THE INTERSTELLAR RADIATION FIELD AND ITS INTERACTION WITH THE INTERSTELLAR MATTER

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1. A HISTORICAL OVERVIEW

Most stars emit most of their radiation in the wavelength range between the far ultraviolet (FUV) and near-infrared (IR). Eddington (1926) first estimated for the solar vicinity a mean radiation intensity of the interstellar radiation field (ISRF) equivalent to that of blackbody radiation of ~3 K but with a spectral distribution that can be approximated by ~10,000 K blackbody radiation diluted by a factor $\approx 10^{-14}$.

This ISRF interacts with the interstellar medium (ISM), which is a mixture of gas and dust. At wavelengths shorter than its ionization limit, gas absorbs radiation continuously, and the transition between fully ionized gas (e.g., an H II or C II region) and neutral H I or C I gas is rather sharp if dust does not absorb most of the photons. The kinetic gas temperatures are determined by an equilibrium between heating due to ionization or electron collisions and cooling due to collisional excitation of atomic, molecular, and ionic lines. These temperatures are typically 8000 K in H II regions and range from more than 1000 K in the diffuse H I intercloud gas (C II region) to as low as ~10 K in the denser H_2 clouds. The high temperatures in H II regions can be readily explained by photoionization of hydrogen and other elements by Lyman continuum photons (heating) on the one hand and collisional excitation of forbidden ionic lines (cooling) on the other hand. However, if ionization of heavier elements by FUV photons (912–2000 Å) were the only source of heating of the neutral gas, temperatures even in the diffuse gas would hardly exceed 20 K. To explain the observed considerably higher kinetic gas temperatures, cosmic ray heating with an ionization rate of 10^{-16}–10^{-15} s^{-1} was invoked (for early references see Spitzer 1968 and Spitzer and Tamasko 1968), but such high ionization rates were found to be incompatible with observed ionization rates that were lower by one to two orders of magnitude. Grain photoelectric heating by FUV photons first suggested by Watson (1972) now seems a more likely heating source at least for the diffuse gas phase and the photodissociation regions at the interfaces of molecular clouds (see, e.g., the recent review by Hollenbach 1989).

Dust grains also absorb photons continuously but with absorption cross sections which rapidly decrease with frequency ($\sigma_\lambda \propto \lambda^{-m}$, $m \approx 1.5$ for $40 \leq \lambda_{\mu m} \leq 100$ and $m \approx 2$ for $\lambda_{\mu m} \leq 100$). The absorbed energy is reradiated as quasi-blackbody emission of spectral shape $\nu^m B_\nu(T_d)$. Due to both this wavelength dependence of dust opacity and the spectral distribution of the ISRF, temperatures of interstellar dust, as first noted by van de Hulst (1949) are considerably higher than the equivalent blackbody temperature of the ISRF of ~3 K. Typical size-averaged equilibrium temperatures of silicate and graphite grains with sizes ranging from a~0.25μm to ~50 Å (Mathis, Rumpl, and Nordsieck 1977) and heated by the general ISRF (referred to as "cold dust") are ~20 K in the solar vicinity, ~24 K in the molecular ring and ~27 K in the Galactic Center. Inside quiescent molecular clouds, temperatures of "very cold

S. Bowyer and C. Leinert (eds.), The Galactic and Extragalactic Background Radiation, 63–73.

dust'' could be as low as 10 K, while luminous stellar objects embedded in these clouds heat substantial masses of ''warm dust'' in their immediate vicinity to average temperatures of ~50–100 K.

Figure 1, from Cox and Mezger (1989*a*), shows the spectrum of the diffuse galactic dust emission from inside the solar circle. The far-IR spectrum $\lambda \geq 30$ μm can be fit by the above-mentioned three components of warm, cold, and very cold dust. However, a substantial fraction (~30%) of the diffuse galactic IR radiation is emitted at wavelengths $\lambda \leq 30$ μm. Emission in this wavelength range is thought to be due to small grains ($a \approx 50$–10 Å) and to very small particles (sizes $a \leq 10$ Å), which contain ~50–200 carbon atoms and which bridge the gap between interstellar molecules and the ''normal'' silicate and graphite grains. By absorption of a single energetic photon, these small grains—which may be members of a family of stable policyclic aromatic hydrocarbon molecules such as coronene, $C_{24}H_{12}$, in general referred to as PAH—are temporarily heated to (nonequilibrium) temperatures up to ~1000 K. PAH particles have a series of emission bands between $\lambda \approx 3$–15 μm and therefore emit most of the absorbed energy in this wavelength range. To explain the diffuse IR emission shortward of 30 μm, Puget, Léger, and Boulanger (1985) suggested that PAH particles are a ubiquitous component of the ISM. (See also the contributions by Boulanger and by Giard et al. 1989, this volume.)

At high gas densities, collisions between dust particles and molecules become the dominant source of heating (for $T_d > T_{gas}$) and cooling ($T_d < T_{gas}$) of the interstellar gas (Goldreich and Kwan 1974). The cooling (or heating) rate is determined by the volume densities of dust and molecules on the one hand and by an ''accommodation'' coefficient α on the other hand, which measures the fraction of all hydrogen molecules that hit grain surfaces and become adsorbed (Leung 1975; Goldsmith and Langer 1978). This coefficient is not very well known; estimates range from $\alpha \approx 0.1$–1 (Hollenbach and Salpeter 1971) to values $\alpha \approx 1$ (Burke and Hollenbach 1983).

In the following review, I differentiate between the ''primary'' ISRF provided directly by the stars and the ''secondary'' ISRF provided by dust particles which absorb and reradiate the primary ISRF. I will mainly discuss the integrated mean intensity of the primary ISRF rather than its precise spectral shape. I do this in spite of the explicit warning of my friend and former co-author John Mathis who wrote me: ''In fact they (i.e., the actual measurements of the ISRF) don't agree very well with one another especially in the UV. You should clearly state this so that the audience will know that you haven't become one of those who would rather calculate what something looks like than look at it.'' I will leave the discussion of observational disagreements to reviewers in this conference who are more competent in these areas and who did in fact live up to John Mathis' expectations, as for example F. Paresce (1989, this volume) and S. Bowyer (1989, this volume) for the UV.

My invited paper will concentrate on the variation of the ISRF with galactocentric distance D_G. And with John Mathis' warning in mind, I will not only rehash our model computations, but also stress the importance of accurate measurements of dust surface brightnesses and luminosity-to-gas mass ratios as a new and elegant means of exploring the integrated mean intensity of the primary ISRF and its variation within the galactic disk.

2. THE ISRF IN THE SOLAR VICINITY

For earlier work on this subject I refer to Zimmermann (1964); to Habing (1968), who reevaluated the FUV part of the ISRF; to Mattila (1980*a*,*b*), who calculated the integrated

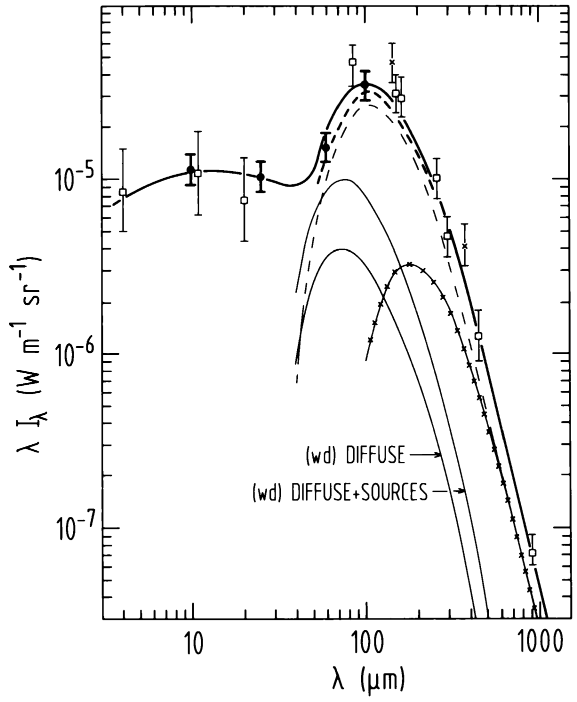

Figure 1. Spectrum of the dust emission between 4 μm and 900 μm from the inner part ($D_G \leq 8$ kpc) of our Galaxy, averaged over galactic longitude 3°–35° and latitude $|b| \leq 1°$. This composite spectrum includes both the diffuse component and the sources (see Cox, Krügel, and Mezger 1986). Light curves represent the contributions of the individual dust components (*crosses* for the very cold dust, *dotted line* for the cold dust, *solid line* for the warm dust, diffuse component and sources as indicated). The heavy dotted line represents the total contribution of the diffuse components, whereas the heavy solid line represents the total contribution from both diffuse components and sources. The solid line shortward of 40 μm is a simple extrapolation through the observed points.

starlight between 0.3 μm and 1 μm and specifically investigated the effect of a clumpy dust distribution as well as the dependence of the ISRF on positions off the galactic plane; and last but not least to references given in these papers.

In 1982, Mathis, Mezger, and Panagia started a series of papers on the origin of the diffuse galactic far-IR/submillimeter (submm) emission which should lead to a self-consistent model of the distribution of interstellar matter and of stellar populations on the one hand, and the observed spectral distribution and total luminosity of the dust IR emission on the other hand. The dust temperature as the observable quantity depends on the energy absorbed by the grains and, hence, if the dust characteristics are known, on the mean intensity of the primary ISRF. To model the dust emission we first needed a model of the ISRF, not only in the solar vicinity but anywhere in the galactic disk.

The dust temperature is

$$T^{4+m} \propto 4\pi \int_0^\infty J_\lambda \sigma_\lambda \, d\lambda, \tag{1}$$

https://doi.org/10.1017/S0074180900240400 Published online by Cambridge University Press

with $4\pi J_\lambda$ the mean radiation intensity of the ISRF, σ_λ the dust absorption cross section, and m an exponent describing the wavelength dependence of the dust opacity at far-IR/submm wavelengths. Putting together all measurements of the mean radiation intensity at wavelengths $\lambda \leq 3.4$ µm available at that time and assuming that $4\pi J_\lambda = 0$ for $\lambda < 0.09$ µm (the Lyman continuum limit) and $\lambda < 8$ µm, Mezger, Mathis, and Panagia (1982) derived for the solar vicinity an integrated mean intensity of the ISRF of

$$4\pi \int_{0.09}^{8\mu m} J_\lambda^\odot \, d\lambda = 1.69 \; 10^{-2} \text{ erg s}^{-1} \text{ cm}^{-2} . \quad (2)$$

As first shown by the Chicago bolometer group, this integrated mean radiation intensity of the ISRF can be checked observationally. A quiescent cloud (i.e., a molecular cloud without internal sources of heating) of large enough optical depth at optical/near-IR wavelengths will absorb all of the incident ISRF and reradiate it at far-IR/submm wavelengths. Keene (1981), from the integrated flux density spectrum of nine globules, obtained a mean value of the specific intensity of $(2.1^{+1.2}_{-0.8})$ 10^{-6} W m^{-2} sr^{-1}, which translates into a mean radiation intensity of 2.64 $\times 10^{-2}$ erg s^{-1} cm^{-2}. Comparison with the above value indicates that we had severely underestimated the mean intensity of the ISRF in the solar vicinity.

In a subsequent paper, Mathis, Mezger, and Panagia (1983, hereafter referred to as MMP) following a suggestion by Jura (1979), included the near-IR emission of a population of cool stars (~3000 to 4000 K) whose distribution and specific intensity had been investigated by various Japanese groups (see the review by Okuda 1982 and references given in MMP). The contribution of these cool stars to the ISRF increased its mean radiation intensity to

$$4\pi \int_{0.09}^{8\mu m} J_\lambda^\odot \, d\lambda = 2.17 \times 10^{-2} \text{ erg s}^{-1} \text{ cm}^{-2}, \quad (3)$$

a value which is still some 20% lower than Keene's measurement.

In model computations of the ISRF, one adopts a spatial distribution for both the different stellar populations and for the interstellar dust (see, e.g., Kaplan and Pikelner 1970). MMP for the first time also included the reemission at IR/submm wavelengths of the absorbed stellar radiation which results in a secondary maximum of the spectrum of the ISRF at $\lambda \approx 100$ µm (see Figure 2) For the integrated mean radiation intensity of the dust emission, MMP obtained

$$4\pi \int_{8}^{1000\mu m} J_\lambda^\odot \, d\lambda = 5.0 \times 10^{-3} \text{ erg s}^{-1} \text{ cm}^{-2}, \quad (4)$$

yielding a total mean intensity of 2.67×10^{-2} erg s^{-1} cm^{-2}. The excellent agreement with Keene's observed value is probably fortuitous, since only a small fraction of the secondary ISRF is reabsorbed by dust and thus contributes to its heating.

The spectral distribution of the ISRF in the solar vicinity ($D_G^\odot = 10$ kpc) according to the MMP model is shown in Figure 2. Four stellar components were used to reproduce the starlight-dominated spectrum of the ISRF: component $l = 1$ relates to early-type stars and matches the observations, components $l = 2$ and 3 relate to disk population stars with $T_{\rm eff} =$ 7500 K and 4000 K, and component $l = 4$ represents red giants with $T_{\rm eff} = 3000$ K.

Integration of the available IR sky surveys after subtraction of zodiacal light contribution allows one to test the MMP model of the secondary ISRF. The filled squares in Figure 2 were obtained by Pérault et al. (1989) for λ = 12, 25, 60, and 100 µm from the *IRAS* maps and at 5 µm from a rocket survey by Matsumoto, Akiba, and Murakami (1988). Whereas observations

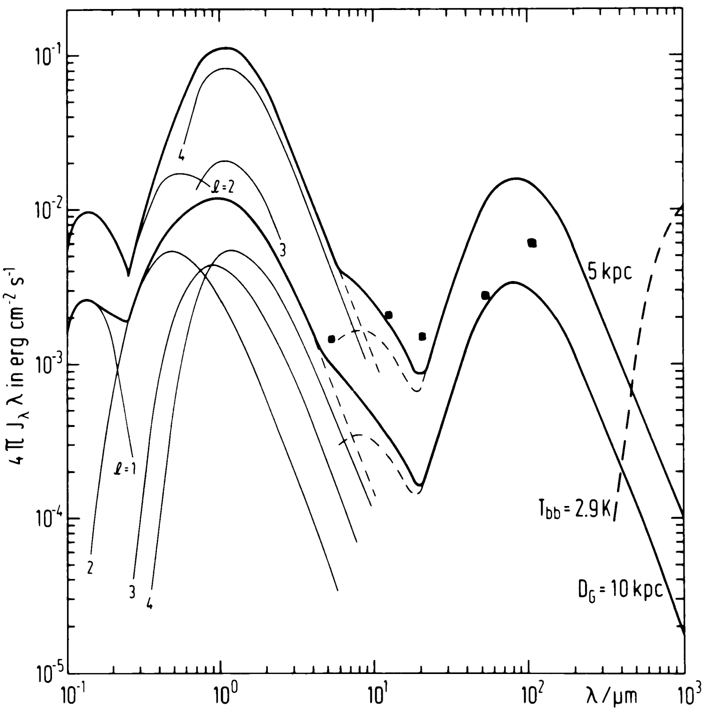

Figure 2. The interstellar radiation field (ISRF) at galactocentric distances D_G = 5 kpc and 10 kpc. Curves labelled l = 1, 2, 3, and 4 relate to the contributions of the four stellar components to the ISRF as mentioned in the text. For wavelengths ≥5 µm the ISRF is dominated by reemission from dust grains (MMP). The filled squares represent the ISRF at D_G = 10 kpc as derived by Pérault et al. (1989) from the *IRAS* data (12, 25, 60, and 100 µm) and from a rocket survey at 5 µm by Matsumoto, Akiba, and Murakami (1988).

and model computations of the secondary ISRF for $D_G^{\odot}$ = 10 kpc agree reasonably well at far-IR wavelengths and again at $\lambda \approx 5$ µm, the observed mean intensities at λ = 12 µm and λ = 25 µm lie nearly an order of magnitude above the MMP model. This enhancement is thought to be due to emission from small dust and very small PAH grains that were not included in the MMP model. This enhanced mid-IR intensity of the ISRF due to non-equilibrium emission from small grains plays an important role in the heating of molecular clouds (see section 5).

3. THE ISRF IN THE GALACTIC DISK

To extrapolate the starlight-dominated spectrum of the primary ISRF to other galactocentric distances, MMP approximated the variation with galactocentric distance D_G kpc of the volume emissivities of both the four stellar components and of the dust opacity by exponential functions with different exponents, cutoff radii, and scale heights. The secondary ISRF was modeled using the following assumptions: i) the galactic disk is optically thin (which is only marginally correct at mid-IR wavelengths); ii) the spectral distribution is independent of D_G although, in fact, one expects in the inner Galaxy a slight shift of the spectrum towards shorter wavelengths (since the mean intensity of the ISRF increases with decreasing D_G); and iii) the variation of the volume emissivity of dust is that derived by Boissé et al. (1981) from their survey in the wavelength band 114–196 μm and is shown in Figure 3*b*. In Figure 2 is shown as an example the MMP model spectrum of the ISRF for D_G = 5 kpc.

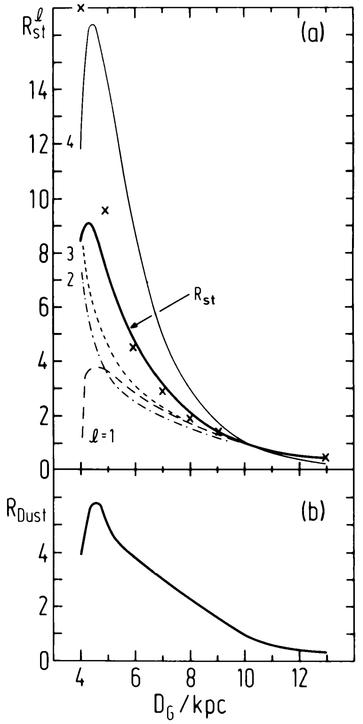

Figure 3. (*a*) Integrated intensities of the four stellar components as a function of the galactocentric distance D_G relative to the corresponding integrated intensities at D_G = 10 kpc. R_{st} refers to the total integrated spectrum of the primary ISRF between 0.09 μm and 8 μm. Crosses show the variation of the luminosity-to-hydrogen mass ratio of cold dust as determined by Pérault et al. (1989; see text). (*b*) The corresponding variation of the intensity of the secondary ISRF between 8 μm and 1000 μm, which is dominated by the reemission from dust grains (MMP).

The relative variation with D_G of the integrated intensities of the starlight-dominated (primary) spectrum of the ISRF and the individual contributions from the four stellar components are shown in Figure 3*a*. Using a variant of the method developed by J. Keene (1981; see previous section) this predicted variation can be observationally tested. The temperature (and hence the emission) of dust grains located in the diffuse interstellar atomic hydrogen and in the outer skins of molecular clouds is proportional to both the integrated mean intensity of the ISRF and to the dust absorption cross section per H-atom (see equation [1]). With the usual assumption that the dust absorption cross section per H-atom varies with the metallicity, i.e., $\sigma_\lambda^H(D_G) \approx (Z(D_G)/Z_\odot)\sigma_\lambda^H(\odot)$ one expects an increase of the absorption cross section by a factor of ~2 from D_G = 10 kpc to 4 kpc (Mezger et al. 1979).

To derive the average luminosity-to-hydrogen mass ratio, Pérault et al. (1989) constructed *IRAS* 100 μm longitude profiles of the diffuse IR emission at different galactic latitudes $|b|$ = 0, 1, 2, and 3 arc degrees, separated the contribution from dust in the diffuse atomic gas and in molecular clouds, and compared the derived IR surface brightnesses with an empirical model of the distribution of atomic and molecular hydrogen based on H I and CO surveys. They found this quantity to increase by a factor of ~17 from $D_G^{\odot}$ = 10 kpc to $D_G \approx 4$ kpc (see crosses in Figure 3*a*) which—after correction for the increase in metallicity—translates into an increase of the mean intensity of the ISRF by a factor of ~8.5. Such an increase is in good agreement with the variation by a factor of ≥9 predicted by the MMP model (Figure 3*a*, *heavy solid curve*).

4. THE ISRF IN THE CENTRAL REGION OF THE GALAXY

Because of its complexity, the central region was omitted in the MMP model. The inner region of ~1 kpc diameter accounts for ~5–10% of the total mass and luminosity of the disk within the solar circle. Hence surface densities and IR brightnesses of the central region are factors of ten and more higher than in the galactic disk.

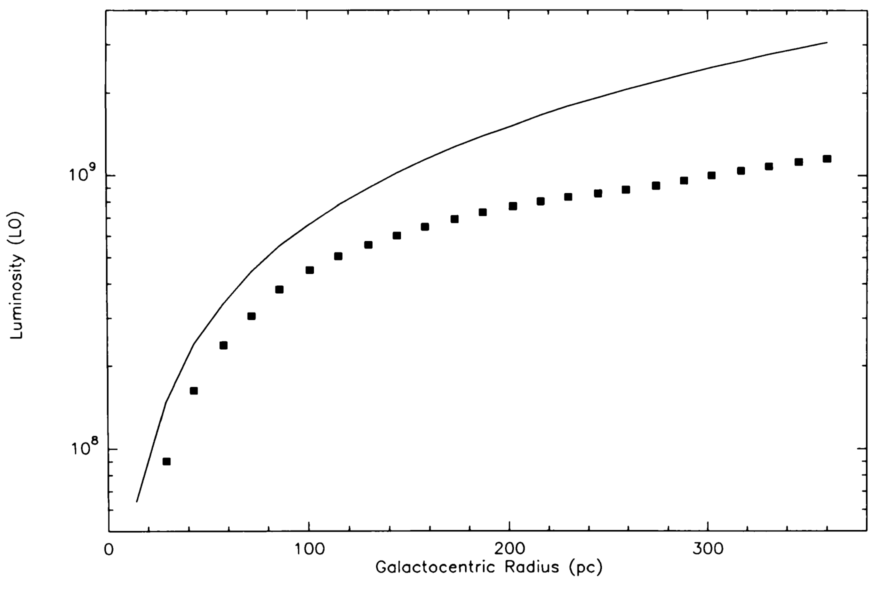

Figure 4. Radial distribution of the IR luminosity associated with the galactic center as derived from the *IRAS* data (*squares*). The full line shows the total luminosity available from the old stellar population (from Cox and Laureijs 1989; and Cox and Mezger 1989*b*).

A rough estimate of the mean intensity of the ISRF can be obtained from Figure 4, which shows the accumulated stellar and IR luminosities of the central part of the Galaxy as a function of galactocentric distance. The majority of stars in the central cluster are believed to be M and K giants with $T_{\rm eff} \approx 4000$ K. These stars are observationally traced through their surface brightness at $\lambda 2.2$ µm. The IR emission comes from dust with an average temperature of ~27 K (Cox and Laureijs 1989; Cox and Mezger 1989*b*). For the central region at $D_G \leq 200$ pc we can derive from Figure 4 an intrinsic stellar luminosity of $L_* = 1.6 \times 10^9 \, L_\odot$, and a secondary dust luminosity of $L_{IR} \approx 8 \times 10^8 \, L_\odot$. This means that about 50% of the stellar radiation is absorbed and reemitted by dust, as opposed to ~20–30% in the galactic disk. Using the approximation

$$4\pi \int J_\lambda \, d\lambda \approx L/4\pi D_G^2 = 3.2 \times 10^{-5} \frac{L/L_\odot}{D_G^2/\mathrm{pc}^2} \ \mathrm{erg\ s^{-1}\ cm^{-2}}, \quad (5)$$

we obtain about equal mean radiation intensities for the star- and dust-dominated spectra of the ISRF in the galactic center, i.e.,

$$4\pi \int_{0.09}^{5\mu m} J_\lambda \, d\lambda \approx 4\pi \int_{5}^{1000\mu m} J_\lambda \, d\lambda \approx 6.4 \times 10^{-1} \ \mathrm{erg\ s^{-1}\ cm^{-2}}\,. \quad (6)$$

The total mean radiation density in the inner 400 pc of the central region thus is ~50 times higher than in the solar vicinity and ~6 times higher than in the molecular ring ($D_G \approx 4$ kpc). Maxima in the spectrum of the galactic center ISRF should be located at $\lambda \approx 1.3$ µm and $\lambda \approx 113$ µm.

5. THE ISRF INSIDE MOLECULAR CLOUDS

The ISM forms a flat layer of some ~100 pc width in the plane of the galactic disk. About 1–2% of the volume occupied by the ISM is filled with molecular clouds which, due to their much higher density, account however for ~40% (or ~$1.5 \times 10^9 \, m_\odot$) of the total gas content of the Galaxy. Giant molecular clouds (GMCs) are the birthplace of stars. In the immediate vicinity of young and luminous stars, dust is heated to temperatures of 100 K and more, but at distances of ~1 pc the dust temperature drops to values <30 K. Model computations by Natta et al. (1981) show that, due to secondary dust emission, up to 40% of the luminosity of the embedded heating source is used to heat dust inside the cloud to temperatures of ~20 K.

With a total star formation rate in the galactic disk of $\psi(t) \approx 2.6 \, m_\odot \, \mathrm{yr}^{-1}$ and a star formation efficiency (i.e., the fraction of the cloud mass M_{cl} which is transformed into stars during the lifetime τ_{cl} of the cloud) of

$$\varepsilon = M_{cl}^{-1} \int_0^{\tau_{cc}} \psi(t) \, dt \approx 10^{-9} \, \tau_{cl} \, \mathrm{yr}^{-1} \approx 1\text{–}10\% \quad (7)$$

(depending on the assumed average lifetime $\tau_{cl} = 10^7$–10^8 yr of GMCs, Mezger 1988), "warm" GMCs are in the minority and the bulk of molecular gas is heated by the general ISRF, whose UV and optical spectrum is absorbed within a thin layer of $A_V \approx 3$ mag. The average dust temperature in this skin is ~0.75 times the temperature of dust grains in the diffuse atomic gas.

The ISRF inside a spherical dust cloud has been computed previously by Werner and Salpeter (1969) and Sandell and Mattila (1975). MMP modeled the ISRF penetrating a dense molecular cloud as a function of visual extinction counted from the surface of the cloud. As shown in Figure 5 with increasing A_V, first the UV, then the optical, and finally the near-IR part of the ISRF are absorbed and transformed into far-IR radiation. This adds to the far-IR part of the general ISRF and—since dust in the cloud skins is colder—shifts the peak of the

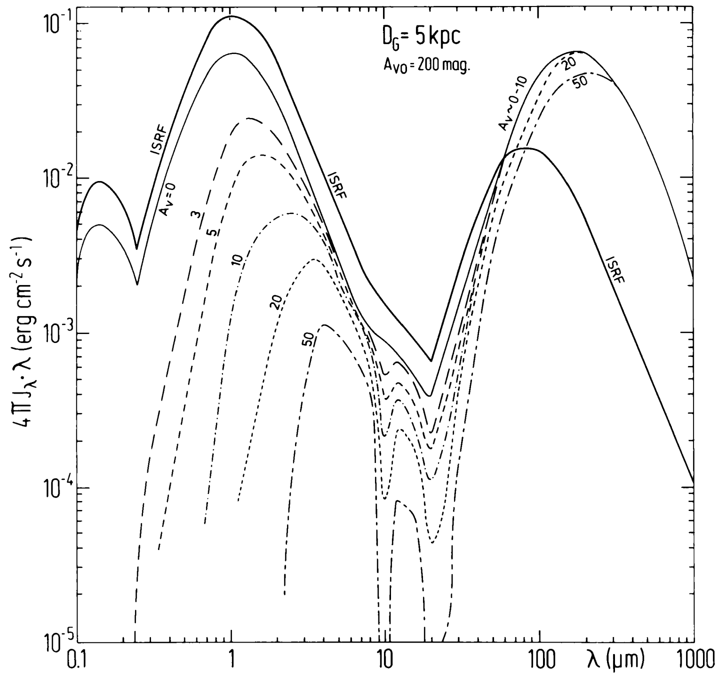

Figure 5. The radiation field inside a giant molecular cloud, located at D_G = 5 kpc and with a visual extinction to its center of A_V = 200 mag. ISRF refers to the radiation field at large distances from the cloud, A_V = 0 is the radiation field at the surface of the cloud, A_V = 3, 5, 10, etc., is the radiation field inside the cloud at distances corresponding to visual extinction of A_V =3, 5, 10 mag., etc., measured from the surface of the cloud (MMP).

secondary ISRF inside clouds to longer wavelengths.

While the secondary ISRF prevents grain temperatures to drop as low as 3 K even in the densest condensations, an equally important heating source of dust deep inside quiescent GMCs is the near-IR/mid-IR part of the ISRF. MMP, on the basis of their ISRF model and dust absorption cross sections, computed dust temperatures of ~10 K at the center of GMCs. With the improved dust absorption cross sections by Draine and Lee (1984) and the observed increase of the ISRF at near-IR/mid-IR wavelengths relative to the MMP model due to emission from very small particles (see Figure 2), an average temperature of dust grains in quiescent GMCs of ~14 K, as estimated by Puget (1985), appears to be more realistic and is also in good agreement with the model fit to the submm part of the galactic dust emission spectrum (Cox and Mezger 1989*a*).

6. INTERACTION OF THE ISRF WITH THE INTERSTELLAR MATTER

The heating of dust grains by absorption of stellar radiation is well understood. The size distribution of earlier grain models was arbitrarily truncated at upper and lower limits of 0.25 μm and 50 Å, respectively, since only grains within these size limits were needed to explain the extinction curve observed at UV, optical, and near-IR wavelengths. However, recent evidence shows that the size distribution of interstellar grains extends well beyond these limits. (For small grains, see, e.g., the review by Cox and Mezger (1989*b*), section 3; for observational evidence regarding the existence of large grains in dense and cool molecular clouds, see Mezger et al. 1987, and references therein). The temperature of "normal grains" decreases with grain size according to $T^{4+m} \propto a^{-1}$ so that very large grains in dense clouds may attain rather low temperatures. Very small grains, on the other hand, after absorption of an energetic photon during a short time interval, attain temperatures that are much higher than the equilibrium temperatures of "normal grains" (see Puget, Léger, and Boulanger 1985, and references therein). This can lead to a situation where the gas temperature is higher than the dust color temperature, even if gas-grain collisions are the principal heating source (Krügel and Walmsley 1984).

Since gas can cool only by line emission, its cooling rate is low at temperatures ≤100 K it is typically only a few percent of the cooling rate by quasi-blackbody emission of dust grains at equal temperatures. Hence heating rates of gas are correspondingly lower, too. But in contrast to dust heating, the sources of gas heating are not yet well understood. I refer to a recent review by Hollenbach (1989) for a critical review of the various suggested heating mechanisms.

Outside of fully ionized H II regions, heating of the gas appears to be mainly a secondary effect of the interaction of the ISRF with grains. As mentioned in section 1, the efficiency of gas-grain collisional heating depends critically on gas density and the accommodation coefficient α. For $\alpha \approx 1$ and "normal" grains, gas and dust should be thermally coupled at densities $n_H \geq 10^5$ cm^{-3} so that this mechanism can work only in dense cloud cores. Observations indicate that at densities $n_H \approx 10^5$ cm^{-3}, $T_d \approx 0.5\, T_g$, while at $n_H \approx 10^7$ cm^{-3}, $T_d \approx T_g$ (Mezger, Wink, and Zylka 1989). This suggests values $\alpha \ll 1$ which require even higher gas densities for thermal coupling of gas and dust.

Grain and PAH photoelectric heating, where UV photons are absorbed and energetic electrons are ejected from grain surfaces that subsequently interact with the gas, may dominate the heating of intercloud gas, of diffuse clouds, and of the outer skins (photodissociation regions) of denser clouds. As in the case of gas-grain collisions, this mechanism is rather inefficient, with only ~1% of the energy of the UV photons being used to heat the gas. This mechanism requires energetic photons but—in contrast to gas-grain collisional heating—also works at low gas densities.

Another grain-gas heating mechanism has been suggested by Takahashi et al. (1983), where H_2O molecules absorb far-IR photons emitted by grains. The excited molecules then are collisionally deexcited, thus transferring energy into gas heating. This mechanism dominates over photoelectric heating only in opaque clouds.

Acknowledgments—I would like to thank J. Lequeux, J. Mathis, J.-L. Puget, and M. Walmsley for their comments.

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K. Mattila: *I suppose that the clumping of dust in a molecular cloud would help the UV and optical radiation to penetrate into the central parts?*

P.G. Mezger: Yes, clumping will. So will coagulation of grains, which will decrease drastically extinction in the optical/UV range but will not affect strongly absorption cross-sections at far infrared and sub-mm wavelengths.