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A model of the stellar radiation field in the UV

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Abstract. This work is the first step in a systematic effort to understand and predict the different components of the UV (912 Å - 3000 Å) radiation field over the entire sky. We have developed a model to predict the ISRF in the UV within a few hundred parsecs of the Sun using the Hipparcos star catalog. We have checked the model through a comparison with the observations of the Belgian/UK UV sky survey telescope (S2/68) on the ESRO TD-1 satellite.

Keywords : Interstellar radiation field (ISRF), diffuse background

1. Introduction

In order to understand the diffuse sky background - which is largely due to either scattering in the ultraviolet (UV) and visible or thermal emission in the infrared (IR) from interstellar dust grains - we must first understand the local radiation field, that is, the radiation field at the location of the grains. The most commonly used model of the interstellar radiation field (ISRF) has been that of Mathis et al. (1983) but this is intended as a global representation and not a prediction at any specific location. Therefore, as a first step in our modeling of the diffuse radiation field, we have built a model for the ISRF at any point in space within a few hundred pc of the Sun. Most of the contribution to the total ISRF comes from the hot early type stars (see Fig.1) for which the maximum emission is in the UV. Therefore we have concentrated our efforts in that spectral region, where the modeling is also easier (Murthy & Henry 1995).

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Table 1. Data accessed from Hipparcos digital catalog.

Field	Description
H1	Hipparcos digital catalog Number.
H5	V (Johnson) Magnitude of the stars.
H8	$\alpha(J1991.25)$, Right Ascension in degrees.
H9	$\delta(J1991.25)$, Declination in degrees.
H11	π Trigonometric Parallax in milliarcsec.
H37	Johnson Color index, B − V.
H76	Spectral Type, MK-Classification.

Although our primary purpose in creating this model is for our study of the diffuse radiation field, we expect that there might be more general uses of a program to simulate the UV sky. For instance, we are using this work as a basis for a simulation of the sky as observed by two upcoming UV spacecraft — TAUVEX (Brosch 1996) and ASTROSAT/UVIT (Agrawal 2001). Thus we have made a special effort to ensure that these programs are portable across a wide variety of systems and are generally available, either through application to the authors or through the website http://www.iiap.res.in/personnel/murthy/uv_model/ModelingtheUVSky.html.

2. Model

Murthy and Henry (1995) used information from the SKYMAP star catalog (Gottlieb 1978) to model the ISRF but now much better stellar information is available from the Hipparcos mission (Perryman et al. 1997). Hence we have used the Hipparcos digital catalog as our source of stars as well as their location, distance, spectral type and brightness (Table 1). Based on the spectral type of the star, we have derived a temperature and effective gravity using information from Allen (2000), Colina (1995) and Lang (1982) and calculated a spectral energy distribution for each star using the appropriate Kurucz models[1] (Kurucz 1992). The Kurucz models have long been a standard in calculating stellar profiles and are readily available. However other models are available (e.g., Lejeune et al. 1997,1998) and may be easily substituted into our program structure.

In order to calculate the intrinsic UV flux of the star, we used the Kurucz model flux of the appropriate spectral type and scaled to the observed visual magnitude using the formula:

$$\frac{\Upsilon \mathrm{K}(5500\text{Å})}{4\pi \mathrm{r}^2} \cdot e^{-\tau} = 3.64 \times 10^{-9} \times 10^{-\mathrm{V}/2.5},$$

[1]The Kurucz stellar flux data can be obtained from: *http://www.stsci.edu/science/starburst/Kurucz.html*

where Υ is the scaling factor; K(5500) is the Kurucz flux at 5500 Å; V is the Johnson magnitude and τ allows us to correct for interstellar absorption where

$$\tau = \mathrm{A_v}/1.0863 = (\mathrm{E(B-V)} \cdot \mathrm{R_v})/1.0863.$$

E(B − V) was calculated from the observed B − V and the intrinsic (theoretical) B − V as derived from the Kurucz model spectrum.

Of the 118,218 stars in the Hipparcos digital catalog, 107,514 were included in our model. In many cases multiple or complex spectral types were associated with a single star; in such cases, we used the closest spectral type. There are 25 white dwarfs in the catalog, which we have modeled using blackbody curves of the appropriate temperature. We have not included 10,704 stars of which 248 are of spectral type R, S, N, or C which will have a negligible UV flux and the remaining are of unknown spectral type. We will show below that the impact of these stars are negligible in our model.

Because we want to calculate the ISRF at an arbitrary location in space, we must know the amount of starlight absorbed between each star and the location of interest. For the interstellar extinction, we assume a synthetic extinction cross-section[2] $\sigma_{\mathrm{ext}}(\lambda)$ from Weingartner & Draine (2001) with an interstellar reddening parameter $\mathrm{R_V} = 3.1$ (Cardelli et al. 1989). We do plan to develop a realistic model for the dust distribution within a few hundred pc of the Sun but at this stage in our modeling we simply use a uniform dust distribution.

The total integrated stellar radiation field (in erg $\mathrm{cm^{-2}\ s^{-1}}$ $\mathrm{Å^{-1}}$) from the TD-1 observation (with solid angle of 1 arcmin) is plotted at four different wavelengths 1565 Å(FWHM=330 Å), 1965 Å(330 Å), 2365 Å(330 Å) and 2740 Å(310 Å) (asterisks) in Fig. 1 along with our predicted radiation field for an interstellar gas density n(H) = 1.45 (thick solid line) and 1.2 $\mathrm{cm^{-3}}$ (thin solid line). We found that the best fit came for n(H) = 1.45 $\mathrm{cm^{-3}}$, close to the canonical interstellar gas density of 1.2 $\mathrm{cm^{-3}}$ (Spitzer 1978). The largest fraction of the light in the ISRF in the UV comes from B stars (dotted line),and A stars (dashed line) with O stars (dot-dashed line) contributing a small part.

B type stars constitute ∼10% of the total number of stars in our model, at distances between 20 pc and 100,000 pc, and ∼99% of these lie outside the local bubble. According to Parravano et al. (2003) almost all FUV ISRF originates within ∼500 pc, with the contribution from more distant stars falling rapidly as a result of attenuation by dust. Therefore only B stars or its associations within 500 pc contribute significantly to the total ISRF. We have confirmed this result using our model, finding that the contribution to the total ISRF from stars farther away than 500 pc from the Sun is less than 1%.

[2]Synthetic Extinction Cross-section:
http://www.astro.princeton.edu/∼draine/dust/dustmix.html

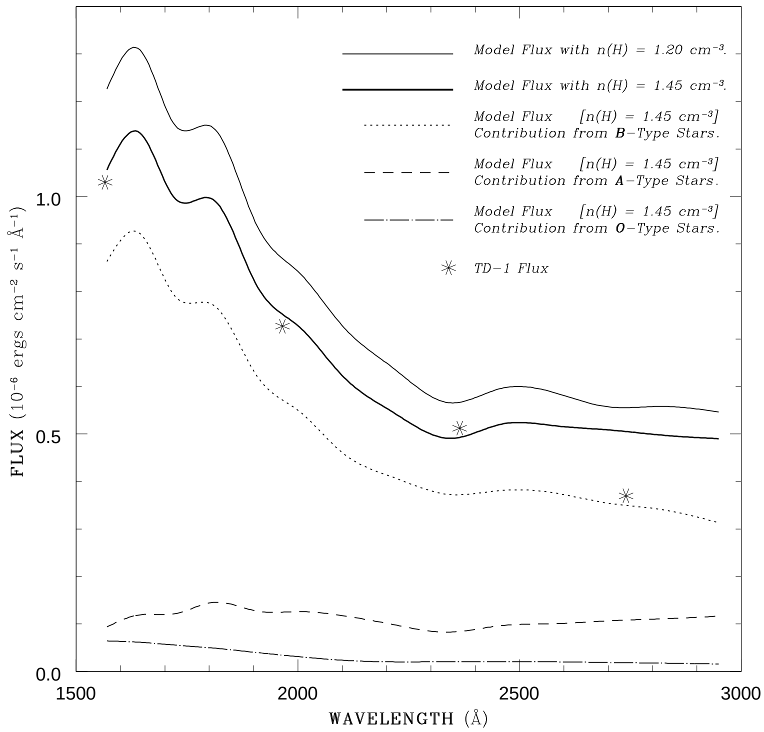
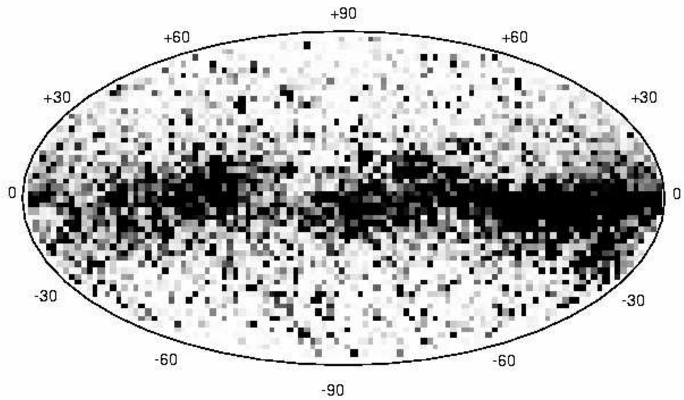


Figure 1. The total integrated stellar radiation field (over the entire sky) at the Earth from the TD-1 observations is plotted at four different wavelengths, 1565 Å, 1965 Å, 2365 Å, 2740 Å(asterisks), along with the predictions using the model for n(H)=1.45 cm^{-3} and 1.2 cm^{-3} and the individual contributions by O, B and A stars assuming n(H)=1.45 cm^{-3}. The major contributor to the ISRF is B stars followed by A stars with O stars contributing a very small part of the total. The unit of y-axis is 10^{-6} erg cm^{-2} s^{-1} $Å^{-1}$.

3. Testing the model

To date, the only observations of the entire sky in the UV have come from the TD-1 satellite (Humphries et al. 1976; Boksenberg et al. 1973) with 4 passbands and a limiting sensitivity on the order of 10^{-12} erg cm^{-2} s^{-1} $Å^{-1}$ (i.e., the observation is thought to be complete down to fluxes of 1.0 x 10^{-12} erg cm^{-2} s^{-1} $Å^{-1}$ at each wavelength). According to Gondhalekar (1990), the contribution by stars fainter than this limit to the total ISRF is found to be negligible (< 10% of the total) at these wavelengths.

We have therefore compared our predictions at the Earth to the actual observations of TD-1. The overall appearance of our modeled sky is very similar to that observed by TD-1 (Fig. 2). The asymmetry of ISRF in both galactic longitude and latitude is very



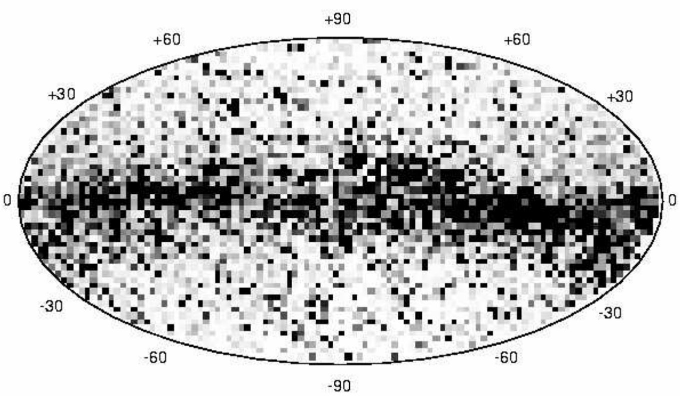


Figure 2. Comparision of the net radiation field at the Earth (in 3^o bins) observed by the TD-1 satellite at 1565 Å(top) with our predictions (bottom), corresponding to a gas density of 1.45 cm^{-3}, at 1569 Å, in which, the degree of darkness represents the degree of brightness of the location. The galactic center $(0^o, 0^o)$ is at the center of the figures with the longitude increasing towards left.

clear in this figure. According to Henry (1977), 78% of the total ISRF originates from $180^o < l < 360^o$ while just more than 78% of the total ISRF originates from $|b| < 21^o$. It should be noted that our model incorporates many more stars than were detected by the TD-1 satellite (107,514 in our model versus 31,215 in the TD-1 catalog).

Another comparison of our prediction for the ISRF with TD-1 observation is shown in Fig. 3, where we have plotted the logarithmic value of the predictions from our model (in erg cm^{-2} s^{-1} $Å^{-1}$) for the net radiation field in 10^o bins for standard space density of 1.45 cm^{-3} (dark line) and the corresponding logarithmic value of observed flux by the TD-1 satellite (faint line) at different latitudes -40^o, -5^o and +20^o with galactic longitude (l) along the x-axis. Again the fit is good with the differences being due to our assumption of a uniform dust distribution.

We have integrated the spectral energy density U_λ (in erg cm^{-3} $Å^{-1}$) for different wavelengths in the immediate neighbourhood of the Sun over the entire sky. Our results are in good agreement with previous studies especially with Habing's (1968) (see Parravano et al. 2003 for a summary of previous works). The previous calculations were made for a space averaged energy density in the solar neighbourhood, whereas, we have taken into account the anisotropic nature (see Fig. 2 & Fig. 3) of the radiation field and calculated a direction dependent energy density.

Parravano et al. calculated the time dependent FUV field for random positions in the ISM at the solar circle in H_2 band (912Å- 1100Å), FUV band (912Å- 2070Å) and at a wavelength of 1400Å. His typical value (or median) at 1400Å ($\sim$7.5) is $\sim$1.6 times higher than our local value at 1400Å ($\sim$4.7). Much of this difference is because Parravano et al. include scattering by dust grains (the median value U_{scatt} is $\sim$18% of the U_{total}) while our model is intended only to calculate the direct star light. Apart from this, his result is based on the global Star Formation Rate (SFR) in the Galaxy and is not based on the local SFR at the present time whereas ours is based on the observed sources in the Hipparcos catalog. We believe that the difference mentioned above will be further reduced when we incorporate the effects of scattering and absorption in our model, as our next work.

4. Applications and future directions

This work forms the first part of our project to understand the diffuse UV sky. However, it is our hope that the programs we have written will be of use in other applications and so we have made them available from the URL
(http://www.iiap.res.in/personnel/murthy/uv_model/ModelingtheUVSky.html)
or by application to the authors. All programs are written in ANSI C and are self documenting and should be easy to modify to one's own application.

We have used the model described here as an input into a simulation of the UV sky which will be used for the mission planning for two upcoming UV spacecraft (TAUVEX and ASTROSAT).

We are also applying this model to our continuing study of the diffuse UV radiation field. Murthy et al. (1997) and Murthy & Sahnow (2004) have obtained a number of observations of the diffuse FUV (below 1200 Å) radiation field in many different locations. We plan to apply the model described in this work to these data to help determine the nature of the interstellar dust grains.

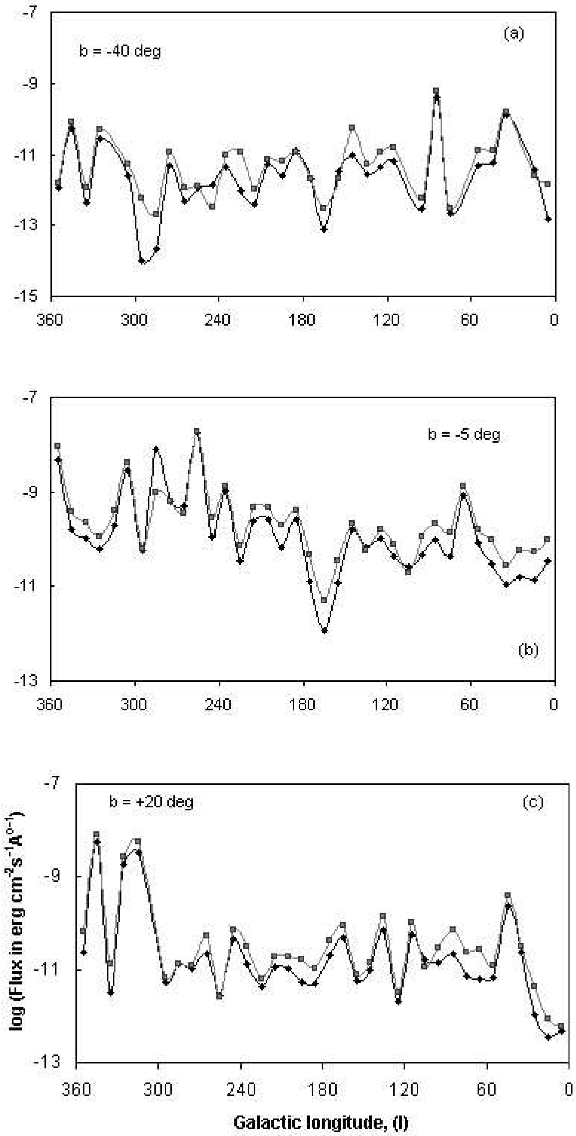


Figure 3. Comparision of the total modeled flux in 10^o bins for n(H)=1.45 cm^{-3} at 1569 Å(dark line) with that of the TD-1 observation (faint line) at 1565 Å. The logarithamic value of flux plotted against galactic longitude (l) for different latitudes (a) b=-40^o,(b) b=-5^o and (c) b=+20^o.

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