Galactic Latitude Dependence of Near-infrared Diffuse Galactic Light: Thermal Emission or Scattered Light?

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Abstract

Near-infrared (IR) diffuse Galactic light (DGL) consists of scattered light and thermal emission from interstellar dust grains illuminated by the interstellar radiation field (ISRF). At 1.25 and 2.2 μm, a recent observational study shows that intensity ratios of the DGL to interstellar 100 μm dust emission steeply decrease toward high Galactic latitudes (b). In this paper, we investigate the origin(s) of the b-dependence on the basis of models of thermal emission and scattered light. Combining a thermal emission model with the regional variation of the polycyclic aromatic hydrocarbon abundance observed with Planck, we show that the contribution of the near-IR thermal emission component to the observed DGL is lower than ~20%. We also examine the b-dependence of the scattered light, assuming a plane-parallel Galaxy with smooth distributions of the ISRF and dust density along the vertical direction, and assuming a scattering phase function according to a recently developed model of interstellar dust. We normalize the scattered light intensity to the 100 μm intensity corrected for deviation from the cosecant-b law according to the Planck observation. As the result, the present model that considers the b-dependence of dust and the ISRF properties can account for the observed b-dependence of the near-IR DGL. However, the uncertainty in the correction for the 100 μm emission is large, and other normalizing quantities may be appropriate for a more robust analysis of the DGL.

Key words: dust, extinction – infrared: ISM – scattering

1. Introduction

Dust is a minor constituent by mass in the universe, but plays crucial roles in various astrophysical phenomena. As a basic property of dust grains, they scatter starlight and absorb the radiation energy. Subsequently, they release the absorbed energy as thermal emission in infrared (IR) wavelengths. In the diffuse interstellar medium (ISM), the scattered light component is dominant from ultraviolet (UV) to near-IR wavelengths (~0.2–2 μm). From near- to mid-IR (~2–50 μm), very small grains and large molecules (e.g., polycyclic aromatic hydrocarbon; PAH) heated by the interstellar radiation field (ISRF) radiate thermal emission. From UV to near-IR, the scattered light and thermal emission in the diffuse ISM are conventionally referred to as “diffuse Galactic light (DGL).”

The DGL observation is useful to investigate interstellar dust properties such as grain albedo and the PAH abundance. As a tracer of the DGL, far-IR 100 μm dust emission has been used, because this dust and the DGL are expected to correlate linearly with each other in optically thin fields (e.g., Brandt & Draine 2012; hereafter BD12). The 100 μm map based on all-sky observations of the Infrared Astronomical Satellite (IRAS) and the Cosmic Background Explorer (COBE) has been used frequently (Schlegel et al. 1998; hereafter SFD98). From UV to near-IR, several studies have observed the diffuse light in high Galactic latitudes (b) and found linear correlations against the 100 μm emission (e.g., Witt et al. 2008; Matsuoka et al. 2011; Tsumura et al. 2013; Arai et al. 2015; Sano et al. 2015, 2016a; Kawara et al. 2017). These results are shown in Figure 1 with model spectra of the scattered light (BD12) and thermal emission (Draine & Li 2007; hereafter DL07). The models are based on recent interstellar dust models developed by Weingartner & Draine (2001; hereafter WD01) and Zubko et al. (2004), assuming the ISRF spectrum in the solar neighborhood (Mathis et al. 1983; hereafter MMP83). As shown in Figure 1, the near-IR DGL is expected to consist of the scattered light and thermal emission, indicating that both components should be taken into account in a detailed study.

Mie (1908) and Debye (1909) formulated the absorption and scattering properties of spherical grains for an electromagnetic wave (Mie theory). According to the Mie theory, forward-throwing scattering is dominant when the wavelength (λ) is comparable to the grain size (a); this is referred to as “Mie scattering.” In contrast, forward and backward scattering become comparable for λ ≫ a (Rayleigh scattering). A fraction of the scattered intensity toward a scattering angle θ is represented by the scattering phase function φθ(θ). As an indicator of the scattering anisotropy, the first moment of a phase function is defined as

\[ g_\lambda \equiv \langle \cos \theta \rangle = \int \Phi_\lambda(\theta) \cos \theta \, d\Omega, \]  

(1)

where Ω denotes the solid angle. According to this definition, the g-factor range is \(-1 \leq g_\lambda \leq 1\), and forward scattering becomes dominant as it is higher. For interstellar scattering, Henyey & Greenstein (1941; hereafter HG41) introduced an analytical form of the phase function to be consistent with Equation (1):

\[ \phi_\lambda(\theta) = \frac{1}{4\pi} \frac{1}{(1 + g_\lambda^2 - 2g_\lambda \cos \theta)^{3/2}}. \]  

(2)

Considering the scattering anisotropy in the diffuse ISM, Jura (1979; hereafter J79) expected the scattered light intensity as a function of |b|, assuming the HG41 phase function and

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uniform illuminating sources in an infinite Galactic plane. According to their numerical calculation, intensity ratio of the scattered light ($I_{\text{sc}}$/em) to interstellar 100 $\mu$m emission ($I_{100}$) is expressed as

$$I_{\text{sc}}/I_{100} \propto 1 - g_s \sqrt{\sin |b|}. \quad (3)$$

This formulation indicates that the $b$-dependence of the intensity ratio becomes steeper as the $g$-factor is higher.

In high-$b$ regions ($|b| \gtrsim 20^\circ$), Sano et al. (2016b; hereafter Paper I) found that the intensity ratios of the near-IR DGL (1.25 and 2.2 $\mu$m) to 100 $\mu$m emission steeply decrease toward the high-$b$ region by analyzing all-sky maps of Diffuse Infrared Background Experiment (DIRBE) on board COBE. By assuming the presence of scattered light alone, the observed $b$-dependence is fit by Equation (3) with a $g$-factor of 0.8$^{+0.3}_{-0.1}$ at 1.25 and 2.2 $\mu$m. The derived $g$-factor is too large to be explained with the WD01 dust model predicting $g_s \lesssim 0.3$ in the near-IR: the Rayleigh regime for the WD01 typical grain size ($\sim 0.1 \mu$m).

The steep $b$-dependence can be attributed to the following possibility. On the one hand, the near-IR thermal emission also contributes to the $b$-dependence at 1.25 and 2.2 $\mu$m through regional variations of the ISRF and/or the PAH abundance. Although the near-IR thermal emission has not been found in the diffuse ISM, it has been detected in some reflection nebulae (e.g., Sellgren et al. 1992, 1996). On the other hand, there is room for improving the J79 model of scattered light. For instance, Draine (2003b; hereafter D03) reported a discrepancy of the phase function between the HG41 form and the WD01 dust model in the near-IR. In addition, J79 suggested a large uncertainty of a factor of 1.5 in Equation (3). Based on these concerns, the high $g$-value derived from the J79 model is unreliable.

In this paper, we adopt models of thermal emission and scattered light to investigate the contribution of these components to the $b$-dependence of the near-IR DGL. The WD01 model is adopted as interstellar dust properties since it reportedly reproduces the observed extinction curve (e.g., Fitzpatrick 1999; Draine 2011). To investigate the contribution of the thermal emission, we adopt the DL07 model. We evaluate the contribution of the scattered light, adopting a plane-parallel galaxy model such as BD12. The present analysis is also based on the all-sky observation with Planck.

The remainder of this paper is organized as follows. Sections 2 and 3 describe the models of scattered light and thermal emission, respectively. In Section 4 we discuss origins of the $b$-dependence of the near-IR DGL by comparing the observation with the models. Summary and conclusion appear in Section 5.

2. Near-infrared Thermal Emission

Here, we assume intensity ratios of the near-IR thermal emission to the 100 $\mu$m emission ($I_{\text{em}}$/em) as a function of $|b|$, based on Planck results and the DL07 model.

2.1. Planck Observation

Planck Collaboration et al. (2016) investigated regional variations in the properties of interstellar dust and the ISRF from all-sky maps in a wide wavelength range ($10 \mu$m $\lesssim \lambda \lesssim 1000$ $\mu$m), including Wide-field Infrared Survey Explorer (WISE), IRAS, and Planck. Combining the DL07 model spectra
with the all-sky maps, they fit the spectral energy distribution (SED) in each field of the sky and created maps of interstellar dust and ISRF properties.

In the analysis of thermal emission, crucial parameters in the DL07 model are the mass fraction of very small grains with PAH to the total dust, \( q_{\text{PAH}} \), and the scaling factor of the MMP83 ISRF, \( U \). As \( q_{\text{PAH}} \) increases, near-IR and mid-IR dust emissions become more dominant. In general, the quantity \( U \) depends on the parameter \( \gamma \), indicating a fraction of the photodissociation region (PDR). In the DL07 model, a fraction \( 1-\gamma \) of the dust mass is illuminated by single ISRF intensity \( U_{\text{min}} \), while the remaining fraction \( \gamma \) is heated by various ISRF intensities between \( U_{\text{min}} \) and \( U_{\text{max}} \). As shown in the all-sky maps of each parameter (Figure 1 of Planck Collaboration et al. 2016), the parameter \( \gamma \) can be approximated as zero in high-\( b \) regions, indicating little contribution of the PDR component. According to this result, the parameter \( U \) can be assumed as \( U_{\text{min}} \) in high-\( b \) regions. We thus focus on the single ISRF parameter \( U = U_{\text{min}} \) and \( q_{\text{PAH}} \) in the DL07 model.

Figure 2 shows the \( b \)-dependence of the parameters \( U \) and \( q_{\text{PAH}} \), taken from the Planck maps (Planck Collaboration et al. 2016). The parameter \( U \) tends to increase toward the high-\( b \) region. The dust temperature (\( T \)), another indicator of the ISRF intensity, exhibits a similar trend in the all-sky \( T \) map created by Planck Collaboration et al. (2014). Since the high-\( b \) regions are mostly optically thin, interstellar dust may be intensively exposed by the Galactic disk emission. In contrast, the parameter \( q_{\text{PAH}} \) tends to decrease toward the high-\( b \) region. Hensley et al. (2016) reported a similar trend from the analysis of the WISE 12 \( \mu \)m map. They showed that the ratio of the 12 \( \mu \)m emission to the dust radiance, an indicator of the PAH abundance, increases toward a low-\( b \) region. In addition, the Planck-derived value of \( q_{\text{PAH}} \) is consistent with the DIRBE observation at 3.5 \( \mu \)m in high-\( b \) regions (Sano et al. 2016a). Data products created by Planck are available via the Planck Legacy Archive (PLA): https://www.cosmos.esa.int/web/planck/pla.

2.2. Modeling of the Thermal Emission as a Function of \( |b| \)

To model the \( b \)-dependence of \( \lambda_{\text{em}}/I_{100} \), we express \( U \) and \( q_{\text{PAH}} \) as a linear function of \( |b| \) according to the Planck observation (Figure 2):

\[
U = 0.00516|b| + 0.330,
\]

\[
q_{\text{PAH}} = -0.0420|b| + 7.03.
\]

Figure 3 illustrates \( \nu I_{\lambda_{\text{em}}}/I_{100} \) as a function of \( q_{\text{PAH}} \) for different values of \( U \) in the DL07 model. The figure is created by interpolating \( \nu I_{\lambda_{\text{em}}}/I_{100} \), calculated at discrete values of \( U \) and \( q_{\text{PAH}} \) in the DL07 model.

The Planck observation predicts parameter values of 0.4 \( \lesssim U \lesssim 0.8 \) and 4\% \( \lesssim q_{\text{PAH}} \lesssim 6\% \) in the high-\( b \) region (Figure 2). In these ranges, the intensity ratios \( \nu I_{\lambda_{\text{em}}}/I_{100} \) are not sensitive to \( U \) but are largely dependent on \( q_{\text{PAH}} \) (Figure 3). We then approximate \( \nu I_{\lambda_{\text{em}}}/I_{100} \) as a function of \( q_{\text{PAH}} \):

\[
\nu I_{\lambda_{\text{em}}}/I_{100} = 0.07 \pm 0.01 q_{\text{PAH}},
\]

\[
\nu I_{\lambda_{\text{em}}}/I_{100} = 0.08 \pm 0.01 q_{\text{PAH}}.
\]

By combining relations of Equations (6) and (7) with Equation (5), \( \nu I_{\lambda_{\text{em}}}/I_{100} \) is expressed as a function of \( |b| \).

3. Near-infrared Scattered Light

3.1. Single Scattering in a Plane–parallel Galaxy

To estimate the \( b \)-dependence of the scattered light, we employ a plane–parallel galaxy in which the solar system is located in the Galactic plane (BD12). The model assumes single scattering by dust grains, which is reasonable for the near-IR high-\( b \) region. In the numerical calculation of the scattered light, dust and stellar distributions are expressed as a function of distance \( z \) and \( z_s \) from the plane, respectively. Considering dust extinction in a line of sight, the scattered intensity is calculated as

\[
I_{\lambda_{\text{scat}}} = \int_0^{\tau(0)} d\tau \int_0^{\pi} d\theta \int_0^{R_s} R dR \int_0^{2\pi} d\phi \frac{4\pi}{4\pi[(z-z_s)^2 + R^2]} \int_0^{R_s} P_{\lambda}(z_s) dz_s,
\]

where \( \tau(0) \) is the optical depth at the plane, and \( R_s \) is the radius of the system. The parameter \( \lambda \) is expressed as a function of \( |b| \) and \( q_{\text{PAH}} \) (Figure 2). The parameter \( \mu \) is the cosine of the angle between the line of sight and the direction of the incident radiation. The function \( P_{\lambda}(z_s) \) is the wavelength-dependent contrast function that describes the scattering properties of the dust grains. The contrast function is given by

\[
P_{\lambda}(z_s) = \frac{\lambda}{\lambda + k_s z_s} + \frac{k_s z_s}{\lambda + k_s z_s}
\]

where \( k_s \) is the extinction coefficient at the wavelength of interest.
where $\omega_\ell$ and $\sigma_{\text{ext}}(\lambda)$ denote albedo and extinction cross section, respectively. These dust properties are assumed to be independent of $b$. The quantities $P_\ell(z_s)$ and $\rho(z)$ are the surface power density of the stellar sheet and dust density, respectively. Once these values are supplied, the scattered intensity is calculated by Equation (8) without free parameters.

$$\tau(\alpha) \equiv \int_{\alpha}^{\infty} \chi_{\text{ext}}(\lambda) \rho(z')dz', \quad (9)$$

$$A(\alpha, z_s, R) \equiv |\tau(\alpha) - \tau(z_s)| \sqrt{\frac{(z - z_s)^2 + R^2}{|z - z_s|}}, \quad (10)$$

where $\omega_\ell$ and $\sigma_{\text{ext}}(\lambda)$ denote albedo and extinction cross section, respectively. These dust properties are assumed to be independent of $b$. The quantities $P_\ell(z_s)$ and $\rho(z)$ are the surface power density of the stellar sheet and dust density, respectively. Once these values are supplied, the scattered intensity is calculated by Equation (8) without free parameters.

### 3.1.1. Phase Function

In the calculation of the scattered light from Equation (8), the phase function $\Phi_\ell$ should be expressed as a function of scattering angle, such as the HG41 form (Equation (1)). In the near-IR, however, D03 showed that the phase function of HG41 deviates from that of the WD01 dust model assuming the Mie theory. Therefore, D03 developed a new analytic form to reproduce the WD01 phase function:

$$\phi_\ell(\theta) = \frac{1}{4\pi} \frac{1 - g_\alpha^2}{(1 + g_\alpha^2 - 2 g_\alpha \cos \theta)^{3/2}} \frac{1 + \alpha \cos^2 \theta}{1 + (1 + 2 g_\alpha^2)^{3/2}}, \quad (11)$$

where $g_\alpha$ and $\alpha$ are adjustable parameters. When $g_\alpha = 0$ and $\alpha = 1$, this form represents the phase function of the Rayleigh scattering. For $\alpha = 0$, it is reduced to the HG41 form (Equation (1)). The parameters $g_\alpha$ and $\alpha$ can be derived by comparing the first and second moments of the WD01 phase function with those of the D03 form. See the Appendices of D03 for details.

In Figure 4 the WD01 phase function is compared with the HG41 and D03 forms at $1.25 \mu m$ and $2.2 \mu m$. In each panel, the black dashed curve represents the WD01 phase function assuming the $R_v = 3.1$ dust. Red and blue curves indicate the HG41 and D03 phase function formalized by Equations (1) and (11), respectively. The $g$-factor in the HG41 form comes from the first moment of the WD01 phase function. In the D03 form, the parameters $g_\alpha$ and $\alpha$ are determined to reproduce the WD01 phase function. The black dotted curve indicates the phase function of the Rayleigh scattering.
the WD01 dust properties at 1.22 and 2.19 \( \mu m \), close to the two DIRBE bands (1.25 and 2.22 \( \mu m \)). In the adopted WD01 model, the grain abundances are reduced by a factor of 0.93 from the original one to be consistent with the interstellar extinction (Draine 2003a). The data of the WD01 model are available at the website http://www.astro.princeton.edu/~draine/.

### 3.1.2. The 100 \( \mu m \) Emission as a Function of \(|b|\)

To predict the \( b \)-dependence of \( I_{100} \), we estimate the \( b \)-dependence of the 100 \( \mu m \) intensity. In the BD12 model, the 100 \( \mu m \) intensity can be estimated from the total IR intensity reradiated from dust grains, which is defined as

\[
I_{100} = \int I_{\text{csc}} d\lambda.
\]

In the plane–parallel galaxy model, the \( b \)-dependence of the total IR intensity is expressed as

\[
I_{100} \propto \csc |b|.
\]

To estimate the \( b \)-dependence of \( I_{100} \) from the \( I_{100} \), the \( b \)-dependence of \( U \) and \( q_{\text{PAH}} \) should be taken into account because the dust emission SED changes as functions of these quantities in the DL07 model. The \( b \)-dependence of \( U \) and \( q_{\text{PAH}} \) can be estimated from the parameter maps of Planck Collaboration et al. (2016).

Now we define the correction factor \( f(b) \) as the intensity ratio of the 100 \( \mu m \) emission to the total IR emission, which reflects the deviation of \( I_{100} \) from the simple \( \csc |b| \) law:

\[
f(b) \equiv \nu_{100}/I_{100}. \tag{13}
\]

We can estimate \( f(b) \) from the dust SED of the DL07 model in combination with the \( b \)-dependence of \( U \) and \( q_{\text{PAH}} \) (Figure 2). From Equations (12) and (13), \( \nu_{100} \) is expressed as

\[
\nu_{100} = f(b)I_{100} \propto f(b)\csc |b|.
\]

Therefore, the quantity of interest, \( I_{100}(b)/I_{\text{csc}}(b) \), can be written as

\[
I_{100}(b)/I_{\text{csc}}(b) = I_{100}(b)/[f(b)I_{100}(b)] \tag{15}
\]

\[
\propto f_{\text{csc}}(b)/f(b) \csc |b|.
\]

We estimate the correction factor \( f(b) \) from the DL07 model. Figure 5(a) shows \( f(b) \equiv \nu_{100}/I_{100} \) as a function of \( q_{\text{PAH}} \) for different values of \( U \) in the model. According to the Planck result (Figure 2), the parameters \( U \) and \( q_{\text{PAH}} \) change from 0.4 to 0.8 and from 6% to 4%, respectively, toward high-\( b \) regions (\(|b| > 20^\circ\)). By adapting the \( b \)-dependence of these parameters to Figure 5(a), the quantity \( f(b) \equiv \nu_{100}/I_{100} \) supposedly changes from 0.35 to 0.5 when \(|b| \) runs from 20° to 90°. An approximation of this \( b \)-dependence of \( f(b) \) as a linear function of \(|b|\) results in

\[
f(b) = 0.00214|b| + 0.307. \tag{17}
\]

This formula is used in the following analysis.

Figure 5(b) compares the modeled \( I_{100} \) with the observation (SFD98). The \( I_{100} \) models are expressed as \( \propto \csc |b| \) and \( \propto f(b)\csc |b| \). The SFD98 map should contain the isotropic cosmic infrared background (CIB) component in addition to the interstellar 100 \( \mu m \) emission. Therefore, the CIB intensity at 100 \( \mu m \) of \( I_{\text{CIB}} = 0.78 \pm 0.21 \) MJy sr\(^{-1}\) derived from Lagache et al. (2000) is added to the \( I_{100} \) models. As expected from the functional form of \( f(b) \) (Equation (17)), the model with the correction factor \( f(b) \) shows a gentler \( b \)-dependence than the simple \( \csc |b| \) model.

The black circles in Figure 5(b) represent the interstellar 100 \( \mu m \) intensity averaged in a low-100 \( \mu m \) region of less than 5 MJy sr\(^{-1}\). Since such fields dominate the high-\( b \) sky, the averaged intensity is assumed as comparable values for the \( I_{100} \) models. Although the model with the correction factor \( f(b) \) should be more preferable from the physical point of view, the dispersion of the SFD98 100 \( \mu m \) emission is too large to calibrate the \( I_{100} \) model. We thus estimate the uncertainty of \( f(b) \) in comparison with the SFD98 100 \( \mu m \) intensity. If an ideal model of \( I_{100} \) exists, it should be fit to the averaged values of the SFD98 100 \( \mu m \) emission (black dots in Figure 5(b)). Therefore, the difference between the black dots and the model of \( f(b)\csc |b| + I_{\text{CIB}} \) can be regarded as the uncertainty of the correction factor \( f(b) \). In Figure 5(b) the red dotted curves represent the \( I_{100} \) model with a ±50% uncertainty of \( f(b) \), i.e.,

\[
\nu_{100} \frac{I_{100}}{I_{\text{csc}}} = \nu_{100} \frac{I_{100}}{I_{\text{csc}}} + \nu_{100} \frac{I_{100}}{I_{\text{csc}}} \text{csc} |b| \pm 50%.
\]
1.5f(b)\csc |b| + I_{CB} and 0.5f(b)\csc |b| + I_{CB}. The values of the black dots are approximately within these two curves throughout the high-$b$ region. We thus evaluate the $f(b)$ uncertainty as $\sim\pm50\%$.

### 3.1.3. Vertical Distributions of Interstellar Dust and Stars

In the calculation of the scattered light, we assume functional forms of $\rho(z)$ and $P_1(z,\zeta)$ according to observations of vertical distributions of interstellar dust and stars. Numerous studies have investigated the interstellar dust distribution (e.g., Lyngå, 1982; Méndez & van Altena 1998; Malhotra 1995; Nakanishi & Sofue 2003). Taking into account these observations, we adopt the following two forms of $\rho(z)$. One is a Gaussian distribution with its variance of $\sigma_1 = 250$ pc (Malhotra 1995; Nakanishi & Sofue 2003), and the other is an exponentially decreasing density with a scale height of $\sigma_2 = 110$ pc (Lyngå, 1982). Therefore, they are expressed as

$$
\rho_1(z) \propto \exp(-z^2/2\sigma_1^2),
$$

$$
\rho_2(z) \propto \exp(-z/\sigma_2).
$$

The dust density following formula (19) decreases more steeply toward the vertical direction than that following formula (18).

Similarly, a number of studies have explored the vertical distribution of Galactic stars (e.g., Gilmore & Reid 1983; Rana & Basu 1992; Binney & Merrifield 1998; Girardi et al. 2005). In the present analysis, we assume the following three $P_1(z,\zeta)$: Case 1, Case 2, and Case 3. In Case 1, stellar distribution is expressed as the sum of two exponential functions:

$$
P_{1,\lambda}(z,\zeta) \propto 0.9 \exp(-z_\lambda/h_1) + 0.1 \exp(-z_\lambda/h_2),
$$

with $h_1 = 300$ pc and $h_2 = 1350$ pc, corresponding to the scale height of the thin and thick disk, respectively (Gilmore & Reid 1983; Binney & Merrifield 1998). This model is the same as that adopted in the previous calculation of BD12.

In Case 2, the stellar distribution is assumed as a linear combination of the squared hyperbolic secant:

$$
P_{2,\lambda}(z,\zeta) \propto 0.9 \text{sech}^2[0.5z_\lambda/h(t)] + 0.1 \text{sech}^2(0.5z_\lambda/h).
$$

This form is preferred by Girardi et al. (2005), who developed a star-counts model assuming a three-dimensional stellar distribution, age–metallicity relation, and star formation rate in the Milky Way. In formula (21), the scale height of the thin disk $h(t)$ is expressed as a function of the stellar age $t$, based on an observational study of the age–metallicity relation of various stars (Rana & Basu 1992):

$$
h(t) = z_0(1 + t/t_0)^\beta,
$$

where $z_0$, $t_0$, and $\beta$ are adjustable parameters. Girardi et al. (2005) calibrated the model according to the real star-counts and determined the parameters of $z_0 = 94.7$ pc, $t_0 = 5.55$ Gyr, and $\beta = 1.67$, which are adopted in the present analysis. To investigate the sensitivity of the $b$-dependence of the scattered light to the stellar age, we set $t$ to 1, 5, and 10 Gyr in each calculation, which correspond to $h(t) = 125, 277,$ and 529 pc, respectively (Equation (22)). In the near-IR, the red stellar population classified as K- or M-type stars of $t \geq 10$ Gyr is thought to dominate the sky brightness of the Milky Way. The scale height of the thick disk is set to $h = 800$ pc since it supposedly comprises the old stellar population of $t \geq 10$ Gyr (Girardi et al. 2005). The density fraction of the thick disk to the thin disk is assumed to be 10%, the same as in formula (20). This fraction is marginally consistent with the star-counts model (Girardi et al. 2005), indicating a dominant contribution of the thin disk to the $b$-dependence of the scattered light.

In Case 3, all stars are assumed to exist in the Galactic plane, which corresponds to $z_\zeta = 0$ in Equation (8). This extreme and unrealistic stellar distribution was adopted in a previous estimation of the $b$-dependence of the scattered light (J79).

### 3.2. Scattered Light in a Dusty Slab

In addition to the single scattering, we evaluate the effect of multiple scattering. Multiple scattering is usually treated by a Monte Carlo simulation according to the theory of random numbers. Using the simulation, several studies have investigated the multiple scattering in diffuse ISM or clumpy media, such as reflection nebulae (e.g., Witt 1977; Witt & Gordon 1996; Murthy 2016). Fortunately, in the Galactic scale, an analytic form of the scattered light intensity is present as a solution of the radiative transfer in a dusty slab (HG41). Since such an analytic solution is easy to deal with, we adopt the scattered light model to estimate the effect of the multiple scattering.

According to HG41, the differential equations of radiative transfer of starlight $I_{\lambda,\text{star}}$ and scattered light $I_{\lambda,\text{sca}}$ through a dusty slab are expressed as

$$
cos \Theta \frac{dI_{\lambda,\text{star}}}{d\tau_{\lambda}} = I_{\lambda,\text{star}} - a_{\lambda},
$$

$$
cos \Theta \frac{dI_{\lambda,\text{sca}}}{d\tau_{\lambda}} = I_{\lambda,\text{total}} - \int \omega_{\lambda} I_{\lambda,\text{total}} \Phi_{\lambda} d\Omega - a_{\lambda},
$$

where $\Theta$ is an angle from the vertical direction of the Galaxy (i.e., $\Theta = 90^\circ - |b|$). The quantity $a_{\lambda}$ is the ratio of stellar emission to the absorption coefficient. By adopting the HG41 phase function (Equation (1)) and several approximations, the scattered light intensity is expressed as

$$
I_{\lambda,\text{sca}} = \frac{a_{\lambda}}{1 - \omega_{\lambda}} \left[ \omega_{\lambda} + (1 - \omega_{\lambda}) \exp(-\tau_{\lambda,\infty} \sec \Theta) \right. \\
- \exp[-\tau_{\lambda,\infty}(1 - \omega_{\lambda} g_{\lambda}) \sec \Theta] - \frac{\omega_{\lambda}(1 - g_{\lambda})}{1 - \omega_{\lambda} g_{\lambda}} \\
\left. \times \left[ 1 - \frac{3M - \omega_{\lambda}}{1 - \omega_{\lambda} g_{\lambda}} \cos^2 \Theta \\
\times \frac{\cos p_{\lambda} \tau_{\lambda,\infty} + \frac{p_{\lambda}}{1 - \omega_{\lambda} g_{\lambda}} \cos \Theta \sin \phi_{\lambda} \tau_{\lambda,\infty}}{\cos p_{\lambda} \tau_{\lambda,\infty} + \frac{2p_{\lambda}}{3(1 - \omega_{\lambda} g_{\lambda})} \sin \phi_{\lambda} \tau_{\lambda,\infty}} \right] \\
\times p_{\lambda}^2 = 3(1 - \omega_{\lambda})(1 - \omega_{\lambda} g_{\lambda})
$$

where $\tau_{\lambda,\infty}$ is defined as the half-thickness of the slab in a plane–parallel galaxy, i.e., the optical thickness toward the $|b| = 90^\circ$ direction. The probability of multiple scattering is thought to be higher as the quantity $\tau_{\lambda,\infty}$ increases. Therefore, the effect of the multiple scattering can be assessed by changing the values of $\tau_{\lambda,\infty}$.
4. Result and Discussion

4.1. Contribution of the Thermal Emission Component

Using the relation between \( I_{\lambda,\text{em}}/I_{100} \) and \( |b| \) as described in Section 2, we compare the thermal emission component with the observed \( b \)-dependence (Paper I). Figure 6 shows the relative contribution of the thermal emission component. The red dashed and dotted lines represent the minimum and maximum cases in Equations (6) and (7), respectively, i.e., \( I_{\lambda,\text{em}}/I_{100} = 0.06 q_{\text{PAH}}(0.07 q_{\text{PAH}}) \) and \( 0.08 q_{\text{PAH}}(0.09 q_{\text{PAH}}) \) at 1.25 \( \mu \text{m} \) (2.2 \( \mu \text{m} \)). Furthermore, the residual scattered light component derived by subtracting the thermal emission from the observed DGL is indicated by the blue dashed and dotted curves.

In both bands, the difference between the minimum and maximum cases is small enough to regard them as identical, considering the uncertainties associated with the observation. At 1.25 \( \mu \text{m} \), the thermal emission component is smaller than 10\% of the total DGL, which is also implied in Figure 1. Therefore, the observed \( b \)-dependence can be largely attributed to the scattered light component in this band. At 2.2 \( \mu \text{m} \), the contribution of the thermal emission is higher than that at 1.25 \( \mu \text{m} \) and the ratio to the total DGL is \( \sim 20\% \). As shown in Figure 6, a low contribution of \( I_{\lambda,\text{em}}/I_{100} \) makes the \( b \)-dependence of the residual scattered light rather gentler in the high-\( b \) region. However, the near-IR thermal emission component expected from the DL07 model does not fully account for the observation.

4.2. Contribution of the Scattered Light Component

On the basis of the \( b \)-dependence of the scattered light (Figure 6), we search for the origin in comparison with the various scattered light models described in Section 3. To focus on the steepness of the \( b \)-dependence, the results of \( I_{\lambda,\text{sca}}/I_{100} \) are scaled to unity at \( |b| = 20^\circ \).

4.2.1. Effect of the Different Phase Functions

To investigate the contribution of the different forms of the phase function (HG41 or D03) to the \( b \)-dependence, the 100 \( \mu \text{m} \) intensity is assumed to be proportional to \( \text{csc} |b| \) without the correction factor \( f(b) \). In the single scattering model (Equation (8)), the dust density is set as the Gaussian form. The stellar distribution is assumed as Case 1 or Case 3.

Figure 7 compares the \( b \)-dependence of \( I_{\lambda,\text{sca}}/I_{100} \) expected from the HG41 and D03 phase function. At both 1.25 and 2.2 \( \mu \text{m} \), the model assuming the D03 phase function is closer to the observed \( b \)-dependence by more than 10\%. This trend is rather distinct at 2.2 \( \mu \text{m} \). This may indicate that both forward and backward scattering are critical to cause a steeper \( b \)-dependence of the scattered light, as seen in the shapes of the phase function (Figure 4). However, this scattered light model is not enough to explain the observed steepness.

Of the scattered light models illustrated in Figure 7, the model assuming the D03 phase function and Case 1 should be most close to the real situation in terms of the current understanding of interstellar dust properties and vertical structures of the Milky Way. We thus assume this as our default model in the following discussion.

In Figure 7, the models adopting Case 3 and the HG41 phase function (red dashed curves) should be close to the J79 form (Equation (3)). In comparison, the J79 form is represented by black dotted curves with the \( g \)-factor set to the first moment of the WD01 phase function, i.e., 0.289 and 0.131 at 1.22 and 2.19 \( \mu \text{m} \), respectively. The difference between our calculation and the J79 model is within \( \sim 10\% \) in both bands. The discrepancy may be caused by the different assumption of the dust distribution: J79 did not consider the density gradient toward the vertical direction since they assumed a single high-\( b \) cloud.

4.2.2. Effect of the \( b \)-dependence of the 100 \( \mu \text{m} \) Emission

Figure 8 compares the quantities \( I_{\lambda,\text{sca}}/I_{100} \) assuming the default model of the scattered light with or without the \( I_{100} \) correction factor \( f(b) \). At both 1.25 and 2.2 \( \mu \text{m} \), models with \( f(b) \) exhibit a steeper \( b \)-dependence. This is because the \( b \)-dependence of \( I_{100} \) with \( f(b) \) is gentler than that without \( f(b) \) by a factor of 1.5 at the maximum (Figure 5(b)). As a result, the models of \( I_{\lambda,\text{sca}}/I_{100} \) can account for the observed \( b \)-dependence in most of the high-\( b \) region. At this stage, the observed \( b \)-dependence of \( I_{\lambda,\text{sca}}/I_{100} \) can be reproduced by the scattered light models assuming the recent interstellar dust properties (WD01) and the \( \text{csc} |b| \)-corrected \( I_{100} \) based on the Planck observation.
This result indicates that the quantity $I_{\text{sca}}/I_{100}$ is sensitive to the $b$-dependence of $I_{100}$. As estimated in Section 3.1.2, the correction factor $f(b)$ includes a $\pm 50\%$ uncertainty in comparison with the $b$-dependence of the SFD98 map of the 100 $\mu$m emission. Owing to the large uncertainty of the 100 $\mu$m emission in terms of the $b$-dependence, it may be
useful to investigate other normalizing quantities of the DGL, e.g., the optical depth at 100 μm. Such a study will be helpful for a more robust analysis of the DGL.

4.2.3. Effect of the Vertical Structure of the Milky Way

To estimate the sensitivity of the b-dependence to the vertical distributions of interstellar dust and stars, we compare the single scattering models assuming the various functional forms (Section 3.1.3). Figure 9 compares the various scattered light models calculated by the two dust densities with the three stellar distributions of the different stellar age. These results are scaled by the default model of the scattered light.

In terms of the effect on the b-dependence, the stellar age (scale height) of the thin disk is more influential than the dust distribution (Figure 9). As the scale height increases, the relative ratio rises toward the high-b region, indicating that the b-dependence of the scattered light is gentler. Deviations of the individual models from the default model are within ~5% throughout the high-b region. Considering the real situation of a mixture of various stellar populations, the deviation may be smaller than 5%. This result indicates that the variety in the assumed vertical distribution of the Milky Way is less influential to the b-dependence than the other factors discussed in Sections 4.2.1 and 4.2.2.

4.2.4. Effect of the Multiple Scattering

The effect of the multiple scattering is estimated by using the analytic form of the scattered light intensity (Section 3.2). According to the definition of the half-thickness $\tau_{V,\infty}$ large $\tau_{V,\infty}$ is expected to cause a high probability of multiple scattering. Figure 10 illustrates the near-IR b-dependence of $v I_{\lambda,scel}/I_{900}$ derived from Equation (26) and $I_{900} \propto f(b)\csc |b|$ along with that in the near-UV (0.3 μm) and optical V band (0.55 μm). In Equation (26), the albedo and g-factor at each wavelength are taken from the WD01 dust model assuming $\rho_{i}(z), P_{i,l}(z)$, and the HG41 phase function.

\textbf{Figure 10.} Comparison of $v I_{\lambda,scel}/I_{900}$ as a function of $|b|$, expected from the analytic form of the scattered light intensity with $I_{900} \propto f(b)\csc |b|$ in the four wavelengths; (a) 0.30, (b) 0.55, (c) 1.25, and (d) 2.2 μm. In each panel, the black, red, and blue solid curves represent the analytic models with a 0.55 μm half-thickness of $\tau_{V,\infty} = 0.05, 0.10$, and 0.15, respectively. In the other wavelengths, $\tau_{V,\infty}$ is estimated from $\tau_{V,\infty}$ by using the interstellar extinction of the WD01 dust model. Figure 10 illustrates the near-IR $b$-dependence of the near-IR scattered light is nearly independent of multiple scattering.
The analytic form of the scattered light is based on the HG41 phase function. In comparison with the analytic model, the single scattering model adopting the HG41 phase function is plotted in Figures 10(c) and (d). The difference between the models of single and multiple scattering is approximately less than a few percent. We thus conclude that the effect of multiple scattering does probably not contribute to the \(b\)-dependence of the near-IR scattered light.

4.3. Possible Contributions of Other Factors

4.3.1. Fluctuation of the Cosmic Infrared Background

Particularly in high-\(b\) regions, the SFD98 100 \(\mu\)m map is reportedly influenced by the CIB component, which is not associated with the interstellar dust emission (Yahata et al. 2007; Meisner & Finkbeiner 2015). Several studies have claimed that the CIB observed in both near-IR and far-IR shows spatial fluctuation caused by galaxy clustering or other hypothetical sources including first stars, intra-halo light associated with outer galaxies, or direct collapse of black holes in the early universe (e.g., Lagache et al. 2007; Matsumoto et al. 2011; Matsuura et al. 2011; Cooray et al. 2012; Yue et al. 2013; Zemcov et al. 2014). If the CIB fluctuations in the near-IR and far-IR correlate with each other, this might affect the intensity ratio of the near-IR DGL to the interstellar 100 \(\mu\)m emission.

Typical angular scales of the fluctuation created by the extragalactic sources are expected to be smaller than about 1\(^\circ\), while the scale of radiation from interstellar dust (i.e., DGL or far-IR emission) is thought to be larger than this (e.g., Lagache et al. 2007; Matsuura et al. 2011). Therefore, the effect of the CIB fluctuation should be taken into account if the DGL analysis is conducted in the angular scale of \(\lesssim\)1\(^\circ\). However, we focus on the much larger scale of \(\gtrsim\)10\(^{\circ}\) in the correlation analysis of the DGL and 100 \(\mu\)m emission (e.g., Matsuoka et al. 2011; BD12; Paper I). On this large scale, the contribution of the CIB fluctuation is presumably small enough to regard the CIB component as uniform. Therefore, it is unlikely that the CIB fluctuation is influential in the analysis of the \(b\)-dependence of the DGL.

4.3.2. Size and Shape of Dust Grains

Although the present analysis is based on the WD01 dust model, several studies have suggested the presence of \(\mu\)m-sized large grains in addition to the WD01 dust. For example, Wang et al. (2015) added \(\mu\)m-sized grains to the WD01 model and reproduced the flat extinction curve observed in \(\sim\)3–10 \(\mu\)m (Lutz 1999; Jiang et al. 2006; Flaherty et al. 2007; Gao et al. 2009; Nishiyama et al. 2009; Wang et al. 2013; Indebetouw et al. 2005). Notably, this modification does not violate the observed extinction curve from UV to near-IR. The presence of large grains has also been suggested by the derivation of the high albedo in the near-IR (Block et al. 1994; Witt et al. 1994; Lehtinen & Mattila 1996). The large-grain population is expected to cause a stronger forward-throwing phase function in the near-IR since the Mie scattering becomes more dominant. This effect may also influence the \(b\)-dependence of the scattered light.

In addition to the controversy concerning the dust size, there is no guarantee that interstellar dust grains are spherical. In calculating the scattering anisotropy, the Mie theory cannot be applied to the nonspherical dust. To estimate the scattering properties of such grains, including porous dust aggregates, several studies have developed various numerical methods, such as the discrete dipole approximation and the \(T\)-matrix method (e.g., Purcell & Pennyacker 1973; Draine & Flattau 1994; Mishchenko et al. 1996; Tazaki et al. 2016). These effects on the \(b\)-dependence will be investigated in the future.

5. Summary and Conclusion

To reveal the origin of the steep \(b\)-dependence of the intensity ratios of near-IR (1.25 and 2.2 \(\mu\)m) DGL to interstellar 100 \(\mu\)m emission, we presented an analysis according to the models of thermal emission and scattered light with the assistance of the Planck observation.

We predict the intensity ratios of the interstellar near-IR to 100 \(\mu\)m emission as a function of \(|b|\), using the DL07 dust emission model and the \(b\)-dependence of the PAH abundance derived from Planck. We find that the intensity ratio increases toward the low-\(b\) region, but the contribution of the thermal emission to the observed DGL is lower than \(\sim\)20\% at both 1.25 and 2.2 \(\mu\)m. We then proceed with the analysis in terms of the \(b\)-dependence of the scattered light component.

To express the scattered light intensity as a function of \(|b|\), we adopt a plane–parallel galaxy model in which single scattering occurs according to the vertical structures of interstellar dust and stars. Since the classical HG41 phase function reportedly deviates from the recently developed dust model (WD01), we modify the form according to the D03 approximation. We also evaluate the \(b\)-dependence of the 100 \(\mu\)m emission by applying the correction factor to the simple \(\text{csc}|b|\) law, based on the regional variations of the PAH abundance and the ISRF intensity derived from the Planck observation. We find that models assuming these factors cause a steeper \(b\)-dependence of the intensity ratio of the scattered light to the 100 \(\mu\)m emission, and this can account for the observed steep \(b\)-dependence. However, the correction factor of the 100 \(\mu\)m emission includes a large uncertainty of \(\sim\)\(\pm\)50\% in comparison with the observed dispersion of the 100 \(\mu\)m emission. In future work, it will be useful to find a more robust tracer of the DGL, if it exists.

In addition to these two factors, we investigate the effects of various assumptions of the vertical structures and multiple scattering by taking these factors into account in the calculation of the scattered light. We find that these two factors are less influential to the \(b\)-dependence than the corrections of the phase function and 100 \(\mu\)m emission.

In conclusion, the observed \(b\)-dependence of the near-IR DGL can be explained by the scattering anisotropy expected from the recent interstellar dust model with a low contribution of the near-IR thermal emission based on the same dust model. Our analysis thus suggests that the recent interstellar dust model (WD01) is successful in accounting for the \(b\)-dependence of the near-IR DGL as well as other observations of interstellar dust.

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