The Interstellar Radiation Field

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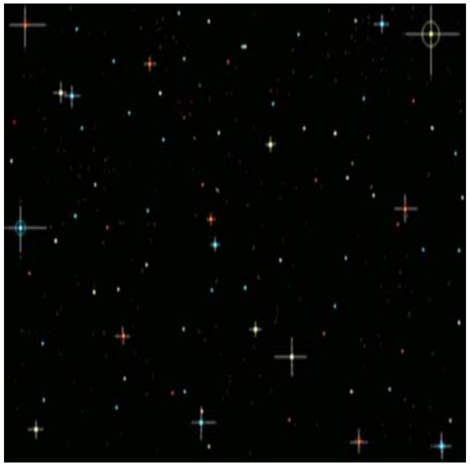
Outline

- ISRF critical for IC emission
- Naturally want the best model possible
- Two key 'ingredients'
  - Stellar emissivity model
  - Dust/gas model
- Basic 'equation' :



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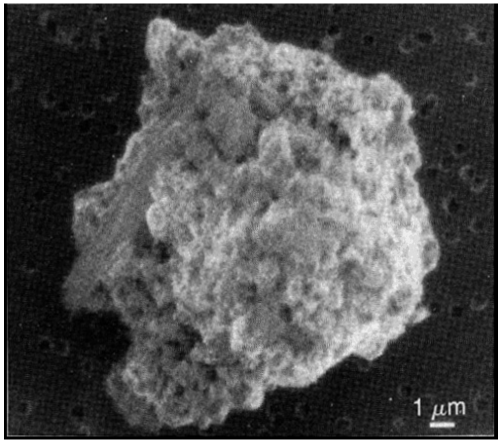
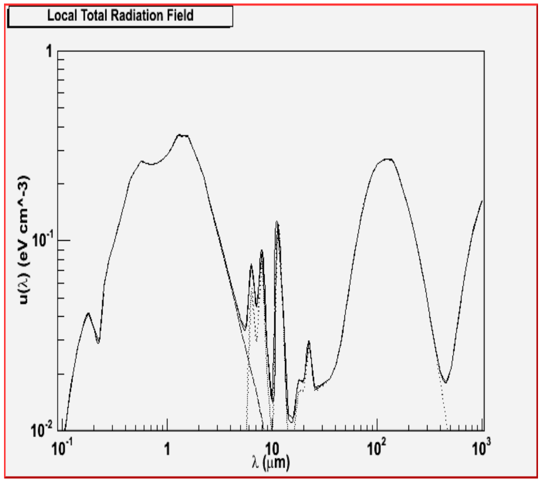


+ 'maths' =



Then ...

- EGRET background model used MMP (1983) RF
- 20+ years old!
- Constructed to maximise consistency with Gondhalekar et al. (1980) (based on S2/68), other limited-coverage UV surveys
- 4 stellar components, fairly simple IR model (no PAHs, pure equilibrium heating)

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ASTRONOMY AND ASTROPHYSICS

Interstellar radiation field and dust temperatures in the diffuse interstellar matter and in giant molecular clouds

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Summary. In Paper I (Mezger et al., 1982) we have investigated the emission spectrum of dust in both the diffuse interstellar matter (ISM) and in Giant Molecular Clouds (GMC's). This included an estimation of dust absorption cross sections from the Lyman continuum to the submm range and a redetermination of the interstellar radiation field (ISRF) using the most recent observations. In this paper we reevaluate the ISRF as a function of galactocentric distance D_G, taking into account the results of recent surveys of the galactic 2.4 μm and 3.4 μm emission as well as of FIR surveys of the galactic plane as discussed in Paper I, and using an improved model of the variation of dust opacity in the galactic plane. We then determine the radiation field inside GMC's, including the radiation from the GMC itself, as a function of both D_G and the extinction A_V measured from the surface of the cloud. Next, we calculate the dust temperatures of the MRN composite graphite/silicate dust model (Mathis et al., 1977) in the radiation field within the cloud. The main results are: (i) The ISRF between 0.09 and 8 μm is dominated by stellar radiation and between 8 and 1000 μm is dominated by reemitted radiation from dust grains. The total energy density of the ISRF between $D_G=10$ and 5 kpc increases by a factor seven. The ISRF attains its intensity maximum at ~1 μm. (ii) The dominant sources of heating in GMC's are stellar radiation for graphite grains and FIR heating for silicate grains. The contribution of normal field stars embedded in GMC's to the heating of dust is normally negligible. This may be different in a cloud which contains many low-mass pre-MS stars. While the temperatures of graphite grains in the diffuse ISM and in the outer sheaths of GMC's are twice as high as the temperatures of silicate grains, both types of grains attain approximately equal temperatures between 5 and 7 K deep inside GMC's. (iii) The stellar radiation absorbed in the outer layers of GMC's is practically all converted into FIR radiation whose integrated mean intensity is about five times that of the diffuse galactic FIR emission.

Key words: dust – interstellar matter – interstellar radiation field

1. Introduction

In a recent paper (Mezger et al., 1982, hereafter referred to as Paper I) we have tried to explain the origin of the diffuse galactic FIR/submm emission. We found that: (i) The observed dust extinction cross-sections between the Lyman continuum (Lyc) and 1 mm can be reasonably reproduced by the MRN (Mathis et al., 1977) dust model, which consists of a mixture of graphite (Gr) and silicate (Si) grains with a size distribution $f(a) \propto a^{-3.5}$. (ii) The diffuse emission at wavelengths ≳20 μm can be explained by contributions from dust heated by O stars to temperatures of $T_{gr} \sim 40$ K and $T_{si} \sim 30$ K, respectively (~80%); and dust associated with the diffuse atomic intercloud gas which is heated by the the general interstellar radiation field (ISRF) to temperatures of $T_{gr} \sim 19$ K and $T_{si} \sim 10$ K, respectively (~20%). (iii) The mean intensity of the ISRF is practically independent of the distance from the galactic center. (iv) The contribution from dust associated with quiescent molecular clouds (i.e. clouds containing no luminous sources of heating such as OB stars) to the total diffuse FIR/submm emission is small (≲7%).

Nevertheless the temperature of dust inside quiescent molecular clouds is of great interest for both their energy balance and for the possibility of detecting density structures of these clouds through observations of the thermal radiation of dust. Furthermore, the overwhelming fraction of molecular hydrogen appears to be contained in quiescent clouds rather than in clouds with very young OB stars embedded (see Sect. 5.2). In Sect. 2 of this paper we reinvestigate the intensity of the ISRF in the vicinity of the sun and its variation with galactocentric distance, D_G, taking into account the latest observational data and their interpretation. It is found that we have strongly overestimated the variation of dust opacity with D_G and that we have neglected the contribution from M-type giants, whose presence is revealed through observations of the unexpectedly strong 2.4 μm and 3.4 μm emission from the galactic plane. Taking these effects into account, an increase of the integrated mean intensity of the ISRF between $D_G=10$ and 5 kpc by a factor of ~7 is found. Furthermore, we have included in our considerations the presence of diffuse galactic FIR emission between 8 and 1000 μm from circumstellar and interstellar dust.

In Sect. 3 of this paper we recompute the temperature of dust grains in the diffuse interstellar matter (ISM) which is now found to vary for graphite grains from 25.4 K at the galactocentric distance $D_G=5$ kpc to 16.6 K at 13 kpc, and for silicate grains from 12.8 K at 5 kpc to 8.9 K at 13 kpc. It is also found (Sect. 5) that radiation from grains associated with diffuse atomic gas and heated by the general ISRF may contribute ~40% to the diffuse galactic FIR/submm emission rather than ~20% as found in Paper I.

In Sect. 4 of this paper we compute the radiation field inside Giant Molecular Clouds (GMC's), taking into account direct stellar radiation and FIR reemission from dust grains, and we

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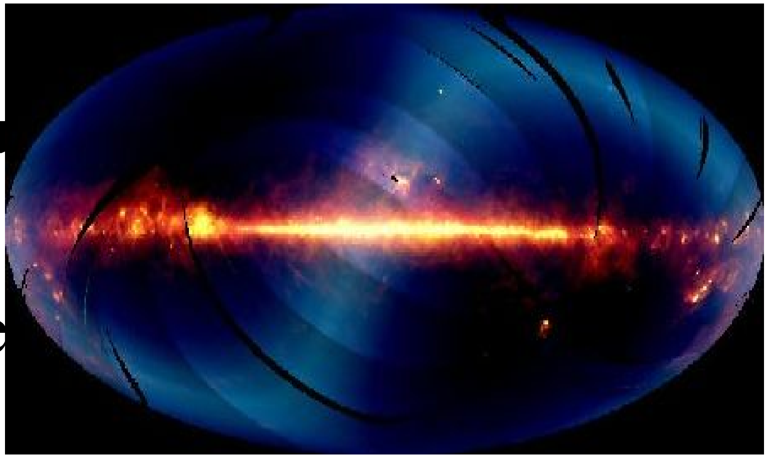
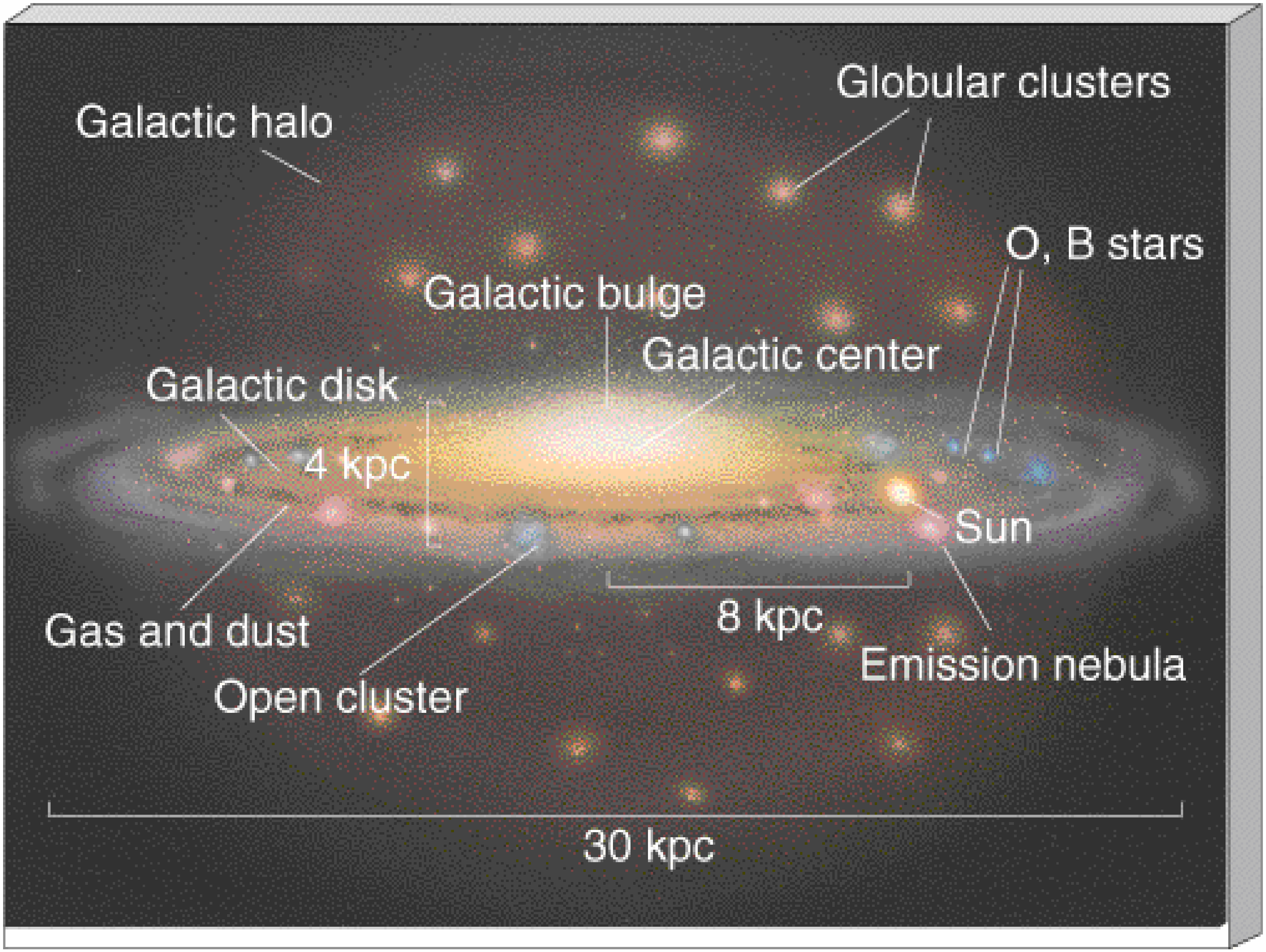
... and Now



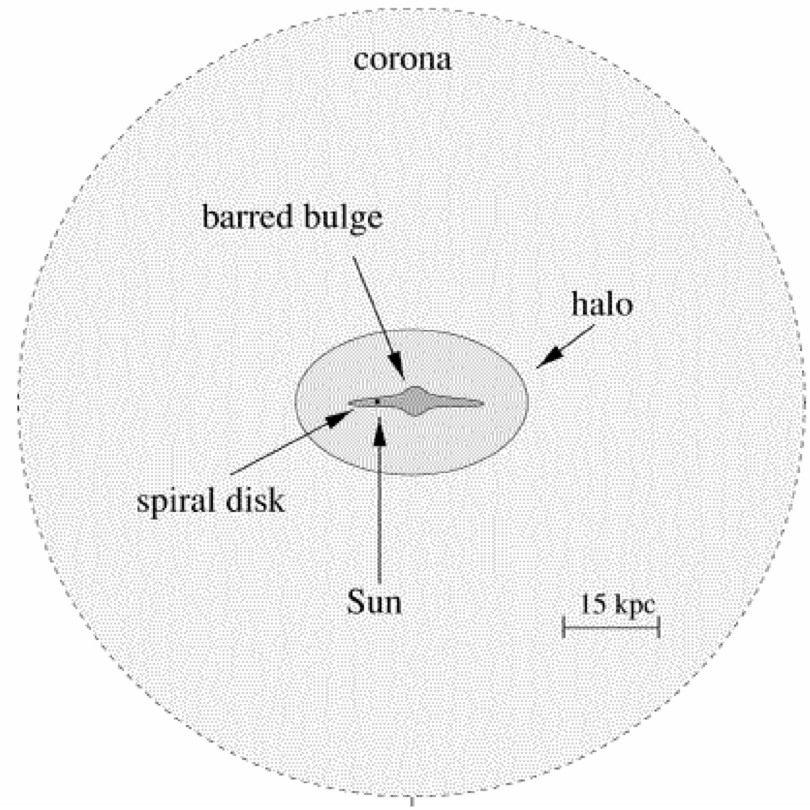
- Better surveys available
  - 2MASS, MSX, DeNIS, SDSS
- Better IR background data
  - DIRBE, FIRAS
- Advances in understanding starlight-du interaction
- Faster computers with more memory, e
- We can do better now!

Milky Way Galaxy



Galactic Structure

- Central bulge/bar
  - Triaxial with offset bar
  - Range of metallicity
- Flat disc
  - $\sim 10^{11}$ stars (mostly Pop I.)
  - ~90% of starlight
  - Gas and dust
- Halo
  - $\sim 10^{9}$ stars
  - Old, metal poor (Pop II.)
  - $\sim 10^{2}$ globular clusters



Galactic Structure - Bulge/Bar

- Bulge, bar, or combination?
- Star counts in plane asymmetric in inner Galaxy
- 2MASS, DENIS : long, thin bar, 1/2-length ~ 4 kpc, width ~500 pc, disc-like pop.; triaxial or boxy bulge, mainly old stars

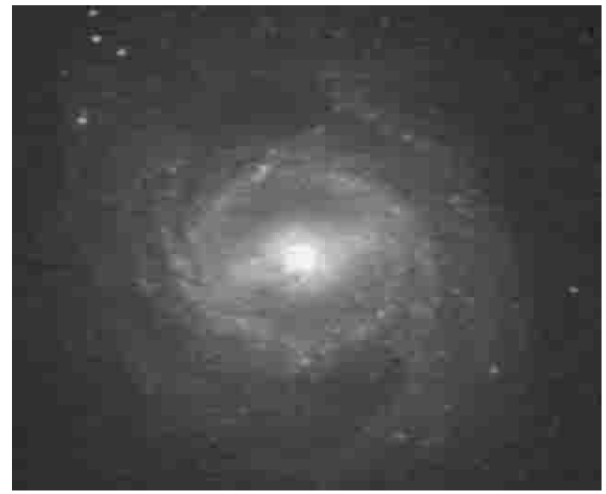
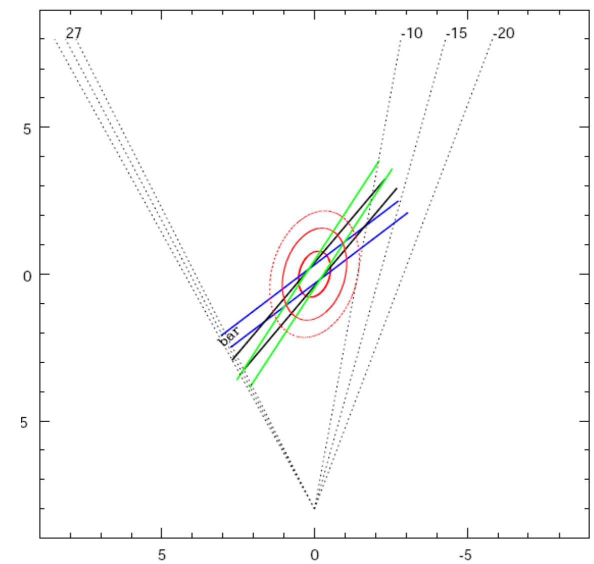


Fig. 1. POSSII(*J*-Blue) image of the spiral galaxy M 95 (NGC 3351). Note the presence of a bar apart from the prominent bulge in the centre of the galaxy.



Galactic Structure – Disc

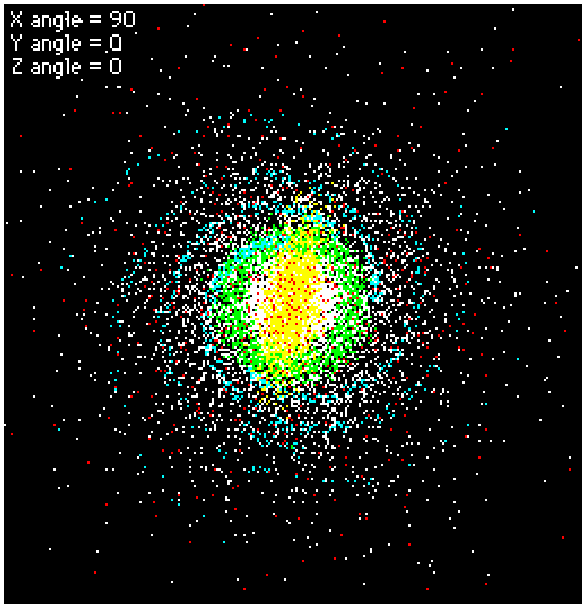
- Disc complicated system containing axisymmetric disc, ring, arms, dust/gas
- Thin and thick disc
  - Thin disc : h_z~300 pc, h_R~2.8 kpc
  - Thick disc : h_z~800 pc, h_R~3.7 kpc
- Thick disc density ~4% thin (Ohja 2001, 2MASS)
- May be truncated in inner Galaxy

$$\rho(R,z) = \rho_0 \cdot e^{-|z-z_0|/h_z} \cdot e^{-(R-R_0)/h_R}$$

R_0 = 8 .5 kpc; z_0~ 20 pc (Cohen et al. 1995)

Galactic Structure – Disc

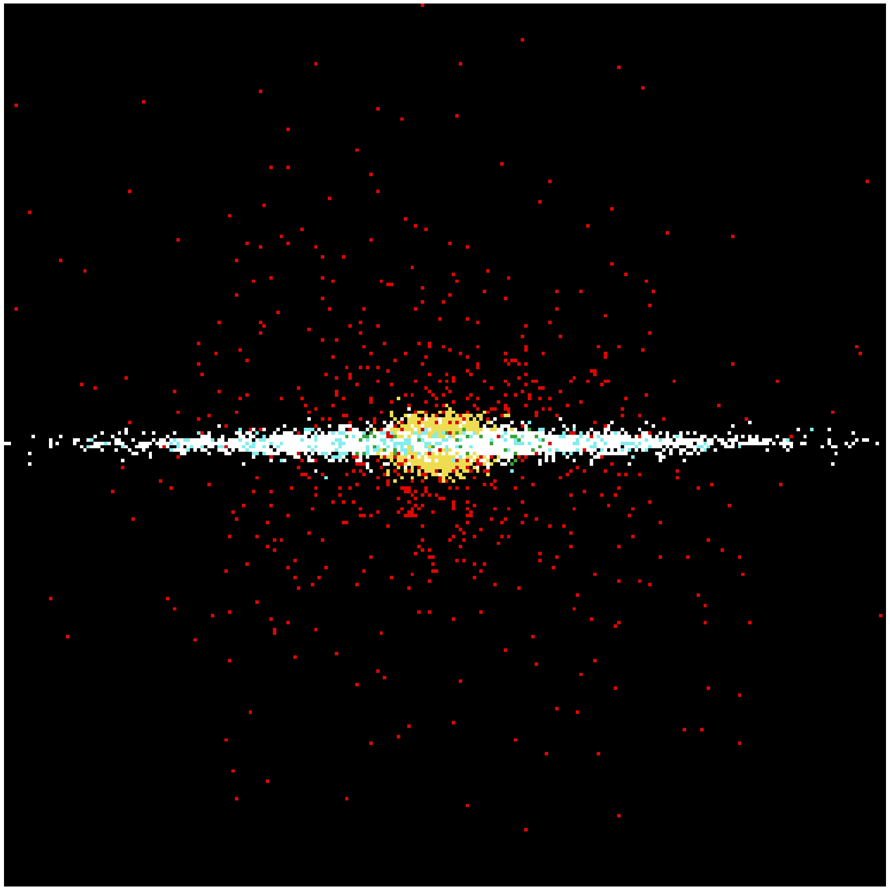
- Thin disc : young – intermediate aged stars, range of metallicity
- Thick disc : older, Pop II.
- Spiral arms, ring – similar to thin disc, different spatial distribution
- MW might look like this



White: thin disc; Green : ring; Blue : arms

Galactic Structure – Halo

- Age 12-13 Gyr
- Metallicity [Fe/H] ~ -1 to -3
- Flattened spheroid, axisymmetric
- Density ~ 1/600 Disc
- Extended emission in halo + high latitude stellar counts



Red : halo; White : disc; Yellow : bulge

Galactic Stellar Model

- Assume discrete galactic components, e.g., arms, disc, etc.
- Stellar classes with spatial density, spectrum, luminosity, etc.
- Need to compare against stellar counts (# of stars/magnitude/degree^2)
  - Obtained via stellar statistics equation
- Star count comparison allows us to refine model parameters, improve, reject

Stellar Statistics Equation

- Calculate star counts over region of sky using :

$$N(m) = \omega \int_0^\infty \Phi\left[M\right] \rho(r) r^2 dr$$

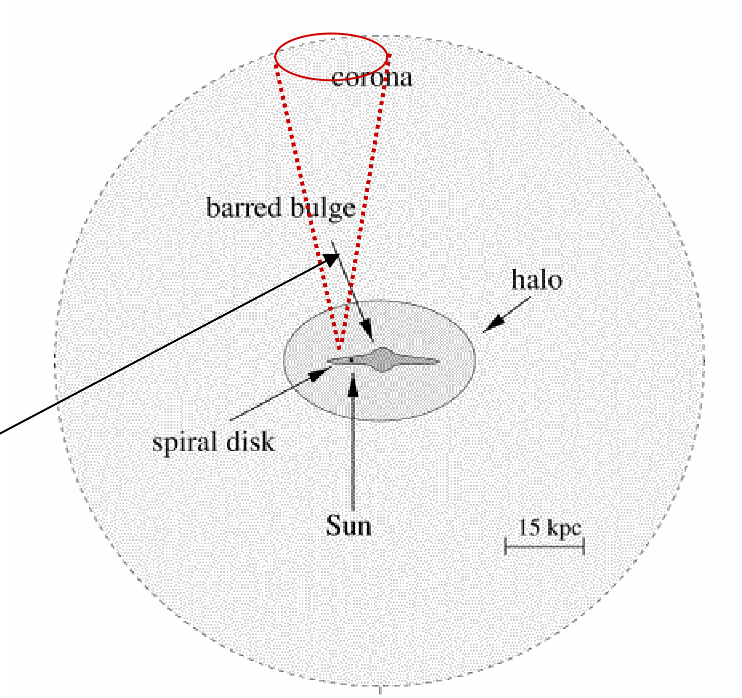
$$M = m + 5 - 5\log r - A(r)$$

$\Phi\left[M\right] =$ Luminosity function

$\rho(r) =$ Density function

$A(r) =$ Extinction

$\omega =$ Solid angle



Our Stellar Models

- Models have 87 classified stellar types (normal stars, AGB, T-Tauri) – taken from Wainscoat et al. (1992)
- Six components : arms, bar, bulge, disc, halo, ring
- Can use observational or synthetic stellar spectra (only normal stars for now)
- Comparison of model(s) to star counts ongoing

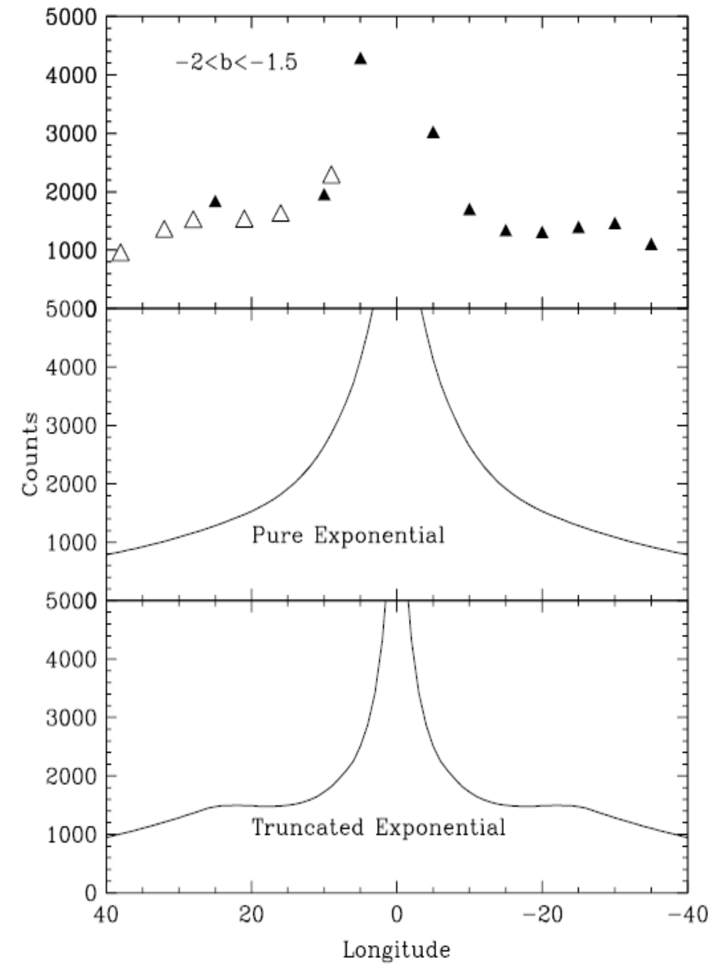
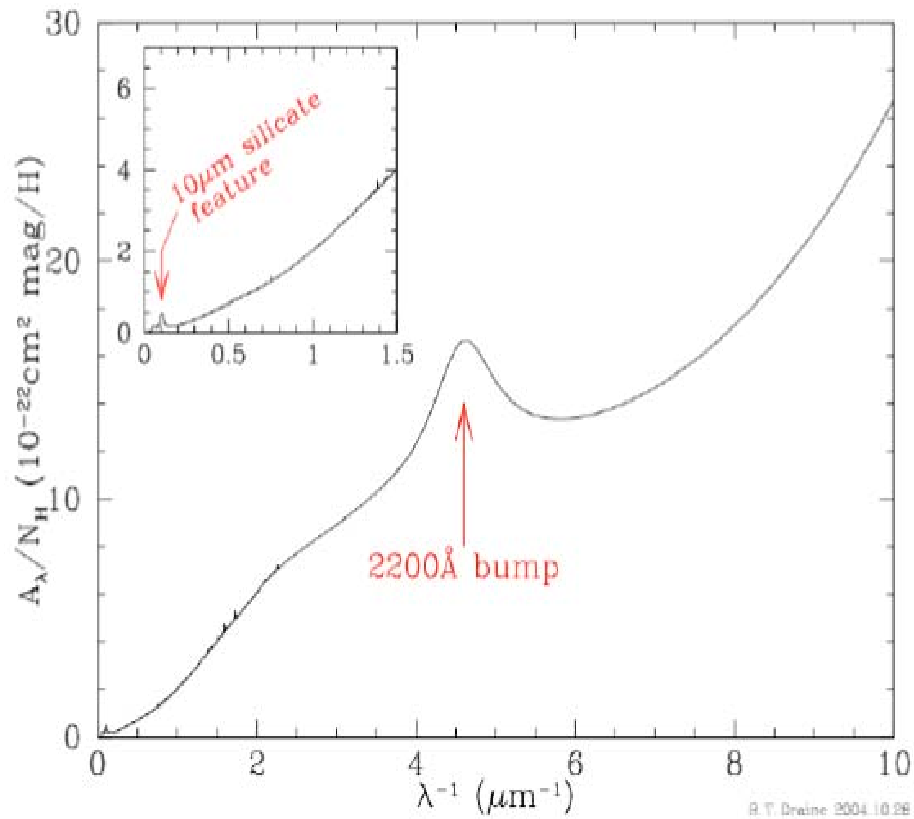


Fig. 5. Star counts with $m_K \leq 9.0$ for $-1.5° > b > -2°$ and the predicted counts using two simple disc–bulge models

Star counts from DENIS - Lopez-Corredoira et al. (2001)

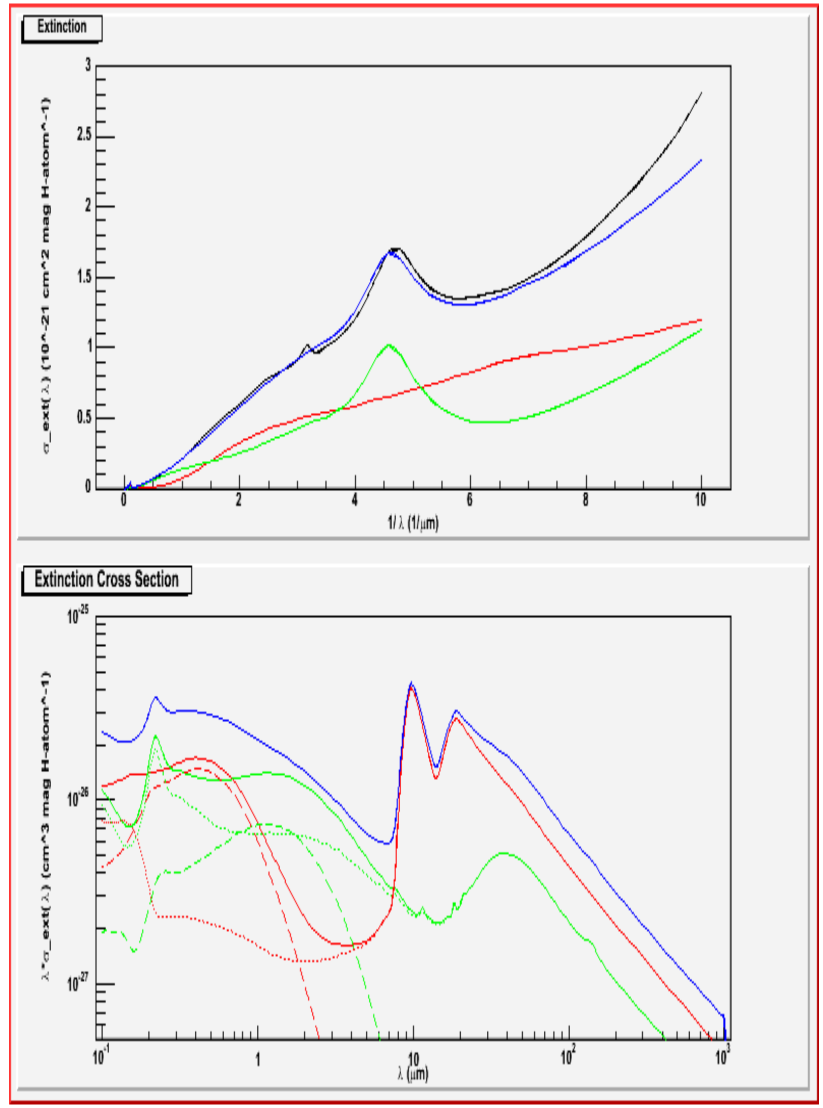
Dust Model and Extinction

- Observed extinction constrains dust model
- Bump at 0.22 microns probably PAH/graphite
- Need grain size distribution from < 0.01 µm to > 0.3 µm to get wavelength dependence



Dust Model and Extinction

- Extinction = scattering + absorption
- Use dust model of Weingartner & Draine (2001), Li & Draine (2001); others possible (Zubko, Dwek & Arendt 2004)
- Smooth distribution in ISM
- Mix of silicate and carbonaceous grains
- Smallest carbon grains are PAHs
- Large silicate/graphite approximated as spheres



black, blue, red, green = CCM1989, total, silicate, carbonaceous
solid, long-dash, short-dash = total, scattering, absorption

Modelling Scattering

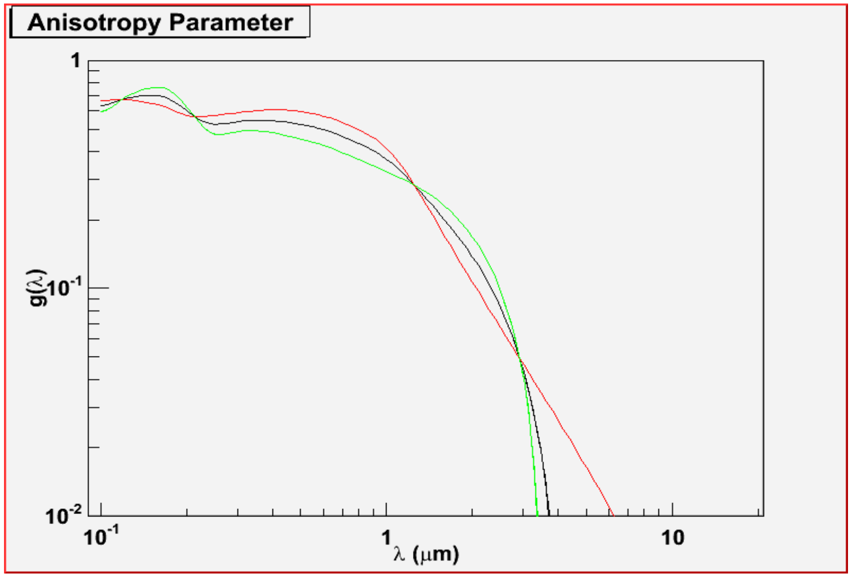
- Scattered light comprises ~10-20% total (so-called Diffuse Galactic Light (DGL))
- Scattering anisotropic and wavelength dependent
- Need two things
  - Anisotropy factor g derived from assumed grain model
  - Scattering 'phase' function giving angular distribution of scattered light

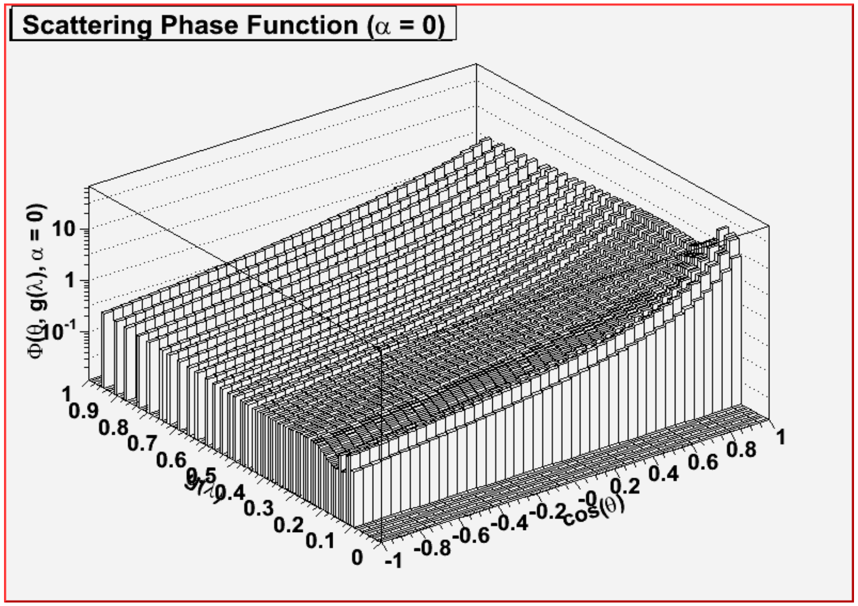
Modelling Scattering

- For 'phase' function, assume Henyey-Greenstein (1941) form :

$$p_{\lambda,HG}(\theta) = \frac{1 - g(\lambda)^2}{(1 + g(\lambda)^2 - 2g(\lambda)\cos\theta)^{3/2}}$$

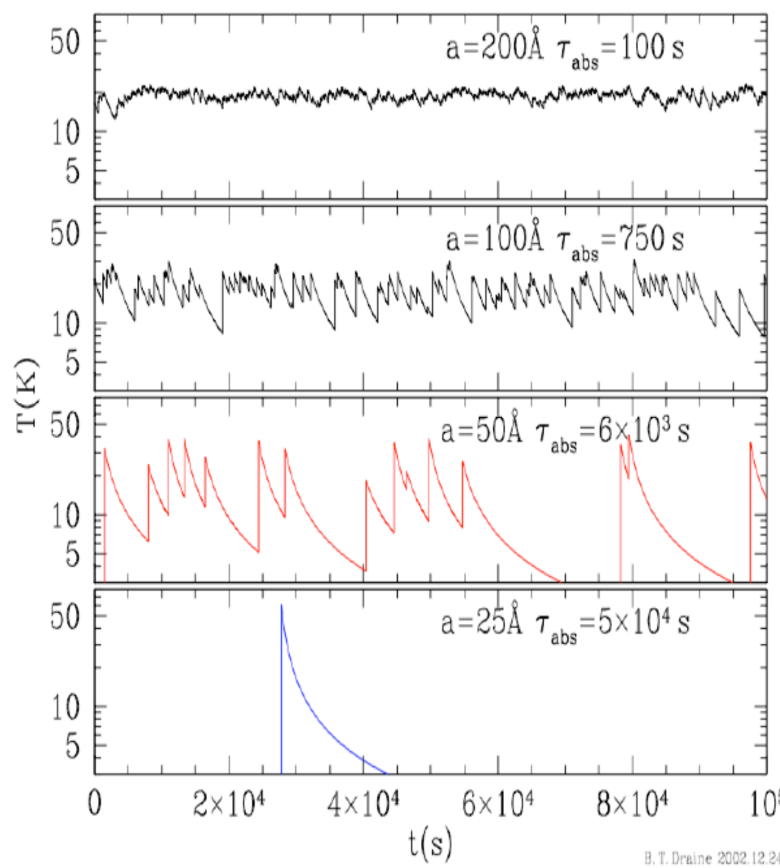
- Maybe can use better one (Draine 2003), but for future





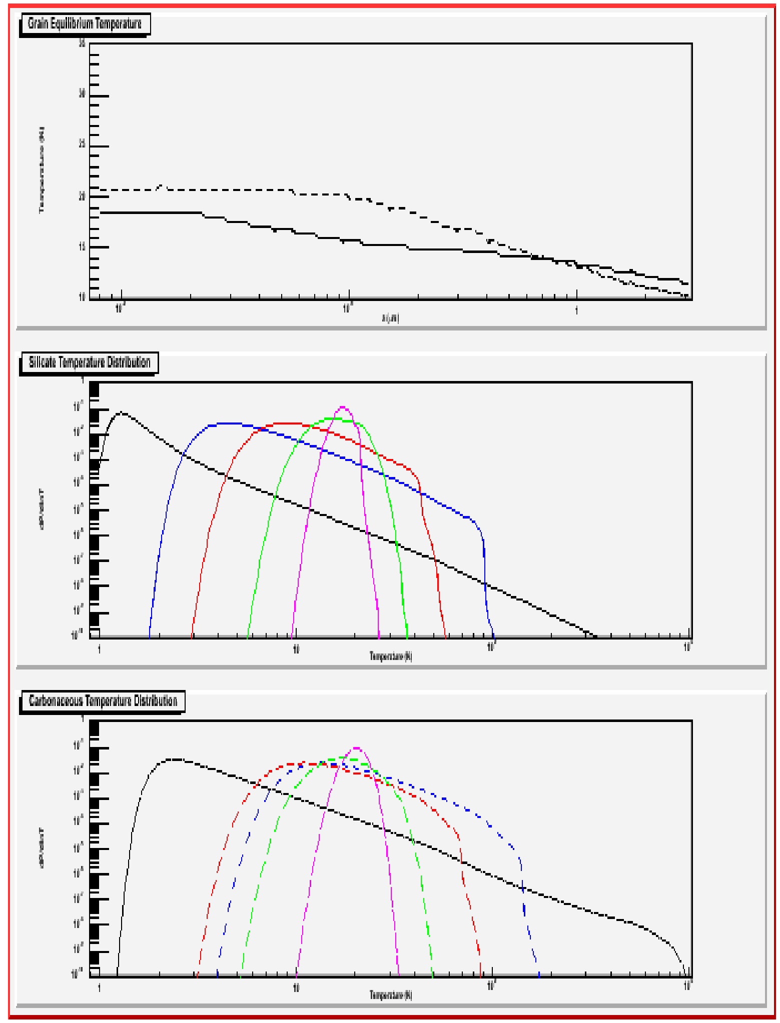
Modelling Absorption and IR Emission

- Grains absorb starlight and re-emit in IR
- IR emission from grains radiating at different temperatures
- For 'small' grains temperature is stochastic due to single photon heating
- 'Large' grains attain 'equilibrium' temperature T_eq



Modelling IR Emission

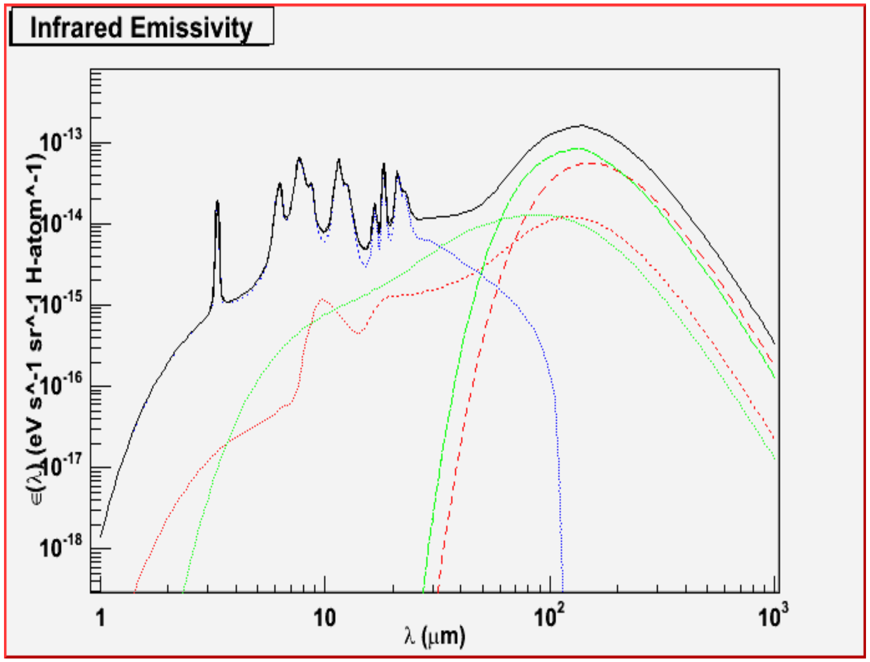
- 'Optical' RF varies throughout Galaxy
- Calculate $P_j(T; u, a)$ for different grain types j, RFs, and grain sizes a
- P_j approaches delta function about T_{eq} for 'large' grains

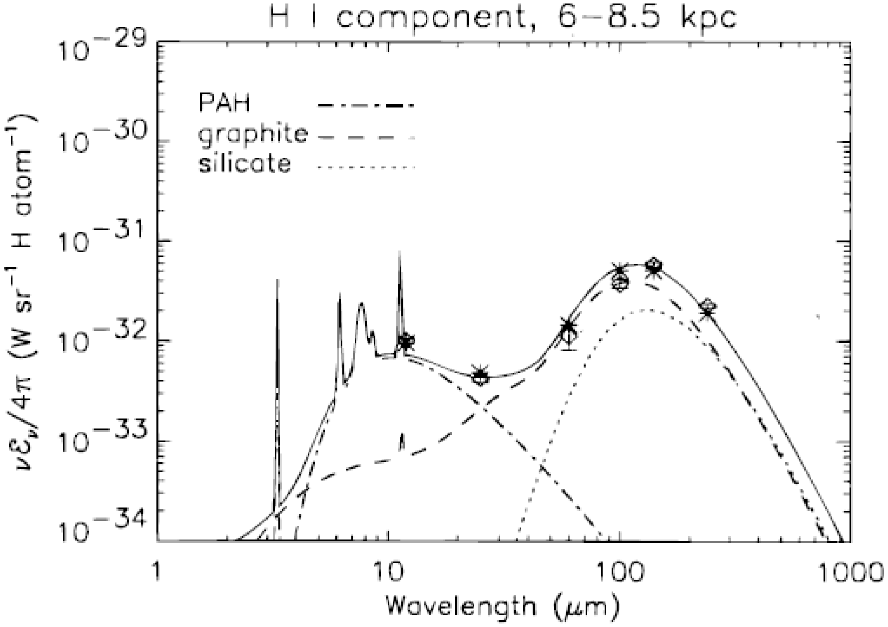


solid = silicate, dashed = carbonaceous
black, red, blue, green, magenta = 5e-4, 2.5e-3, 5.e-3, 1.e-2, 2.e-3 microns

Modelling IR Emission

- Emission spectrum : sum over grain types, integrate over grain sizes and P_j
- Calculation takes into account different RFs; assumed GalProp IR emissivity can't
- Similar shape to GalProp assumed IR emissivity, more near to mid-IR structure





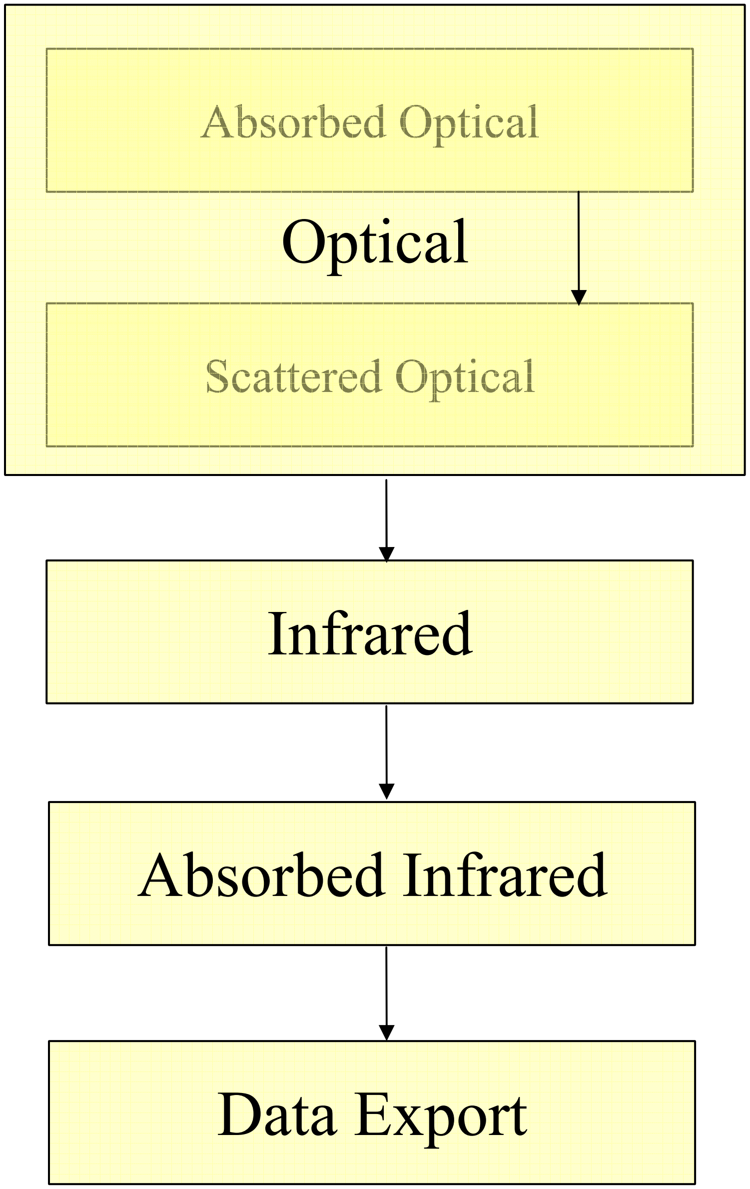
Upper : black = total; blue = PAH; red = graphite; green = silicate; dotted = transient; dashed = equil.
Lower : Dwek et al. (1997); Sodroski et al. (1997)

Putting it all together ...

- Have stellar emissivity from structure model
- Dust model for scattering and absorption + IR heating
- Gas model taken from GalProp (since dust and gas probably distributed similarly) + smooth HII (no arms) from Lazio & Cordes (2001)

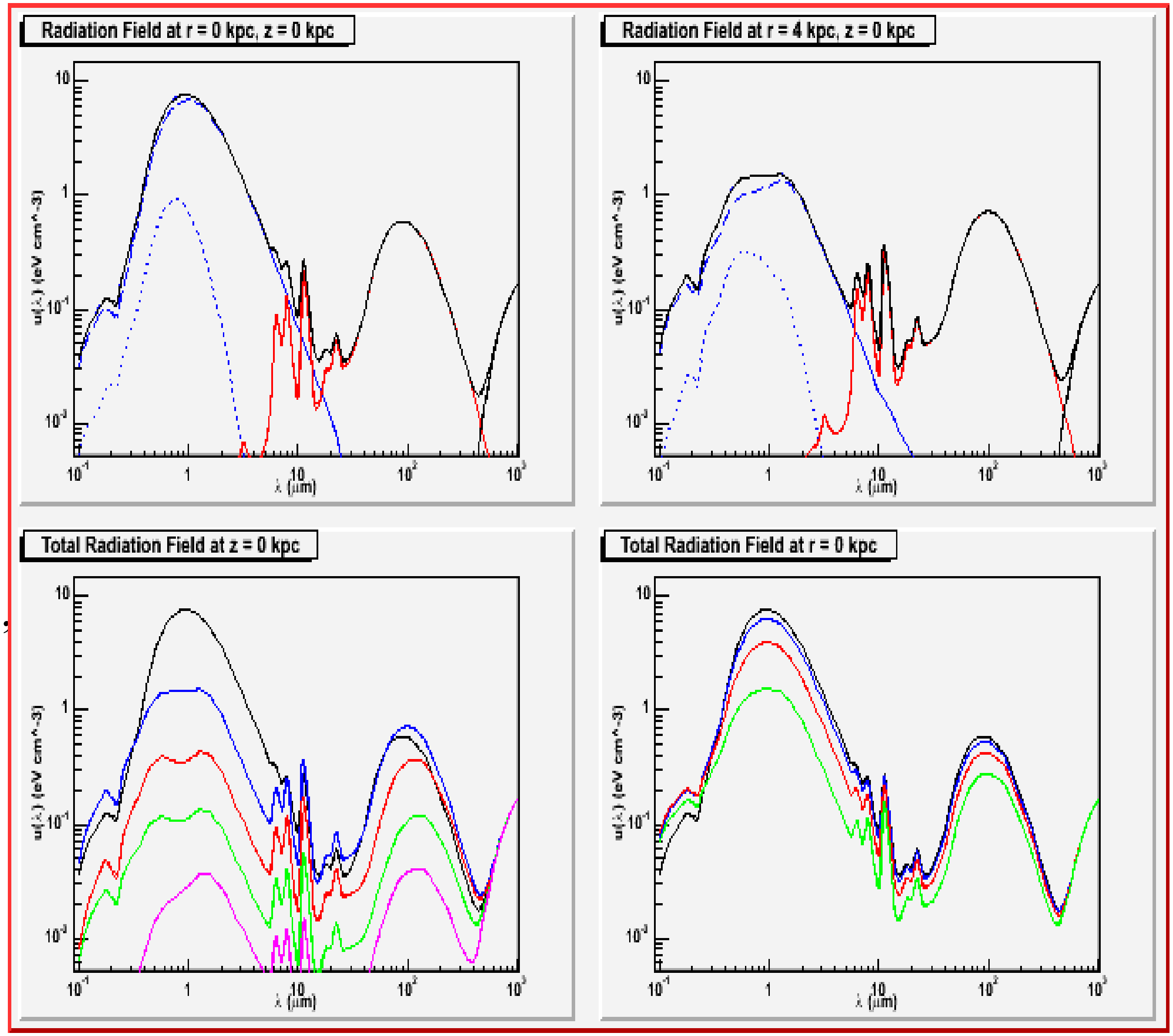
Radiation Field Calculation

- Proceed in steps, since result of one step is input for next step
- Volume integration over cylindrical Galaxy – obtain RF for each volume element
- Axisymmetry assumed gives faster calculation
- Flow : absorbed optical, first scattered, ..., nth scattered, infra-red, absorbed infra-red
- Can export to FITS for GalProp at end

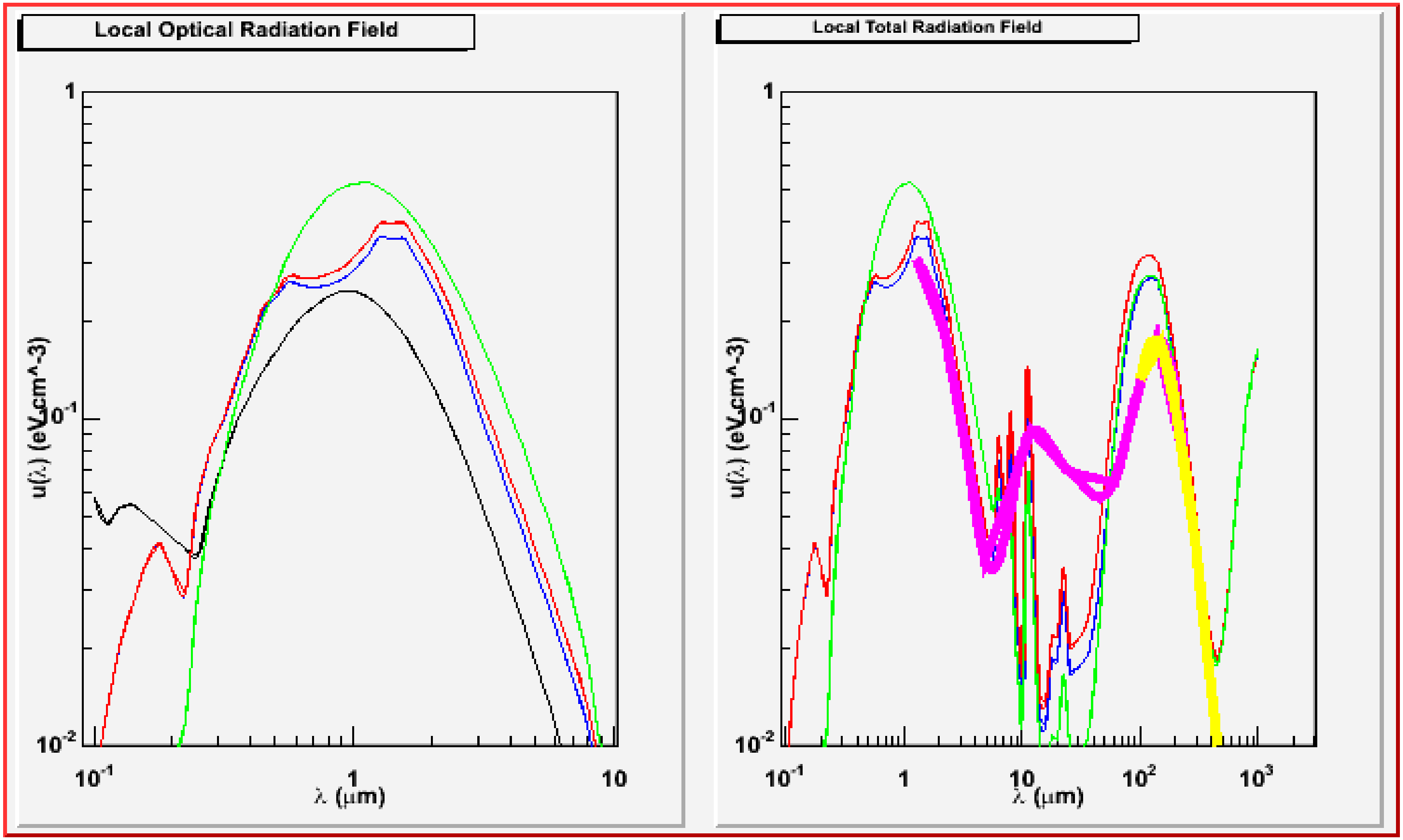


Example Results

- 2D RF calculated for
  - Rmax = 20 kpc
  - Zmax = 5 kpc
  - ΔR = 1 kpc
  - ΔZ = 0.1 kpc
- Scattered light ~ 10%
- Upper panels : Optical (blue), IR (red), Total (black)
- Lower panels : RF at different R (z = 0 kpc), and z (R = 0 kpc)



Local RF



Black : Mathis (1983); Green : Wainscoat (1992); Blue : GalProp + arms; Red : GalProp + bulge + arms

Green : Wainscoat (1992) + IR; Blue : GalProp + arms + IR; Red : GalProp + bulge + arms + IR; Magenta : DIRBE; Yellow : FIRAS (data courtesy D. Finkbeiner)

What Now?

- Need to finalise stellar emissivity model
- 3D necessary? If so, need better gas distribution
- Improve scattering calculation, compare with Pioneer
- Comparison with DIRBE/FIRAS
- Give full angular distribution of calculated RFs – anisotropic IC (M&S 2000)
- Data format?