

Modelling the interstellar radiation field of the Milky Way at parsec scale resolution

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The interstellar radiation field (ISRF) is the result of emission by stars, and the scattering, absorption, and re-emission of absorbed starlight by dust in the interstellar medium (ISM). Current state-of-the-art 3D models for the ISRF have been developed using spatially smooth distributions for stars and dust in the Milky Way. Recently, spatial reconstructions of the dust distribution have been made using stellar extinction data that now probe down to parsec scales nearby the Solar system. Moreover, the distribution of hot, luminous OB stars has been obtained with high degree of completeness out to $\sim 2\text{--}3$ kpc from the Solar system. We describe our new models that incorporate these features into the 3D models that we formerly developed using only the smooth spatial distributions. The new ISRF models have a significant degree of inhomogeneity in the distribution of the spectral intensities, particularly at ultraviolet and infrared frequencies. Comparison with multi-wavelength data shows good agreement with the new model predictions.

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1. Introduction

The ISRF is the result of emission by stars, and the scattering, absorption, and re-emission of absorbed starlight by dust in the ISM, and its wavelength range generally covers from the UV to far infrared (FIR). It plays an important role in the propagation (energy losses) and γ -ray emission of cosmic-ray (CR) electrons, via Compton scattering. Also, it is a major component of the diffuse interstellar medium (ISM) that influences astrochemical processes, as well as providing a pressure with comparable energy density to the CRs, and turbulent processes in the diffuse gas and Galactic magnetic field.

The current state-of-the-art 3D ISRF models for the MW were developed using the FRANKIE radiation transfer code [1]. The ISRF models have designations F98 and R12 and similarly reproduce data from DIRBE and IRAS (see Figs. 4 and 7 from [1], respectively), but neither is an overall best match with each having different shortcomings. The R12 model provides better correspondence toward the spiral arm tangents, but does not display the asymmetry associated with the bar (R12 has an axisymmetric stellar bulge), and the stellar disc scale length is incompatible with the near-IR profiles. Meanwhile, the F98 model has the disc scale-length in better agreement with the near-IR data, incorporates the bulge/bar asymmetry, but has none of the structure associated with the spiral arms. Their integrated energy density distributions throughout the Galaxy are also different. Consideration of $\gamma\gamma$ -pair-production attenuation effects on the spectra of the VHE γ -rays from toward the GC using both models [2] shows that they are providing bounding solutions for the MW ISRF spectral intensity interior to the Solar circle.

The F98 and R12 models are based on smooth distributions for the MW stars and dust, and as such the predicted ISRF distributions are also smooth and do not trace details $\lesssim 100$ pc spatial scales. Since the original work to produce them, much progress has been made tracing the stellar and interstellar dust distributions to finer scales. Hot/luminous (OB types) stars have long been expected to provide localised strong enhancements ($\times 10$ – 100) of the ISRF spectral intensities, particularly in the UV and near-UV, within ~ 10 – 50 pc of their spatial vicinities, e.g., [3]. Data from missions such as *Hipparcos* and *Gaia* provide fairly complete samples with well determined astrometry tracing their distributions out to heliocentric distances ~ 2 – 3 kpc. Moreover, determinations of the dust distribution using 2MASS, *Gaia*, and other instruments, e.g., [4, 5] now provide a much more detailed picture $\lesssim 3$ kpc about the Solar system that is highly structured compared with the smooth distributions employed by the F98/R12 models.

The localised enhancements both for the stellar luminosity input and dust densities from the above will produce an inhomogeneous distribution both for the UV and near-UV as well as the mid- to FIR wavelength ranges of the ISRF. In this contribution, we describe new MW ISRF models that include such details, and compare their predictions with the available multi-wavelength data. The new models include the background from the rest of the MW as well as the fine structure so that the ISRF is predicted down to scales $\lesssim 10$ pc for distances $\lesssim 3$ kpc of the Solar system.

2. Modelling Improvements

The input spectral luminosity model for both F98 and R12 models is based on the spectral type table of the SKY model [6], with improvements made by [7] based on Kurucz atmospheric

models [8] that provide good representations from the UV to infrared. The spectral types include main sequence stars and giants, with sub-type groupings into B and OB classes, along with others. For the B and OB types, for a 3 kpc region surrounding the Solar system we remove the smooth distributions describing these from the F98 and R12 models and ‘in paint’ the individual stars of these types taken from catalogues. Later stellar types are treated using smooth distributions as before, because the individual stars for, e.g., F and G main sequence stars are neither hot nor luminous enough to warrant such treatment.

We identify individual O and B stars using the *Hipparcos* catalogue [9] and the *Gaia* golden OBA sample [10]. The samples are matched based on count histograms for the individual types binned in heliocentric distance. The astrometry for each catalogue is retained for the respective regions that they cover. For each star we determine a categorisation as described below, and assign to it a spectrum according to its grouping within stellar type table for the luminosity model described above.

The *Hipparcos* catalogue provides MK types and luminosity class specifications for most stars in it. We used *Vizier* cross-matching to check for anomalous classifications. After doing so, if stellar type and luminosity class information was available, we assigned it the spectral model for the grouping in the luminosity model table. For cases where the stellar type was O/B but luminosity class information was not available, we assumed it as a main sequence star. Also, if sub-type stellar information was ambiguous (e.g., between 2 types) we assumed that it was the least luminous. If this information was missing, we assumed properties for the star of the least luminous member in its class.

For sources taken from the *Gaia* catalogue, we interpolated using photospheric-determined parameters (effective temperature, surface gravity, etc.) and transformed using tables from [11, 12] to an appropriate MK spectral type. The corresponding spectral luminosity model in the F98/R12 table was then used for each one. For the B stars most have well determined photospheric parameters, and the assignment for a corresponding spectral model was straightforward. However, there were cases with anomalous parameters, and for these we assumed the star as main sequence and assigned it as the least luminous type. For O stars, photospheric parameters are not as well determined. However, because the SKY model has the broad classification for these rarer stars (the ‘Young OB’ type), we simply assigned all *Gaia* O stars using the spectral model for this type.

For the same 3 kpc region surrounding the Solar system that we changed the hot/luminous star model, we also modified the dust distribution to reflect the high spatial resolution structure. For both F98/R12 models, we removed the smooth distribution and replaced it with a composite model based on reconstructions using stellar reddening. We used the recent determination by [5] for the dust distribution from nearby the Solar system out to the 1.25 kpc boundary of their data cube. The reconstruction is on a spherical grid with variable radial spacing (~ 2 pc nearby Solar system up to ~ 7 pc at boundary). Multiple equivalent posterior samples are provided, and we selected one that was interpolated to the multi-scale cartesian grid employed for the FRaNKIE simulations (see below). Beyond the 1.25 kpc spherical heliocentric boundary, we used the distribution given by [4] for the dust distribution out to the edge of the ‘in paint’ region where a smooth join is made to the large-scale F98/R12 dust models.

To enable tracing of high-resolution structure, individual sources, and smooth lower resolution components all within the same simulation, FRaNKIE has been modified to use a binarised octree

scheme [13]. This data structure is more memory- and CPU-efficient than standard octree schemes, and allows the simulations be made at comparably high statistics by about an order of magnitude quicker than our prior calculations.

3. Results

Figure 1 shows all-sky intensity maps for model predictions using the F98 model and its improved version, and data for 3 wavebands: COBE/DIRBE $1.25\mu\text{m}$ [14], WISE $12\mu\text{m}$ [15], and IRIS $100\mu\text{m}$ [16]. The COBE/DIRBE data has the lowest angular resolution on a HEALPix Nside=256 isopixelisation scheme, and we rebinned the other data images to the same resolution. The model predictions are made at the same Nside=256 HEALPix resolution and folded with the respective instrumental band passes for direct comparison with the data. For the COBE/DIRBE and IRIS data, no source subtraction has been made. (The WISE map has been processed to remove point sources.) No cosmic infrared background subtraction from the data for any waveband has been made.

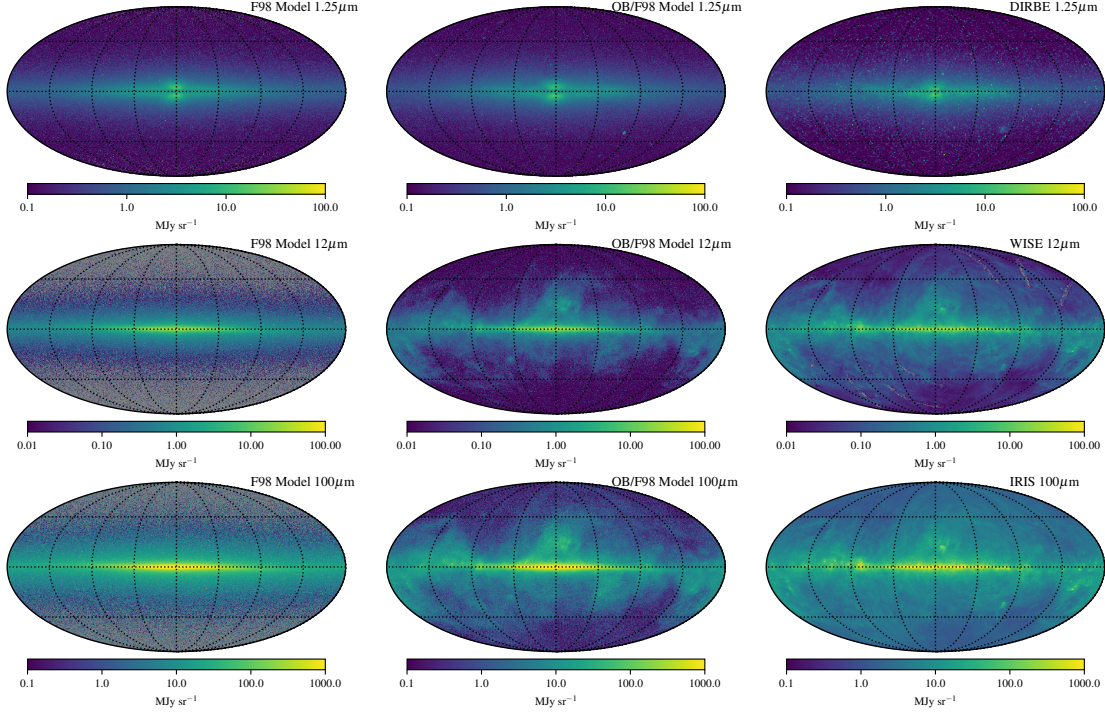


Figure 1: All-sky intensity maps for model predictions and data. Wavebands from top to bottom: COBE/DIRBE $1.25\mu\text{m}$, WISE $12\mu\text{m}$, and IRIS $100\mu\text{m}$. Columns from left to right: original F98 model, new F98 model with individual OB stars and high-resolution dust, and data from respective missions. Model predictions have been folded with the respective instrumental band passes for direct comparison with data. The WISE map is processed removing point sources, but the DIRBE and IRIS maps do not have source subtraction. Because of this, some extragalactic sources are visible, e.g., LMC, SMC, M31. The cosmic infrared background has not been subtracted from any of the data intensity maps.

For the COBE/DIRBE $1.25\mu\text{m}$ maps, the model prediction for the original F98 model is bright about the Galactic plane where the bar and disc are fairly well defined. The new model with the

high-resolution dust and individual OB stars has similar features, but they appear more diffused and slightly dimmer about the plane. This is due to the high-resolution dust distribution. The new model intensity map appears more similar to the data than the original F98 one, although the latter was clearly giving a reasonable representation.

For the WISE $12\mu\text{m}$ maps, the original F98 model prediction is reproducing the general features, but clearly different in detail to the data. Meanwhile, the new model with the in-painted high-resolution dust and individual OB stars as heating sources predicts many of the high-latitude spatial features evident in the data, e.g., various loops and arcs, the structure toward Orion and also the outer Galaxy.

The situation is similar for the IRIS $100\mu\text{m}$ intensity maps, where the original F98 model predicts an intensity about the plane similar to the data. However, it fails at reproducing fine spatial structures particularly out of the plane. As for the $12\mu\text{m}$ map, the new model looks very similar to the data. The predicted intensity about the plane follows a similar distribution as the data, but perhaps not quite as bright for some regions (e.g., toward Cygnus). Out of the plane, toward the inner Galaxy the spatial distribution of the model predictions also displays close similarity to the data. Meanwhile, toward the outer Galaxy loops and arcs, and regions with concentrations of embedded stars (e.g., Orion) appear to also follow the features seen in the IRIS map.

Figure 2 shows intensity longitude profiles about the Galactic plane for the same instrumental band passes as for Fig. 1. For each panel, the observations are shown as a black line, while the model predictions are the coloured lines. The original F98 model is coloured cyan, while the revised model with the smooth OB component for the nearby region removed but using the high-resolution dust is shown as red, and the revised model including also the individual OB stars is shown as green.

For the COBE/DIRBE $1.25\mu\text{m}$ band the original F98 model on average reproduces the profile, while missing many individual details. This is expected to some degree, because it uses smooth distributions for the stars and dust that will not include fine details for either. Meanwhile, the profile for the new model follows the observations much closer. The emissions from the OB stars for this waveband are sub-dominant to those from the more numerous cooler (e.g., F and later) types comprising the bulk of the stellar luminosity distribution, and so the closer correspondence with the data is almost entirely due to the effect of scattering and absorption on the high-resolution dust distribution within ~ 3 kpc of the Solar system.

The situation is similar for the WISE $12\mu\text{m}$ band where the original F98 model on average produces a comparable intensity profile to the data, but cannot describe the many peaks that may be associated with individual or collections of sources heating locally dense dust. The profile for the new model, on the other hand, does much better following the overall structure of the intensity profile particularly outside the Solar circle. This is due to combination of the OB stars heating the nearby dust, sitting on the background heating also of the same dust from the other luminous components over the inpainting region as well as that from the rest of the Galaxy. The agreement with the profile structure for the green line is very good, but the overall intensity for the outer Galaxy is $\sim 50\%$ lower compared to the data.

For the IRIS $100\mu\text{m}$ band the original F98 model on average produces a similar intensity profile to the data, but again cannot reproduce the fine structure. As for the $12\mu\text{m}$ profiles, the new model including the individual OB stars and high-resolution dust does much better following the features in the data. For the outer Galaxy region where this is most evident, the intensity predicted from

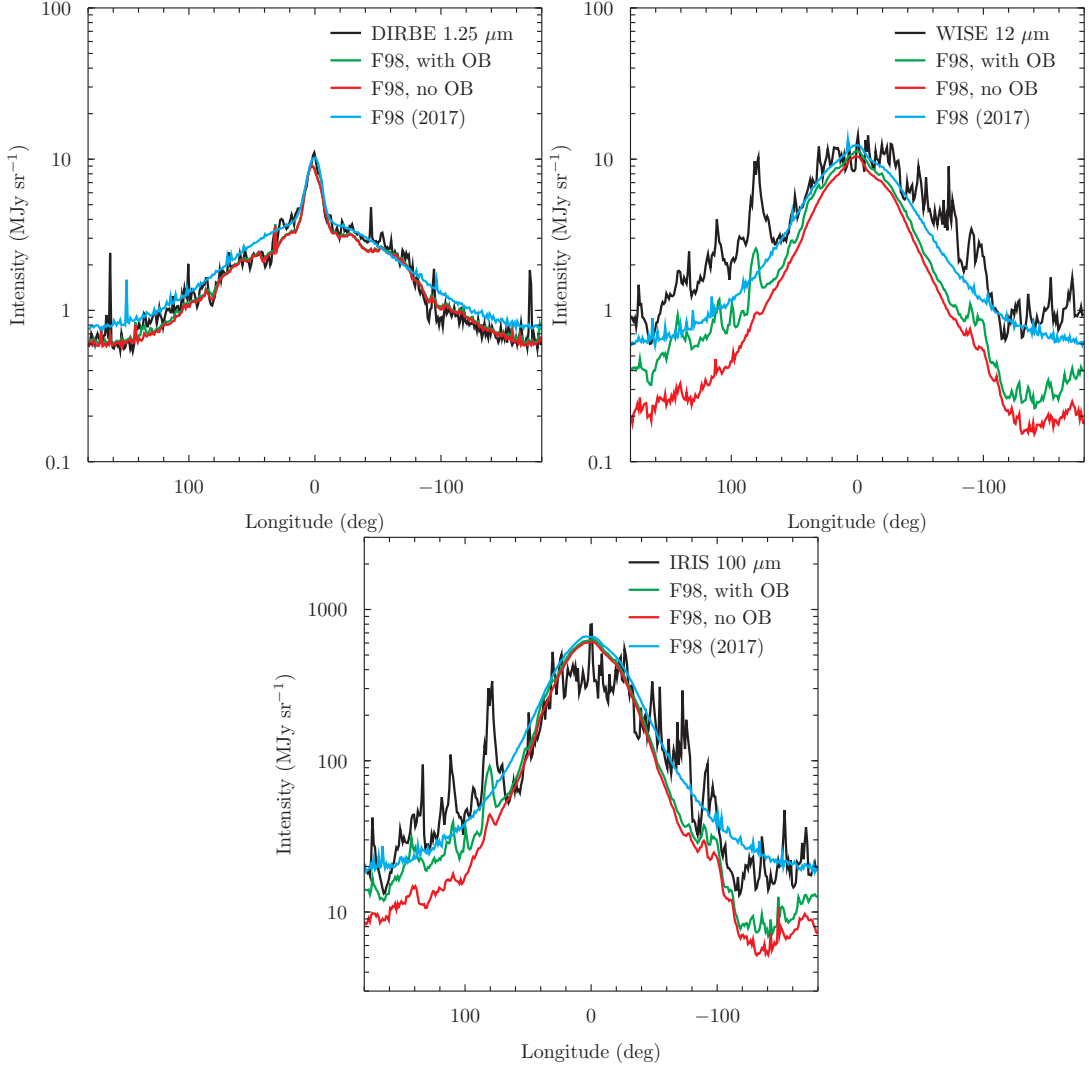


Figure 2: Intensity longitude profiles averaged over Galactic latitudes $|b| < 5^\circ$ about the plane for the COBE/DIRBE $1.25 \mu\text{m}$ band (top left), WISE $12 \mu\text{m}$ band (top right), and IRIS $100 \mu\text{m}$ band (bottom). The observations have been plotted for each waveband without source subtraction and removal of the cosmic infrared background. The model predictions have been folded with the respective instrumental response for each waveband to enable a like-for-like comparison with the data. Line colours: black, observations; cyan, original F98 model; red, F98 model with high resolution dust but smooth OB component removed for the region described in the text; green, F98 with individual OB stars included and high resolution dust model.

the new model is quite close to that of the data for the 2nd quadrant, and $\sim 20\text{-}30\%$ lower for the 3rd quadrant.

4. Discussion

There are clear improvements when we include the individual OB stars together with the high-resolution dust maps compared to the earlier generation of ISRF models. Tracing the fine structure in the intensity maps, particularly out of the Galactic plane, in the mid- and FIR appears quite

successful. It is evident that concentrations of sources in proximity of higher density dust produces corresponding more intense regions that match the data fairly well (e.g., Cygnus, Orion).

The longitude profiles also show favourable correspondence with the data. Indeed, the inclusion of the high-resolution dust now seems to enable the model to very closely trace the COBE/DIRBE NIR data, where for the original model it was only reasonably giving the general behaviour of the profile. For the mid- and FIR the locations of peaks and troughs in the new model profiles match fairly well the data but the intensities are still somewhat low. However, that predicted longitude profiles closely follow features in the data shows that we are at least identifying reasonably well where much of the nearby emissions are being produced.

The differences between the intensities predicted for features in the profiles and the data indicate deficiencies in the model, possibly coming from our relative broad classification of luminosity spectra for individual stars. For the O stars that are providing much of the heating our classification with a single luminosity spectrum is simplistic. But we also note that the dust the reconstructions are not perfect, and the density distributions are also a likely factor. We are investigating how to address these to further optimise the models.

Moving beyond, because the new models provide better understanding of the sources of ISRF emissions from the relatively nearby region about the Solar system, we can use this information to develop better models for the large-scale contribution from the rest of the MW. More details, including further improvements and comparison with results for the R12 model, will be given at the conference and in a forthcoming publication [17].

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