SKYSURF: Constraints on Zodiacal Light and Extragalactic Background Light through Panchromatic HST All-sky Surface-brightness Measurements: II. First Limits on Diffuse Light at 1.25, 1.4, and 1.6 μm

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Received 2022 May 13; revised 2022 August 10; accepted 2022 August 18; published 2022 October 4

Abstract

We present the first results from the HST Archival Legacy project “SKYSURF.” As described in Windhorst et al., SKYSURF utilizes the large HST archive to study the diffuse UV, optical, and near-IR backgrounds and foregrounds in detail. Here, we utilize SKYSURF’s first sky-surface-brightness measurements to constrain the level of near-IR diffuse Extragalactic Background Light (EBL) in three near-IR filters (F125W, F140W, and F160W). This is done by comparing our preliminary sky measurements of >30,000 images to zodiacal light models, carefully selecting the darkest images to avoid contamination from stray light. Our sky-surface-brightness measurements have been verified to an accuracy of better than 1%, which when combined with systematic errors associated with HST, results in sky-brightness uncertainties of ~2%–4% ~ 0.005 MJy sr^-1 in each image. When compared to the Kelsall et al. zodiacal model, an isotropic diffuse background of ~30 nW m^-2 sr^-1 remains, whereas using the Wright zodiacal model results in no discernible diffuse background. Based primarily on uncertainties in the foreground model subtraction, we present limits on the amount of diffuse EBL of 29, 40, and 29 nW m^-2 sr^-1, for F125W, F140W, and F160W, respectively. While this light is generally isotropic, our modeling at this point does not distinguish between a cosmological origin or a solar system origin (such as a dim, diffuse, spherical cloud of cometary dust).

Unified Astronomy Thesaurus concepts: Star counts (1568); Galaxy counts (588); zodiacal cloud (1845); Hubble Space Telescope (1845); Cosmic background radiation (317)

1. Introduction

The cosmic optical and near-IR Extragalactic Background Light (EBL), derived from the integrated luminosity of all extragalactic objects over all redshifts, represents a fundamental test of our understanding of extragalactic astronomy (e.g., McVittie & Wyatt 1959; Partridge & Peebles 1967a, 1967b; Hauser & Dwek 2001; Kashlinsky 2005; Lagache et al. 2005; Finke et al. 2010; Dominguez et al. 2011; Dwek & Krennrich 2013; Khaire & Srianand 2015; Driver et al. 2016; Koushan et al. 2021; Saldana-Lopez et al. 2021). If our census of galaxies and their luminosities is truly complete, the total EBL level should equal that of all discrete objects. On the other hand, if the EBL is found to be in excess of predictions from galaxy counts, that suggests that galaxy surveys may be missing some discrete or diffuse sources. Despite the importance of this measurement, direct EBL measurements have yet to arrive at a value that agrees with predictions from galaxy number counts (for a recent review, see Cooray 2016). Project SKYSURF (Windhorst et al. 2022) aims to study this discrepancy with the vast archive of HST images.

Because of the difficulty of characterizing the foreground signal of Earth’s atmosphere, observational attempts at constraining the EBL level directly are primarily done with space missions, such as COBE (e.g., Puget et al. 1996; Dwek & Arendt 1998; Fixsen et al. 1998; Hauser et al. 1998; Finkbeiner et al. 2000; Cambrésy et al. 2001; Sano et al. 2020), Spitzer (Dole et al. 2006), HST (Bernstein et al. 2002; Bernstein 2007), IRS (Matsumoto et al. 2005, 2011), and AKARI (Matsuura et al. 2011; Tsumura et al. 2013). These observations have large errors and are often discrepant with each other because of the limited number of observations and the difficulty of subtracting the instrumental, zodiacal, Galactic, and astrophysical foregrounds (Cooray 2016). Regardless, these direct measurements consistently arrive at EBL levels of ~20–50 nW m^-2 sr^-1, significantly above the predictions from galaxy counts of ~10 nW m^-2 sr^-1 (e.g., Driver et al. 2011; Andrews et al. 2018). Recent advances have been made with the CIBER...
Galaxies in clusters (The large population of recently identified physical sources have been hypothesized as contributing to it. S. S. Collaboration et al. 2013) also parallel indirect approach, using observations of attenuated foreground by using Ca absorption features and by leaving the more unidentified represents one possible source of diffuse light, although many more unidentified UDGs would have to be present to contribute significantly to the EBL (Jones et al. 2018). Diffuse light in the outskirts of galaxy halos (IGL) may contribute as well (Conselice et al. 2016), although a number of studies (e.g., Ashcraft et al. 2018; Borlaff et al. 2019; Cheng et al. 2021) have found that halo light, or light in galaxy outskirts, only represents 15% of the luminosity of bright galaxies. Alternatively, significant levels of difficult-to-detect diffuse intracluster (Bernstein et al. 1995) or intragroup light (Mihos et al. 2005) may contribute to the diffuse EBL. More exotic explanations, such as light from reionization (Santos et al. 2002; Cooray et al. 2004; Kashlinsky et al. 2004) have been put forward as well.

The SKYSURF project, introduced in Windhorst et al. (2022), aims to better understand the EBL level by using a two-pronged approach to analyze the large volume of archival HST observations. First, it will use HST’s remarkable stability and precision as an absolute photometer to conduct precise sky-brightness measurements for over 200,000 HST images. Second, it will use the depth and large volume probed by those images to search for possible sources of diffuse EBL.

For the full motivation and overview of the SKYSURF project, and an overview of its methods, see Windhorst et al. (2022); we will henceforth refer to that paper as SKYSURF–1. In this paper, we describe the first results of SKYSURF surface-brightness measurements at 1.25, 1.4, and 1.6 microns. In Section 1.1, we further outline the diffuse foreground sources necessary to consider for SKYSURF’s EBL constraints. In Section 2, we briefly describe our measurement procedure. Sections 3 presents our results, Section 4 includes a discussion of those results, and Section 5 summarizes our conclusions. Throughout, we use Planck cosmology (Planck Collaboration et al. 2016; $H_0 = 66.9$ km s$^{-1}$ Mpc$^{-1}$, matter density parameter $\Omega_m = 0.32$, and vacuum energy density $\Omega_\Lambda = 0.68$. When quoting magnitudes, our fluxes are all in AB-magnitudes (hereafter AB-mag), and our SB values are in AB-mag arcsec$^{-2}$ (Oke & Gunn 1983) or MJy sr$^{-1}$, using flux densities $F_\nu = 10^{-0.4(AB−8.90\text{ mag})}$ in Jy. Further details on the flux density scales used are given in Figure 10 and the table footnotes in Section 3.

1.1. Foregrounds

The main goal of SKYSURF is to characterize the components of sky-surface brightness present in HST images, including a possible diffuse EBL component, in detail. Below, we summarize the relevant astronomical foregrounds and backgrounds that exist in the SKYSURF images. In summary, they are the following: Zodiacal Light (ZL), Diffuse Galactic Light (DGL), discrete stellar and extragalactic light, and diffuse EBL. The Zodiacal Light (ZL) is the main foreground in most HST images, and SKYSURF will measure and model it as well as possible with available tools. All stars in our galaxy (except the Sun) and all other galaxies are beyond the InterPlanetary Dust (IPD) cloud, so the ZL is thus always referred to as a “foreground.” Similarly, the Diffuse Galactic Light, caused by scattered starlight in our Galaxy, can be a background (to nearby stars), or a foreground (to more distant stars and all external galaxies). Most objects in an average moderately deep (AB $\lesssim$ 25–26 mag) HST image are faint galaxies close to the peak in the cosmic star formation history at $z \lesssim 2$ (e.g., Madau & Dickinson 2014). Most of the Extragalactic Background Light (EBL) therefore comes from distant galaxies and AGN, and is thus referred to as a “background.”

Before SKYSURF can quantify and model these astronomical foregrounds and backgrounds, it needs to address the main contaminants, which are residual detector systematics, orbital phase-dependent stray light from the Earth, Sun, and/or Moon, and the WFC3/IR thermal dark signal. Instrumental and stray-light contaminants, as well as the contribution of discrete objects to the SKYSURF EBL constraints, are discussed in SKYSURF–1. Below, we discuss the diffuse zodiacal, Galactic, and Extragalactic foregrounds in more detail.

1.1.1. Zodiacal Foreground

By far, the brightest component of the sky-brightness is zodiacal light from the IPD cloud, i.e., from distances less than 5 au, representing over 95% of the photons with 0.6–1.25 $\mu$m wavelengths in the HST archive (see Figure 10). Given its extremely diffuse nature, as well as its time variability, it has been a challenge to understand in detail; observations with all-sky space missions such as COBE/DIRBE are required in order to fully model it. For example, the Kelsall et al. (1998) and Wright (1998) zodiacal models use the COBE/DIRBE data to model the zodiacal emission, considering multiple dust components scattering sunlight toward Earth. The absence of an all-sky optical survey means that such modeling cannot be done in the optical to a similar extent; most authors simply assume that the zodiacal spectrum is a solar or slightly reddened solar spectrum (e.g., Leinert et al. 1998). Future SKYSURF studies will utilize its UV-to-optical database to improve constraints on the zodiacal spectrum, but here we only consider observations with wavelengths similar to COBE/DIRBE wave bands for which a detailed zodiacal model is obtainable.

1.1.2. Discrete and Diffuse Light from Kuiper Belt Objects

The darkness of the night sky, “Olbers’ Paradox,” was one of astronomy’s oldest mysteries: an infinite and infinitely old universe full of stars and galaxies would have a sky as bright as the surface of an average star. The resolution of this “paradox”—an expanding universe of finite age—is, of course, the central tenet of Big Bang cosmology, where the galaxy surface density is a finite integral over the galaxy luminosity function and the cosmological volume element (Tyson 1988; Driver et al. 1995; Metcalfe et al. 1995; Odewahn et al. 1996). Because of their very steep observed number counts, Kuiper Belt Objects (KBOs) can also appear to violate Olbers’
Paradox, producing an apparently diverging sky integral when the smallest objects are taken into account (e.g., Kenyon & Windhorst 2001). To not exceed the observed the ZL sky-SB, the counts of KBOs at distances $\gtrsim 40$ au must turn over from the nonconverging power-law slope $\gamma \approx 0.6$ dex $^{-1}$ observed for $R \lesssim 27$ mag (Fraser et al. 2014) to a converging slope flatter than $\gamma = 0.4$ dex $^{-1}$ at $R$-band fluxes of $AB \gtrsim 45$–55 mag, in combination with a limited volume over which KBOs occur (Kenyon & Windhorst 2001). Assuming albedos of a few percent (e.g., Kenyon & Luu 1999) and a physical size distribution of $N(r) \propto r^{-3.5}$, such a slope change in the KBO number counts implies that the size-slope of unresolved solar system debris at $\sim 40$ au must flatten from $\beta \approx 4$ for larger objects to $\beta \lesssim 3.25$–3.5 for objects with sizes $r \sim 0.05$–5 m. A flattening of the size distribution of the planetesimal population with radii $r \gtrsim 10$ km from $\beta \approx 4$ to $\beta \lesssim 3.5$ is consistent with simulations for the debris population with $r \lesssim 1$ km, which suggest that collisions with $r \lesssim 100$ m objects tend to produce debris rather than larger planetesimals (Kenyon & Luu 1999; Kenyon & Bromley 2004, 2020). It is also consistent with ground-based observations of KBOs with $r \lesssim 50$ km (e.g., Fuentes et al. 2009; Shankman et al. 2013), and with New Horizons (NH) crater counts on Pluto and Charon, which suggest a flattening of the KBO count slope for $r \lesssim 1$ km (e.g., Singer et al. 2019).

To refine these constraints across the Kuiper Belt, SKYSURF will measure the panchromatic zodiacal foreground in the ecliptic plane in places where other foregrounds are small. Better SB limits on the small KBO population may constrain the slope of the KBO counts, and hence the total Kuiper Belt mass at 35–50 au. Time-tagged monitoring of the sky-SB in the ecliptic may also yield constraints to the integral of Plutinos in Neptune’s L4 and L5 Lagrange points, which have moved significantly in ecliptic Longitude ($l^H$) during the 32 yr HST mission. Kelsall et al. (1998) fit the data from the Cosmic Background Explorer/Diffuse InfraRed Background Experiment (COBE/DIRBE) as a family of 3D (flaring) disk models of decreasing density with increasing radius and distance from the ecliptic plane. This model accounts for the variation with solar phase angle for realistic properties of dust grains. Other ZL models and refinements were presented by, e.g., Reach et al. (1997), Leinert et al. (1998), Wright (1998), Wright (2001), Jørgensen et al. (2021), Arendt (2014), and Arendt et al. (2016). Kelsall et al. (1998) adopt an albedo at 1.25 $\mu$m wavelength for their zodiacal “Smooth Cloud,” “Dust Bands,” and “Ring+Blob” components of $a = 0.204 \pm 0.0013$. Recent thermal IR observations of Trans-Neptunian Objects (TNOs) with typical sizes of $\sim 20$–400 km imply geometric albedo values of $\lesssim 20\%$–30\%, whereas TNOs have albedos as large as $\sim 60\%$ (e.g., Vilenius et al. 2012, 2014, 2018; Duffard et al. 2014; Kowalenko et al. 2017), possibly indicating a more icy surface for some TNOs. We further discuss possible variations in solar system objects, and the impacts that they may have on our results, in Section 4.

1.1.3. Diffuse Galactic Light

Diffuse Galactic Light (DGL) in the UV–optical is mainly caused by scattered light or reflection nebulae from early-type (O and B) stars, scattered by dust and gas in the Interstellar Medium (ISM). The DGL is thus a strong function of Galactic coordinates ($l^B$, $b^B$). SKYSURF’s SB measurements may thus also constrain the DGL at low Galactic latitudes ($b^B \lesssim 20^\circ–30^\circ$), although these fields are very likely not useful for background galaxy counts. The All-sky Infrared Astronomical Satellite (IRAS; Soifer et al. 1984; Helou & Walker 1985), COBE/DIRBE (Kelsall et al. 1998; Schlegel et al. 1998), Planck (Planck Collaboration et al. 2016), Wide-field Infrared Survey Explorer (WISE; Wright et al. 2010), and AKARI (Tamura et al. 2013) maps in the near to far-IR help identify Galactic infrared cirrus and regions of likely enhanced Galactic scattered light. Possible high spatial frequency structures in the DGL appear in deep ground-based images of low Galactic latitude at SB levels of $B \approx 26$–27 mag arcsec$^{-2}$, and at much fainter levels sometimes also at high Galactic latitudes (e.g., Guhathakurta & Tyson 1989; Szomoru & Guhathakurta 1998). While not a main goal of SKYSURF, the DGL needs to be estimated and subtracted in order to better estimate the levels of the ZL and the EBL at higher Galactic latitudes, as discussed in Section 3. Panchromatic HST constraints on the DGL in the Galactic latitude $(|b|^H | \lesssim 20^\circ)$ are interesting in their own right, and they are a byproduct of SKYSURF. We refer to Section 3.5 for the DGL levels we subtract from any diffuse light levels implied by the comparison between our HST sky-SB measurements and the ZL models.

2. Measurements

An overview of the SKYSURF database and our sky measurement procedure can be found in SKYSURF–1. Further details on the multiple sky measurements procedures, as well as the full results of the sky surface brightness measurements across the entire SKYSURF database, will come in R. O’Brien et. al. (2022, in preparation). For context, we give a brief overview of the database and methods here.

First, the HST archive was searched for images taken with its wide-band filters, excluding grism images, quad(linear) ramp or polarizing filters, subarray images, time-series, moving targets, or spatial scans. This resulted in 249,861 images that made up the initial database. Further cuts on target selection, HST orbital phase, and exposure time will be conducted to avoid possible contamination and minimize measurement errors.

To measure the sky background of these images, the SKYSURF team tested multiple sky-measurement algorithms on realistic simulated images in order to identify the most robust method of estimating the uncontaminated sky background. All algorithms that were tested had an accuracy of better than 0.2\% for flat images, and slightly worse for images with gradients (Figure 8 in SKYSURF–1). At this point, it is worth identifying the general philosophy of the SKYSURF program as aiming to identify the Lowest Estimated Sky (LES) value—defined as the lowest sky-SB in an image—as the fiducial sky measurement. While electronic errors within the cameras can introduce either positive or negative errors in sky estimation, errors deriving from contamination (i.e., stray light from nearby bright sources like the Earth and the Sun or thermal emission from the telescope) are more common and more significant. To make full use of our large data set, we aimed to develop and use algorithms that are the most robust across our database, which contains a wide variety of images. The full results with the most robust algorithms will be presented in O’Brien et. al. (2022, in preparation); here, we present the first results using an initial estimation done by fitting a Gaussian to the sigma-clipped image (described as method 2 in O’Brien et. al. (2022, in preparation) and SKYSURF–1).
Combining the sky measurement uncertainties with the systematic uncertainties associated with HST’s detectors, the overall absolute uncertainty on the sky measurements is \( \sim 2.7\% \) for the F125W, \( \sim 2.8\% \) for the F140W, and \( \sim 3.8\% \) for the F160W filter. The systematic uncertainties come from bias/dark-frame subtraction (\( \leq 1.0\% \)), the global flat-field correction (0.5\%–2\%), zero-point accuracy (\( \sim 1.5\% \)), and thermal dark subtraction (\( \sim 0.2\% \) for F125W, 0.5\% for F140W, and \( \sim 3.8\% \) for F160W).

3. First SKYSURF Results on Diffuse Near-IR Sky-SB Estimates at 1.25–1.6 \( \mu m \)

For the final analysis of 249,861 SKYSURF images, we expect \( \leq 50\% \) to be usable for sky-SB measurements. Although these images are not completely randomly distributed on the sky, they on average provide \( \sim 4400 \) sky-SB measurements in each of the 28 broadband SKYSURF filters. In this section, we will use two complementary analyses of the HST sky-SB estimates to make our first assessment of available ZL models, identify any diffuse light that may be present, and check on the consistency of our methods.

The results from both methods will be compared to the Kelsall et al. (1998) and Wright (1998) models, which predict the ZL brightness as a function of sky position and time of the year. Both the Kelsall et al. (1998) and Wright (1998) models are fit to COBE/DIRBE measurements at 1.25–2.2 \( \mu m \). The Kelsall et al. (1998) model is a physical model that contains multiple dust components, whereas the Wright (1998) model is a more parametric model normalized at 25 \( \mu m \) to ensure zero residual diffuse light at the ecliptic poles. Because their ZL model predictions are anchored to the COBE/DIRBE 1.25–2.2 \( \mu m \) data, we will limit our analysis in this paper to the SKYSURF WFC3/IR filters F125W, F140W, and F160W. We will deal with the uneven sky-sampling of the HST data by comparing the HST sky-SB data with the corresponding ZL model predictions. Again, our premise throughout is that the lowest estimated sky-SB values measured among the HST images in each direction will be the least affected by HST systematics or discrete foreground objects, and therefore they are the closest to the true sky-SB in that direction.

The first approach uses the LES-SB values from the HST images. Both the HST LES data and the Kelsall et al. (1998) model predictions are fit with analytic functions as a function of ecliptic latitude (\( b^{\text{Ecl}} \)) in the darkest parts of the Galactic sky. These fits will be referred to as the Lowest Fitted Sky-SB (“LFS”) method. To avoid regions with significant DGL, the LFS method will first select the LES data and model predictions as a function of Galactic latitude (\( b^{\text{G}} \)), to identify the darkest regions of the Galactic sky.

Next, the LFS method will identify the lowest sky-SB as a function of ecliptic latitude (\( b^{\text{Ecl}} \)) to constrain the ZL+EBL sky-SB in each direction (see Figure 2). For \( |b^{\text{G}}| \geq 20^\circ \), where the DGL contribution is lower, the LFS fits provide analytical functions describing the lowest sky-SB as a function of ecliptic latitude for both the HST data and the model predictions in the same directions of the sky. The limitation of the LFS method is that not all sky-SB measurements are done at constant Sun angles (\( SA \); defined as the Sun–HST–target angle), which ranges from \( SA \approx 85^\circ–180^\circ \) at the ecliptic to \( SA = 90^\circ \) at the ecliptic poles. Although many HST observations are scheduled around \( SA \sim 90^\circ \), many others are done with higher solar elongations for which the zodiacal sky-SB is lower (the zodiacal sky-SB reaches a minimum in the ecliptic at solar elongations of \( 120^\circ–150^\circ \) (Leinert et al. 1998). This method will thus focus on observations with \( SA \sim 150^\circ \) in the ecliptic plane and \( SA \sim 90^\circ \) at the ecliptic poles. However, because the analysis is conducted on the zodiacal models in parallel, this is not expected to bias our results. In particular, this method aligns with the SKYSURF philosophy that most sources of error are positive, and thus the lowest sky values are likely the most accurate.

The second method more closely follows the actual selection of the COBE/DIRBE data, on which both the Kelsall et al. (1998) and Wright (1998) models were based. The COBE/DIRBE data were measured at Sun angles \( SA \approx 94^\circ ± 30^\circ \) (e.g., Leinert et al. 1998). The HST data are observed over a range of Sun angles, but a significant fraction are also observed at \( SA \approx 90^\circ ± 10^\circ \), i.e., over a Sun angle range similar to, but somewhat narrower than, that of the COBE/DIRBE data. Hence, our second method will only select the HST LES data and COBE/DIRBE-based model predictions in the Sun angle range of \( SA \approx 90^\circ ± 10^\circ \). This “SA90 method” has the advantage of the selected HST data being more directly comparable to the COBE/DIRBE based models, but because of their SA selection, it may also have somewhat higher levels of (unrecognized) earthshine. The HST data from the SA90 method may thus be systematically somewhat higher than the minimum zodiacal sky-SB level that is traced with the LFS method.

Stated differently, the LFS method fits a (sech) function to the lowest sky-SB levels observed at each ecliptic latitude, and is thus based on fewer data points. The LFS method is therefore more reliable, but statistically less precise, than the SA90 method. The SA90 method fits regions with sky-SB more comparable to the COBE/DIRBE SA range. Thus, it has better statistics in this SA range, but is also subject to higher stray-light levels. A comparison between the two methods will then give us an assessment of the uncertainties in any remaining diffuse light. In this initial analysis, as we are simply looking for a possible diffuse excess above the Kelsall et al. (1998) and Wright (1998) models, these approaches work well. Future SKYSURF analysis will investigate stray-light contamination, as well as the structure of offsets between SKYSURF sky values and model predictions, in more detail.

3.1. HST 1.25–1.6 \( \mu m \) Sky-SB Measurements Compared to COBE/DIRBE Predictions

In this section, we present our first SKYSURF results from 34,412 images observed in the WFC3/IR filters F125W, F140W, and F160W. Figures 1 and 2 show the sky-SB in F125W, F140W, and F160W as a function of Galactic latitude and ecliptic latitude, respectively. In these figures, we simply attempt to find the minimum sky-SB signal in the darkest parts of the sky.

For example, in Figure 1(a), the sample of WFC3/IR sky-SB measurements is first plotted versus Galactic latitude to find and exclude the regions with significant DGL. Figure 2 and Figure 3 then plot the sky-SB versus ecliptic latitude to find in this subset the regions with the lowest LES values of all images in each \( b^{\text{Ecl}} \) bin. Next, Figure 1(b) plots the predictions of the 1.25 \( \mu m \) sky-SB for all HST locations in the sky and at the same Sun angles at the time of the HST observations as provided by the zodiacal COBE/DIRBE model of Kelsall et al. (1998). Given the large range in sky-SB values, and the fact that most of the relevant information is at the low end of the SB range in all these figures, the bottom panels in Figures 1(c) and (d) provide enlargements of the top panels in Figures 1(a) and (b).
The WFC3/IR ZPs used in the F125W, F140W, and F160W filters are 26.232, 26.450, 25.936 AB-mag, respectively, for an object with 1.000 e^{-} pixel^{-1} s^{-1}. Figure 4 shows the HST WFC3/IR F125W and the COBE/DIRBE J-band total system responses compared to the solar spectrum in \( F_\nu \) (e.g., Arvesen et al. 1969), which is fairly flat across both these filters. From this, we calculate that, for a solar-type spectrum like the ZL, the \( \Delta(HST \text{ data} - \text{Kelsall COBE/DIRBE model}) \) flux is \(-0.0061\) AB-mag, due to the small J-band filter differences. This was calculated in three independent ways: using integration in \( F_\lambda \), pylsynphot, and blackbody interpolation between the two very similar filters, resulting in a scaling factor of \( HST/\text{Kelsall} = 1.00557 \pm 0.0008 \). That is, for an SED with a zodiacal spectrum, the HST 1.25 \( \mu \)m fluxes will be \(~0.56\%\) brighter than in the COBE/DIRBE J-band filter. Hence, we will multiply the Kelsall et al. (1998) model predictions, which

\[ \Delta(HST \text{ data} - \text{Kelsall COBE/DIRBE model}) \]

\[ F_\nu \]

\[ HST/\text{Kelsall} = 1.00557 \pm 0.0008 \]

\[ \sim 0.56\% \]
are based on COBE/DIRBE observations, by 1.00557 to bring them onto exactly the same J-band flux scale as the HST WFC3/IR F125W filter for a solar-type spectrum. ZL model predictions for the HST WFC3/IR F140W and F160W filters were derived by interpolation between the Kelsall et al. (1998) COBE/DIRBE J-band and K-band predictions using the slope of the slightly reddened near-IR zodiacal spectrum of Aldering (2001), with uncertainties that include the errors in the Kelsall et al. (1998) model. While HST and COBE are at different orbits, MSISE-90 upper atmospheric models of the Earth\textsuperscript{13} list the mean atmospheric pressure as $2.27 \times 10^{-7}$ Pa at 540 km and $1.04 \times 10^{-8}$ Pa at 885 km, so it is unlikely that the differences in altitudes between HST and COBE contribute significantly to systematic differences in sky-SB levels between the two missions.

Because of the $\sim$60° inclination of the Galactic plane with respect to the ecliptic, the darkest sky-SB occurs for $20^\circ \lesssim |b| \lesssim 60^\circ$ and not at the Galactic poles. Fields with $|b| \lesssim 20^\circ$ have significant DGL, and they are ignored in the analysis of Sections 3.1–3.4. Figure 2 shows all HST WFC3/IR F125W, F140W, and F160W sky-SB measurements as in Figure 1, but now plotted versus ecliptic latitude. The orange and blue sech

\textsuperscript{13} http://www.braeunig.us/space/atmos.htm

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{Figure2}
\caption{All SKYSURF F125W, F140W, and F160W sky-SB measurements vs. ecliptic latitude for HST data (left subpanels) and the Kelsall COBE/DIRBE models (right subpanels). The orange and blue sech functions and error wedges outline the darkest $\sim$1% of the sky-SB measurements (magnify the PDF figure as needed to see this). Bottom subpanels give enlargements of the top subpanels. As in Figure 1, the upper left plot is for F125W, the upper right plot is for F140W, and the lower left plot is for F160W. The short-dashed blue line represents the upper envelope for the Kelsall et al. (1998) model predictions, and the long-dashed orange line the correspondingly scaled upper envelope for the HST data that do not suffer excessive DGL or stray light, as described in Section 3.1 and Table 1.}
\end{figure}
functions and their error wedges outline the dimmest 1% of the sky-SB measurements as described below. Figure 3 shows the SKYSURF F125W, F140W, and F160W sky-SB values versus ecliptic latitude as in Figure 2, but only for the darkest Galactic regions with $20^\circ \leq |b| \leq 60^\circ$ (see Figure 1). As in Figure 1, the upper left plot is for F125W, the upper right plot is for F140W, and the lower left plot is for F160W. The orange and blue sech functions and error wedges outline the darkest ~1% of the sky-SB measurements (magnify the PDF figure as needed to see this). Bottom panels give enlargements of the top panels.

Figure 3. All SKYSURF sky-SB measurements vs. ecliptic latitude for HST data (left subpanels) and the Kelsall COBE/DIRBE models (right subpanels), but only for the darkest Galactic regions with $20^\circ \leq |b| \leq 60^\circ$ (see Figure 1). As in Figure 1, the upper left plot is for F125W, the upper right plot is for F140W, and the lower left plot is for F160W. The orange and blue sech functions and error wedges outline the darkest ~1% of the sky-SB measurements (magnify the PDF figure as needed to see this). Bottom panels give enlargements of the top panels.

Natural fits to galaxy disks seen edge-on are sech($z$) functions (e.g., van der Kruit 1988; de Grijs et al. 1997), written as SB in AB-mag versus vertical distance $z$ from the edge-on disk’s central plane:

$$\text{SB} = a_4 - 2.5 \log \left[ a_1 \text{sech} \left( \frac{z}{a_2} \right) + a_3 \right]. \quad (1)$$

According to these authors, the sech model provides a better fit to the vertical or $z$-direction SB distribution of flattened or ellipsoidal light distributions seen edge-on than do cosine, Gaussian, exponential, single, or squared hyperbolic secant functions. The IPD cloud has a number of modeled components that Kelsall et al. (1998) identify as “Cloud,” “Bands,” and “Ring,” around the Sun, within which the Earth orbits. These zodiacal components have a ratio of their size in the ecliptic plane to their vertical ecliptic height of approximately 4:1, i.e., a rather flattened or “edge-on” distribution as viewed from the Earth. As we will see, sech functions describe the vertical ZL distribution as a function of ecliptic latitude as observed from the Earth remarkably well.

Inspired by the work that resulted in Equation (1), we will use sech-type functions to describe the LFS as a function of
ecliptic latitude \( \delta^\text{Ecl} \). While the actual dependence of ZL brightness with \( \delta^\text{Ecl} \) may be more complicated than Equation (1) in reality (notably having a significant Sun angle dependence as discussed below), we find that Equation (1) is a good description of the dimmest 1% of the sky-SB values for both the HST sky-SB measurements and the Kelsall et al. (1998) model predictions. Furthermore, this fitting procedure allows us to focus on the lower envelope of measurements, which we assume are the least affected by stray light. By repeating the same fitting procedure on the lowest 1% of the Kelsall et al. (1998) model predictions, which predict the ZL brightness for the same direction and at the same time of the year as the HST sky-SB measurements, we can search for any systematic offset between HST measurements and the Kelsall et al. (1998) predictions. This offset could be an additional unrecognized thermal dark component (Section 3.3), a dim spherical or mostly spheroidal zodiacal component not present in the model, a dim spherical diffuse EBL component, or some combination of these possibilities.

In the case of HST F125W, F140W, and F160W sky-SB measurements, we use the following sech functions that are simpler than Equation (1) and linear in flux density to represent the lowest 1% envelope of both the HST data and the Kelsall et al. (1998) models in Figures 2 and 3. The LFS of the HST data is best represented by

\[
\text{LFS (HST)} = a_1(\text{HST}) \text{ sech} \left( \frac{b_{\text{Ecl}}}{a_2(\text{HST})} \right) + a_3(\text{HST}) \quad \text{[MJy sr}^{-1}] ,
\]

while the lowest 1% envelope of the COBE model predictions by Kelsall et al. (1998) is best represented by

\[
\text{LFS (Kelsall)} = a_1(\text{Kel}) \text{ sech} \left( \frac{b_{\text{Ecl}}}{a_2(\text{Kel})} \right) + a_3(\text{Kel}) \quad \text{[MJy sr}^{-1}] .
\]

Here, \( a_1 \) is the plateau value that the sech function attains when \( b_{\text{Ecl}} \) reaches \( \pm \infty \). Next, \( a_1 \) is a constant that captures the maximum vertical amplitude that the sech function reaches at \( b_{\text{Ecl}} = 0^\circ \) above this plateau. Last, \( a_2 \approx 19^\circ.5 \) measures the effective thickness of the zodiacal disk (or “vertical scale height”) as seen edge-on from HST. Coefficient \( a_4 \) in Equation (1) is a constant that converts the SB in MJy sr\(^{-1}\) to AB mag arcsec\(^{-2}\), and is not used in the linear flux density representation of Equations (2)–(3). The best estimate parameters of the sech constants \( a_1, a_2, \) and \( a_3 \) are given in Table 1 for both the lower envelope to the HST data and the Kelsall models at 1.25–1.6 \( \mu m \). The upper and lower sech envelope \( a_2 \) values are best determined from F160W measurements, which have the best statistics, so we adopt the same \( a_2 \) values and their errors for the F125W and F140W filters in Table 1, which seem to bound the Kelsall et al. (1998) model predictions well for the F125W and F140W measurements. These sech functions are indicated by the bottom orange and blue lines plus their uncertainty wedges in Figures 2–3, respectively. The main result we are after in Table 1 is the (boldfaced) difference in the bottom envelopes (or \( a_3 \) values) between the HST data and the ZL models.\(^{14}\) Because the best-fit \( a_1 \) and \( a_2 \) values turn out to be very similar in Table 1 for both the HST data and the ZL models, we adopt the differences in \( a_3 \) values as a direct measure of the HST-ZL model differences.

The first four lines of Table 1 also list the same \( a_1, a_3 \) parameters (and their estimated uncertainties) for the upper envelope for the Kelsall models in the rightmost panels, and for the HST data in the leftmost subpanels of Figures 2–3 (upper blue and orange dashed lines, respectively). The sech upper envelope for the Kelsall et al. (1998) models was directly estimated from the predictions in Figures 2–3, which show a very good empirical sech-type fit to the upper envelope of the Kelsall et al. (1998) model values.

The amplitude of the upper envelope to the HST data was scaled upward using the (HST–Kelsall) difference from the lower envelopes in Figure 2 and Table 1. The orange dashed lines indicating the upper envelopes to the HST data in Figure 2(a) thus provide another way to identify HST exposures with excessive sky-SB, which could be due to several reasons: (a) targets with higher DGL; (b) large nearby galaxy targets, such as the LMC or M31; or (c) exposures with higher stray-light levels, including those that got too close to the Earth’s limb. The presence of such images is most noticeable in the F160W filter.

Figure 5 shows a comparison of SKYSURF’s F125W, F140W, and F160W sky-SB measurements from the HST data to the Kelsall COBE/DIRBE models as a function of ecliptic latitude (the top subpanels show all data, and the bottom subpanels show data only for the darkest Galactic regions at \( 20^\circ \leq | \delta^\text{Ecl} | \leq 60^\circ \) as selected from Figure 1). The left subpanels give the HST/Kelsall model flux density ratio, while the right subpanels give the linear flux density difference between the HST data and the Kelsall COBE/DIRBE models for the same subsample. In the top subpanels of Figure 5, the orange sech functions in Equations (2)–(3), and their error wedges outline the darkest sky-SB measurements from Figure 2. The bottom subpanels of Figure 5 give enlargements of the top subpanels, and they show a significant ecliptic latitude dependence of the HST/Kelsall model flux ratios.

\(^{14}\) The restriction of our data to \( \pm 90^\circ \) means that the derivative of the model is not continuous at the ecliptic poles. However, the difference between the value at \( 90^\circ \) and \( \pm \infty \) is < 2% for our fits, and this detail does not affect our fitting procedure regardless.
suggesting that the differences between the bottom envelopes of the HST data and the Kelsall models are not due to a flux density scale issue.

The green wedges in the bottom right panels of Figure 5 indicate our most likely estimates of the Δ(HST–Kelsall) offsets. For each filter, these linear flux density differences between the bottom envelopes of the HST data and the Kelsall models are fairly constant for \(|b^\| \geq 20^\circ\) and well above zero, suggesting a somewhat wavelength-dependent constant linear offset between the bottom envelopes of the HST data and the Kelsall models. For \(|b^\| \lesssim 20^\circ\), the differences between the data and model have more scatter, suggesting that complex and subtle adjustments to the Kelsall model in the ecliptic plane may be required. We thus discard all data with \(|b^\| \lesssim 20^\circ\) to estimate the LFS difference between the HST data and Kelsall models.

The LFS values from Figure 1 are summarized in Table 1. For example, Table 1 shows that the plateau value \(a_3\) of the sech function in Equations (2)–(3) that best captures the LFS values at high ecliptic latitudes in the F125W filter amounts to \(a_3(HST)=+0.093\pm0.006\) MJy sr\(^{-1}\), which best fits the lowest \(\sim1\%\) of the sky-SB values, while for COBE/DIRBE model predictions for the same sky pointings and filters, observing day of the year, and Sun angles, the Kelsall et al. (1998) model predicts a lowest \(\sim1\%\) envelope with sech parameter

\[a_3(\text{COBE})=+0.093\pm0.006\ \text{MJy sr}^{-1}\].

The most likely HST–Kelsall difference from Figure 5(d) is thus \(\sim(0.108\pm0.003)^{\pm0.008}\) MJy sr\(^{-1}\), which includes the correction for the \(-0.0061\) mag ZP difference between the HST F125W and COBE/DIRBE J-band flux scales. Similar but somewhat larger values are listed in Table 1 for the F140W and F160W filters, where the Kelsall et al. (1998) models were interpolated between the COBE/DIRBE predictions at 1.25 and 2.2 \(\mu\)m following the discussion in Section 3.2. This interpolation also results in somewhat larger \(a_3\) errors for the lower envelope for the Kelsall et al. (1998) model predictions in the F140W and F160W filters in Table 1 (see Section 3.2), and in somewhat larger errors of \(-0.009\) MJy sr\(^{-1}\) in the F140W and F160W HST–Kelsall difference signal listed in Table 1.

### Table 1

| Filter       | — F125W / J-band \(^a\) — | — F140W / JH-band — | — F160W / H-band — |
|--------------|----------------------------|---------------------|--------------------|
| Sech parameter | \(a_1\) \(\text{MJy sr}^{-1}\) | \(a_2\) \(\text{ MJy sr}^{-1}\) | \(a_3\) \(\text{MJy sr}^{-1}\) |
| HST upper    | 0.838 (5)                  | 0.125               | 0.084 (0.007)      |
| Kelsall upper| 0.846 (2)                  | 0.110               | 0.084 (0.007)      |
| Figs. \(^d\)| [Figure 2]                |                     | [Figure 2]         |
| HST lowest   | 0.112 (0.005)              | 0.108               | 0.120 (0.005)      |
| Kelsall lowest | 0.117 (0.006)           | 0.093               | 0.117 (0.007)      |
| Figs. \(^d\)| [Figure 3]                |                     | [Figure 3]         |
| HST–Kelsall  | 0.0145 (0.008)            | 0.025               | 0.012 (0.009)      |
| LFS (MJy sr\(^{-1}\)) | (0.008)            |                     | (0.009)           |
| Figs. \(^d\)| [Figure 5]                |                     | [Figure 5]         |
| HST–Kelsall  | 35.2 \(^d\)              | 54.6                | 94.2               |
| (nW m\(^{-2}\) sr\(^{-1}\)) | (19)              |                     | (19)               |

Notes.

\(^a\) The effective central wavelengths used for the WFC3/IR F125W, F140W, and F160W filters are \(\lambda = 1.2364, 1.3735,\) and 1.5278 \(\mu\)m, or central frequencies of 2.4248 \(\times 10^{14}\), 2.1827 \(\times 10^{14}\), and 1.9622 \(\times 10^{14}\) Hz.

\(^b\) The second row of the \(a_3\) parameter gives its estimated errors in parentheses. The estimated errors in \(a_1\) and \(a_2\) from Equations (2)–(3) are not independent from the error in \(a_3\), and are of the same order. Hence, only the error in \(a_3\) is listed, which is most relevant for estimating the resulting diffuse sky-SB limits in the bottom five rows.

\(^c\) The estimated values of \(a_2\) are approximately the same for all three filters F125W, F140W, and F160W for both the HST data and the Kelsall models to within the errors (approximately \(\pm1\)), so the same value is adopted for all filters. The \(a_2\) values are slightly narrower for the upper envelope to the Kelsall models compared to the lower-bound \(a_2\) values, and were assumed to be equally narrow for the upper envelopes of those HST data where the sky-SB was not enhanced by the Earth’s limb.

\(^d\) Between square brackets we list the figure numbers, from which the sech coefficients on the lines directly above were determined.

\(^e\) The Kelsall et al. (1998) COBE/DIRBE J-band model prediction has been corrected for the \(-0.0061\) mag ZP difference between the HST F125W and COBE/DIRBE J-band flux scales. The ZL model predictions for the HST WFC3/IR F140W and F160W filters were derived by interpolation between the Kelsall et al. (1998) J-band and K-band predictions. The errors in the HST–Kelsall differences in MJy sr\(^{-1}\) are derived in quadrature from the \(a_3\) fitting errors in the previous rows. Kelsall et al. (1998) reported errors in their ZL model of 15 nW m\(^{-2}\) sr\(^{-1}\) at 1.25 \(\mu\)m and 6 nW m\(^{-2}\) sr\(^{-1}\) at 2.2 \(\mu\)m, respectively (see their Table 7). We propagate these also into the errors of our adopted HST–Kelsall differences at 1.25–1.6 \(\mu\)m in nW m\(^{-2}\) sr\(^{-1}\) (bottom row; see also Table 2), which correspond to \(~47–18\%) errors in these differences at 1.25–1.6 \(\mu\)m, respectively.

\(^f\) The units in these last two rows were converted from MJy sr\(^{-1}\) to nW m\(^{-2}\) sr\(^{-1}\), using multipliers of 2425, 2183, and 1962 \(=10^{11}\) c/\(\lambda\), respectively, yielding the upper limit to the total diffuse light in nW m\(^{-2}\) sr\(^{-1}\).
resembles a power law in the form of

$$\log(F_\lambda) = \alpha (\lambda - 0.61\mu m)$$

$$\times [\text{erg cm}^{-2}\text{s}^{-1}\text{Å}^{-1}\text{arcsec}^{-2}],$$

(4)

following Aldering (2001), who adopted a power-law slope

$$\alpha = 0.730$$

for wavelengths 0.61 \(\lesssim \lambda \lesssim 2.20\ \mu m$$. Hence, in our

analysis, we will use Equation (4) to represent the zodiacal spectrum for 0.61 \(\lesssim \lambda \lesssim 2.20\ \mu m$$. Figure 6(a) shows the spectral index distribution $N(\alpha)$ when interpolating the Aldering et al. (1998) zodiacal sky-SB prediction in the COBE/DIRBE $J$- and $K$-band filters for all HST pointings in the F160W filter (which is very similar to the distribution of slopes for all HST.
pointsings in the F140W filter). The resulting median spectral index and its 1σ range is \( \alpha = 0.713 \pm 0.023 \), consistent with the value adopted by Aldering (2001) for the power-law approximation of Equation (4) to within the error. We verified through numerical integration that the power-law interpolation in Equation (4) produces a \( \lesssim 2\% \) error in the prediction of the reddened zodiacal spectrum at 1.4–1.6 \( \mu m \) wavelengths, compared to the Kelsall et al. (1998) model that was fit to the COBE/DIRBE 1.25 and 2.2 \( \mu m \) data and interpolated to 1.4–1.6 \( \mu m \). This is folded into the error budget of Table 1, resulting in somewhat larger \( a_\beta \) errors for the lower envelope to the Kelsall et al. (1998) model predictions in the F140W and F160W filters.

3.3. Assessment of the WFC3/IR Thermal Dark Signal Levels

Possibly the most significant source of uncertainty regarding our measurement of the near-IR diffuse light is the level of WFC3 thermal dark signal. Based on onboard temperature measurements and emissivity calculations, the WFC3 IHB lists the IR thermal dark signal levels as 0.052 \( e^- pixel^{-1} s^{-1} \), 0.070 \( e^- pixel^{-1} s^{-1} \), and 0.134 \( e^- pixel^{-1} s^{-1} \) for the F125W, F140W, and F160W filters, respectively (Dressel 2021). However, modest changes in HST component temperatures (\( \pm 2.5 \) K) can impact the TD signal at a level comparable to the diffuse signal. For example, Figure 6(b) shows how much changing the overall telescope temperature can affect the TD signal. A sequel paper (T. Carleton et al. 2022, in preparation) will explore the TD signal as a function of orbital phase and
HST component temperatures in more detail. Here, we show a preliminary analysis constraining the TD signal in SKYSURF data by fitting the spectral energy distribution (SED) of the near-IR sky with a zodiacal component and a temperature-dependent thermal signal.

We queried the HST archive for IR images that were taken of the same target within two days of each other, such that the overall zodiacal sky-SB level does not change substantially. We further identified image sets where at least one image was in the WFC3/IR F125W filter and another in either the F098M, F105W, F110W, F125W, F127M, F139M, F140W, F159M, and/or the F160W filter. We then ran the adjusted calibration program for the individual WFC3/IR ramps, as described in SKYSURF—1, and measured the minimum sky-SB levels in these images. Based on the orbital phase-dependent stray-light constraints in Figure 10 of SKYSURF—1, we only selected those WFC3/IR exposures in the above filters that have minimal stray light, in order to better estimate the most likely TD levels. This resulted in a sample of over 500 useful images in these filter pairs, predominantly from the BORG pure-parallel program PID 12572 (PI: M. Trenti). By dividing the sky value in each filter’s image by the sky in the associated F125W filter taken in that same direction, we construct a spectral energy distribution of the zodiacal sky.

The sky-SB levels in the F140W and F160W filters can be significantly elevated due to the foreground thermal dark signal. To model this thermal signal, we use the pysynphot package, modeling each component in the optical path as a blackbody with an effective temperature and emissivity. The fiducial temperatures and emissivities are taken from the HST database. Using these fiducial temperatures and emissivities, the synphot model recovers the published TD values. Subtracting this TD signal from the F140W and F160W sky values makes them match the power law in Equation (4) better. However, it is unclear whether the fiducial temperatures are the ones that best fit all available HST data. To identify the HST temperatures that best fit the data—which we take as more accurately reflecting the real HST temperatures producing the thermal dark signal—we take the given effective temperatures as free parameters and allow them to vary as

\[ T = T_{\text{ref}} + \Delta T, \]

where \( T_{\text{ref}} \) is the ambient temperature of components listed in the HST references files, and \( \Delta T \) is a parameter describing the average change in temperature (compared to \( T_{\text{ref}} \)) of the HST components that is most consistent with the data below. Note that small values of \( \Delta T \) consistent with onboard measurements can alter the TD signal significantly, especially in the F160W filter, and thereby affect the values of any inferred diffuse light levels: e.g., a \( \pm 1 \) K change in temperature corresponds to a \( \pm 0.04 \) MJy sr\(^{-1} \) change in the thermal dark signal level in F160W. For the above WFC3/IR filter pairs, we define the goodness of fit as

\[ \chi^2 = \frac{[\text{Sky}_j/\text{Sky}_j\text{(obs)} - \text{Sky}_j/\text{Sky}_j\text{(model)}]^2}{[\sigma_1^2/\text{Sky}_j^2 + \sigma_2^2/\text{Sky}_j^2]}, \]

where \( \sigma \) is the error in the sky-SB measurements, index \( j \) indicates the F125W filter, and \( i \) indicates any of the other available WFC3/IR filters that paired up with a given F125W observation within two days. Next, we find the best-fit model by minimizing \( \chi^2 \). The F105W and F110W exposures with F105W/F125W and F110W/F125W ratios \( \geq 1.20 \) in Figures 6(c) and (d) were not used, because they may have significant geocoronal HeII line emission at 1.083 \( \mu \)m that could elevate their sky-SB. Using the data described above, we obtain a formal best fit of \( \Delta T \sim \pm 1.52 \) K for the Aldering (2001) zodiacal power-law slope of \( \alpha = 0.73 \) (Figure 6(c)). If the slope \( \alpha \) is allowed to vary as well, we can obtain temperatures as low as \( \Delta T = -1.62 \) K for a slope of \( \alpha = 0.65 \) (Figure 6(d)). Hence, the best-fit \( \Delta T \) and \( \alpha \) are correlated such that somewhat larger \( \Delta T \) values imply a warmer telescope and therefore larger synphot TD values primarily in the longer-wavelength WFC3/IR filters, which—when subtracted from the above data—imply a zodiacal spectrum with a somewhat steeper power-law slope in Figures 6(a)–(d). The best \( \chi^2 \) fit occurs for \( \alpha = 0.66 \) and \( \Delta T = -1.15 \) K, which we adopt in the tables of Section 3.4 as our nominal TD case. Nonlinearities in the zodiacal spectrum have a relatively small impact on the implied thermal background. For example, adding a \( \sim 7\% \) bump in the spectrum from 1.4 to 1.6 microns, similar to what is seen in Matsuura et al. (2017), changes the best-fit slope to 0.69 and the \( \Delta T \) to \( -2.72 \) K (which is consistent with our estimated uncertainties of \( \sim 2 \) K).

The results are shown in Figures 6(c) and (d) for this range of \( \Delta T \) and \( \alpha \) values, with their associated range in thermal dark signal values given in Figure 6(b). The cases shown in Figures 6(b)–(d) bracket the likely range in telescope ambient temperature values (Appendix A). This results in a plausible range of F125W–F160W thermal dark signal values, with the most plausible ones subtracted from any diffuse sky-SB signal in Section 3.4. The error range resulting from the TD signal predictions is summarized in Figure 11 and brackets the range of \( \Delta T \) temperature variations that the above analysis implies (see Section 3.4).

### 3.4. Implications for Limits on Diffuse Light at 1.25–1.6 \( \mu \)m

In Figure 10 and Figure 11, we compute and plot our limits to any diffuse light at 1.25–1.6 \( \mu \)m as follows. Summarizing Figure 5, Table 1 suggests average offsets of the HST LFS values minus the Kelsall et al. (1998) COBE/DIRBE model predictions of 0.0145, 0.025, and 0.048 MJy sr\(^{-1} \) at the effective wavelengths of the F125W, F140W, and F160W filters, respectively. Below, we will convert these differences to our limits on diffuse light.

#### 3.4.1. The HST WFC3/IR Sky-SB Corrected for Thermal Dark Signal

First, we need to subtract the true WFC3/IR thermal dark signal, which has not yet been subtracted in any of the processing. Here, we cannot simply use the F125W thermal foreground of 0.052 e\(^{-1} \) pixel\(^{-1} \) s\(^{-1} \) from Table 7.11 in the WFC3 IHB (Dressel 2021), as it is larger than our 1.25 \( \mu \)m SB upper limit. The reason that the IHB thermal foreground is higher is that it includes a modeled thermal dark signal from the instrument housing, which is subtracted during dark-frame removal. All SKYSURF’s WFC3/IR images have been dark-frame subtracted, and so our modeled thermal dark signal values do not contain the instrument housing contribution. The
thermal dark signals predicted with synphot (in units of $e_0 \text{pixel}^{-1} \text{s}^{-1}$) for the plausible range in the temperatures of the HST optical and instrument components across a typical orbit are listed in the first set of three columns of Table 2 for the F125W, F140W, and F160W filters, respectively. With the WF3/IR pixel scale and zero points of Section 4 of SKYSURF–1, these are converted to equivalent sky-SB values in units of MJy sr$^{-1}$ and nW m$^{-2}$ sr$^{-1}$. The conversion factors needed for these calculations are also given in the footnotes of Tables 1–3. These TD values are subtracted from the net HST data–Kelsall model differences listed in boldface on the bottom line of Table 1, which are repeated on the top line of Table 2.

To give a specific example, for the nominal temperature difference of $\Delta T = (T - T_{\text{ref}}) = -1.15$ K (Section 3.3), the thermal dark value in the F125W filter is predicted to be $0.00399 \ e_0 \text{pixel}^{-1} \text{s}^{-1}$, which corresponds to 0.00123 MJy sr$^{-1}$. This value is subtracted from the HST–Kelsall difference of 0.0145 MJy sr$^{-1}$ in F125W listed in Table 1, to arrive at the net signal of 0.0133 MJy sr$^{-1}$ listed in Table 2 (second column for F125W) or 32.1 nW m$^{-2}$ sr$^{-1}$ (third column for F125W). To be conservative, we quote the values derived in the third column for each filter in Table 2 (in nW m$^{-2}$ sr$^{-1}$) as upper limits, given the uncertainties in the $\Delta T$ to be used for the TD subtraction, the absolute errors in the HST optical and instrument components across a typical orbit are listed in the first set of three columns of Table 2 for the F125W, F140W, and F160W filters, respectively. With the WF3/IR pixel scale and zero points of Section 4 of SKYSURF–1, these are converted to equivalent sky-SB values in units of MJy sr$^{-1}$ and nW m$^{-2}$ sr$^{-1}$. The conversion factors needed for these calculations are also given in the footnotes of Tables 1–3. These TD values are subtracted from the net HST data–Kelsall model differences listed in boldface on the bottom line of Table 1, which are repeated on the top line of Table 2.

3.4.2. The iEBL Component Already Subtracted from the Diffuse Light Limits

One of the strengths of the SKYSURF experiment is that it is very effective at removing discrete object light from our diffuse EBL constraint. As discussed in SKYSURF–1, the median SKYSURF exposure is complete down to a limit of $\sim 26 m_{\text{AB}}$, whereas most discrete extragalactic light comes from galaxies between 17 and 22 $m_{\text{AB}}$. Here, we describe the magnitude of this discrete object light, for context with other diffuse EBL measurements.

The $J$-band sky-SB integral of detected objects over 40 flux bins from AB = 10 mag to AB = 30 mag amounts to 1.396 $\times$ 10$^{-26}$ W Hz$^{-1}$ m$^{-2}$ deg$^{-2}$ when extrapolating the converging integral to AB $= \infty$ following Driver et al. (2016) (see also Figure 2 of SKYSURF–1). Because the sky integral converges strongly for AB $> 22$ mag, integrating to AB = $\infty$ only increases this sum by $\sim 0.7\%$ compared to when integrating to AB = 30 mag. In the units of nW m$^{-2}$ sr$^{-1}$ used in Driver et al. (2016) and Figure 10 here, this integral corresponds to a total sky-SB in the F125W filter of $n_{\text{J}}L_{\text{J}} \simeq 1.396 \times 10^{-26}$ W Hz$^{-1}$ m$^{-2}$ deg$^{-2}$

$$\times 10^7 \text{ nW W}^{-1} \times 2.4246 \times 10^{14} \text{ Hz}$$

$$\times 3282.8 \text{ deg}^2 \text{sr}^{-1} \approx 11.11 \text{ nW m}^{-2} \text{sr}^{-1}.$$  

Similarly, in SKYSURF–1 we find that the F160W sky-SB integral of objects detected to AB $\leq 30$ mag amounts to a total sky-SB of 1.813 $\times$ 10$^{-26}$ W Hz$^{-1}$ m$^{-2}$ deg$^{-2}$ or 11.68 nW m$^{-2}$ sr$^{-1}$. The fraction of these integrals that comes from discrete objects detected to AB $\leq 26.5$ mag is 10.74 nW m$^{-2}$ sr$^{-1}$ in the F125W filter, and 11.31 nW m$^{-2}$ sr$^{-1}$ in the F160W filter, respectively. Hence, to AB $\leq 26.5$ mag, even the average shallow single HST/WFC3 exposures in the F125W and F160W filters already resolve and detect $\geq 96.6$–96.8% of the total discrete EBL, respectively.

Many published direct EBL measurements—or upper limits—do include the full discrete iEBL+eEBL signal above, since these methods traditionally measure the total diffuse+$\text{discrete}$ galaxy light. By the nature of our SKYSURF methods, we have already removed almost all of the discrete iEBL signal, except for the last $\sim 0.4$–0.6 nW m$^{-2}$ sr$^{-1}$ that comes from unresolved objects with AB $\geq 26.5$ mag (see Section 3.4.3). Other direct EBL limits should appear higher than our diffuse light limits, in part because their values include the discrete EBL signal of 11.11–11.68 nW m$^{-2}$ sr$^{-1}$ at 1.25–1.6 $\mu$m, while our SKYSURF method already has subtracted $\geq 96.7\%$ of the discrete EBL signal from the typical 500 sec HST WFC3/IR exposures.

3.4.3. The eEBL Component Yet To Be Subtracted from the Diffuse Light Limits

While the discrete EBL down to $\sim 26 m_{\text{AB}}$ is already automatically excluded from the diffuse EBL limits, we do need to subtract from the upper limits in Tables 2–3 the expected eEBL sky integral of galaxies beyond the detection limits of the typical short F125W, F140W, and F160W exposures in which the HST sky-SB measurements were made. In SKYSURF–1, we showed that, for typical exposure times of $\tau_{\text{exp}} \approx 500$ s, the WFC3/IR detection limit is AB $\leq 26.5$ mag for compact objects in the F125W filter. For similar median exposure times, this detection limit is about 0.3 mag shallower in the F160W filter (see Table 1 and Figure 10 of Windhorst et al. (2011)). Hence, we assume that all objects with $J_{\text{AB}} \geq 26.5$ mag or $H_{\text{AB}} \geq 26.2$ mag have been undetected in SKYSURF’s individual $\sim 500$ sec WFC3/IR F125W or F160W exposures, respectively, and so their sky integral is still included in the diffuse sky-SB measurement. We will therefore estimate and subtract it here.

First, we need to correct the total sky-integral values of all objects—including low-SB objects—discussed in Section 3.4.2 for the SB incompleteness that sets in at AB $\geq 22$ mag due to the galaxy size distribution. This correction is identified in SKYSURF–1 for the F125W filter and repeated below as Equation (8):

$$\text{Incompleteness Correction} = 1.0 + [1.00 + 6.184 (J_{\text{AB}} - 22.0 \text{mag})]/100\%.$$  

This incompleteness correction was also applied to the F160W counts, accounting for the fact that the F160W catalogs have $\sim 0.3$ mag lower sensitivity per unit time. This is justified by the similarity of the $J$- and $H$-band versions of Figure 11 of SKYSURF–1, and as shown in Figure 10 of Windhorst et al. (2011). Figure 2 of SKYSURF–1 showed that 75% of the discrete EBL has already been reached for objects with AB $\leq 22.0$ mag in the F125W filter, so in essence, this procedure corrects the faintest 25% of the EBL integral for SB incompleteness of objects known to exist in deeper HST images. The potential impact of very low-SB discrete objects that are beyond the SB limits of all HST images including the HUDF—and thus not captured by Equation (8)—will be discussed in Section 4.

As yet uncorrected for SB incompleteness, the fraction of the discrete EBL detected to AB $\geq 26.5$ mag is $\sim 96.8\%$. When we fold in the SB incompleteness correction of Equation (8), this
Table 2
WFC3 Thermal Dark Signal, HST Data–Kelsall Model LFS Summary, and Diffuse Sky-SB Limits

| $\Delta T$ | $\alpha$ | $\frac{e^{-}}{F_{\lambda}}$ | TD | (HST–TD)–Kelsall | TD | (HST–TD)–Kelsall | TD | (HST–TD)–Kelsall |
|-----------|------|----------------|------|-----------------|------|-----------------|------|-----------------|
| (K)       |       | e$^{-}$ pix$^{-1}$ s$^{-1}$ | MJy sr$^{-1}$ | nW m$^{-2}$ sr$^{-1}$ | e$^{-}$ pix$^{-1}$ s$^{-1}$ | MJy sr$^{-1}$ | nW m$^{-2}$ sr$^{-1}$ | e$^{-}$ pix$^{-1}$ s$^{-1}$ | MJy sr$^{-1}$ | nW m$^{-2}$ sr$^{-1}$ |
| Raw$^a$   | 0.0145 | 35.2 | (0.008) | 19 | 0.0250 | 54.6 | (0.009) | 19 | 0.0480 | 94.2 | (0.009) | 17 |
| +2.44     | 0.76   | 0.00678 | 0.0124 | 30.1 | 0.0308 | 0.0173 | 37.7 | (0.009) | 19 | 0.1138 | 0.00254 | 4.99 |
| +2.0      | 0.75   | 0.00636 | 0.0125 | 30.4 | 0.0297 | 0.0177 | 38.5 | (0.009) | 19 | 0.1086 | 0.00464 | 9.10 |
| +1.84     | 0.74   | 0.00421 | 0.0126 | 30.5 | 0.0287 | 0.0178 | 38.9 | (0.009) | 19 | 0.1067 | 0.00538 | 10.6 |
| +1.19     | 0.72   | 0.00564 | 0.0127 | 30.9 | 0.0266 | 0.0183 | 40.0 | (0.009) | 19 | 0.0995 | 0.00826 | 16.2 |
| +0.90     | 0.71   | 0.00541 | 0.0128 | 31.1 | 0.0257 | 0.0186 | 40.5 | (0.009) | 19 | 0.0964 | 0.00949 | 18.6 |
| +0.48     | 0.70   | 0.00509 | 0.0129 | 31.3 | 0.0245 | 0.0189 | 41.2 | (0.009) | 19 | 0.0921 | 0.0112 | 22.0 |
| +0.0      | 0.69   | 0.00474 | 0.0130 | 31.6 | 0.0231 | 0.0192 | 41.9 | (0.009) | 19 | 0.0875 | 0.0131 | 25.6 |
| −0.30     | 0.68   | 0.00453 | 0.0131 | 31.7 | 0.0223 | 0.0194 | 42.4 | (0.009) | 19 | 0.0847 | 0.0142 | 27.8 |
| −1.15     | 0.66   | 0.00399 | 0.0133 | 32.1 | 0.0201 | 0.0200 | 43.6 | (0.009) | 19 | 0.0772 | 0.0172 | 33.7 |
| −2.0      | 0.64   | 0.00351 | 0.0134 | 32.5 | 0.0182 | 0.0204 | 44.6 | (0.009) | 19 | 0.0703 | 0.0199 | 39.1 |
| −3.19     | 0.62   | 0.00293 | 0.0136 | 32.9 | 0.0157 | 0.0211 | 46.0 | (0.009) | 19 | 0.0617 | 0.0234 | 45.8 |
| Adopt$^b$ | 0.0133 | 32.1 | 0.0200 | 43.6 | 0.0172 | 33.7 |
| DGL$^c$   | $\geq 0.0009$ | $\geq 2.1$ | $\geq 0.0015$ | $\geq 3.2$ | $\geq 0.0021$ | $\geq 4.1$ |
| eEBL$^d$  | $\sim 0.0002$ | $\sim 0.6$ | $\sim 0.0003$ | $\sim 0.6$ | $\sim 0.0003$ | $\sim 0.6$ |
| (AB $\geq 26$) | $\leq 0.0122$ | $\leq 29$ | $\leq 0.0182$ | $\leq 40$ | $\leq 0.0148$ | $\leq 29$ |
| Diff.Lim$^b$ | $\leq 0.0122$ | $\leq 29$ | $\leq 0.0182$ | $\leq 40$ | $\leq 0.0148$ | $\leq 29$ |

Notes.

$^a$ The raw HST–Kelsall LFSs are the differences from Table 1 repeated in MJy sr$^{-1}$ and nW m$^{-2}$ sr$^{-1}$ before TD subtraction.

$^b$ $\Delta T$ is the reference temperature minus the synphot temperature for $T < 3.2 \leq \Delta T \leq 3.4$ and the assumed $\alpha$ value.

$^c$ Assumed power-law spectral index in $F_{\lambda}$ of the zodiacal spectrum for that model. Changing this from the fiducial value of $\alpha = 0.66$ results in different best-fit $\Delta T$ values and predicted TD signal levels.

$^d$ The first column for each filter lists the predicted synphot dark signal (TD) in e$^{-}$ pix$^{-1}$ s$^{-1}$ at the quoted $\Delta T$ (Section 3.3). Dividing by 3.25, 3.99, and 2.50 to fold in the F125W, F140W, and F160W filter ZPs, respectively, converts this TD to MJy sr$^{-1}$. In each filter’s second column, this TD is subtracted from the raw lower-envelope HST synch values in MJy sr$^{-1}$ at the top. Each filter’s third column converts the (HST–TD)–Kelsall difference from MJy sr$^{-1}$ to nW m$^{-2}$ sr$^{-1}$ using footnote f of Table 1.

$^e$ The (HST–TD)–Kelsall differences adopted for the TD values as predicted for the best-fit $\Delta T = -1.15$ K.

$^f$ Estimated lower limit for the diffuse Galactic light for the used SKYSURF regions also subtracted from the adopted values, using the IPAC IRSA DGL estimator as in Section 3.5.

$^g$ Our HST SKYSURF analysis already automatically subtracted from the diffuse signal most of the discrete EBL integral from discrete objects with AB $\geq 26.5$ mag, but the undetected eEBL integral for AB $\geq 26.5$ mag, which amounts to 0.56 nW m$^{-2}$ sr$^{-1}$ (see Section 3.4.3), is also subtracted here, resulting in the boldface limits on the bottom row.

$^h$ The last row lists our resulting estimated limits for any remaining diffuse light (boldface in MJy sr$^{-1}$ and nW m$^{-2}$ sr$^{-1}$).
In conclusion, we subtract \( \sim -0.56 \text{nW m}^{-2} \text{sr}^{-1} \) to obtain the diffuse light limits in Tables 2–3 in order to account for the sky integral of discrete objects that remain undetected in typical SKYSURF exposures at \( AB \geq 26.5 \text{mag} \) in both the F125W, F140W, and F160W filters. Our diffuse light limits thus have the \( \text{discrete} \) integrated and extrapolated EBL (\( \text{iEBL}+\text{eEBL} \)), as well as the zodiacal model prediction, fully removed from the HST sky-SB data.

3.5. Corrections for Diffuse Galactic Light

The DGL is subtracted using the IPAC IRSA model,\(^1\) as shown in Table 2. The IRSA tool presents a model for the emission from the diffuse interstellar medium of our Galaxy, which uses a combination of the Arendt et al. (1998) Galactic emission and Schlegel et al. (1998) dust maps. These models are anchored to the COBE/DIRBE data at a 100 \( \mu \text{m} \) wavelength, where the ZL is minimal. This DGL model relies on accurate 100 \( \mu \text{m} \) maps and a dust emission model describing the ratio of NIR-to-100 \( \mu \text{m} \) emission. COBE/DIRBE galactic maps have zero-point uncertainties of \( \sim 3 \text{nW m}^{-2} \text{sr}^{-1} \) (Schlegel et al. 1998). Systematic uncertainties related to converting 100 \( \mu \text{m} \) emission to our near-IR wavelengths may be up to a factor of 2 (Onishi et al. 2018) and have a complex Galactic latitude dependence due to differing amounts of thermal emission and scattered light (Sano & Matsuura 2017). However, this uncertainty typically corresponds to \( \sim 0.002 \text{MJy sr}^{-1} \), much less than other systematic uncertainties in our analysis. The IRSA tool also includes an estimate of diffuse scattered starlight down to a wavelength of 0.5 \( \mu \text{m} \), based on the Zubko et al. (2004) model integrated with observations of Brandt & Draine (2012). The DGL correction to our HST–Kelsall differences in Figure 5 is small (typically \( < 0.003 \text{MJy sr}^{-1} \)) because the darkest Galactic and ecliptic regions have already been subselected. Furthermore, there is no discernible trend between HST–Kelsall and Galactic latitude, suggesting that our measurements are not sensitive to the uncertainties in DGL described above.

From the HST–Kelsall differences, corrected for the most plausible TD values in Table 2, we plot the resulting upper limits to the amount of diffuse light at 1.25, 1.37, and 1.53 \( \mu \text{m} \) as the brown downward-pointing arrows in Figure 10 and Figure 11. This includes an orange shaded uncertainty wedge in Figure 11 that captures the TD values predicted for \( -3.2 \leq \Delta T \leq 2.4 \text{K} \). Given the uncertainty in the thermal dark signal subtraction (Section 3.3 and Table 2, as well as uncertainties in the ZL models (Section 3.1), we will quote these values as upper limits, even though in the nominal range of HST component temperatures (\( \Delta T \leq 2 \text{K} \)), the remaining TD-subtracted diffuse light signal in the F125W and F140W filters remains significant (Figure 11).

3.6. Comparison of the (HST–TD–DGL) Estimates versus the Kelsall and Wright Zodiacal Light Models

For the WFC3/IR F125W, F140W, and F160W filters, respectively, the top three panels of Figures 7–9 show the following comparison. The top left panels show the HST WFC3/IR sky-SB measurements versus ecliptic latitude after subtracting the best WFC3/IR thermal dark signal estimate for each exposure from Section 3.3, and the DGL signal from Section 3.5. The top middle panels of Figures 7–9 show the Kelsall et al. (1998) zodiacal model prediction for the same observation date and SA as the HST data. The top right panels similarly show the Wright (1998) ZL model prediction with parameters that were updated by Gorjian et al. (2000), as provided by the IRSA tool.

In Figures 7–9, black dots indicate all observations from Figure 2, and the red dots are only those with Sun angle \( SA = 90^\circ \pm 10^\circ \). Both the Kelsall et al. (1998) and the Wright (1998) ZL models were fit to the COBE/DIRBE data that were taken at a comparable but somewhat wider SA range (\( SA = 94^\circ \pm 30^\circ \)). The blue-filled circles indicate one-sided clipped medians of the \( SA = 90^\circ \pm 10^\circ \) points in each 10° bin, and the blue line indicates the best sech fit to these medians following Equations (2)–(3).

The middle row of panels in Figures 7–9 shows the clipped medians for each \( \beta_{\text{Ecl}} \) bin from the top panels separately for clarity, together with their respective best-fit sech models and their coefficients. The bottom two panels show the \textit{difference} between each (HST–TD–DGL) data point from the top left panel after subtracting either the Kelsall et al. (1998) ZL model prediction (bottom middle) or the Wright (1998) prediction (bottom right). The difference in the (HST–TD–DGL)–Kelsall

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\( ^1 \) https://irsa.ipac.caltech.edu/applications/BackgroundModel/.
or (HST–TD–DGL)–Wright sech fits is indicated by the thin full-drawn blue lines.

The HST–Kelsall sky-SB differences clearly show positive offsets similar to those in Figure 5, where the best-fit TD and DGL were not yet subtracted. For $|b_{\text{Ecl}}| \lesssim 30^\circ$, the HST–Kelsall differences show a somewhat stronger dependence on ecliptic latitude than at higher $|b_{\text{Ecl}}|$ values. Specifically, the HST–Kelsall differences for $|b_{\text{Ecl}}| \lesssim 30^\circ$ are either slightly smaller (in F125W) or slightly larger (in F140W and F160W) than at higher ecliptic latitudes. For ecliptic latitudes $|b_{\text{Ecl}}| \gtrsim 30^\circ$, these
difference plots have an almost straight bottom envelope that is above zero. We therefore quantified these positive net HST–Kelsall offsets for \(|b_{\text{Ecl}}| \geq 30^\circ\) as a single constant using a two-sided 1σ clipped median for the HST–Kelsall differences at \(SA = 90^\circ \pm 10^\circ\). These numbers are given in Table 3 and indicated by the thick green dashed lines in the lower left panels of Figures 7–9. These offsets are our best estimate for any difference in diffuse light that may remain between the (HST–TD–DGL) sky-SB values and the Kelsall et al. (1998) ZL model predictions using the SA90 method.
Formally, these average (HST–TD–DGL)–Kelsall differences for $|b_{Ecl}| \gtrsim 30^\circ$ in Table 3 indicate a detection of a positive signal within the quoted errors using the SA90 method. However, the bottom middle panels Figures 7–9 show some ecliptic latitude and wavelength dependence of these differences across all $b_{Ecl}$ values, more so than in Figure 5 using the LFS method. Because the precise cause of this ecliptic latitude or wavelength dependence is not known, we quote the (HST–Kelsall) differences from the SA90 method as upper limits in Table 3. Because the upper limit values from the
SA90 method are somewhat larger than those from the LFS method in Table 2 (due to the nature of both methods discussed at the start of Section 3), we plot the latter as the *upper limits* in Figures 10 and 11, and the larger values of the former as the *upper envelope* of the allowed range, which is indicated by the orange wedge in Figure 11.

The HST–Wright sky-SB differences are mostly negative in the F125W, F140W, and F160W filters, especially for ecliptic latitudes $|b|^{Ecl} \lesssim 30^\circ$. The *ratios* of the Wright (1998) and Kelsall et al. (1998) ZL model predictions for all HST observations at their respective observing dates and Sun angles are as follows: Wright/Kelsall 1.346 ± 0.05 in F125W, 1.268 ± 0.05 in F140W, 1.223 ± 0.05 in F160W, respectively. These ratios are not quite uniform with $|b|^{Ecl}$, which may suggest some remaining ecliptic latitude dependence in the Wright (1998) model, and also some wavelength dependence at 1.25–1.6 μm. In Figures 7–9, some latitude dependence remains visible in the HST–Wright sky-SB differences even at high ecliptic latitudes of $40^\circ \lesssim |b|^{Ecl} \lesssim 90^\circ$. As noted on the IRSA tool, Wright (1998) and Gorjian et al. (2000) adopted a “strong no-zodiacal” condition at 25 μm wavelength, which requires that the minimum 25 μm residual at high Galactic latitude after subtraction of a ZL model from the COBE/DIRBE observations has to be zero. At this wavelength, the thermal zodiacal dust contribution is indeed approximately maximal compared to the zodiacal scattered sunlight contribution (brown dotted–dashed and green dotted lines in Figure 10, respectively). Kelsall et al. (1998) do not enforce this condition, and thereby obtain lower values for the ZL intensity, also at shorter wavelengths. In conclusion, the net HST–Wright differences are consistent with being ≤0 in the F125W and F140W filters, and for $|b|^{Ecl} \lesssim 30^\circ$, they are at most $\lesssim 0.0077$ MJy sr$^{-1}$ (or $\lesssim 15$ nW m$^{-2}$ sr$^{-1}$) in the F160W filter. These numbers are also given in Table 3. Based on our preliminary results, these offsets are thus our best current limits for any difference in diffuse light that may exist between the (HST–TD–DGL) sky-SB values and the Wright (1998) ZL model predictions.

We end with a cautionary note that our current near-IR diffuse light limits in Figure 11 may still contain some residual *time-varying* WFC3/IR thermal dark signal as a function of HST temperature and orbital phase. All our diffuse light values in Tables 2–3 and Figure 11 are derived using average orbital component temperatures, and for this reason (in addition to the uncertainties in ZL model subtraction) our near-IR diffuse light values are listed as upper limits.

4. Discussion of SKYSURF’s First Results

In conclusion, the HST data–Kelsall et al. (1998) model allows for a diffuse light component of $\lesssim 29–40$ nW m$^{-2}$ sr$^{-1}$ at 1.25–1.6 μm wavelength (Table 2). Given the relatively constant values of these HST–Kelsall offsets at most ecliptic latitudes (Figures 7–9), these values may indicate a very dim, possibly spherical or ellipsoidal component of diffuse light in the net HST data that is not present in the Kelsall et al. (1998) model. This diffuse light level could be due to a number of causes: (a) a remaining HST orbital phase and temperature-dependent TD component, which may need to include a thermal earthshine component; (b) a dim (nearly) spherical component missing in the Kelsall et al. (1998) zodiacal light model; (c) a spherical diffuse EBL component (Sano et al. 2020); or (d) some combination of these possibilities. The Wright (1998) model leaves little or no room for diffuse light after subtracting the thermal dark signal and DGL in Figures 7–9 and Table 3. In this context, we compare our HST results with the following recent results by other groups:

(1) Matsuura et al. (2017) analyze CIBER rocket spectra, and find that the sky-SB of diffuse light at 1.4 μm wavelength is $\sim 42.7^{+11.7}_{-10.3}$ nW m$^{-2}$ sr$^{-1}$, compared to the Kelsall et al. (1998) model. After subtraction of a 1.4 μm iEBL+eEBL signal of $\sim 11.8$ nW m$^{-2}$ sr$^{-1}$ (Section 3.4.3), this would correspond to a net diffuse light signal of $\sim 31$ nW m$^{-2}$ sr$^{-1}$. They find no significant excess in diffuse light, compared to the Wright (1998) model. They suggest that, compared to the Kelsall et al. (1998) model, their results may require “a new diffuse light component, such as an additional foreground or an excess EBL with a redder spectrum than that of the ZL...”. Kornogut et al. (2022) use subsequent CIBER spectra to estimate the Equivalent Width (EW) of the Ca triplet around 8542 Å, and suggest a simple modification to the Kelsall et al. (1998) model that adds a constant (spherical) component of 46 ± 19 nW m$^{-2}$ sr$^{-1}$ to best fit their inferred zodiacal level at 1.25 μm. The Kornogut et al. (2022) CIBER experiment directly estimates the depth of the Ca triplet Fraunhofer lines in the zodiacal spectrum, so it is plausible that much of this excess diffuse light is of zodiacal origin. Within the errors, our 1.25–1.4 μm HST–Kelsall differences of $\lesssim 29–40$ nW m$^{-2}$ sr$^{-1}$ are consistent with the diffuse light signal suggested by both Matsuura et al. (2017) and Kornogut et al. (2022). Given that the lower envelopes of our 1.25–1.6 μm HST data–Kelsall model differences are rather constant at all higher ecliptic latitudes, it is thus possible that a dim, large, and largely spherical component may need to be added to the Kelsall et al. (1998) model with an amplitude of $\lesssim 29–40$ nW m$^{-2}$ sr$^{-1}$ at 1.25–1.6 μm as seen from low Earth orbit.

Kornogut et al. (2022) discuss that the heliocentric isotropic IPD distribution in the inner solar system at 10–25 au may be supplied by debris from long-period Oort Cloud Comets (OCC; Oort (1950); see also, e.g., Nesvorný et al. (2010) and Poppe (2016)), and suggest that such a component may need to be added to the Kelsall et al. (1998) model with possibly a 5% amplitude. Our upper limits to the 1.25–1.6 μm sky-SB of $\lesssim 29–40$ nW m$^{-2}$ sr$^{-1}$ in Table 2 and Figure 10 suggest that any diffuse light is $\lesssim 10\%$ of the zodiacal sky-SB at these wavelengths. Hence, if most of this light were due to a missing component in the Kelsall et al. (1998) ZL model, such a component must be dim and extend to high ecliptic latitudes. Future work is needed to add such a component to the Kelsall et al. (1998) model and match it to the SKYSURF observations. Revised models may need to include (a) collisional processes in the solar system that can make the zodiacal dust smaller over time, and (b) solar radiation pressure that may drive these smaller dust particles further out into the solar system, perhaps forming a tenuous ellipsoidal or more spherical cloud of dust around the Sun compared to the known zodiacal IPD cloud.

The Kelsall et al. (1998) model includes IPD model uncertainties and lists possible changes that could improve the IPD modeling. Quoting their paper, one of their suggested improvements is “7. Permit a variation of the albedo for the shorter wavelength bands to accommodate the clues in the observations that point to a variation with (Ecliptic) latitude, which may well result from the differences in the dust contributed by comets as compared to that coming from
In Table 2 of Kelsall et al. (1998), they adopt an albedo at 1.25 μm wavelength for their zodiacal components of $a = 0.204 \pm 0.0013$. Recent thermal IR observations of TNOs imply geometric albedos of $\lesssim 20\% - 30\%$, while some have albedos as large as $\sim 60\%$ (e.g., Vilnius et al. 2014, 2014, 2018; Duffard et al. 2014; Kovalenko et al. 2017), possibly indicating a more icy surface for some TNOs. The four small satellites of Pluto have albedos ranging from 55\%–85\% (Weaver et al. 2016). While the nature of any OCC dust component at higher ecliptic latitudes may be substantially different from that of TNOs and their collision or scattering products, these results suggest that albedos higher than the $a = 0.2$ value adopted by Kelsall et al. (1998) are possible. Future improvements of zodiacal IPD models may therefore need to consider a different albedo distribution for any additional OCC dust component at higher ecliptic latitudes, including albedos as appropriate for a larger fraction of dust particles with icy surfaces. For example, Sano et al. (2020)
analyze DIRBE results, and find that the observed Sun angle dependence of the mid-IR and near-IR background is consistent with an additional diffuse isotropic component with an amplitude of ∼5% of the Kelsall et al. (1998) IPD cloud.

(2) Lauer et al. (2021) present 0.6 μm object counts from New Horizons images of seven fields taken around Pluto’s distance, where the zodiacal sky-SB is substantially lower than in LEO. They suggest a possible excess diffuse signal of unknown origin with an amplitude in the range (8.8–11.9) ± 4.6 nW m⁻² sr⁻¹ at 0.6 μm. These data are plotted with their two quoted error ranges as the blue points in Figures 10 and 11. Lauer et al. (2022) add a single new NH field with lower DGL contribution, which has a similar 0.6 μm excess diffuse signal with a smaller error bar: 8.1 ± 1.9 nW m⁻² sr⁻¹ (shown as the dark blue point in Figures 10 and 11). While their number of NH fields is limited, their images do provide a 0.6 μm diffuse light sky-SB estimate in the very dark sky environment at a distance of 43–51 au from the Sun. Figures 10 and 11 suggest their 0.6 μm upper value at 43–51 au is about 8–10 nW m⁻² sr⁻¹ above the integrated and extrapolated discrete EBL of Driver et al. (2016) and Koushan et al. (2021), respectively, while our HST WFC3/IR 1.25–1.6 μm upper limits in Figure 11 are about 29–40 nW m⁻² sr⁻¹ above the discrete EBL values at 1.25–1.6 μm.

The possible origin of 8–10 nW m⁻² sr⁻¹ of cosmological diffuse light remains an open question. For example, Conselice et al. (2016) and Lauer et al. (2021) suggested that some missing light could be caused by the galaxy counts rapidly steepening at V ∼ 24 mag, because existing surveys are missing a substantial population of low-SB objects. Given the decreasing abundance of low-SB objects with AB ∼ 24 and large sizes (e.g., Greene et al. 2022; Zaritsky et al. 2022), as well as recent limits on the abundance of low-SB galaxies (e.g., Jones et al. 2018), it is hard to imagine that a factor of two or
more in sky-SB comes from faint, undetected low-SB objects at $V \gtrsim 24$ mag. Accounting for this diffuse light from even fainter galaxies becomes more difficult given that they would have to be even more abundant to account for their corresponding faintness (e.g., Figure 2 of SKYSURF–1). Further investigation of this possibility, as well as a more detailed analysis of the impact of surface brightness and confusion-based completeness on EBL estimations, will be conducted with future SKYSURF analyses (e.g., Kramer et al. 2022).

Any missing diffuse EBL would then also need to be present in our HST–Kelsall comparison, which allows for $\lesssim 29\rightarrow 40$ nW m$^{-2}$ sr$^{-1}$ of diffuse light at 1.25–1.6 $\mu$m. If, for instance, $\lesssim 10$ nW m$^{-2}$ sr$^{-1}$ of our HST–Kelsall difference were due to truly diffuse EBL of cosmological origin (i.e., very faint, low-SB objects), then the Kelsall et al. (1998) model would only need an additional $\sim 20$ nW m$^{-2}$ sr$^{-1}$ of the uniform zodiacal component. However, our HST data–Wright model comparison does not require this, and in fact, leaves little or no room for any additional diffuse light components, neither an unrecognized HST thermal dark signal component, nor an additional zodiacal component, nor a diffuse EBL component.

In conclusion, the darkest $\sim 1\%$ of our 34,000 HST WFC3/IR 1.25–1.6 $\mu$m images closely follow the shape of the Kelsall et al. (1998) model, and suggest that the Kelsall et al. (1998) model may need an additional (nearly spherical) component of $\lesssim 29\rightarrow 40$ nW m$^{-2}$ sr$^{-1}$, while HST shows no such excess over the Wright (1998) model. A possible explanation is that the Kelsall model may be missing $\lesssim 29\rightarrow 40$ nW m$^{-2}$ sr$^{-1}$ of high-albedo OCC dust as seen from 1 au, which Wright (1998) included by default, because of his assumed strong no-zodiacal condition at 25 $\mu$m wavelength.

Through the “Sungrazer” project (Sekanina & Kracht 2013), orbiting Solar observatories like SOHO and STereo have found thousands of comets since 1995 that are getting in close proximity to the Sun. Silsbee & Tremaine (2016) have modeled the nearly isotropic population of comets that are expected to show up in very large numbers—also at larger distances from the Sun—with the Rubin Telescope. Hence, updated zodiacal IPD models may be able to include a more spherical component from such cometary dust left behind in the inner solar system.

HST studies of KBOs at $\sim 10–100$ au show remarkably blue colors in the WFC3/IR medium-band filters F139M–F153M (e.g., Fraser & Brown 2012; Fraser et al. 2015), which have similar central wavelengths but are narrower than our F140W and F160W filters. While it remains to be seen whether OCC dust in the outer solar system has similar blue near-IR colors and high reflectance, scattering models of icy particles (including amorphous and crystalline H$_2$O ice) do suggest that high albedos with a near-IR wavelength dependence are possible. ZL model refinements may need to include such considerations in more detail to better match the LFS envelopes of the HST data at all ecliptic latitudes. We will consider this in future papers when the full panchromatic SKYSURF database has been processed, including all the UV–optical and remaining near-IR filters. Once zodiacal light models have been updated to fully match the panchromatic SKYSURF data, this may result in firmer limits on, or estimates of, the amount of diffuse light that can come from beyond our solar system, including diffuse EBL.

5. Summary and Conclusions

In this paper, we present the first results from the Hubble Space Telescope Archival project “SKYSURF,” first outlined in (SKYSURF–1). Sky-SB measurements conducted on HST data are confirmed to be stable and precise, in line with the $\sim 2\%$–$4\%$ errors estimated in SKYSURF–1. By comparing measured HST sky-SB measurements with predictions describing zodiacal and Galactic foregrounds, we place competitive limits on the presence of an isotropic diffuse light component, either within the solar system or at cosmological distances.

1. Without having reprocessed the entire HST imaging Archive for SKYSURF as yet, we illustrate our methods and first results from 34,412 images in the HST Wide Field Camera 3 IR filters F125W, F140W, and F160W. Compared to the COBE/DIRBE 1.25 $\mu$m and K-band zodiacal sky-SB predictions of Kelsall et al. (1998), our darkest WFC3 F125W, F140W, and F160W sky-SB measurements appear to be on average $\sim 15$–$55\%$ higher (or $\sim 0.0145 \pm 0.008$, 0.025 $\pm 0.009$, and 0.048 $\pm 0.009$ MJy sr$^{-1}$, respectively) than the Kelsall et al. (1998) model predictions. With both taken at face value, this places an upper limit of $\lesssim 29\rightarrow 40$ nW m$^{-2}$ sr$^{-1}$ on any 1.25–1.6 $\mu$m diffuse light in excess of the Kelsall et al. (1998) ZL model components.

2. The largest uncertainty in our darkest HST WFC3/IR sky-SB measurements comes from the WFC3/IR thermal dark signal subtraction at 1.6 $\mu$m. From multiwavelength WFC3/IR images, we assess and subtract the WFC3/IR thermal dark signal for a range of HST orbital temperatures ($-3 \leq \Delta T \leq 3$ K). In the F160W filter, the thermal dark signal may be as large as the value of our upper limit on any remaining diffuse light, if HST were to run hotter than nominal by $\gtrsim 2$ K, leaving in that case little room for a significant diffuse light component. However, for the best-fit $\Delta T = -1.15$ K below the HST reference temperature, the nominal F160W thermal dark signal is $\sim 0.077$ e$^{-}$ pix$^{-1}$ s$^{-1}$ (or $\sim 0.031$ MJy sr$^{-1}$), resulting in a fairly consistent net diffuse light signal in all three HST filters less than 29–40 nW m$^{-2}$ sr$^{-1}$, the Kelsall et al. (1998) model predictions that were made for the same sky pointings and filters, observing day of the year, and Sun angle.

3. Compared to the Wright (1998) ZL model, HST appears to detect no significant 1.25–1.6 $\mu$m diffuse light within the current uncertainties. The lower envelope of the HST data–Wright model values suggests no remaining signal in the F125W and F140W filters, or perhaps a slightly negative one. In the F160W filter, the HST data–Wright model values suggest a remaining diffuse signal of at most $\sim 0.0077$ MJy sr$^{-1}$ (15 nW m$^{-2}$ sr$^{-1}$). Hence, if the Wright (1998) model best represents the ZL, this model would leave little or no room for additional diffuse light components.

4. In conclusion, given our lowest fitted Sky-SB measurements in the HST WFC3/IR F125W, F140W, and F160W filters, an update of the Kelsall et al. (1998) ZL model may be needed to better understand and constrain any additional diffuse light components that may come from beyond our solar system.
from the outer solar system. Once those are modeled in more detail and over a wider range of wavelengths, better constraints may also be obtained on any remaining diffuse light component, including diffuse EBL. This will be addressed in future SKYSURF papers.

We thank Annalisa Calamida, Phil Korngut, and Tod Lauer for helpful discussions. Additionally, we thank John Mather for his helpful comments regarding his suggestion of a spherical model for helpful discussions. Additionally, we thank John Mather for his reference to the Sungrazer project. We thank HST Archive staff at STScI for their expert advice on HST component temperatures. All of the data presented in this paper were obtained from the Mikulski Archive for Space Telescopes (MAST). This project is based on observations made with the NASA/ESA Hubble Space Telescope and obtained from the Hubble Legacy Archive, which is a collaboration between the Space Telescope Science Institute (STScI/NASA), the Space Telescope European Coordinating Facility (ST-ECF/ESA), and the Canadian Astronomy Data Centre (CADC/NRC/CSA).

We thank Ms. Desiree Crawl, Prof. Thomas Sharp, and the NASA Space Grant Consortium in Arizona for consistent support of our many undergraduate SKYSURF researchers at ASU during the pandemic. We acknowledge support for HST programs AR-09955 and AR-15810 provided by NASA through grants from the Space Telescope Science Institute, which is operated by the Association of Universities for Research in Astronomy, Incorporated, under NASA contract NAS5-26555. Work by R.G.A. was supported by NASA under award number 80GSC21M0002.

We are grateful to the anonymous referee, whose suggestions greatly improved this paper.

We also acknowledge the indigenous peoples of Arizona, including the Akimel O’odham (Pima) and Pee Posh (Maricopa) Indian Communities, whose care and keeping of the land has enabled us to be at ASU’s Tempe campus in the Salt River Valley, where this work was conducted.

Software: Astropy: http://www.astropy.org (Astropy Collaboration et al. 2013, 2018); IDL Astronomy Library: https://idlastro.gsfc.nasa.gov (Landsman 1993); Photutls: https://photutls.readthedocs.io/en/stable/ (Bradley et al. 2020); ProFound: https://github.com/asgr/ProFound (Robotham et al. 2017); ProFit: https://github.com/ICRAR/ProFit (Robotham et al. 2018); Source Extractor: https://www.astromatic.net/software/sexttractor/ or https://sexttractor.readthedocs.io/en/latest/ (Bertin & Arnouts 1996).

Facilities: Hubble Space Telescope Mikulski Archive https://archive.stsci.edu; Hubble Legacy Archive (HLA) https://hla.stsci.edu; Hubble Legacy Catalog (HLC) https://archive.stsci.edu/hst/hsc/.

### Appendix A

### Thermal Behavior of HST

Temperatures of the HST components are monitored through various thermal sensors throughout the telescope and WFC3. The HST component temperatures utilized as reference temperatures in Section 3.4.1 were taken from tables in https://www.stsci.edu/hst/instrumentation/reference-data-for-calibration-and-tools/synphot-throughput-tables, and are summarized below in Table 4. Here, we also reproduce some representative values of relevant telescope components directly from the STScI HST telescope group (private communication), which are not all directly available through the HST image FITS headers or the imafit or jfit-files. The $T_{ref}$ values are generally consistent with temperatures measured by sensors on the telescope to a few degrees C.

HST’s thermal variations across each orbit will matter the most for WFC3/IR, as the IR detector is most sensitive for measurable thermal variations at wavelengths $\lambda \geq 1.4 \mu m$. To avoid excessive thermal dark signal in the $H$ band, the WFC3/IR detector was therefore designed to cut out all wavelengths $\lambda \geq 1.73 \mu m$, so that the WFC3/IR F160W filter therefore is really a “short $H$-band” filter with $\lambda_{eff} \approx 1.53 \mu m$.

During 2020, typical temperatures measured were (working backward from the IR detector, with all in units of degrees C): IR detector = $-127.8 \, ^\circ C$; IR shield = $-100.2 \, ^\circ C$ (the black inner housing surrounding the detector); outer IR detector housing = $48.75 \, ^\circ C$; housing of the IR Filter Select Mechanism (FSM) = $-55 \, ^\circ C$; Refractive Corrector Plate (RCP) = $-33.62 \, ^\circ C$; and the WFC3/IR Cold Enclosure (CE) = $-33.6 \, ^\circ C$. These are the temperatures of the components seen by the WFC3/IR detector directly, and can vary by a couple degrees C.

When the (aluminum) blank is selected for Dark Current (DC) measurements in the WFC3/IR FSM, it blocks the detector’s view of the WFC3/IR RCP, so only indirect illumination from the CE is possible. This blank has higher emissivity than the WFC3/IR filters, so a measured DC frame looking at the aluminum blank will contain additional thermal dark signal and have a somewhat higher amplitude than the dark frame that is applicable to most filters. WFC3 does not have a temperature sensor on the FSM filters and the blank, but their temperatures are likely somewhere between the FSM housing at $-55 \, ^\circ C$ and the RCP at $-33.6 \, ^\circ C$. All of this thermal emission comes from the entire passband of the IR detector (i.e., 0.6–1.73 $\mu m$). Therefore, when a WFC3/IR dark frame is taken to form a DC calibration file to be subtracted in the WFC3 pipeline, only the thermal sources between the blank and the detector listed above plus the actual detector generated DC are measured.

The WFC3/IR filters have very high transmission and will also transmit some thermal dark signal from the camera and the telescope, which are at different temperatures but come from much smaller solid angles. The dark current calibration required thus does depend upon which filter was used for the science observation. With a WFC3/IR filter in place, we see the RCP, four mirrors within the WFC3 optical bench cold enclosure, and the WFC3 Pick-Off Mirror (POM) in the OTA Hub Area. The temperatures of these are somewhat less precisely known, due to the lack of close temperature sensors. The POM picks up more thermal radiation from the Earth.

| Component                                 | Temperature (°C) |
|-------------------------------------------|------------------|
| Primary Mirror                            | 15.15            |
| Mirror Pads                               | 15.15            |
| Secondary Mirror                          | 17.15            |
| Pick of Mirror                            | 14.75            |
| IR Channel Select Mechanism               | 0.15             |
| Fold Mirror                               | 0.15             |
| WFC3IR Mirror 1                          | 0.15             |
| WFC3IR Mirror 2                          | 0.15             |
| WFC3IR Refractive Corrector Plate         | −35.85           |
| WFC3IR Filter                             | −35.85           |
during occultation, which subsequently cools off when the observations start during the next darker part of an orbit. The four mirrors inside the WFC3 enclosure are at temperatures of about 0–4 °C. They are all silver-coated and thus have fairly low emissivity (slightly lower than that of gold) within the IR filter passbands.

The WFC3 optical bench and all of its associated baffles provide an environment kept colder than +4 °C, but with higher emissivity. The cold mask at the location of the RCP has about the same temperature as the RCP and should block all direct views of these high-emissivity surfaces, i.e., the WFC3 detector only has a direct view of HST’s mirrors. The WFC3 POM consists of a MgF2 flat substrate overcoated with aluminum to ensure excellent near-UV performance. Its temperature is less certain, because of the lack of nearby temperature sensors, but the arm to which it is attached is at +12.5 °C, and the “snout” leading into the WFC3 optical bench is at +7.9 ± 0.7 °C. The POM sees the illuminated Earth during most orbits and therefore fluctuates in temperature. It is unknown by exactly how much, as this depends on the Earth scenes transiting during bright time, but it is likely that the POM varies between 10–15 degrees C. The OTA primary and secondary mirrors, and their associated baffles, are also typically at 10–17 °C, although the baffles will not matter much for thermal dark signal estimates.

All these surfaces with their measured or estimated temperatures and approximate geometries have been modeled using simple blackbody approximations in the *py.synphot* tool and the appropriate emissivities and solid angles as seen from the detector. Given the incomplete knowledge of exact temperatures and their ranges, as well as of all the precise geometries inside WFC3 and HST, these *py.synphot* predictions of the WFC3/IR thermal dark signal will have their limitations. Hence, in Section 3.3, we present the best available *py.synphot* estimates of the WFC3/IR thermal dark signal based on these *average* temperatures in order to analyze our WFC3/IR sky-SB measurements, including a plausible temperature range of HST’s main components as modeled in *py.synphot*. We refer to T. Carleton et al. (2022, in preparation) for a detailed analysis of the most likely thermal dark signal for each WFC3/IR exposure in the SKYSURF database.

**Appendix B**

**Acronyms Used in SKYSURF**

Here we provide a list of acronyms used in sKYSURF papers and their meanings.

| Acronym | Explanation |
|---------|-------------|
| AB-mag | −2.5 log (object flux/zero-point flux) |
| ACS | Advanced Camera for Surveys |
| AGN | Active Galactic Nucleus |
| APT | Astronomers Proposal Tool |
| ASU | Arizona State University |
| AWS | Amazon Web Services |
| CCD | Charge-Coupled Device |
| CDM | Cold Dark Matter |
| CERES | Clouds and the Earth’s Radiant Energy System |
| CIB | Cosmic Infrared Background |
| COB | Cosmic Optical Background |
| COBE | Cosmic Background Explorer |
| COS | HST’s Cosmic Origins Spectrograph |
| CR | Cosmic Ray |
| CTE | Charge Transfer Efficiency |
| CV | Cosmic Variance |
| CVZ | Continuous Viewing Zone |
| DC | (Electronic) Dark Current |
| DGL | Diffuse Galactic Light |
| DIRBE | Diffuse Infrared Background Experiment |
| EBL | Extragalactic Background Light |
| EDIBE | diffuse Extragalactic Background Light |
| eEBL | extrapolated Extragalactic Background Light |
| IEBL | integrated Extragalactic Background Light |
| ERS | (HST WFC3) Early Release Science program |
| FOC | HST’s Faint Object Camera |
| FOS | HST’s Faint Object Spectrograph |
| FOV | Field of View |
| FWHM | Full Width at Half Maximum |
| GDC | Geometrical Distortion Corrections |
| GOODS | Great Orbiting Observatories Deep Survey |
| H_AB | H-band (1.6 μm) AB-mag |
| HDF | Hubble Deep Field |
| HLC | Hubble Legacy Catalog |
| HST | Hubble Space Telescope |
| HUDF | Hubble UltraDeep Field |
| HWHM | Half Width at Half Maximum (=0.5 × FWHM) |
| ICL | IntraCluster Light |
| IEF | Illuminated Earth Fraction |
| IGL | IntraGroup Light |
| IPD | InterPlanetary Dust |
| IRAF | Image Reduction and Analysis Facility |
| ISM | Interstellar Medium |
| J_AB | J-band (1.25 μm) AB-mag |
| Jy | Jansky or flux density unit (=10−26 W m−2 Hz−1) |
| KBOs | Kuiper Belt Objects |
| LA | Earth’s Limb Angle |
| LEO | Low Earth Orbit |
| LES | Lowest Estimated Sky-SB |
| LFS | Lowest Fitted Sky-SB |
| MA | Moon Angle |
| MAST | Mikulski Archive for Space Telescopes |
| NED | NASA Extragalactic Database |
| NEP | North Ecliptic Pole |
| NICMOS | Near-Infrared Camera and Multi-Object Spectrograph |
| OCC | Oort Cloud Comets |
| OTA | Optical Telescope Assembly |
| PAM | Pixel Area Map |
| PSF | Point-Spread Function |
| QSOs | Quasi-Stellar Objects |
| RA | HST Roll Angle |
| R.A. | |
| RC3 | Third Reference Catalog of Bright Galaxies |
| SAA | South Atlantic Anomaly |
| SA | Sun Angle |
| SB | Surface Brightness |
| SDSS | Sloan Digital Sky Survey |
| SED | Spectral Energy Distribution |
| SEP | South Ecliptic Pole |
| SFR | Star Formation Rate |
| SF | Star-forming |
| SM | Servicing Mission |
| STIS | Space Telescope Imaging Spectrograph |
| STScI | Space Telescope Science Institute |
| TD | Thermal Dark signal |
| TNOs | Trans-Neptunian Objects |
| UVIS | WFC3 UV–Visual channel |
| UV | Ultraviolet (−0.1–0.3 μm) |
| WFC3 | HST’s Wide Field Camera 3 |
