REANALYSIS OF THE NEAR-INFRARED EXTRAGALACTIC BACKGROUND LIGHT BASED ON THE IRTS OBSERVATIONS

T. Matsumoto1,5, M. G. Kim2, J. Pyo3, and K. Tsumura4
1 Institute of Astronomy and Astrophysics, Academia Sinica, Taipei 10617, Taiwan
2 Seoul National University, Seoul 151-742, Korea
3 Korea Astronomy and Space Science Institute, Daejeon 305-348, Korea
4 Frontier Research Institute for Interdisciplinary Science, Tohoku University, Sendai, Miyagi 980-8578, Japan
5 Institute of Space and Astronautical Science, Japan Aerospace Exploration Agency, Kanagawa 252-5210, Japan

Abstract

We reanalyze data of the near-infrared background taken by IRTS using up-to-date observational results of zodiacal light (ZL), integrated star light, and diffuse Galactic light. We confirm the existence of residual isotropic emission, which is slightly lower but almost the same as previously reported. At wavelengths longer than 2 μm, the result is fairly consistent with the recent observation with AKARI. We also perform the same analysis using a different ZL model by Wright and detect residual isotropic emission that is slightly lower than that based on the original Kelsall model. Both models show residual isotropic emission that is significantly brighter than the integrated light of galaxies.

Key words: methods: data analysis – cosmology: observations – infrared: diffuse background

1. INTRODUCTION

The extragalactic background light (EBL) has been observed over a wide range of wavelengths to examine the energy density of the universe. In particular, the near-infrared EBL has been thought to provide an important clue to our understanding of the early universe and the evolution of galaxies. The Cosmic Background Explorer (COBE; Gorbjan et al. 2000; Wright & Reese 2000; Cambresy et al. 2001; Levenson et al. 2007) and the InfraRed Telescope in Space (IRTS; Matsumoto et al. 2005, hereafter referred to as Paper I) discovered that a significant fraction of the near-infrared isotropic emission cannot be explained with known foreground emission. Recent AKARI observations (Tsumura et al. 2013d) also show a consistent result with COBE and IRTS at wavelengths longer than 2 μm. This excess background emission in the near-infrared sky is particularly interesting in light of the recent discovery of the large excess fluctuation of the near-infrared sky (Kashlinsky et al. 2005, 2007a, 2007b; Matsumoto et al. 2011; Zemcov et al. 2014).

The results of Paper I attracted wide interest due to the high accuracy enabled by the unique low resolution spectroscopy of IRTS and its point source detection limit (∼11 mag), which was much deeper than COBE. However, as Mattila (2006) pointed out, Paper I did not take the contribution of the diffuse Galactic light (DGL) into account. Uncertainty in the zodiacal light (ZL) model has also been raised, since ZL is the dominant foreground emission with spectrum similar to the residual isotropic emission (Dwek et al. 2005).

In response to these concerns, we decided to reanalyze the IRTS data using up-to-date observations of ZL, integrated star light (ISL), and DGL. While in Paper I we adopted the Kelsall et al. (1998) ZL model, in this work we perform the same analysis using a different ZL model (the so-called Wright model; Wright 1998), and examine the differences between the two models.

The overall outline of this paper is as follows. In Section 2, we briefly present the IRTS observation and the acquisition of raw data. In Section 3, we estimate the contribution of foreground emission, ZL, ISL, and DGL based on the latest observations. In Section 4, we search for the residual isotropic emission for two ZL models based on the correlation with the sky brightness after subtracting the ISL and DGL. Finally, in Section 5, we discuss the astrophysical implications of the detected excess brightness.

2. IRTS OBSERVATIONS

We now give a brief description of the IRTS mission and the data acquisition process. Details of the IRTS mission can be found in Murakami et al. (1996) and Paper I.

IRTS was one of the mission experiments on the small space platform, Space Flyer Unit, which was launched on 1995 March 18. On a low-inclination near-Earth orbit, IRTS continuously surveyed the sky, avoiding both the Sun and the Earth. IRTS observations lasted for about 30 days, during which 7% of the sky was surveyed.

The Near InfraRed Spectrometer (NIRS) is one of the focal plane instruments of IRTS and was optimized to obtain spectra of the diffuse background (Noda et al. 1994). Details of the flight performance of NIRS can be found in Noda et al. (1996). NIRS covered a wavelength range from 1.4 μm to 4.0 μm with a spectral resolution of 0.13 μm, providing 24 independent wavelength bands. The beam size was 8 arcmin2 and the detection limit for point sources was ∼11 mag, and both are considerably better than those of COBE. The limiting magnitudes at wavelengths shorter and longer than 2.5 μm are dominated by sky fluctuation and readout noise, respectively (Noda et al. 1996; Paper I).

The NIRS detectors were of the non-destructive charge-integrating type and the ramp curves with one cycle of 65.54 s were sent to the ground for all of the 24 wavelength bands. We took the signal difference over 5 s in the ramp curve, during which no distinguishable stars and no cosmic ray hits were detected in any band. We obtained signals of the sky brightness after subtracting the dark current when the cold shutter was closed. During each 5 s integration, the telescope axis moved about 20 arcmin along a great circle, resulting in a trapezoidal
beam pattern, 8 × 20 arcmin in area. To make the contribution of stars and Galactic emission less effective, high Galactic latitude \((b > 40^\circ)\) data were extracted from the full data set for the background radiation analysis. The highest Galactic latitude was 58\(^\circ\), while the ecliptic latitude ranged from 12\(^\circ\) to 71\(^\circ\) in the selected sky. Complete spectra of the sky were secured at 1010 fields. The sky coverage of 1010 fields is \(~60\%\) of the surveyed area.

3. FOREGROUND EMISSION

3.1. Zodiacal Light (ZL)

The ZL is the emission component of the solar system which consists of scattered sunlight and thermal emission by interplanetary dust. In Paper I we adopted the model by Kelsall et al. (1998), which is a physical model constructed using the seasonal variation of the ZL observed with the Diffuse Infrared Background Experiment (DIRBE) on COBE. At the same time, Wright (1998) proposed a different physical model based on the so-called “strong zodi principle” assuming no residual emission at 25 \(\mu m\) toward the ecliptic pole. In this paper, we use both models and examine the difference of residual isotropic emission. As for the Wright model, we used the model revised by Gorjian et al. (2000).

We retrieve the brightness of the ZL in the DIRBE bands corresponding to the 1010 IR\(^T\)S fields at the epoch of the IR\(^T\)S observations for both models and construct the ZL model brightness for the IR\(^T\)S bands. We obtain the model spectrum for the scattering and thermal emission parts separately. For the scattering part, we simply normalize the spectral shape of the Sun (ASTM G173-03 Reference System\(^6\)) at the K band model brightness. For the thermal part, we extrapolate the M band model brightness to the shorter IR\(^T\)S wavelengths, assuming a 300 K blackbody in accordance with recent AKARI observations (Tsumura et al. 2013b). The ZL model spectrum is obtained by summing the scattering part with the thermal emission part. Compared to the model used in Paper I, the ZL component at wavelengths longer than 3 \(\mu m\) is slightly brighter. In the L band, our adopted models show a \(~6\%) brighter value than the original model, but still within the uncertainty of the models. The validity of the adopted ZL spectrum will be compared with observations in Section 4.

3.2. Integrated Star Light (ISL)

The ISL for stars fainter than the limiting magnitudes comprises a portion of the foreground emission. The best way to estimate the ISL is to sum the brightness of stars in the 2MASS catalog that fall within the beam; however, the uncertainty of the attitude determination and irregular beam pattern elongated along the scan path makes this analysis difficult. While in Paper I we applied the SKY model (Cohen 1997) and assume a simple cosec\((b)\) law to the model ISL at three selected fields, in this paper we obtain the model ISL based on an improved model, that is, the TRILEGAL Galaxy model (Girardi et al. 2005). We further calculate ISL for 12 equally spaced fields along the scan path for the I, J, H, K\(_{\text{S}}\), L, and L\(_{\text{s}}\) bands.

Since the fluctuation of the ISL is not negligible, we perform 50 Monte Carlo simulations for a 1 deg\(^2\) field for all TRILEGAL stars fainter than the IR\(^T\)S limiting magnitude and assign their average values to be those of TRILEGAL ISL. However, the overall uncertainty of the TRILEGAL model is so large that we must calibrate the TRILEGAL ISL by comparing with the 2MASS ISL for the H and K bands. The 2MASS ISL is obtained by summing the ISL for the 2MASS stars fainter than the IR\(^T\)S limiting magnitudes and that for stars fainter than 2MASS limiting magnitudes (15.8 mag for the J band and 15.1 mag for the H band; Skrutskie 2006), which are estimated by adopting the TRILEGAL model. Contribution of the latter part to the 2MASS ISL is only a few percent. Figure 1 shows the correlation between the TRILEGAL ISL and the 2MASS ISL for the 12 selected fields. The left and right panels indicate the results for the H and K bands, respectively. Horizontal error bars in Figure 1 represent the 1\(\sigma\) dispersion of the TRILEGAL ISL as a result of these Monte Carlo simulations and indicate the expected fluctuation of TRILEGAL ISL. Figure 1 clearly indicates that the 2MASS ISL is brighter than the TRILEGAL ISL for both the H and K bands, and the scatter of the 2MASS ISL is consistent with that expected from the TRILEGAL model. Based on this analysis, we finally obtain the model ISL by multiplying the TRILEGAL ISL by 1.23 with 8\% error. The ISL for the 1010 fields observed with IR\(^T\)S was obtained by interpolating the two neighboring model fields assuming a cosec\((b)\) law. The ISL for 24 of the IR\(^T\)S bands was estimated by interpolating the model ISL using the blackbody spectrum with the same limiting magnitudes as in Paper I.

Aside from the model errors, we calculate the model ISL for variation of \(\pm 0.5\) mag in the limiting magnitude and assigned the difference to be peak-to-peak errors. This error is a little lower than the error due to the uncertainty of the model ISL. The model ISL thus obtained gives a more reliable brightness and spatial distribution than Paper I.

3.3. Diffuse Galactic Light (DGL)

The DGL was not taken into account in Paper I as foreground emission, as mentioned in Mattila (2006), since no reliable observation of DGL had been reported at that time and the contribution of DGL to the overall sky brightness was thought to be small. Recently new observations of the near-infrared DGL have been attained, and we attempt to estimate the DGL for the IR\(^T\)S fields and bands. Tsumura et al. (2013c) obtained low resolution spectra of the diffuse sky with AKARI for wavelengths ranging from 2 to 5 \(\mu m\), detecting a clear correlation between the near-infrared sky brightness and the far-infrared emission (100 \(\mu m\); Schlegel et al. 1998). A polycyclic aromatic hydrocarbon (PAH) band at 3.3 \(\mu m\) was clearly detected; however, the detection was limited to the Galactic plane at \(b < 15^\circ\). Arai et al. (2015) performed a similar correlation analysis with data from the Low Resolution Spectrometer (Tsumura et al. 2013a), one of the instruments on the sounding rocket experiment, CIBER (Cosmic Infrared Background ExpeRiment; Zemcov et al. 2013). They also detected a clear correlation with the far-infrared emission for the wavelength range from 0.95 to 1.65 \(\mu m\) at high Galactic latitudes.

Figure 2 summarizes their results. The ratio of the DGL to the far-infrared (100 \(\mu m\)) emission is shown in units of \(\text{nW m}^{-2} \text{sr}^{-1}/\mu\text{W m}^{-2} \text{sr}^{-1}\). Filled and open circles represent the result of CIBER and AKARI, respectively. The CIBER result indicates scattered star light by interstellar dust, and the
result shows the thermal emission of the fine dust particles transiently heated by a single UV photon. We fit the scattered part with the ZDA04-BC03 (Brandt & Draine 2012) model recommended by Arai et al. (2015), shown with the dotted line. As for the thermal part, it is not clear that the AKARI result can be applied to the DGL at high Galactic latitudes, since Tsumura et al. (2013c) reported lower levels of thermal DGL than expected from Figure 2 at higher Galactic latitudes. Therefore, we first assume that no thermal part exists at IRTS fields where Galactic latitudes are higher than 40°. The thermal contribution, especially from the 3.3 μm PAH feature, will be discussed again in Section 4. Adopted values for IRTS bands are shown by open squares in Figure 2 for which an error of ±1σ was applied.

We used the far-infrared map compiled by Schlegel et al. (1998) and retrieved the 100 μm brightness for a 12 arcmin diameter field of view for the 1010 IRTS fields. Using the ratio of the DGL to the 100 μm brightness (Figure 2), we are able to obtain DGL for 24 IRTS bands and for 1010 IRTS fields.

4. RESIDUAL ISOTROPIC EMISSION

We attempt to obtain the residual isotropic emission using the same procedure as Paper I. First, we subtract the ISL and DGL from the observed sky brightness and make a correlation analysis with the model ZL brightness. The upper sets of data points in Figure 3 show typical correlation diagrams at 1.8 μm both for the Kelsall model (left panel) and the Wright model (right panel). For both models, we find an excellent linear correlation for all wavelength bands, and the intersection of the linear fit line at x = 0 provides the residual isotropic emission. The lower sets of data points in Figure 3 show the individual residual emission for the 1010 IRTS fields at 1.8 μm after subtracting all foreground emission components, demonstrating that the residual emission is fairly isotropic. Since error levels are almost the same for the two models, it must be noted that there is no clear preference between these two models.

Figure 1. Correlation between the TRILEGAL ISL (the integrated light for stars fainter than the IRTS limiting magnitude based on the TRILEGAL Galaxy model) and the 2MASS ISL (the integrated light for 2MASS stars fainter than the IRTS limiting magnitude and for stars fainter than the 2MASS limiting magnitude based on the TRILEGAL Galaxy model) for the 12 selected IRTS fields. The left and right panels show the case for the H and K bands, respectively. Horizontal error bars represent the standard deviation of the TRILEGAL ISL, which was obtained using Monte Carlo simulations. Straight lines show the best fit for linear correlation, and the dotted lines indicate the adopted ±1σ error.

Figure 2. Ratio of the DGL to the far-infrared (100 μm) emission, shown in units of nW m⁻² sr⁻¹ (DGL)/μW m⁻² sr⁻¹ (FIR). Filled and open circles represent the result of CIBER (Arai et al. 2015) and AKARI (Tsumura et al. 2013c), respectively. Dotted line shows the model ZDA04-BC03 in Brandt & Draine 2012 recommended by Arai et al. (2015) and open squares indicate the adopted ratio for IRTS bands.

AKARI result shows the thermal emission of the fine dust particles transiently heated by a single UV photon. We fit the scattered part with the ZDA04-BC03 (Brandt & Draine 2012) model recommended by Arai et al. (2015), shown with the
Figure 3. Upper set of data points shows the correlation diagram between the surface brightness after subtracting ISL and DGL from observed sky brightness at 1.8 μm and model ZL brightness. The left and right panels indicate the case for the Kelsall and Wright models, respectively. Solid lines are best fit lines for linear correlation. The lower set of data points represents individual residual emission after subtracting all foreground emission from observed sky brightness in which solid lines show residual emission obtained by linear correlation analysis.

Figure 4. Dependence of residual emission at 1.8 μm on the Galactic latitudes for the case of the Kelsall model. Filled circles and open circles represent the result of this work and that of Paper I, respectively. Data are taken by averaging individual residuals for 10° along Galactic longitude.

Figure 5. Wavelength dependence of the slopes of the linear fit lines in the upper part of Figure 3. Slopes represent ratios to the solar spectrum. Filled and open circles represent the case for the Kelsall model and the Wright model, respectively.

Figure 4 shows the dependence of the residual emission at 1.8 μm on the Galactic latitudes in the case of the Kelsall model. Data points indicate averaged values for 10° along the Galactic longitude. Filled circles and open circles indicate the result of the present work and that of Paper I, respectively. The large-scale structure observed in Paper I disappeared, and the data points of the present work show random scatter. This improvement is mainly due to our revision of the ISL model.

Figure 5 shows the slopes of the linear fit line for both the Kelsall and Wright models. In both models, slopes are a few percent larger than 1.0, which is consistent with Paper I. We regard this as the deviation of the ZL spectrum from the solar spectrum, which reflects the physical properties of interplanetary dust. The ZL spectrum can be obtained by multiplying the solar spectrum by these values, showing reddening of the ZL color at near-infrared wavelengths. The observed spectrum smoothly connects to the ZL spectrum from 0.75 to 1.6 μm as observed with CIBER and is consistent with the J band brightness of the Kelsall model based on the DIRBE data (see Figure 9 in Tsumura et al. 2010).

Figure 6 shows the residual isotropic emission obtained for both the Kelsall and Wright models, with two different sets of error bars. The inner and outer error bars indicate the random
and total error, respectively. Aside from the random error, the systematic error makes the spectrum change in the same direction. Random errors include fitting errors from correlation analysis, ISL errors due to limiting magnitudes, calibration errors, and DGL errors. Systematic errors are due to model errors of ZL and ISL. As in Paper I, errors in the ZL model are estimated by interpolating the uncertainties in the original model (Table 7 in Kelsall et al. 1998). The ZL model error is the dominant source of error and amounts to $\sim 80\%$ of the total error. Table 1 indicates the numerical values for the residual emission and their error for the two models.

Compared with the residual emission in Paper I, which is based on the Kelsall model, the peak brightness of the residual emission of the present work is $\sim 11\text{ nW m}^{-2}\text{ sr}^{-1}$ lower. The residual emission at wavelengths longer than 2 $\mu$m is almost the same as that of Paper I. A flat spectrum for the three shortest wavelength bands is a characteristic feature found in this analysis. The residual emission obtained by adopting the Wright model for the ZL provides a $\sim 7\text{ nW m}^{-2}\text{ sr}^{-1}$ lower peak value than that obtained by adopting the Kelsall model, but the spectral shapes are very similar. Figure 6 implies that there exists excess near-infrared isotropic residual emission independent of the choice of the two ZL models used here.

Additionally, we make the same analysis including the thermal part of the DGL. In this case, residual emission at 3.28 $\mu$m PAH feature is estimated to be $\sim 20\%$ ($\sim 2.6\text{ nW m}^{-2}\text{ sr}^{-1}$) lower than that of Figure 6, causing a sharp absorbing feature in the spectrum of the residual emission. We also find that the sky brightness at 3.28 $\mu$m after subtracting ZL and ISL shows no correlation with far-infrared sky brightness. These results favor the non-existence of the PAH feature at high Galactic latitudes; however, this is not conclusive given that random noise at 3.28 $\mu$m is so large. In any case, the contribution of the thermal part of DGL is almost negligible and does not significantly change the final result.

Figure 7 shows the breakdown of the emission components whose spectra are obtained as the average brightness at high ecliptic latitudes ($\beta > 70^\circ$) and high Galactic latitude ($b > 45^\circ$) for the case of the Kelsall model. Filled circles, bars, filled squares, open circles, and open diamonds indicate the observed sky brightness, zodiacal light (ZL), residual isotropic emission, integrated star light (ISL), and diffuse Galactic light (DGL), respectively.

---

**Table 1**

| Wavelength ($\mu$m) | Kelsall | Wright |
|---------------------|---------|--------|
|                     | Residual | Total Error | Residual | Total Error |
| 3.98                | 16.0    | 4.0    | 15.6    | 4.1         |
| 3.88                | 15.8    | 3.6    | 15.4    | 3.7         |
| 3.78                | 12.9    | 3.3    | 12.8    | 3.4         |
| 3.68                | 10.6    | 3.7    | 10.9    | 3.9         |
| 3.58                | 14.0    | 3.0    | 13.9    | 3.1         |
| 3.48                | 12.7    | 3.1    | 12.6    | 3.3         |
| 3.38                | 12.9    | 3.0    | 12.7    | 3.2         |
| 3.28                | 11.6    | 3.1    | 11.6    | 3.3         |
| 3.17                | 15.1    | 3.0    | 14.9    | 3.2         |
| 3.07                | 18.5    | 3.0    | 18.2    | 3.3         |
| 2.98                | 17.1    | 3.2    | 16.6    | 3.4         |
| 2.88                | 19.0    | 3.5    | 18.2    | 3.7         |
| 2.54                | 22.3    | 4.2    | 20.9    | 4.4         |
| 2.44                | 20.5    | 4.6    | 19.2    | 4.9         |
| 2.34                | 23.6    | 4.9    | 21.7    | 5.1         |
| 2.24                | 29.2    | 5.3    | 26.8    | 5.6         |
| 2.14                | 35.4    | 5.9    | 32.2    | 6.2         |
| 2.03                | 38.0    | 6.8    | 34.4    | 7.2         |
| 1.93                | 40.1    | 7.8    | 36.3    | 8.2         |
| 1.83                | 42.4    | 8.7    | 42.8    | 9.0         |
| 1.73                | 53.1    | 10.1   | 47.3    | 10.6        |
| 1.63                | 58.3    | 11.8   | 51.4    | 12.2        |
| 1.53                | 59.9    | 12.7   | 52.8    | 13.3        |
| 1.43                | 58.1    | 13.1   | 51.2    | 13.7        |
already mentioned in Paper I, the blue Rayleigh–Jeans-like spectrum is clearly seen at wavelengths longer than 1.6 μm.

5. DISCUSSION

It has been suspected that the residual isotropic emission is part of the ZL since the spectrum of the residual isotropic emission is similar to that of the ZL (Dwek et al. 2005). However, it is not so easy to construct the new ZL model, which includes the residual isotropic emission, since the residual emission is comparable to the seasonal variation of the ZL. One possible approach is to add the new dust component which has a heliocentric and spherically symmetric distribution. It is, however, difficult to maintain the spherically symmetric distribution of interplanetary dust of the inner solar system due to perturbation by the planets. Maintaining the supply of dust against Pointing–Robertson drag is also difficult. These considerations imply that the new dust component must be beyond the orbit of Jupiter. If we attribute the residual isotropic emission to the sunlight scattered by interplanetary dust, the brightness extrapolated to visible wavelengths amounts to ~100 nW m⁻² sr⁻¹, assuming a solar spectrum. The existence of such a component, however, is not detected with Pioneer 10/11 observations (Hanner et al. 1974). A recent reanalysis of the Pioneer 10/11 data by Matsuoka et al. (2011) confirms that the residual isotropic emission near the orbit of Jupiter is less than 10 nW m⁻² sr⁻¹ at 0.44 and 0.64 μm. These results indicate that the new dust component does not exist, otherwise the new component dust has peculiar optical properties.

The light of the first stars at the re-ionization epoch is another possible emission source that has been thought to be an important clue to delineate the star formation history of the universe. However, recent theoretical works based on high redshift galaxies...
predict much less contribution of the first stars to the near-infrared background (Cooray et al. 2012b; Yue et al. 2013a).

It has been thought that the spatial fluctuation of the sky directly provides the characteristic feature of the EBL, since the fluctuation of the ZL is so low (Pyo et al. 2012). Large fluctuations at angles larger than 100 arcsec that cannot be explained with the known foreground sources are detected with Spitzer at 3.6 and 4.5 μm (Kashinsky et al. 2005, 2007a, 2007b) and AKARI at 2.4, 3.2, and 4.1 μm (Matsumoto et al. 2011). Recent Spitzer (Cooray et al. 2012a; Kashinsky et al. 2012) and AKARI (Seo et al. 2015) observations confirm that flat fluctuation spectra extend to degree scales. The spectrum of fluctuation is blue Rayleigh–Jeans-like (Matsumoto et al. 2011) and clear spatial correlations are found for both AKARI and Spitzer wavelengths.

Zemcov et al. (2014) recently reported the results of sounding rocket observations with CIBER. They detected large fluctuation at 1.1 and 1.6 μm. In Figure 9 we overplot the result of Figure 2 in Zemcov et al. (2014) as large filled squares. The units are shown in right ordinate with the same correlation among 1.1, 1.6, and 2.4 μm. We note that the quoted EBL (ILG plus IHL) to be comparable to that of ILG. It must be emphasized that the quoted EBL is still a few times lower than that of the residual emission obtained in this work.

At present, there is no definite emission source that can explain the observed excess brightness. More observational and theoretical works are needed to delineate the emission source of excess brightness and fluctuation.

6. SUMMARY

The IRTS data were reanalyzed to obtain improved and more reliable measurements of the near-infrared residual isotropic emission. We revised the estimate of the ISL due to faint unresolved stars and the thermal emission part of the ZL spectrum. We take the DGL into account based on recent observations with AKARI and CIBER. Aside from the Kelsall model for the ZL used in Paper I, another model, the Wright model, was examined, too.

The result for the Kelsall model shows a peak value of 60 nW m⁻² sr⁻¹, which is ~11 nW m⁻² sr⁻¹ lower than that of Paper I. This is still considerably brighter than the integrated ILG. The result for the Wright model shows a peak value of 53 nW m⁻² sr⁻¹ which is slightly fainter than that of the Kelsall model. Both models show significant residual isotropic emission that cannot be explained with known foreground emission sources.

The authors thank Shuji Matsuura and Toshiaki Arai for their encouragement and valuable comments. Thanks are also due to Edward L. Wright for his courtesy in providing the code of his zodiacal light model. K.T. was supported by KAKENHI (26800112) from JSPS, Japan. This publication makes use of data products from the 2MASS, which is a joint project of the University of Massachusetts and the Infrared Processing and Analysis Center/California Institute of Technology, funded by the National Aeronautics and Space Administration and the National Science Foundation.

REFERENCES

Arai, T., Matsuura, S., Bock, J., et al. 2015, ApJ, 806, 69
Bernstein, R. A. 2007, ApJ, 666, 663
Brandt, T. D., & Draine, B. T. 2012, ApJ, 744, 129
Cabrera, L., Reach, W. T., Beichman, V. A., & Jarrett, T. H. 2001, ApJ, 555, 563
Cohen, M. 1997, in ASP Conf. Ser. 124, Diffuse Infrared Radiation and the IRTS, ed. H. Okuda, T. Matsumoto & T. Roellig (San Francisco, CA: ASP), 61
Cooray, A., Gong, Y., Smidt, J., & Santos, M. G. 2012b, ApJ, 756, 92
Cooray, A., Smidt, J., de Bernardis, F., et al. 2012a, Natur, 490, 514
Dwek, E., Arensd, R. G., & Krennrich, F. 2005, ApJ, 635, 784
Girardi, L., Gronewegen, M. A., Hatzimigioiu, E., & da Costa, D. 2005, A&A, 436, 895
Gorjian, V., Wright, E., & Chary, R. R. 2000, ApJ, 536, 550
Hanner, M. S., Weinberg, J. L., DeShields II, L. M., Green, B. A., & Toller, G. N. 1974, IGR, 79, 3671
Kashlinsky, A., Arensd, R. G., Ashby, M. L. N., et al. 2012, ApJ, 753, 63
Kashlinsky, A., Arensd, R. G., Mather, J., & Moseley, S. H. 2005, Natur, 438, 45
Kashlinsky, A., Arensd, R. G., Mather, J., & Moseley, S. H. 2007a, ApJL, 654, L5
Kashlinsky, A., Arensd, R. G., Mather, J., & Moseley, S. H. 2007b, ApJL, 666, L1
Keenan, R. C., Barger, A. J., Cowie, L. L., & Wang, W.-H. 2010, ApJ, 723, 40
Kelsall, T., Weiland, J. L., Franz, B. A., et al. 1998, ApJ, 508, 44
Levenson, L. R., Wright, E. L., & Johnson, B. D. 2007, ApJ, 666, 34
Matsumoto, T., Matsuura, S., Murakami, H., et al. 2005, ApJ, 626, 31 (Paper I)
Matsumoto, T., Seo, H. J., Jeong, W.-S., et al. 2011, ApJ, 742, 124
Matsumoto, T., Seo, H. J., Jeong, W.-S., et al. 2011, ApJ, 736, 119
Mattila, K. 2006, MNRAS, 372, 1253
Mattila, K., Lehtinen, K., Väisänen, P., von Appen-Schnur, G., & Leinert, C. 2011, in IAU Symp. 284, The Spectral Energy Distribution of Galaxies, ed. R. J. Tuffs & C. C. Popescu (Cambridge: Cambridge Univ. Press), 429
Matsuoka, Y., Ienaka, N., Kawara, K., & Oyabu, S. 2011, ApJ, 736, 119
Matsiko, K., Lehtinen, K., Yassenen, P., von Appen-Schnur, G., & Leinert, C. 2011, in IAU Symp. 284, The Spectral Energy Distribution of Galaxies, ed. R. J. Tuffs & C. C. Popescu (Cambridge: Cambridge Univ. Press), 429
Murakami, H., Freund, M. M., Ganga, K., et al. 1996, PASJ, 48, L41
Noda, M., Matsumoto, T., Matsuura, S., et al. 1994, ApJ, 428, 363
Noda, M., Matsumoto, T., Murakami, H., et al. 1996, Proc. SPIE, 2817, 248
Schlegel, D. J., Finkbeiner, D. P., & Davis, M. 1998, ApJ, 500, 525
Seo, H. J., Lee, H. M., Matsumoto, T., et al. 2015, ApJ, in press (arXiv:1504.05681)
Skrutskie, M. F. 2006, AJ, 131, 1163
Pyo, J., Matsumoto, T., Jeong, W. S., & Matsuura, S. 2012, ApJ, 760, 102
Totani, T., & Yoshii, Y. 2000, ApJ, 540, 81
Tsumura, K., Arai, T., Battle, J., et al. 2013a, ApJ, 767, 33
Tsumura, K., Battle, J., Bock, J., et al. 2010, ApJS, 197, 394
Tsumura, K., Matsumoto, T., Murakami, H., et al. 2013b, PASJ, 65, 119
Tsumura, K., Matsumoto, T., Matsuura, S., et al. 2013c, PASJ, 65, 120
Tsumura, K., Matsumoto, T., Matsuura, S., et al. 2013d, PASJ, 65, 121
Wright, E. 1998, ApJ, 496, 1
Wright, E. L., & Reese, E. D. 2000, ApJ, 545, 43
Yue, B., Ferrara, A., Salvaterra, R., & Chen, X. 2013a, MNRAS, 431, 383
Yue, B., Ferrara, A., Salvaterra, R., & Chen, X. 2013b, MNRAS, 433, 1556
Zemcov, M., Arai, T., Battle, J., et al. 2013, ApJ, 707, 31
Zemcov, M., Smidt, J., Arai, T., et al. 2014, Sci, 346, 732