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THE DIFFUSE NEAR-INFRARED BACKGROUND SPECTRUM FROM AKARI

Tsumura Kohji[1], Matsumoto Toshio[2,3], Matsuura Shuji[3], Sakon Itsuki[4], and Wada Takehiko[3]
[1]Frontier Research Institute for Interdisciplinary Science, Tohoku University, Japan
[2]Institute of Astronomy and Astrophysics, Academia Sinica, Taiwan, R.O.C.
[3]Institute of Space and Astronautical Science, Japan Aerospace Exploration Agency, Japan
[4]Department of Astronomy, Graduate School of Science, The University of Tokyo, Japan
E-mail: tsumura@astr.tohoku.ac.jp

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ABSTRACT

We analyzed spectral data of the astrophysical diffuse emission obtained with the low-resolution spectroscopy mode on the AKARI InfraRed Camera (IRC) in the 1.8-5.3 μm wavelength region. Advanced reduction methods specialized for slit spectroscopy of diffuse sky spectra have been developed, and a catalog of 278 spectra of the diffuse sky covering a wide range of Galactic and ecliptic latitudes was constructed. Using this catalog, two other major foreground components, the zodiacal light (ZL) and the diffuse Galactic light (DGL), were separated and subtracted by taking correlations with ZL brightness estimated by the DIRBE ZL model and with the 100 μm dust thermal emission, respectively. The isotropic emission was interpreted as the extragalactic background light (EBL), which shows significant excess over the integrated light of galaxies at <4 μm.

Key words: AKARI — diffuse galactic light — extragalactic background light — spectral catalog — zodiacal light

1. INTRODUCTION

The astrophysical sky brightness obtained from outside of the terrestrial atmosphere includes three components.

- Zodiacal light (ZL): the scattered sunlight by interplanetary dust (IPD) at optical and near-infrared (NIR), and thermal zodiacal emission (ZE) from the same IPD at mid-infrared region or longer[1].
- Diffuse Galactic Light (DGL): the scattered starlight by dust particles in interstellar space at / <3 μm, and emissions from the dust particles with some band features at longer wavelengths.
- Extragalactic Background Light (EBL): residual observed brightness after subtraction of all known foreground components. This should be the integrated light of all light sources outside our Galaxy.

Previous measurements of the absolute sky brightness from space by DIRBE (Cambŕesy et al., 2001) and IRTS (Matsumoto et al., 2005) indicated that the EBL brightness at NIR after subtraction of ZL and other foregrounds significantly exceeds the integrated brightness of galaxies. The origin of this excess is still not clear, but some theoretical models such as the first star models (Santos et al., 2002; Salvaterra & Ferrara, 2003; Cooray & Yoshida, 2004; Dwek et al., 2005a; Madau & Silk, 2005; Fernandez & Komatsu, 2006; Fernandez et al., 2010) and the intrahalo light (IHL) model (Cooray et al., 2012b) are suggested.

New observational results of the absolute sky spectrum were obtained by the AKARI InfraRed Camera (IRC) (Tsumura et al., 2013a,b,c). This paper summarizes the result of the absolute diffuse spectrum by AKARI, and adds some discussions about recent results.

[1] Sometimes the term ZL indicates only the scattered component to distinguish it from ZE. However, the term ZL indicates both scattered and thermal components in this paper, while the term ZE indicates only the thermal emission component.

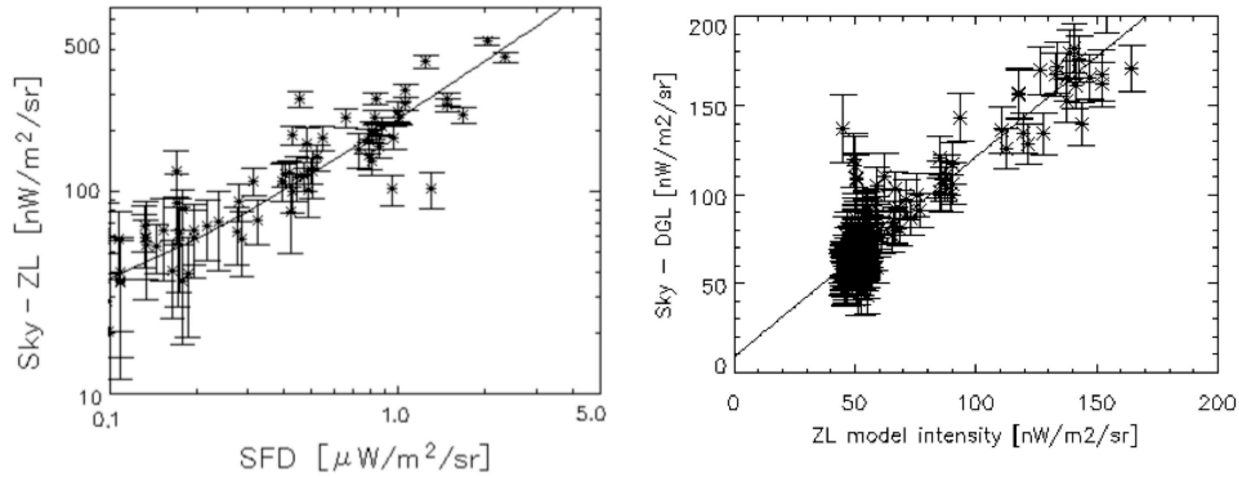

Figure 1. Examples of correlation of AKARI observed sky brightness to the 100 μm far-infrared map (SFD map) (Schlegel et al., 1998) (left) and the ZL model intensity based on Kelsall et al. (1998) (right) at 3.3 μm (Tsumura et al., 2013a,b).

2. OBSERVATIONAL DATA

AKARI is the first Japanese infrared astronomical satellite, equipped with a cryogenically cooled telescope of 68.5 cm aperture diameter (Murakami et al., 2007). IRC is one of two astronomical instruments of AKARI, covering 1.8-5.3 μm wavelength region with a 512×412 InSb detector in the NIR channel (Onaka et al., 2007). It provides low-resolution ($\lambda/\Delta\lambda \sim 20$) slit spectroscopy for the diffuse radiation by a prism (Ohyama et al., 2007).

See Tsumura et al. (2013a) for the details of the data selection and reduction. According to our data selection criteria for the diffuse background analysis, a total of 278 diffuse spectra were selected with wide ranges of ecliptic and Galactic coordinates. This catalog of diffuse sky spectra is available at ISAS/JAXA[2]. Dark current subtraction is essential to obtain the absolute sky brightness, and the uncertainty due to the dark current subtraction is < 3 nWm^{-2}sr^{-1} at 2 μm (Tsumura & Wada, 2011). On the other hand, Spitzer was unable to measure the absolute sky brightness since its cold shutter was not operated in-orbit (Fazio et al., 2004a). This is a great advantage of AKARI over Spitzer.

Point sources brighter than m_K(Vega) = 19 were detected and masked for deriving the diffuse spectrum. It was confirmed that the brightness due to unresolved Galactic stars under this detection limit is negligible (<0.5 % of the sky brightness at 2.2 μm) by a Milky Way star count model, TRILEGAL (Girardi et al., 2005). This is a great advantage over the previous measurements by DIRBE and IRTS, because the integrated light from unresolved Galactic stars for those measurements are not negligible. The sky spectrum includes ZL, DGL, and EBL, i.e.,

$$SKY_i(\lambda) = ZL_i(\lambda) + DGL_i(\lambda) + EBL_i(\lambda) \quad (1)$$

where i is the data index. The cumulative brightness contributed by unresolved galaxies can be estimated by deep galaxy counts, yielding <4 nWm^{-2}sr^{-1} in the K band with a limiting magnitude of $m_K = 19$ (Keenan et al., 2010), which is included in EBL.

3. FOREGROUND SEPARATION

Foreground components are separated by using the different distributions in the sky. For example, DGL is correlatied to the interstellar dust which can be traced by the 100 μm far-infrared map (SFD map) (Schlegel et al., 1998). Thus $SKY_i(\lambda) - ZL_i(\lambda)$ at each wavelength are correlated against dust emission at 100 μm, and this correlated component can be interpreted as DGL.

$$SKY_i(\lambda) - ZL_i(\lambda) = a(\lambda) \cdot I_i^{100\mu m} + EBL(\lambda) \quad (2)$$

The separation method for ZL is also similar to DGL. ZL is correlated against ecliptic latitude, and the distribution of ZL is modeled by Kelsall et al. (1998) using DIRBE data. The ZL template spectrum was derived by differencing the DGL subtracted AKARI spectra at the ecliptic plane (ZL strongest region) and that at the NEP (ZL weakest region), thus the isotropic EBL is removed by differencing. Using this ZL template spectrum and model brightness from Kelsall et al. (1998),

[2] http://www.ir.isas.jaxa.jp/AKARI/Archive/Catalogues/IRC_diffuse_spec/.

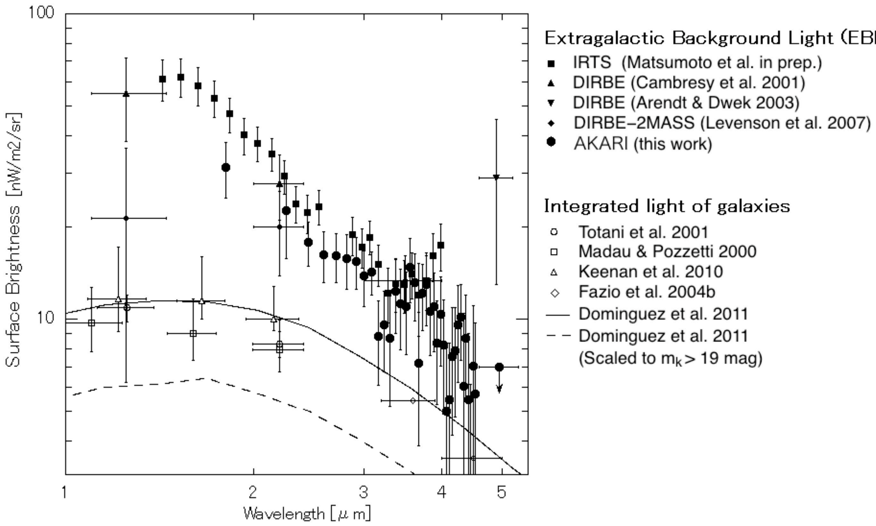

Figure 2. Spectrum of EBL and integrated light of galaxies (Tsumura et al., 2013c). Filled points show various measurement of the EBL from space including this study, and open plots shows the integrated light of galaxies in deep observations. Horizontal bars show the band widths of wide-band data. The solid curve shows a model spectrum of the integrated light of galaxies based on the observed evolution of the rest-frame K-band galaxy luminosity function up to redshift 4 (Domínguez et al., 2011), and the broken curve shows a scaled version of it in case of AKARI's detection limit of point sources ($m_K = 19$).

the ZL model spectrum $ZL_i^{model}(\lambda)$ was obtained. The correlation analysis between $SKY_i(\lambda) - DGL_i(\lambda)$ and $ZL_i^{model}(\lambda)$ was conducted at each wavelength, and y-intercepts indicate the isotropic EBL.

$$SKY_i(\lambda) - DGL_i(\lambda) = C(\lambda) \cdot ZL_i^{model}(\lambda) + EBL(\lambda) \quad (3)$$

The correlations between DGL and ZL at 3.3 μm are shown in Figure 1. In the real procedure of foreground separation, in practice, the correlation analysis of DGL (equation (2) and Figure 1(left)) and ZL (equation (3) and Figure 1(right)) are iterated, and the best estimates of ZL and DGL are subtracted. See Tsumura et al. (2013b) for more details of the DGL, and Tsumura et al. (2013a) for the ZL.

4. EXTRAGALACTIC BACKGROUND LIGHT

Figure 2 shows the resultant EBL spectrum from our AKARI dataset with various previous results. Our spectrum from AKARI/IRC is basically consistent with the results by IRTS (Matsumoto et al., 2005) and DIRBE (Cambŕesy et al., 2001; Levenson & Wright, 2007), indicating the excess over the integrated light of galaxies. At wavelengths shorter than 3 μm, AKARI shows a slightly lower brightness from IRTS. This difference could be attributed to the difference of the detection limits for point sources. The difference of the integrated light of unresolved galaxies owing to this limiting magnitude difference between AKARI (19 mag) and IRTS (10.5 mag) is estimated to be ∼5 nWm^{-2}sr^{-1} (Keenan et al., 2010) which explains the difference of EBL brightness.

There is a gap in our result between 3.0 μm and 3.5 μm due to the difficulty of modeling the foregrounds in this wavelength region. The diffuse sky brightness in this wavelength range includes all three foreground components (scattered sunlight of IPD, thermal emission from IPD, and DGL with the 3.3 μm PAH band) with similar fractions, which makes the foreground modeling difficult. The gap around 3.3μm could not be due to the EBL, but it was caused by an overestimation of the 3.3 μm PAH band intensity in DGL spectrum at high Galactic latitude regions.

We obtained a new spectral measurement of EBL at >4 μm, and we cannot confirm the excess over the integrated light of galaxies at >4 μm. In addition, our result contradicts the high EBL brightness at 4.9 μm by Arendt & Dwek (2003). Note that the high EBL brightness at 4.9 μm from Arendt & Dwek (2003) is highly uncertain since it is not an observed value but an estimated value from EBL at 1.25, 2.2, 3.5, and 100 μm.

See Tsumura et al. (2013c) for more details of the EBL spectrum.

5. What Is Origin of EBL Excess?

How can we understand the excess EBL over the integrated light of galaxies at <4 μm? First we examine a possible solar system origin. If there is an isotropic component to the ZL, it cannot be subtracted by the correlation method in our study. One candidate isotropic ZL component is a dust shell centred on the Earth, but such a dense dust shell around the Earth must be detected already, if it exists. An isotropic diffuse background from the Oort cloud could be another candidate. However, the very blue spectrum toward 1 μm cannot be generated by thermal emission from very cold dust (<30 K) at the Oort cloud. Scattered sunlight by the Oort cloud is also negligible because sunlight at $\sim 10^4 - 10^5$ au is very weak.

The second possibility is a Galactic origin. Faint stars in the Galactic halo, which were tidally stripped during galaxy mergers and collisions, generate the diffuse intrahalo light (IHL). However, the negative detection of extended halos in external galaxies was reported (Uemizu et al., 1998; Yost et al., 2000). Furthermore, the observed excess emission, $\sim$23 mag/arcsec^2 in the H-band, can be easily detected for external galaxies with e.g. HST/NICMOS (Thompson et al., 2007a,b), but no detection has been reported yet. In addition, recent results by the ultra low surface brightness imaging technique ($\sim$32 mag/arcsec^2 at g-band) (Abraham & van Dokkum, 2014) concluded that the mass fraction of the stellar halo around M101 is less than 0.9% (van Dokkum et al., 2014). These considerations support the assertion that observed excess emission cannot be explained by IHL from our Galaxy.

However, integration of such IHL around galaxies toward the line-of-sight may explain the EBL excess. Such IHL model was suggested by Cooray et al. (2012b) to explain the observed fluctuation of the EBL. The spatial fluctuations of the EBL were observed by CIBER (Zemcov et al., 2014), AKARI (Matsumoto et al., 2011), and Spitzer (Kashlinsky et al., 2005, 2007, 2012) from 1.1 to 4.5 μm in order to avoid uncertainty of the ZL model, since the ZL is known to be spatially smooth (Pyo et al., 2012). The observed fluctuations are consistent with each other and show significant large fluctuations at angular scales larger than 100 arcsec, which cannot be explained by known foreground emission. The IHL model largely explained the obtained fluctuations, but it is still under discussion if the IHL model can explain the absolute intensity of the EBL. recent theoretical models of the first stars indicate both the expected brightness and fluctuations are 10 times lower or more than the observed values (Cooray et al., 2012a; Fernandez et al., 2012; Inoue et al., 2013; Yue et al., 2013).

Results from TeV-γ blazars are problems for the extragalactic origin of the EBL, since a high NIR EBL level makes intergalactic space opaque to TeV-γ photons (Dwek et al., 2005b; Aharonian et al., 2006, 2007; Mazin & Raue, 2007; Raue et al., 2009). However, a recent discovery of a high redshift (z> 0.6) blazar (Furniss at al., 2013) contradicts the standard scenario above, and it requires a new physical process, such as the secondary TeV γ-ray model (Essey & Kusenko, 2010) or the Axion-like particles model (Sánchez-Conde et al., 2007). If these processes take place, the TeV γ-ray and the EBL excess can coexist. The origins of the excess emission and fluctuation are still not clear, and new observations are widely expected to delineate their origins The Cosmic Infrared Background ExpeRiment (CIBER) (Zemcov et al., 2013) will provide the spectrum of the sky at 0.75-1.8 μm with the Low Resolution Spectrometer (LRS) (Tsumura et al., 2010, 2013d). Observation from outside the zodiacal cloud is also highly desirable to conduct an ideal observation of the EBL without the strong ZL foreground. A small infrared telescope, EXo-Zodiacal Infrared Telescope (EXZIT), has been proposed as one of instruments on the Solar Power Sail mission to Jupiter (Matsuura et al., 2014). The measurement of the NIR EBL at 5 AU will be conducted in the 2020s.

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