GALACTIC STRUCTURE FROM INFRARED STUDIES

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Star densities on a galactic scale are traced by far infrared emission of dust heated by young stars and by the 2.4 μm radiation of stars in the red giant phase. Coherent results are obtained, pointing to a very strong star formation rate during the last ∿200 My in a ring 5 kpc from the galactic center. A steepening of the initial mass function compared to that observed in the solar vicinity is also suggested.

Interstellar extinction decreased quickly as the wavelength of the observed radiation increases from visible to infrared. At 2.4 μm it is already possible to observe throughout the galaxy at b = 0'. At this wavelength, emission from stars in the red giant phase are expected to be the dominant component. At longer wavelengths, thermal emission from dust becomes more important. Two very important physical properties of the interstellar dust can be obtained from studies in the infrared: its line-of-sight column density and its average temperature, which is a measure of the energy density of the stellar radiation heating it.

1. REVIEW OF THE EXISTING DATA

Recently partial surveys of the galactic plane at 2.4 μm have been made by several groups (Hayakawa et al. 1976, Ito et al. 1976, Hoffman et al. 1977, Ito et al. 1977, Okuda et al. 1977, and Matsumoto et al. 1977). In Figure 1, a compilation of the data is shown. No significant discrepancy can be seen. Furthermore, a rocket observation has been made by Hayakawa et al. (1978) near ℓ = 182°, b = -9°. In the far infrared, the observations of the diffuse emission are less complete. There is basically no information on the latitude variation and the longitude profile is still incomplete even at ℓ < 30°. Nevertheless, some basic features can be seen on the existing data shown on Figure 2. They include one rocket observation by Pipher (1973), balloon measurements by Serra et al. (1977), Low et al. (1977), and Serra et al. (1978a,b). Data on the structure of this emission have been obtained with an airborne telescope by Rouan et al. (1977) and by Viallefond et al. (1978). On the basis of a simple model in which the stellar

W. B. Burton (ed.), The Large-Scale Characteristics of the Galaxy 105–111.

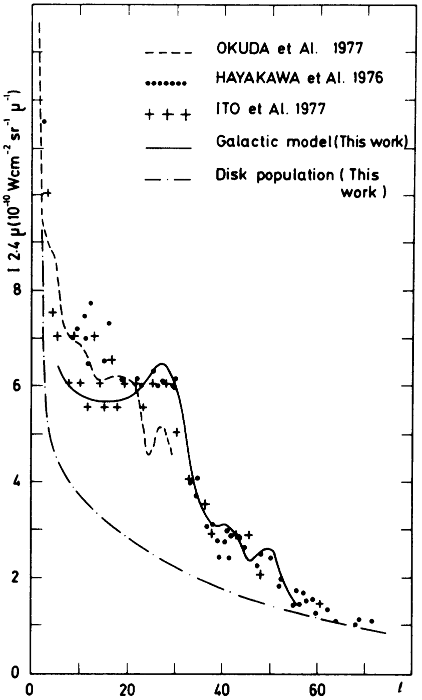

Figure 1. Summary of observations of the λ = 2.4 μm galactic radiation, and values predicted for a conventional mass-to-light ratio and mass model of Galaxy (disc population), and with additional star formation at 5 kpc from the galactic center (see text).

radiation field is uniform in the Galaxy, Stein (1967) and Fazio and Stecker (1976) have predicted values about an order of magnitude lower than what is observed. Much higher values had been predicted by Ryter and Puget (1977) and by Drapatz and Michel (1977), in basic agreement with the data. The significantly higher temperature of the dust predicted in the two later papers is also confirmed by the color temperature found in the balloon observations ($T \sim 25$ K).

2. IMPLICATIONS OF THE 2.4 μm DATA

The values of the brightness observed at $\ell \geq 55°$ in the galactic plane in the anticenter can be compared to that expected from M and K star counts in the solar vicinity, and from the mass distribution in the disc. The good agreement between the computed and the observed fluxes indicates that no unexpected component is detected in these directions (Maihara et al. 1978, Hayakawa et al. 1977, Serra and Puget (1977), Hayakawa et al. 1978). On the other hand, extensive studies of the galactic center have been made in the near infrared; good agreement between the infrared data and the dynamical mass is found (Becklin et al. 1968, Sanders and Lowinger 1972). In the whole range $5° < \ell < 55°$, models based on a standard mass distribution in the disc yields a predicted 2.4 μm emission much below the observed values, as can be seen in Figure 1 (Serra et al. 1978c). The excess is shown in Figure 3 and is quite similar to the longitude profiles of extreme population I tracers (see for example Burton, 1976). We attribute this excess to massive red giants associated with regions of rapid star

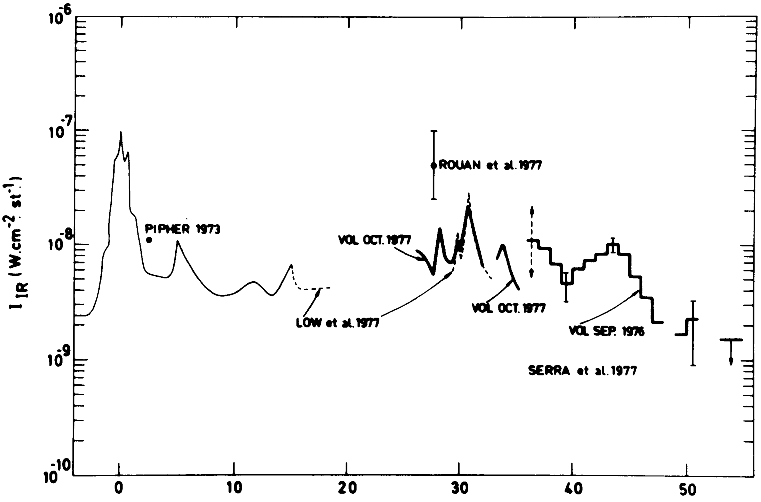

Fig. 2: Summary of observations of the far infrared ($\lambda \gtrsim 50$ to 200 μm) galactic background.

formation. The ratio

$$g = \frac{\int F(t, 2.4\mu)\, dt \Delta\lambda}{\int dt \int F(t, \lambda) d\lambda}$$

where F_λ is the spectral flux density emitted by a star, integrated over the lifetime of the star. It has been computed as a function of star mass. Models of the radial distribution of the 2.4 μm source function have been produced and compared to the data. A high production rate is required in a ring ∿5 kpc from the galactic center, and we deduce that the total luminosity of the main sequence stars associated with the red giants in this region is $L_{tot} \gtrsim 300\ L_\odot\ pc^{-2}$. This very high luminosity implies a star formation rate much higher than that in the solar neighborhood.

3. IMPLICATIONS OF THE FAR INFRARED DATA

A fraction f_1 of the stellar radiation is absorbed by the molecular cloud in which the star was formed, a fraction f_2 is absorbed by dust in the diffuse interstellar medium, and a fraction f_3 is absorbed by all other molecular clouds. An evaluation of these factors as a function of the mass of the star has been made by Serra *et al*. (1978), who found $f = f_1 + f_2 + f_3 \gtrsim 0.3$.

A high infrared luminosity $L \gtrsim 100\ L_\odot\ pc^{-2}$ is needed in a ring at ∿5 kpc from the galactic center to account for the observed flux. Considering the typical value of f, the luminosity is well accounted for by the total luminosity computed from the 2.4 μm excess.

A summary of data and of the results for the solar neighborhood, the 5-kpc ring, and the galactic center, is given in Table 1 and shows clearly that the formation rate of stars with $M < 1\ M_\odot$ per unit mass of

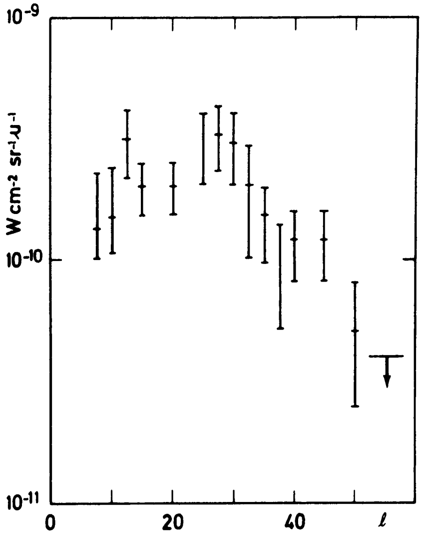

Figure 3. The 2.4 μm intensity in excess of that produced by the disc population, required to account for the observations, and attributed to massive stars in red giant phase.

interstellar gas is much higher in the inner galaxy than in the solar vicinity. If the ratio between the total mass of stars formed below and above one solar mass is everywhere the same as close to the sun (most of the mass goes into stars with $M < 1\ M_\odot$), the gas will be exhausted very quickly in the inner Galaxy (< 100 My). If some stationary state exists, it implies that the initial mass function is not uniform in the Galaxy, or that there is a strong gas infall on the galactic plane or that the gas disc is in radial contraction.

It has also to be noted that a comparison of the total luminosity of the stars recently formed and the Lyman continuum photons produced in the same regions suggest a deficiency of the HII regions in the

TABLE 1 SUMMARY OF DATA AND RESULTS ON DENSITIES AND SOURCE FUNCTIONS IN THE GALAXY

	Mass in Stars	Mass in Gas	$L_{2.4\mu}$ Observed	$L_{2.4\mu}$ Disc	$L_{2.4\mu}$ Excess	$L_{100\mu}$	L_{Lyc}	$\frac{L_{tot,R+I}}{M_{gas}}$	$\frac{L_{Lyc}}{M_{gas}}$
Solar Vicinity	0.145 $M_\odot pc^{-3}$	2.4×10^{-2} $M_\odot pc^{-3}$	1.6×10^{24} $w pc^{-3} \mu^{-1}$	1.6×10^{24} $w pc^{-3} \mu^{-1}$	0		1.1×10^{42} $s^{-1} pc^{-3}$	2 - 4 $\frac{L_\odot}{M_\odot}$	4×10^{43} $s^{-1} M_\odot^{-1}$
	112 $M_\odot pc^{-2}$	5.4 $M_\odot pc^{-2}$	1.2×10^{27} $w pc^{-2} \mu^{-1}$	1.2×10^{27} $w pc^{-2} \mu^{-1}$	0		2.2×10^{44} $s^{-1} pc^{-3}$		
4.5-5.5 kpc ring	0.68 $M_\odot pc^{-3}$	$M_\odot pc^{-3}$	4×10^{25} $w pc^{-3} \mu^{-1}$	8×10^{24} $w pc^{-3} \mu^{-1}$	3.2×10^{25} $w pc^{-3} \mu^{-1}$	2.5×10^{26} $s^{-1} pc^{-3}$	6×10^{42}	15 - 30 $\frac{L_\odot}{M_\odot}$	9.6×10^{43} $s^{-1} M_\odot^{-1}$
	422 $M_\odot pc^{-2}$	14 $M_\odot pc^{-2}$	1.8×10^{28} $w pc^{-2} \mu^{-1}$	5×10^{27} $w pc^{-2} \mu^{-1}$	1.3×10^{28} $w pc^{-2} \mu^{-1}$	4×10^{28} $w pc^{-2}$	1.35×10^{45} $s^{-1} pc^{-2}$		
Galactic Center R<300pc	1.5×10^{10} $M_\odot$	5×10^{7} $M_\odot$	2×10^{10} $L_\odot$			5×10^{8} $L_\odot$	3.5×10^{52} s^{-1}	$20 \frac{L_\odot}{M_\odot}$	7×10^{44} $s^{-1} M_\odot^{-1}$

μ stands for μm .

inner Galaxy, consistent with a steepening of the initial mass function.

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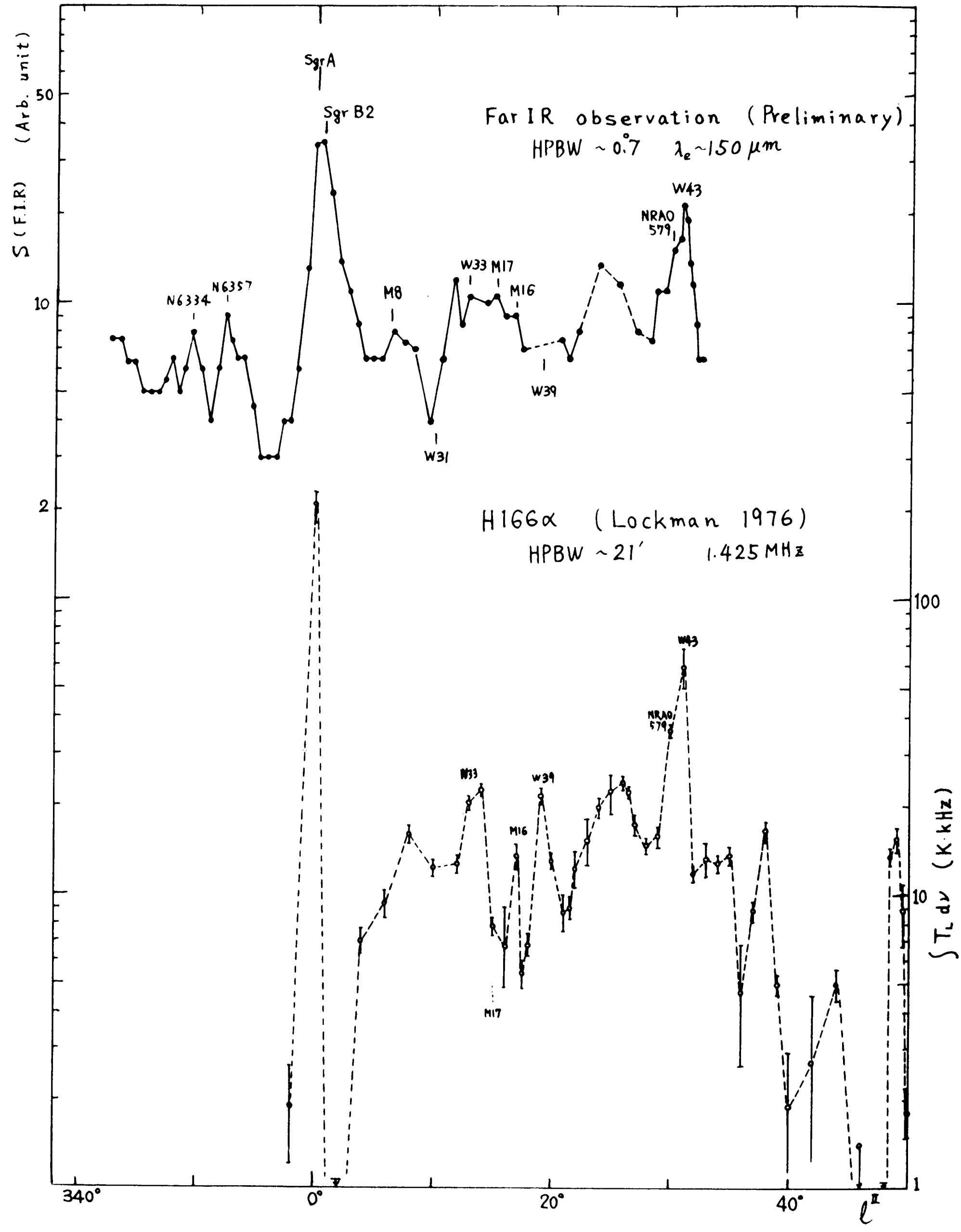
DISCUSSION

Maihara: In connection with Dr. Puget's review, we would like to present a recent far infrared result. We observed an extended area from 345° to 30° in longitude with about 0°.7 resolution at $\lambda_{eff} \simeq 150\ \mu m$. The figure shows the preliminary longitudinal distribution along the ridge of the galactic plane. Our observations have detected a number of discrete sources associated with HII regions. The lower curve is the H166α intensity of Lockman, which may be a good representation of diffuse HII regions. So, we presume that the far infrared emission is concentrated in galactic HII regions. We have tried to detect the diffuse far infrared emission of dust as indicative of the general distribution of interstellar matter.



Mezger: I, and independently Drapatz (both papers to appear in Astron. and Astrophys.), also analyzed the diffuse galactic IR emission and investigated its origin. We agree with Puget that OB stars are the main contributors to the heating of the dust. However, contrary to Puget, we find that the O stars (as observed through their Lyman continuum photon production rate) are sufficient to account for the heating of the dust which is responsible for the diffuse FIR emission. Also, and in contradiction to Puget, both I and Drapatz conclude that the bulk of the FIR emission does not come from the dense molecular clouds which dominate the CO emission but comes from (i) radio HII regions, (ii) extended low-density (ELD) HII regions, and (iii) neutral intercloud gas. To observe dust emission from molecular clouds, one must indeed observe in the wavelength range 0.5-1 mm, as pointed out correctly by Puget.

Puget: Although Dr. Drapatz agrees with you about the fact that there is no need for a different initial mass function, he nevertheless finds that most of the flux comes from molecular clouds and that the heating due to stars other than O stars is more important than the heating due to O stars. We disagree with the statement that the O stars can alone explain the 5-kpc infrared brightness. Using the solar-vicinity ratio of Lyman continuum photon to integrated population I luminosity, we find a luminosity too low by a factor 3 to 6 to account for either the far infrared or the near infrared data. The point is even stronger for the 2.4 μ excess at 5 kpc which cannot, by far, be accounted for by O stars.

Solomon: If you use the mass density of H_2 (35 $M_\odot$ pc^{-2}) at 5.5 kpc from our results, the lifetime of the gas for star formation is only a factor of 2 less at 5.5 kpc than at the Sun.

Puget: In that case the star formation rate per unit mass of gas will only be 2.5 times the value in the solar vicinity.

Scoville: The dust temperatures which you have deduced from 2-color measurements are more typical of what is expected for dust at the boundary of the HII region, not for dust distributed randomly through molecular clouds well away from HII regions. Typical gas temperatures (and presumably dust temperatures if there is equilibrium) in these removed regions are only 10 K.

Puget: In the envelopes of molecular clouds, the densities are not high enough for gas and dust to be in thermal equilibrium. The factor of 2 found in the temperature ratio is about what one expects from the calculations of Goldreich and Kwan.

Lynden-Bell: I wonder if there is equally intense infrared emission at $\ell = 330°$? If our Galaxy has a bar it should have a large HII region at the bar end at 30°, but the other end of the bar should be further away and produce less flux and an asymmetry in the infrared.

Puget: So far no data have been obtained in the southern hemisphere. It certainly is very important to get a longitude profile in the southern hemisphere.