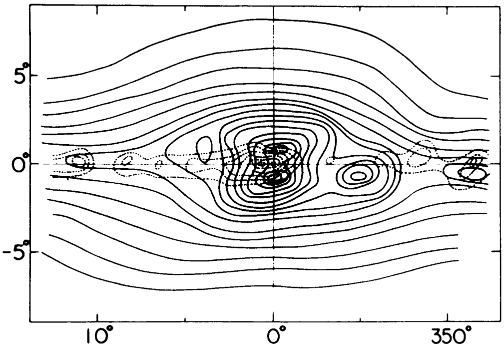

Fig. 2. The detailed map of 2.4 μm emission in the galactic central region (Oda et al. 1979), overlapped with the far infrared contours (Maihara et al. 1979).

The magnitude of the extinction is estimated to be as large as 2.7 mag for 2.4 μm at the center by assuming that the intrinsic brightness distribution follows the universal $r^{1/4}$ law (Maihara et al. 1978). About 1/3 of the extinction is considered to originate in the nuclear region (Oda et al. 1979).

Another conspicuous feature is the flat thin wing extending outward from the bulge, which is abruptly terminated near $\ell = 30°$. This behavior has been noticed commonly in various constituents of the Galaxy, such as the radio continuum, CO-molecular line, as well as the far infrared emissions; this relationship will be discussed later in more detail. In Figure 3, longitude profiles of the relevant constituents are compiled. The shoulder near $\ell = 30°$ is sometimes referred to as the 5 kpc ring (e.g. Burton 1976). In this respect, however, it is interesting to see that the distribution of the near infrared radiation is apparently asymmetrical between the northern and southern hemispheres. This may indicate that the feature is much more concerned with spiral arms rather than the ring. In fact, another shoulder at $\ell = 310°$ seems to be paired with the $\ell = 30°$ shoulder and they correspond well to the Scutum-Crux arm (Georgelin and Georgelin 1976).

A slight deviation of the brightness ridge from the galactic equator is also noticed (Hayakawa et al. 1979); the ridge shifts about 0.5° to negative latitude in the northern sky, while it lies almost on the galactic equator in the southern sky.

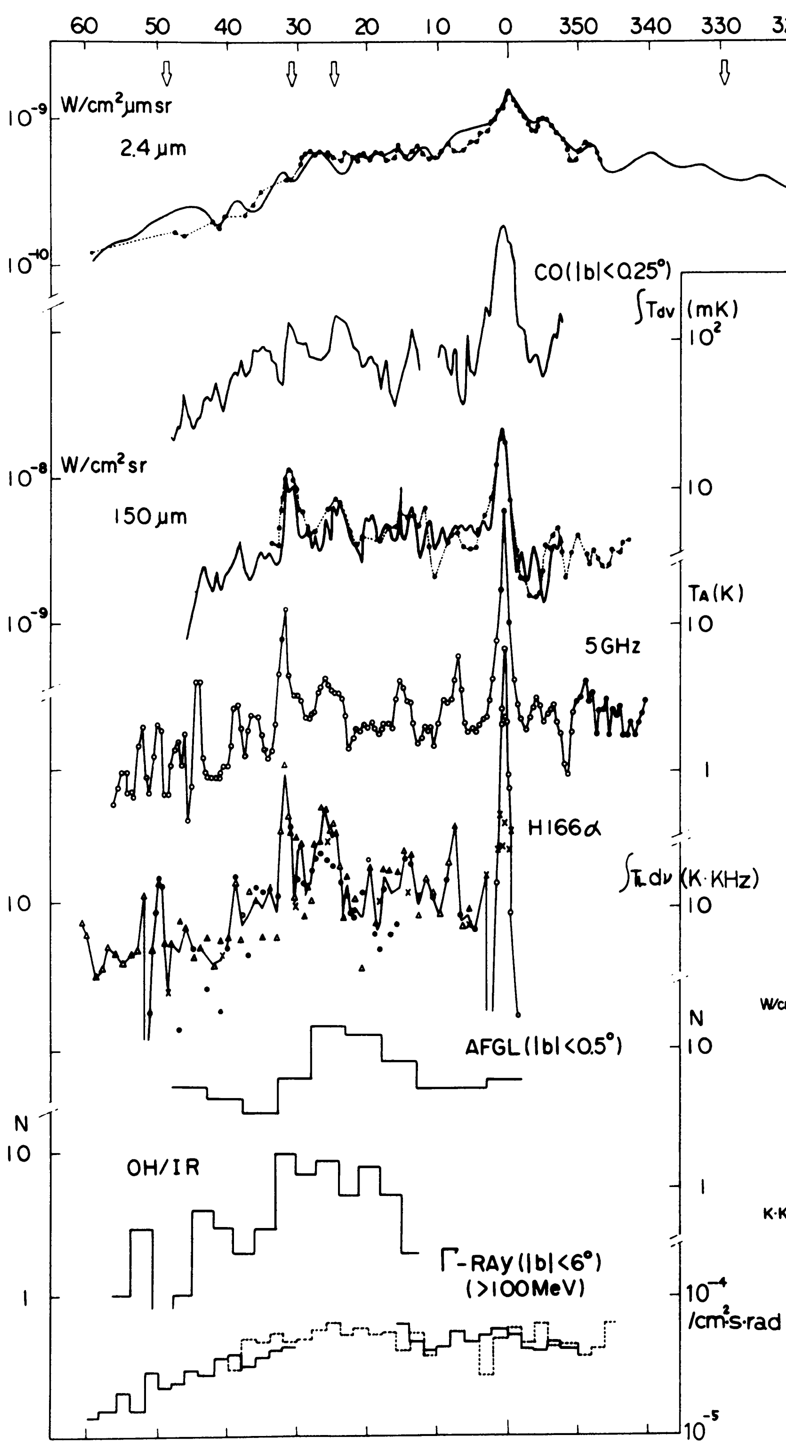

Figure 3

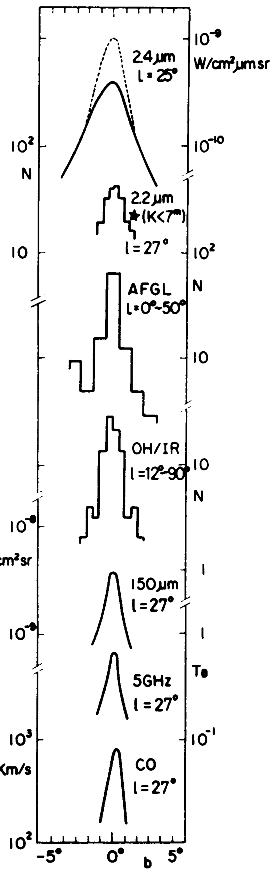

Figure 4

Fig. 3. Galactic longitude profiles of the 2.4 μm emission (—: Hayakawa et al. 1980b, •····• : Oda et al. 1979), CO-emission (Cohen et al. 1980 and Bania 1977), 150 μm emission •—• : Maihara et al. 1979, —: Nishimura et al. 1980), 5GHz continuum emission (Attenhoff et al. 1970), H166α line (• : Lockman 1976, ▵ : Hart and Pedlar 1976), AFGL sources (Price and Walker 1976), OH/IR sources (Bowers, 1978) and cosmic γ-rays (Bennett et al. 1977).

Fig. 4. Galactic latitude profiles corresponding to Fig. 3.

In the smaller amplitude variations in the longitude profile, one can see a clear anti-correlation with the profiles of the CO-emission and the far infrared emission. This is easily understood as an effect of the interstellar extinction, since both the CO- and the far infrared emissions are closely related to dust. The anomaly at ℓ = 355°, b=-1° was supposed to be of the same origin (Oda et al. 1979). It may be a hole in interstellar extinction through which we are looking into the deep space in the central region of the Galaxy. It is interesting to note that the area has the lowest level of the far infrared emission as is mentioned later.

The most striking feature to be pointed out in regard to the wing component is its extreme thinness. If we take into account the effect of interstellar extinction, the intrinsic width would become much thinner, 2-3° in FWHM as shown by a dotted line in Figure 4. This corresponds to a scale height of 100-140 pc even if it is located at the tangential point of the 5 kpc arm. A much smaller value of 50 pc is obtained as an extreme case (Hayakawa et al. 1980b). This is significantly smaller than the scale height of 300 pc or 400 pc for K or M-giant stars, which are presumably the most effective contributor to the near infrared emission.

In order to resolve the contributions to individual sources, a deep sky survey is now being conducted by means of a multicolor photometer (IHKL bands) attached to the groundbased telescopes with finer angular resolution (Kawara et al. 1980). The survey was made in narrow strips or bands across the galactic plane selectively sampled between ℓ = 350° and 45°. The analysis is rather preliminary as yet; however, some results are given in Figure 5. The source distribution behaves quite similarly to the brightness distribution obtained in the balloon observations, i.e., abrupt decrease in number density near ℓ = 30°, and very thin latitudinal distribution. It is particularly interesting that the latitudinal concentration is seen only in the profiles at ℓ = 26-27° and 28°. A similar concentration is found in the distributions of the AFGL sources as well as in the OH/IR sources (see Fig. 4).

Table I. Large scale IR surveys

Observers	(year)	1	b	$\lambda_{\mu m}$	f.o.v.	ref.
Hoffmann et al.	(1971)	358°-2°	±2°	100	12'	1
Houck et al.	(1971)	354°-7°	0°	100	0.25°×1°	2
Pipher	(1973)	2.5°	a profile	100	0.25°×1°	3
Hayakawa et al.	(1976)	25°-70°	±10°	2.4	3°	4
Okuda et al.	(1977)	350°-30°	±10°	2.4	1°	5
Ito et al.	(1977)	350°-33°	±10°	2.4	2°	6
Hofmann et al.	(1977)	348°-10°	±10°	2.4	2°	7
		358°-0.5°	±10°	3.4	2°	
Hofmann et al.	(1978)	352°-8°	±8°	2.45	1°	8
Rouan et al.	(1977)	28°	a profile	71-91	0.7°	9
				114-196	0.7°	
Low et al.	(1977)	348°-32°	0°	60-300	0.25°	10
				150-300	0.25°	
Serra et al.	(1978)	36°-55°	0°	71-91	0.7°	11
				114-196	0.7°	
Hayakawa et al.	(1978)	182°	-9°	2.3	4°	12
Hofmann et al.	(1978)	357°-10°	±10°	2.45	1°	13
Oda et al.	(1979)	345°-32°	±10°	2.4	0.5°	14
Hayakawa et al.	(1979)	288°-23°	±10°	2.4	0.5°,0.8°,1.7°	15
				3.4	2°	
Maihara et al.	(1979)	340°-32°	±3°	100-300	0.6°	16
Owens et al.	(1979)	345°-45°	0°	400-1000	1.6°	17
				1000-3000	1.6°	
Serra et al.	(1979)	26°-40°	0°	71-91	0.5°	18
				114-196	0.5°	
Price	(1979)	0°-30°	±5°	4	0.8°	19
		0°-320°		11	0.8°	
		0°-320°		20	0.8°	
		40°-85°		27	0.8°	
Viallefond et al.	(1980)	27.5°	a profile	114-196	6.3'	20
Nishimura et al.	(1980)	350°-45°	±2°	100-300	0.5°	21
Hayakawa et al.	(1980a)	30°-65°	0°	2.0	1.5°	22
				2.8	1.5°	
				4.8	1.5°	
Boissé et al.	(1980)	0°-85°	0°	71-95	0.4°	23
				114-196	0.4°	
Hauser et al.	(1980)	0°-63°	±3°	106	10'	24
		81°-87°		238	10'	
		129°-135°		270	10'	
		261°-285°				

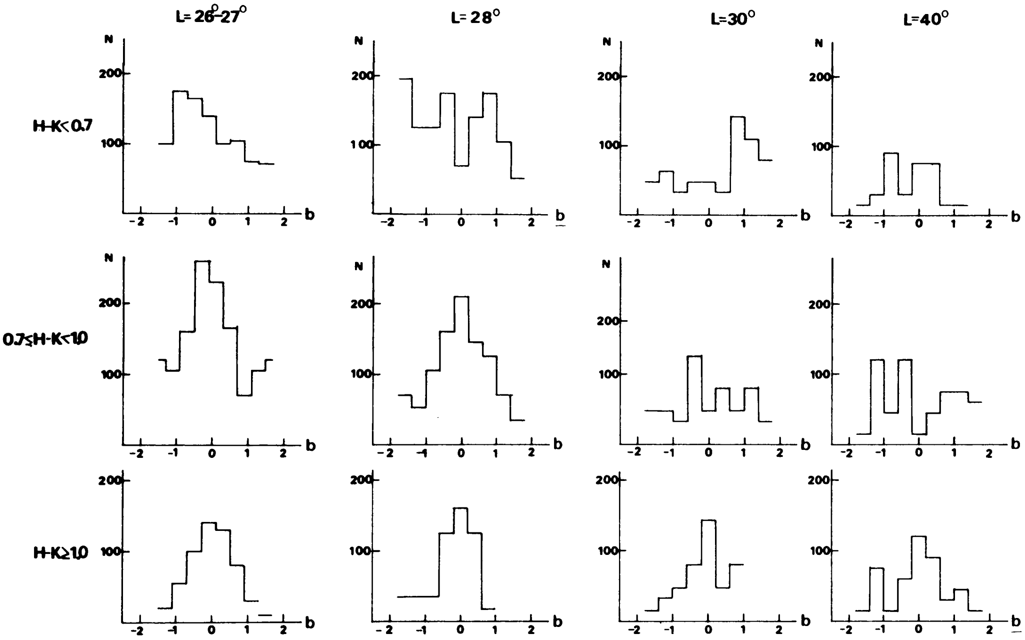

Fig. 5. The number density distribution of the infrared sources detected in the deep IR surveys (Kawara et al. 1980).

From the rocket observations the energy spectrum between 2.0-4.2 μm is found to fit a black body spectrum of 3300 K (Hayakawa et al. 1980a), but a strong enhancement was detected in the AFGL survey at 10-20 μm range (Price 1980).

2) Far Infrared Distribution

The two dimensional maps provided by Maihara et al. (1979) and by Nishimura et al. (1980) were obtained in essentially the same spectral range (100 - 300 μm) but with slightly different resolutions. They cover almost the same area in the galactic plane and show an excellent agreement with each other. The map obtained by Nishimura et al. is shown in Figure 6.

The concentration of the brightness toward the galactic center is prominent, but the distribution is more extended than previously observed in a smaller field of view by Hoffmann et al. (1971). The region is clearly silhouetted as extinction against the near infrared background (see Figure 2). The brightness peaks at Sgr B2 rather than the exact center, Sgr A, while the peak in the shorter spectral range (50-300 μm) coincides with the latter (Hoffmann et al. 1971, Low et al. 1977). This indicates that cold dust is distributed more extensively in the galactic center. In this respect, it is interesting to note that the extent of the CO clouds (Bania, 1977) is closely matched with the far infrared emission, while the thermal radio continuum is, on the other hand, concentrated strongly into the Sgr A region.

Besides the central concentration, the far IR emission is distributed along the galactic plane in a narrow band with almost constant width. As is noticed in Figure 6, the general patterns in the brightness distribution correspond strikingly well with those of the 5GHz radio map (Altenhoff et al. 1970) The relation is, however, not necessarily a priori, for the infrared emission depends on the dust abundance as well as on the heat sources. Several sources are identified with CO-cloud complexes as suggested by Nishimura et al. (1980).

Cohen et al. (1980) have made an extensive survey of CO-emission in the galactic plane and recently supplied a first complete two dimensional map in ℓ = 12°-60° and $|b| \leq 1°$, a part of which is reproduced in Figure 6. Similarity among the three maps is quite impressive; implying that the three components are closely correlated at least spatially and more probably genetically.

In addition to the discrete sources, there exists a background component extending diffusely along the galactic plane in finite width. It may correspond to the ELD HII region proposed by Mezger (1978). The contribution of the discrete sources is, however, dominant and their distribution is very complex; therefore separation of the extended component is not so straightforward. Actually, there is some discrepancy in the observed widths (FWHM) of Maihara et al. (1979); $b_{1/2} \sim 3°$, and Nishimura et al. (1980); $b_{1/2} \sim 1.5°$, probably due to differences in the angular resolutions.

A survey in submillimeter region was conducted by Owens et al. (1979). The observed width of $b_{1/2}=4 \sim 5°$ is considerably broader than that observed in the shorter range. Colder dust might be distributed more diffusely, but extremely large amounts of low temperature dust should be assumed to broaden the distribution to such a width, surmounting the emission of the high temperature dust. A further observation is important.

As for the dust temperature, 50 K and 18 K are estimated for the galactic center and the general diffuse components respectively (Nishimura et al. 1980). A complete set of the bi-spectral observation of the galactic plane has just been presented by Boissé et al. (1980), giving a little higher temperature, 25 $\sim$30K, for the ridge component.

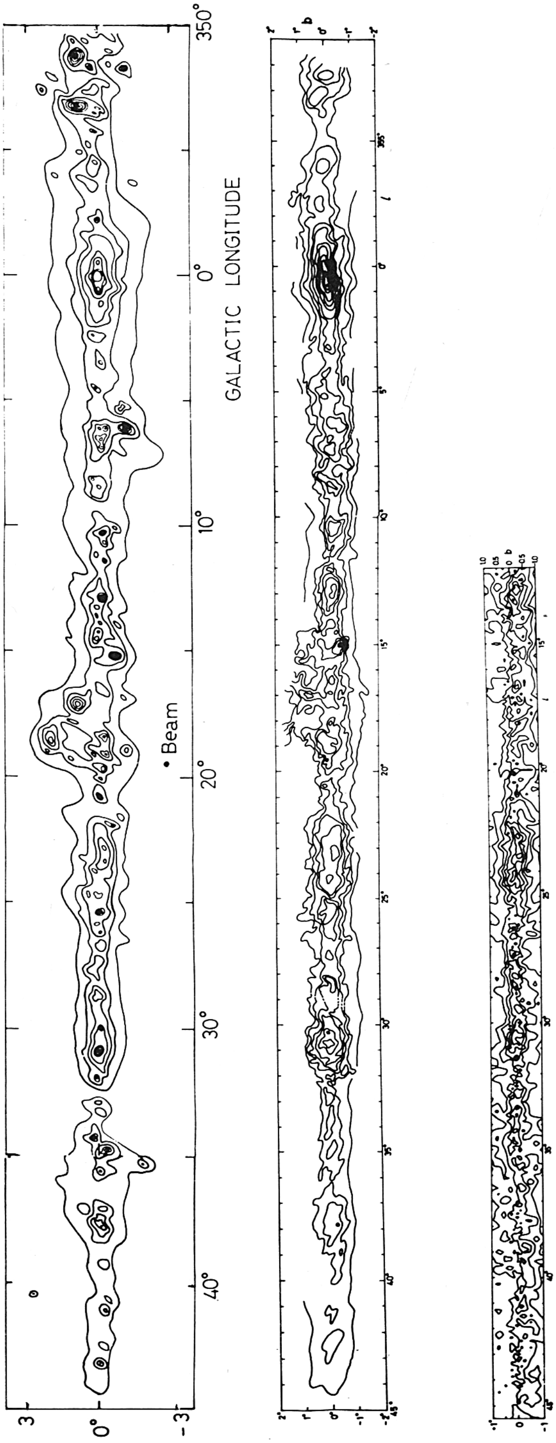

Fig. 6. Comparison of the intensity maps of the 5 GHz radio continuum (Altenhoff et al. 1970), the FIR emission (Nishimura et al. 1980), and CO emission (Cohen et al. 1980).

IV. A BRIEF SKETCH OF THE INNER GALAXY

As has been mentioned so far, the infrared data for the inner region of the Galaxy have been accumulated in considerable amount and variety. Combining these data together with those in radio and other spectral ranges, we are now able to draw a comprehensive picture of the inner structure of the Galaxy. Here we try to sketch it briefly and rather qualitatively.

1) The Galactic Central Region

So far as the central bulge is concerned, it is of medium size ($R \sim 1.5$ kpc) and normal luminosity ($3 \cdot 10^{10}$ $L_\odot$); almost compatible to M31 (Maihara et al. 1978). In contrast with M31, however, the nuclear region is still very active and abundant in gas and dust, forming a giant complex of HII regions and molecular clouds. The far infrared luminosity from the whole region ($R < 300$ pc) amounts to of the order of 10^9 $L_\odot$, from which the total mass of dust is estimated to be $10^5 M_\odot$, if the dust temperature is adopted as 40 K (Nishimura et al. 1980, Maihara et al. 1980). The dust mass thus obtained is consistent with the interstellar extinction of Av=10-15 mag, shared by the Galactic nuclear region (Oda et al. 1979). The concentration of dust in the nuclear region is also well understood from the existence of large complex of CO clouds ($M_{H2}=3 \sim 7 \cdot 10^8$ $M_\odot$, Bania, 1977). Because the far infrared emission has a broader distribution than the radio continuum, some unknown sources must exist to heat the dust; the contribution of starlight from old stars is supposed to be comparable to that from HII regions or young stars (Mezger and Pauls 1978).

2) The 5 kpc Complex

One of the most interesting discoveries in the past few years is that of the so called 5 kpc ring. The near infrared observations extended to the southern sky, however, suggest that it is more like an arm than a ring structure. In any case, it is undoubtedly an extremely active region filled with almost every constituent: young and old stars, dust, gases in neutral and ionized as well as molecular states, and possibly cosmic ray and γ-ray sources.

As for the stellar component, it is suggested from its extremely thin distribution in z-plane ($z_{1/2} \sim 140$ pc) that it consists of predominantly very young objects, the age of which is estimated to be of the order of 10^7 years (Hayakawa et al. 1980) or 10^8 years (Boissé et al. 1980).

The possible candidates for such young objects are OB stars or M-supergiants. The former possibility is, however, excluded simply because too high a stellar density would have to be assumed as compared with that expected from the radio data (see Table 2).

If it were M-supergiants, the relative stellar density required is still a little too high compared with that expected from the general population of stars in the solar vicinity (Allen 1973). The

TABLE 2. STELLAR POPULATION IN THE 5 kpc COMPLEX

	Energy Release Rates			
	Near IR (2.4 μm) 5∼6×10^{35}W/kpc^3			UV(radio continuum) 1∼2×10^{35}W/kpc^3
	M-type Giants	M-type Supergiants	O-type Supergiants	O-type Supergiants
5 kpc (observed)[a]	5×10^{-4}	3×10^{-5}	1×10^{-3}	8×10^{-6}
10 kpc (observed)[b]	10^{-5}	10^{-7}	10^{-7}	10^{-7}
5 kpc (predicted)[c]	10^{-4}	10^{-6}	10^{-6}	10^{-6}
5 kpc excess[d]	5	30	10^3	8

[a] Stellar number density (no/pc^3) at 5 kpc as deduced from energy releases.
[b] Stellar number density (no/pc^3) at 10 kpc taken from Allen (1973).
[c] Observed 10 kpc stellar density multiplied × 10, the mass ratio between 5 and 10 kpc.
[d] Ratio of observed to predicted 5 kpc stellar densities.

excess becomes moderate only when M-giants are assumed to be the main constituent. In this case, however, the z-distribution would become considerably broader ($z_{1/2}$ ∼400-500pc) in contrast with the observed value of 50-140 pc (Hayakawa et al. 1980b, Okuda et al. 1979).

In this regard, it is interesting here to remember that the AFGL sources and OH/IR sources are also confined in the galactic plane in a similar way to the near infrared sources. The AFGL sources are frequently identified as carbon or late M stars with thick dust shells (Allen et al. 1977), while the OH/IR sources are identified as Mira variables with thick circumstellar dust (Bowers 1978). Generally, these stars are believed to be at a rather advanced stage of stellar evolution, and therefore their scale heights should be relatively large, somewhat contradictory to the observed results.

These facts suggest that the stellar population in the region is somewhat different from that in the solar neighborhood. It might be rich in evolutionarily young but apparently late type stars, such as massive stars which evolved quickly with large mass loss and hence are surrounded by a thick dust shell.

On the other hand, the far infrared and radio observations have revealed the fact that the region is full of young objects, i.e. HII regions containing many OB stars, as well as dense molecular clouds in which star formation is actively in progress. This favors the argument that the near IR emission should be attributed mostly to M-supergiants, but in that case their population would become too large compared with the other stellar constituents.

The far infrared, radio continuum and CO emissions are correlated spatially but in a very complicated way. More detailed and extensive observations with higher spatial and spectral resolution are essential for fully understanding their genetic relation. Spectroscopic observations are especially important for studies of physical states or dynamics in the region, as well as for distance determinations of the sources, which are crucial to delineate the galactic structure.

As has been discussed, the inner region of our Galaxy is one of the most intriguing regions to be explored. Infrared techniques are undoubtedly becoming powerful and indispensable tools for its complete understanding together with radio techniques.

The author is very grateful to Drs. T. Nishimura, R. Cohen, J. Serra, S. D. Price, T. Matsumoto, and K. Noguchi for informing him of their unpublished data.

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DISCUSSION FOLLOWING PAPER PRESENTED BY H. OKUDA

T. JONES: What exactly is the cause of the bumps in the 2.4 μm flux in the plane?

OKUDA: I think they are partly due to the anisotropic distribution of sources and partly to variations of interstellar extinction; there is some anti-correlation between peaks in the 2.4 μm and peaks in the mm-wave CO intensity which suggest that molecular clouds may be causing part of the extinction.

T. JONES: If these bumps are due to excess star counts, what is the population type?

OKUDA: We are not yet certain, but I would believe they are either M giants or young M supergiants.

T. JONES: In your histogram [Figure 5] you indicated you needed hundreds of stars per square degree; this would represent a very large number of supergiants.

OKUDA: I agree that not all can be supergiants, but I think that the contribution of supergiant stars is significant.

PUGET: The component of the 2.4 μm distribution which is associated with a young population, namely the one which is narrower in the latitude direction and which peaks at 30° longitude, can be compared with the far infrared luminosity. In making this comparison we find that the 2.4 μm emission is significantly stronger than is expected based on a standard Population I initial mass function. In other words the Population I excess is partly unexplained if you make the assumption that the stellar population is the same throughout the Galaxy.

AARONSON: It will be very interesting to compare the total 2-μm luminosity of our Galaxy with that of other spirals. When will an accurate estimate of this luminosity be available, or do you have such an estimate now?

OKUDA: The faintest regions of the Galaxy are difficult to map from a balloon at 2.4 μm because of atmospheric OH air glow. We will have to do the experiment by rocket or satellite.

BAUD: CO surveys show that the CO midplane lies below the IAU-plane in the first quadrant. Do the FIR and MIR surveys show the same phenomenon?

OKUDA: Yes, they do.