A Measurement of the Extragalactic Background Light with NASA's New Horizons

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The extragalactic background light (EBL) is the total light emitted from sources outside of the Milky Way Galaxy. An accurate measurement of the EBL can be used as a benchmark test to see if there are any extra components other than the light from galaxies. Any discrepancies would imply the presence of new diffuse emission sources and lead to discoveries such as diffuse photons associated with dark matter annihilation. However, ground-based measurements have proven to be very difficult as foregrounds are much brighter than the signal of interest. For example, the zodiacal light is about 100 times brighter than the EBL at near infrared wavelengths when viewed from Earth. In this project, we will be using data from the Linear Etalon Imaging Spectral Array (LEISA) aboard the New Horizons spacecraft to measure the EBL in the near-infrared range. The New Horizons spacecraft's location provides a valuable vantage point where local foregrounds are mitigated, enabling an exciting and unique chance at measuring the EBL.

Introduction

The universe is home to a range of diffuse astrophysical backgrounds that, if measured accurately, can yield important insights into the process of cosmic structure formation. One such background, and the background of interest in this project, is the extragalactic background light (EBL). The EBL is the total emission of all light outside of our Milky Way Galaxy at all wavelengths[2]. Specific wavelength ranges in the EBL are remnants of specific emission sources. One component of this background is the Cosmic Microwave Background (CMB), which was emitted shortly after the Big Bang and is a prime example of how fruitful diffuse background studies can be as it is a major source of information about the early universe[1].

The infrared component of the EBL is referred to as the Cosmic Infrared Background (CIB). It is believed that the CIB is dominated by redshifted starlight[3]. Just as the CMB provides information on the early universe, measuring the CIB could potentially provide new information on stellar and galactic processes as well as reveal other sources of emission[4].

Prior ground-based measurement of the CIB has proven to be extremely difficult as there are numerous diffuse foregrounds that must be taken into account, as well as atmospheric extinction (absorption of light in the target field out of the beam), scattering, and airglow emission[5]. One way around the brightest of these foregrounds is the use of instruments aboard New Horizons[6], a NASA spacecraft sent to survey Pluto, its moons, and other objects in the outer solar system.

In addition to their original purpose, New Horizons instruments can be used for astronomical measurements. This provides a rare and exciting opportunity to measure the EBL as a whole from an outer solar system vantage point that is free from the Earth's atmosphere and substantially decreases the effect of light reflected from interplanetary dust (IPD). In this capstone project, we will be measuring the CIB in the near infrared spectral range with data from the New Horizons instrument known as the Linear Etalon Imaging Spectral Array (LEISA)[6].

Measuring the EBL

The observed EBL is formed by two major energy sources: gravitational and nuclear[7]. The nuclear energy source consists of contributions from nucleosynthesis within stars, which is radiated predominantly in the UV to the near-IR wavelength range[7]. The gravitational source consists of contributions from accreting black holes and other strong-gravity systems[7].

A precise measurement of the EBL can be used as a valuable test where integrated light from discrete sources such as galaxies can be compared[1]. From this, constraints on models of galaxy formation and evolution[2], star formation, and metal and dust production[7] can be determined. Other potential results include discoveries such as diffuse photons associated with dark matter annihilation, the signature of recombination from the epoch of reionization, and the presence of intra-halo light in the intragalactic medium[4].

Local Foregrounds

Despite the potential benefits, direct measurements of the EBL are extremely difficult due to bright diffuse foregrounds including the integrated star light (ISL), zodiacal light (ZL), and the diffuse galactic light (DGL)[4]. While the New Horizons location alone will mitigate most of these foregrounds, we still must take them into account when making our measurements.

The ISL is the total sum of light emitted from stars within the Milky Way Galaxy[10]. It is easy to account for brighter stars, however, there are faint stars that are below the detection threshold of a given image that still contribute to this foreground. Taking advantage of real observations and star population models such as the TRILEGAL model[1] will be needed to estimate the faint stars contribution.

The ZL is caused by solar light scattered by interplanetary dust particles within the plane of the ecliptic[1]. This dust originates from many sources such as comets, asteroids, and Edgeworth-Kuiper Belt objects and disperse after they are ejected from their parent bodies[1]. The ZL is concentrated within the plane of the ecliptic and is less appreciable outside of it[10]. Furthermore, IPD in general is more prominent within the inner solar system, as measurements from Helios, Galileo, and Pioneers 8/9 show a steep decline in IPD density outside of 1AU[4] and confinement to within 30° of the ecliptic plane. Fortunately for us, New Horizons will be so far from the sun (R > 20AU)[8] that the ZL will be effectively zero for our purposes.

In a similar way to the IPD, dust along the plane of the Milky Way scatters light from stars within the galaxy. The resulting foreground is known as the DGL. As the ZL is brightest along the ecliptic, the DGL is brightest in the galactic plane and fainter at higher galactic latitudes[8]. It is important to note that the DGL is due to dust in interstellar space, not interplanetary space. Therefore, outer-solar system location does not mitigate this light contribution and no where in the sky can we ignore this foreground.

LEISA

Launched on January 19, 2006, the New Horizons spacecraft was NASA's first mission to explore Pluto and its moons Charon, Nix, and Hydra[6]. It is currently in an extended mission focused on Kuiper Belt science at heliocentric distances of beyond 50AU[4] and will continue on this mission until at least 2021.

While the main purpose of New Horizons and its instruments is to map the surface geology and composition of these objects[6], its instruments can double as astronomical telescopes with which EBL measurements can be made. One of the core instruments aboard the New Horizons spacecraft is *Ralph*[6], a visible/near-IR multi-spectral imager. It consists of a telescope that feeds two sets of focal planes that are intended to provide color, composition, and thermal maps for the surfaces of Pluto and its moons[6]. One of these focal planes is the Multi-Spectral Visible Imaging Camera (MVIC), while the other is LEISA[9]. LEISA is a wedged filter infra-red spectral imager that creates spectral maps in the 1.25–2.5 micron short wave infrared region, and the instrument of choice for this project.

Figure 1[4] shows the sensitivities of three New Horizons instruments (MVIC, LORRI, and LEISA) as compared to current measurements of the optical and near-IR backgrounds. Compared to MVIC and LORRI, LEISA has a much higher wavelength range (1.25 - 2.5μm), which helps in detecting near-IR sources such as

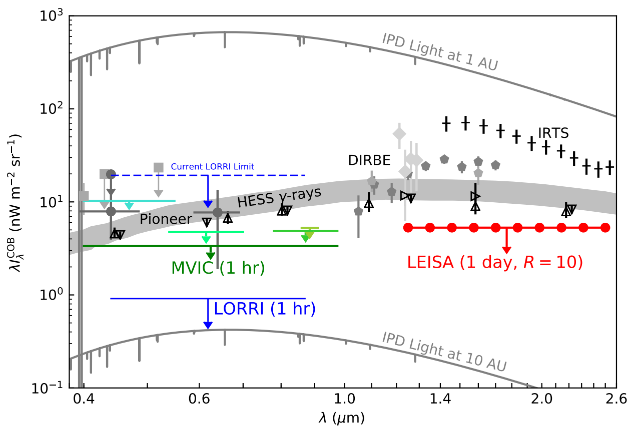

FIG. 1: Measurements of the EBL surface brightness λI_λ^{EBL} in the optical and near-IR. The filled in data points represent direct photometric measurements while the open symbols represent the integrated galactic light. The shaded region indicates the HESS γ-ray constraints on the extragalactic background light. The red bar shows the wavelength range of LEISA and expected sensitivity for an integration time of t_{int}= 1 day. The actual sensitivity[4] is $6 \times 10^4 \mathrm{nW} m^{-2} sr^{-1}$.

LEISA Instrument Parameters	
FOV:	0.9°x 0.9°
Single Pixel FOV:	60.83μrad x 60.83μrad
Pixel Size:	40μm x 40μm Pixels
Telescope Aperture:	75mm
Telescope Focal Length:	657.5mm
Spectral Resolution:	$\lambda/\Delta\lambda = 240$
Dark Current:	40 counts/second
Per-pixel Sensitivity:	$6{\times}10^4 \mathrm{nWm^{-2}sr^{-1}}$
Expected CIB Signal:	$10{\times}10^4 \mathrm{nWm^{-2}sr^{-1}}$

TABLE I: Tabulated parameters for LEISA. All values were found in the Ralph instrument paper[9]. The per pixel surface brightness sensitivity is measured at the maximum integration time of 1 day.

redshifted starlight in galaxies. LEISA also has a large field of view (0.9° x 0.9°)[9], which is good since the EBL is spread throughout the sky. Having a large field of view means measuring a larger area in the sky, which will help get a better sense of the nature of the EBL. LEISA's wavelength range is also important as measurements from 1-3μm have been very challenging on Earth[7] due to the bright foregrounds mentioned.

Although it is in a good vantage point, LEISA's parameters are not optimal for measuring the EBL. In Table I, LEISA's parameters are listed. For example, LEISA's small aperture (75mm) and spectral resolution (R = 240) means that it has a poor per-pixel sensitivity[4]. This in turn requires a significantly longer integration time (~1 day as compared to ~1 hour for MVIC and LORRI)[4] to make a constraining measurement of the

CIB. As a result, LEISA's measurements of the EBL will be both very interesting as well as very challenging.

Data Reduction

Once measurements are taken, we must decide which images to use and which to discard. Any defects such as streaking or blurry images will be discarded, as well as images that are taken at areas at which the foregrounds are especially bright. This is one of the most important steps as it determines how much data we will ultimately have to analyze. In the first step of processing, we will subtract the median of the dark reference pixels and divide a master flat-field image from the accepted science images. The dark field accounts for instrument noise and bias variations over the array while the flat field accounts for image smearing and relative pixel response.

The next step would be to perform astrometric registration, which is the process of pairing each pixel with a pair of right ascension (RA) and declination (Dec) coordinates[1]. This can be done with algorithms such as astrometry.net[8], which detects bright sources, divides them into subsets, and matches them according to a prebuilt index. The final alignment information is recorded and returned to the user in a fits header for each image.

Post-Reduction Analysis

To get a clear measurement of the EBL, we must rid the accepted science images of contamination from the foregrounds mentioned and instrument noise. Equation 1[1] governs the brightness in an arbitrary image of the astronomical sky outside of Earth's atmosphere:

$$\lambda \mathrm{I}_\lambda^{\mathrm{meas}} = \lambda \mathrm{I}_\lambda^{\mathrm{IPD}} + \lambda \mathrm{I}_\lambda^{*} + \lambda \mathrm{I}_\lambda^{\mathrm{RS}} + \lambda \mathrm{I}_\lambda^{\mathrm{DGL}} + \epsilon \mathrm{I}_\lambda^{\mathrm{EBL}} + \lambda \mathrm{I}_\lambda^{\mathrm{inst}} \quad (1)$$

where $\lambda \mathrm{I}_\lambda^{\mathrm{IPD}}$ is the brightness associated with the IPD, $\lambda \mathrm{I}_\lambda^{*}$ is brightness from resolved stars, $\lambda \mathrm{I}_\lambda^{\mathrm{RS}}$ refers to brightness from residual starlight of stars too faint to detect individually, $\lambda \mathrm{I}_\lambda^{\mathrm{DGL}}$ refers to the brightness from the DGL, ϵ is a factor that accounts for absorption in galactic dust, and $\lambda \mathrm{I}_\lambda^{\mathrm{inst}}$ refers to the instrument noise. We can isolate $\lambda \mathrm{I}_\lambda^{\mathrm{EBL}}$ in three steps[8]: remove the effect of $\lambda \mathrm{I}_\lambda^{*}$ by masking bright stars; subtract the diffuse components to isolate the diffuse residual component $\lambda \mathrm{I}_\lambda^{\mathrm{resid}} = \epsilon \mathrm{I}_\lambda^{\mathrm{EBL}}$; and correct the mean residual intensity for the effects of galactic extinction (determine value of ϵ) to yield $\lambda \mathrm{I}_\lambda^{\mathrm{EBL}}$.

Resolved and Residual Starlight

In order to measure the sky brightness, we must exclude the brightness from $\lambda \mathrm{I}_\lambda^{*}$ and $\lambda \mathrm{I}_\lambda^{\mathrm{RS}}$.One way of doing this is to implement image masks to remove signals from unwanted sources. Masking is the process of identifying and removing stars or other sources of light that are near or brighter than the detection threshold from an image[8]. We can identify stars using various catalogues that are publicly available. Successfully implementing masks in our images ensures that we can effectively ignore bright contributions to the sky brightness from stars, hot pixels, and other defects in our images.

When it comes to $\lambda \mathrm{I}_\lambda^{\mathrm{RS}}$, excluding its contribution is not as easy since we cannot take out stars we cannot see. The first step is to determine the number density of stars in the images[10]. To do this, we will employ the TRILEGAL model[8], which models the population of stars as a function of position, photometric system, and various parameters describing the Milky Way's disc, halo, and bulge. From this, we can estimate how much light the stars too faint to be catalogued contribute to our images.

Dark Current

Although the measured reference bias offset will be subtracted from the images as stated above, the dark current of the detector could still act as a potentially important isotropic component[1] of $\lambda \mathrm{I}_\lambda^{\mathrm{inst}}$. LEISA's dark current is $\sim$40 counts/second[9] and drops as the temperature of the focal plane drops. According to the manufacturer[9], the dark current drops by about a factor of two for every five degrees drop in the focal plane temperature. Although the dark current is not very bright, it is significant enough that we will still subtract it from our images.

Interplanetary Dust

As mentioned before, dust particles within interplanetary space reflect sunlight and other sources, creating a diffuse sky brightness. The Student Dust Counter[6] (SDC) aboard New Horizons has measured the flux of 0.5-5μm dust grains from 5 to 30AU. Its findings suggested an order of magnitude drop of the flux from 1 to 5AU, and a flattening of the dust flux to 20AU[8]. A model has been generated[8] that is consistent with these measurements and can be used to predict the IPD light intensity at LEISA's position. Using this we can predict the component of $\lambda \mathrm{I}_\lambda^{\mathrm{IPD}}$ and subtract it from our images.

Diffuse Galactic Light

The dust grains responsible for the DGL not only reflect light from stars in the galaxy, but can also be heated by the interstellar radiation field (ISRF) and release this energy thermally in the far-IR[7]. As a result, the DGL is correlated with 100μm emission where photon scattering is simple[8]. To avoid thick dust, we will only pay attention to high galactic altitudes where the distribution is less dense. This allows us to take advantage of the linear relationship between thermal emission intensity and optical surface brightness[8]. In other words, we know the shape of the DGL in the far-IR and we know the scaling from the far-IR to the near-IR. By multiplying these factors, we can find the DGL contribution in the wavelength range we are measuring (near-IR).

Extinction Correction

After accounting for the foregrounds in our science images, we retrieve the residual sky brightness $\lambda I_{\lambda}^{\mathrm{resid}}$. The per-field measurements will be computed as the weighted mean of the individual exposures, where the weights are the inverse error on the mean in each exposure[8]. To get these field averages to a measurement of the EBL, we must correct for galactic extinction. First, we will compute the mean residual brightness and then apply a generated extinction correction to that quantity.

Using various models[8], we will compute the mean of the extinction measurements weighted by the same uncertainty weights as in the mean intensity computation. This will yield an extinction correction that can be applied to the residual brightness which will then lead to a value for the EBL[8] in the measured spectral range.

Error Analysis

There are many sources of error, both in the image data itself and the data reduction process. The errors in the measurements can be grouped into two main categories[8]: systematics in the instrument and systematics in the foreground accountancy. The instrument errors will be computed from the variance of measurements from each image, and as a result combine a variety of sources of noise[9] (detector, read out, photon, etc.) in an indistinguishable way. According to prior inspection[8], the noise is dominated by bit noise from the analog to digital converter. This means that longer integration times could be beneficial in mitigating this noise.

For the data reduction, the only situation in which such an error could have a measurable impact is if the regions immediately surrounding the reference stars have an inter-pixel response different from the bulk of the detector array[8]. To guard against this, we could use reference stars in random positions on the detector array.

Budget

There are no planned expenses for this project.

Timeline

Capstone I

- Learn about LEISA (3 weeks)
- Data quality assessment and preliminary cuts (6 weeks)
- Analysis pipeline validation and checks (4 weeks)
- Write Paper and Presentation (2 weeks)

Capstone II

- Finalize data cuts (1 week)
- EBL Analysis (4 weeks)
- Systematics and error assessment (6 weeks)
- Scientific Interpretation (2 weeks)
- Write paper and presentation (2 weeks)

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