Irradiance source for exoplanet atmospheric spectra

Savannah Lyons

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Irradiance Source for Exoplanet Atmospheric Spectra

by

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Thesis
Submitted to the Department of Physics and Astronomy
Eastern Michigan University
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for the degree of

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Abstract

The quantity and diversity of the known exoplanets have grown in recent years. This has brought about a need for more efficient methods of narrowing down the list to those exoplanets most likely to sustain life. The Atmosphere in a Test Tube project, which began at the University of Padova, Italy, is accomplishing this in a laboratory setting through examination of exoplanet atmospheric responses to photosynthetic bacteria under simulations of the irradiance conditions of a planet’s host star. The goal of this project was to design and construct a second-generation apparatus at Eastern Michigan University. The team focused on an irradiation source consisting of an interface of LED light channels with differing chromatic emissions controlled by software that allows for the tuning of each LED channel to match a variety of spectral outputs. This paper will demonstrate the progress made on the design and preliminary data that have been collected.
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Chapter 1: Introduction

For many years, scientists and philosophers alike have dreamed of worlds beyond our own. With the advancement of technology and the growth of our cosmological understanding, these new worlds are finally visible. As our understanding of deep space and the bodies that populate it has increased, so has the demand for more efficient methods of organizing them. The discovery of the first exoplanets has brought with it many advancements in physics and astronomy which have taught us that each exoplanet can vary greatly in their physical characteristics. It is through the investigation of these characteristics that we hope to develop a better understanding of these exoplanets and the effects on possible biosynthetic life on their surface.

One of the first steps in this investigation is to identify fundamental characteristics by which we can classify exoplanets. This can be achieved through processes similar to that of stellar classification. In the early 1900’s, Ejnar Hertzsprung and Henry Norris Russell developed a procedure for classifying stars more efficiently. Through their research and development of the H-R diagram, we discovered that a star’s structure is governed by its mass, age, and initial chemical composition. From this observed information, characteristics such as temperature and radius can be determined. This allows for efficient classification of each star tinetti2013spectroscopy. When examining characteristics of the known exoplanets in a similar way, it becomes clear that the most practical way to classify them is by mass and temperature. In doing so, we designate three mass-based and five temperature-based classes. The mass classes are determined by the exoplanet’s mass as
CHAPTER 1. INTRODUCTION

compared to the mass of the Earth with “Earth” and “super Earth” sized planets being those that are less than 10 Earth masses (Alej, 2019). Planets of this size are of particular interest as they tend to be planets with a rocky surface which increases the probability of life existing on their surface. The temperature of the exoplanet depends largely on the type of star it orbits as well as its proximity to the star. Forming a better understanding of the effect these two components have on the exoplanet is fundamental in determining if life could exist on them.

1.1 Red Dwarf Stars and the Circumstellar Habitable Zone

Before examining the possibility of life elsewhere in the universe, it is crucial to build an understanding of the conditions which may be present on the surface of the exoplanet. These conditions differ based on its host star and its proximity to it. Though there are many types of stars in the universe, the most prominent of them are red dwarfs. These stars, often referred to as M-dwarf type stars, reside along the main sequence. They have small masses and low luminosity, which in turn causes them to burn through their nuclear fuel slowly. This extends their life span making it much longer than their larger, more luminous count (Alibert and Benz, 2017). These M-dwarfs make up a majority of the stars in our galactic neighborhood and are often orbited by super-Earth sized exoplanets making them great candidates for observation (Claudi et al., 2020). One of the most important characteristics to examine while observing these exoplanets is whether the zone in which the planets orbit is optimal for the presence of life.
The circumstellar habitable zone (CHZ) is most often defined as the orbital distances in which liquid water can exist on the planetary surface. The outer limit is defined as the point at which liquid water freezes. At this distance, the planet is overcome by the glacier effect and life is unlikely to survive. The inner limit is defined by the runaway greenhouse effect, which is the point in which liquid water vaporizes and escapes into space (Doyle et al., 1998). Since the existence of liquid water is thought to be one of the most fundamental necessities for life, planets that inhabit the CHZ are at an optimal distance from their host star to receive the radiant energy necessary to provide the key frameworks required to support life. Though the CHZ provides an estimation on the most habitable orbital distances, it does not guarantee that planets within it are able to sustain life. Many geographical, biological, and astrophysical factors have a large effect on the planetary surface and atmosphere.

As mentioned above, the abundance and frequency in which M-dwarf stars house super-Earth planets in their CHZ make them of particular interest to the scientific community. In order to build our understanding of the known exoplanets, various methods have been developed to locate and observe them.

1.2 Methods of Observing Exoplanets

Due to the vast distances separating Earth from even the closest of exoplanets, it is necessary that we use advanced remote observational methods when investigating them. Though there are many applicable techniques, the most common are direct imaging, the
CHAPTER 1. INTRODUCTION

radial velocity method, and the transit method. These techniques work well when used in conjunction as they are each used to investigate different planetary categories and determine different characteristics. In the ensuing paragraphs, we will take a deeper look at each of these methods and their limitations.

The direct imaging method is best for examining newly formed planets that maintain a large separation from their host star, as well as temperate planets around younger stars. Direct imaging allows the observer to investigate an exoplanet directly with no dependence on the host star. This method can be used to directly measure a planet’s size, and if used in conjunction with a spectrometer, various chemical and physical properties of the planet can be determined. When collecting spectrometric data there are some issues that must be accounted for. The largest of these arises because the observer is trying to image a planet that is substantially less bright than its host star. This means that the excess light coming from the host star must be removed. There are many advanced techniques and technologies that resolve this issue, but we will not discuss them here. Once the host star’s influence is removed from the images, they can be used to perform various types of photometric and spectrometric measurements. Though direct imagining is useful, it is the least feasible method for studying exoplanets as most of them preside at very large distances from Earth. This increases the number of aberrations that must accounted for. However, for those exoplanets that orbit nearby stars direct imaging is especially powerful (Alei, 2019; Traub et al., 2010).

The radial velocity method identifies exoplanets around stars by observing changes
in the spectral emission of the star caused by Doppler shift. These shifts in the spectrum (both red and blue) are due to small wobbles in the stars rotation caused by the gravitational pull of an orbiting exoplanet. These wobbles in turn affect the radial-velocity of the star and so the orbiting body can be detected. To begin, multiple observations of the stellar emission are made using a spectrograph and any periodic variations of known spectral lines are noted. Analysis on shifts in these spectral characteristics can then be performed and the presence of any exoplanet(s) can be determined. In general, the mass of the planet is substantially less than the mass of the star. Because of this, the changes to the stars radial velocity are only on the order of tens of m/s. Due to this, this method is most effective in identifying exoplanets around old, low-mass stars as they are more likely to be affected by the gravitational pull of any orbiting planet (Madhusudhan, 2019; Wright, 2017).

The transit method and transit spectroscopy are most effective on planets that formed in the outskirts of the planetary disc and then moved inwards, as well as temperate planets around M-dwarf stars. When a celestial body crosses in front of a more distant object with a larger angular diameter, a transit phenomenon has occurred. For the purposes of this paper, we are concerned with transits in which an exoplanet crosses the path of its host star. During these occurrences, the flux difference of the star and planet system can be evaluated before, during and after the transit. This difference can be used to obtain information about the exoplanets’ atmosphere (Madhusudhan, 2019; Tinetti et al., 2013). Particularly, as the planet transits across the star it blocks out a portion of the
stellar photosphere which causes a decrease in the observed flux of the system. As the planet continues to revolve around its host star, different portions of its surface contribute to the total flux which causes a quasi-sinusoidal increase (Alei, 2019). From this we can determine important information about the radius and atmosphere of the exoplanet. Though this method is effective at determining the radius of the planet, when seeking to understand the atmosphere, it is more efficient to collect spectral data.

Transmission spectral data of a transiting planet is obtained by observing the absorption of the host star’s radiation by the atmosphere of the planet (Alei, 2019). This is accomplished by analyzing the intensity of the incoming light at each wavelength. This method allows for a description of the planet’s atmosphere to be formulated. During this process, it can be difficult, or at times even impossible, to identify and remove errors in the spectra caused by things like noise, time-dependent flux and cloud cover. Emission spectral data can also be collected by measuring the variation in the star and planet system spectra at various points during the transit. This allows for individual molecular signatures to be identified (Madhusudhan, 2019). These signatures can play a pivotal role in determining the atmosphere of the planet as well as in understanding the effect the planet’s composition could have on biosynthetic life. For the purposes of this paper, the focus will be on biosignatures as they are a key indicator of biosynthetic life.
1.3 Biosignatures

Biosignatures are properties, such as a chemical compound or cellular component, that suggest the presence of biological processes that are or could be a result of life (Merriam-Webster, 2011). They most often present themselves as physical characteristics and out-of-equilibrium conditions that can not be easily elucidated through abiotic mechanisms. This leads to a conclusion that biological life may be responsible.

Some of the most important evidence of the effectiveness of biosignature analysis was obtained in 1990 during the Earth flyby of the Galileo spacecraft. During its journey, the spacecraft used an assortment of instruments to collect spectrometric data of the earth. The data collected here has aided in confirming the effects life on earth has on the biosignatures of the planet (Scharf, 2009).

One example of this is the high concentration of methane in the atmosphere of our own planet. Due to the fact that methane oxidizes rapidly, an overabundance of it in the atmosphere suggests that an external source must be responsible. This external source is methanogenic organisms on the earth’s surface (Scharf, 2009).
Another example is a phenomenon known as the vegetation red edge, and it is a direct result of the photosynthesis of plants on Earth. When analyzing the wavelengths of light that the chlorophyll molecules in plants absorb during photosynthesis, it can be seen that they most efficiently absorb wavelengths shorter than 450 nm and also wavelengths around 680 nm. However, the reflectivity of the chlorophyll molecules drastically increases between 670 nm and 760 nm and remains there until approximately 1400 nm. This effect can be seen visually by examining the reflectance vs. wavelength relationship shown in Fig. 1.1. This portion of the spectrum where the reflectance remains high is known as the vegetation red edge and demonstrates that the vegetation is quite selective with the light it absorbs and is reflecting most of the stellar energy that it receives (Scharf, 2009). The vegetation red edge provides a distinct spectroscopic characteristic that indicates the existence of photosynthetic life.
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By searching for biosignatures like these in the spectra of known exoplanets, we can begin to determine which of them may have the potential to sustain life. These types of observations are pivotal for filtering and organizing the rapidly growing list of exoplanets.

1.4 The Role of the Irradiance Source

With thousands of already known exoplanets, it is necessary to narrow down the pool to those with the most potential to support life [NASA Exoplanet Archives, 2020]. This is most effectively done by examining M-dwarf stars and determining which of the planets orbiting these stars may reside in the CHZ. Both ground and space-based missions such as SPHERE@VLT, GPI@GEMINI, EPICS@ELT, JWST and ARIEL are seeking to collect spectral data from these exoplanets in order to study their atmospheres (Clampin, 2014).

In order to accomplish this task, the “Atmosphere in a Test Tube” (ATM.ITT) project is attempting to simulate the irradiance conditions of a planet’s host star and study the response of photosynthetic bacteria in the atmosphere (Claudi et al., 2016). The apparatus for this project has various parts, the main device of which is a chamber where photosynthetic bacteria can be placed. The pressure and temperature inside the chamber can be controlled in order for the atmospheric composition to be analyzed for a set of given conditions. The bacteria in this chamber are then exposed to an irradiance source that can be programmed to simulate the spectral output of a specific host star. The effects of the stellar emission on the bacteria can then be observed and the spectral output can be
CHAPTER 1. INTRODUCTION

examined. The spectrometric data of these effects can be compared to the known spectral data of exoplanets orbiting similar host stars and predictions on the planet’s ability to sustain life can be made.

One of the most fundamental components of the ATT.ITT project is the irradiance source. The primary goal of this project is to design and construct this source, as well as develop the program necessary to tune the source to simulate a series of chosen stellar spectra. This will be accomplished in two main sections—an LED analysis and prototype building/testing. The former will be completed by designing a software that allows for the intensity curve of a combination of LEDs to be compared to a known intensity curve of an M7 type star. This comparison will aid in determining which LED wavelengths and how many LEDs at each are necessary. The latter will involve building a prototype voltage source that allows for the control of the voltage provided to the circuit by means of a buck converter. This adjustable voltage will in turn make the intensity variable and therefore enable the source to adequately simulate the necessary stellar emissions.
Chapter 2: LED Power Analysis

2.1 Software Analysis

The main design constraint for the irradiation source is that it should be tunable and capable of replicating the irradiance conditions present at the surfaces of a variety of exoplanets. For this reason, the irradiation source will be composed of LED lights of various chromatic emissions, each fastened to an interface and wired into a computer.

![Figure 2.1: Simplified apparatus interface. Depiction of the irradiance source where a computer program, A, will be attached to a voltage adjustable voltage source, B, that controls an interface of LEDs, C.](image)

Fig. 2.1 displays the basic interface. A program that allows for the adjusting of the luminosity of each individual LED will be developed in order to reproduce the necessary variety of spectra. The primary focus will be on simulating stars that emit strongly in the visible and infrared areas of the spectrum, including M-class stars that are of particular interest to the astro-biology community (Tarter et al., 2007).

Before finalizing the design and beginning the construction process it was necessary to determine which LEDs were needed to construct an irradiance source that could produce
the desired types of spectral outputs. This task was completed by developing software that plotted an intensity profile of a combination of LEDs. Since the wavelength, \( \lambda_0 \), power output, \( P \), and full-width at half-maximum (FWHM) are known, Eq. 2.1 can be used to the LED’s intensity as a function of wavelength.

\[
I = \left( \frac{P}{\sigma \sqrt{2\pi}} \right) \exp \left( -\frac{(\lambda - \lambda_0)^2}{2\sigma^2} \right) \quad (2.1)
\]

Here \( \lambda \) is the range of wavelengths of interest and \( \sigma \) is the standard deviation which is related to the FWHM by Eq. 2.2

\[
FWHM = 2.355\sigma \quad (2.2)
\]

Once the intensity profile of the LED combination was created, the types and quantities of LEDs being plotted could be varied and changes to the total intensity profile could be observed. The spectral output from the software could then be compared to a known stellar intensity profile of a specific star of interest and adjusted until a sufficient profile simulation was achieved with the software.

2.2 LED Determination

While determining the range of LEDs needed to properly simulate the stellar types of interest a sample spectrum of an M7 type V star was chosen. This spectrum was initially chosen by Claudi and his associates as it is an M-dwarf type star that is of particular interest due to their abundance and likelihood for exoplanets in its orbit to
sustain life. For the purposes of this project, it was chosen out of convenience since it had already undergone a smoothing process that allowed for better graphical viewing of the spectral output (Claudi et al., 2020). The red line in Fig. 2.2 depicts the smoothed spectrum that was approximated with the software. The LED ranges and intensities were adjusted manually in order to achieve a rough graphical approximation. This approximation was validate visually as a profound level of accuracy was not required at this stage. The final approximation can be seen in Fig. 2.3.

![Figure 2.2: Smoothed M7 V stellar spectrum (Claudi et al., 2020).](image)

After doing this, it was found that utilizing the high-powered LEDs from the Roithner SMB1N series was advantageous. These LEDs aided in maximizing the intensity output while maintaining a relatively low number of LEDs per channel.
It was determined that a total of 166 LEDs over 16 channels allowed for ample reproduction of the smoothed stellar intensity profile. The complete list of LEDs as well as some of their specifications can be found in Table 2.1. It is possible to decrease the total number of LEDs by utilizing a different series of Roithner high-powered UV LEDs rather than the Thorlabs ones chosen for the approximation.
Table 2.1: LED list. LEDs determined from the software and their specifications.

<table>
<thead>
<tr>
<th>Company</th>
<th>Part Number</th>
<th>Wavelength (nm)</th>
<th>FWHM (nm)</th>
<th>Current (mA)</th>
<th>Quantity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thor Labs</td>
<td>LED385L</td>
<td>385</td>
<td>12</td>
<td>30</td>
<td>20</td>
</tr>
<tr>
<td>Thor Labs</td>
<td>LED395L</td>
<td>395</td>
<td>15</td>
<td>30</td>
<td>20</td>
</tr>
<tr>
<td>Roithner</td>
<td>SMB1N-D450</td>
<td>450</td>
<td>20</td>
<td>350</td>
<td>5</td>
</tr>
<tr>
<td>Roithner</td>
<td>SMB1N-D470</td>
<td>470</td>
<td>20</td>
<td>350</td>
<td>5</td>
</tr>
<tr>
<td>Roithner</td>
<td>SMB1N-490H</td>
<td>490</td>
<td>26</td>
<td>350</td>
<td>5</td>
</tr>
<tr>
<td>Roithner</td>
<td>SMB1N-590</td>
<td>590</td>
<td>14</td>
<td>350</td>
<td>5</td>
</tr>
<tr>
<td>Roithner</td>
<td>SMB1N-620D</td>
<td>620</td>
<td>15</td>
<td>350</td>
<td>5</td>
</tr>
<tr>
<td>Roithner</td>
<td>SMB1N-670D</td>
<td>670</td>
<td>20</td>
<td>600</td>
<td>5</td>
</tr>
<tr>
<td>Roithner</td>
<td>SMB1N-680D</td>
<td>680</td>
<td>20</td>
<td>600</td>
<td>5</td>
</tr>
<tr>
<td>Roithner</td>
<td>SMB1N-720</td>
<td>720</td>
<td>23</td>
<td>600</td>
<td>7</td>
</tr>
<tr>
<td>Roithner</td>
<td>SMB1N-750</td>
<td>750</td>
<td>28</td>
<td>800</td>
<td>5</td>
</tr>
<tr>
<td>Roithner</td>
<td>SMB1N-760D</td>
<td>760</td>
<td>25</td>
<td>800</td>
<td>10</td>
</tr>
<tr>
<td>Roithner</td>
<td>SMB1N-780D</td>
<td>780</td>
<td>24</td>
<td>800</td>
<td>5</td>
</tr>
<tr>
<td>Roithner</td>
<td>SMB1N-830N</td>
<td>830</td>
<td>40</td>
<td>800</td>
<td>25</td>
</tr>
<tr>
<td>Roithner</td>
<td>SMB1N-880D</td>
<td>880</td>
<td>50</td>
<td>800</td>
<td>21</td>
</tr>
<tr>
<td>Roithner</td>
<td>SMB1N-910D</td>
<td>910</td>
<td>37</td>
<td>1000</td>
<td>18</td>
</tr>
</tbody>
</table>

It was also decided it would be most advantageous to set a minimum of five LEDs per channel. This is due to the fact that it would not be efficient to create an entire power supply for only 1 to 2 LEDs. However, it would also be unnecessary to increase the minimum number of LEDs to 10 or above as this would provide more power than would ever be necessary for the desired stellar simulations.
Chapter 3: Prototype LED Driver

3.1 Preliminary Apparatus

To ensure that a multi-channel, tunable voltage source could be developed and controlled a simplified apparatus was built and tested first. This initial apparatus was developed in two stages—the first being a single-channel voltage source, while the second stage implemented a second channel.

The preliminary apparatus was based on an instructable created at Stanford University (Digman, ????). The apparatus is designed to be built on a breadboard for easy prototyping and design modifications. The completed circuit works as a DC-DC buck-converter that enables an incoming voltage to be stepped down so that a smaller, regulated output voltage can be supplied to the LEDs. Fig. 3.1 depicts the circuit diagram for a single-channel apparatus with three LEDs in parallel.

![Figure 3.1: Single-channel apparatus circuit diagram. Completed circuit diagram for the apparatus where the buck-converter (shown in black) regulates the voltage being supplied to the LEDs (shown in blue).](image)

This step down is accomplished through the electrical regulation of the pulse-width modulation (PWM) signal. The PWM signal is adjusted by controlling the time in which
the electrical signal from the power supply is on or off. The ratio of the on time to off time
is known as the duty cycle. As the on time of the electrical signal is increased, so is the
duty cycle of the PWM. Regulated control of this duty cycle allows for control of the
overall voltage being supplied to the system. In the buck converter built for this project,
the buck converters PWM signal is generated from the Arduino and an operational
amplifier (OpAmp). The OpAmp takes the voltage reading of the load and compares it to
a source PWM signal set inside the Arduino software. The OpAmp generates a new PWM
signal that is dependent on the load. This PWM signal is then fed into an electronic switch
known as a mosfet (PMOS used for this system) that is used to control the duty cycle of
the electrical signal. Regulated adjustment of this provides the ability to supply a
constant, stepped down voltage to the circuit of LEDs.

The completed voltage source receives power from a 65W/20V laptop charger and is
controlled by an Arduino Mega 2560. The Arduino along with a graphical user interface
(GUI) program called Processing 4 allows for the regulation and control of the input
voltage for each channel from 0V-12V.

This preliminary apparatus was tested using low-powered red and blue LEDs and
the intensity profile of each channel was measured using a spectrometer. Once the
capabilities of the apparatus are confirmed, its power capabilities were examined and a
plan for implementing the LEDs determined through the software will be developed.
3.2 Building of Preliminary Apparatus

The intention of the preliminary apparatus was only to test that a multi-channel, tunable voltage source could be built and operated for both low and high-powered LEDs. Therefore, there were few changes made to the original Digman design. The most notable of these changes was in switching the Arduino used to interface with the source from an Uno to a Mega 2560. The complete parts list can be found in Table 3.1 The list of components from the table only includes the parts needed for a single channel. In anticipation of the need for multiple channels, additional units of each component were ordered.

Table 3.1: Preliminary apparatus part list. Parts used to build and operate the voltage source.

<table>
<thead>
<tr>
<th>Units</th>
<th>Part</th>
<th>Specifications</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>Breadboard</td>
<td>Small and Large</td>
</tr>
<tr>
<td>1</td>
<td>Arduino</td>
<td>Mega 2560</td>
</tr>
<tr>
<td>1</td>
<td>Laptop Charge</td>
<td>65W/20V</td>
</tr>
<tr>
<td>1</td>
<td>PMOS</td>
<td>1RF9Z34N</td>
</tr>
<tr>
<td>2</td>
<td>Diode</td>
<td>1N5818</td>
</tr>
<tr>
<td>1</td>
<td>Opamp</td>
<td>LT1632CN8</td>
</tr>
<tr>
<td>1</td>
<td>Capacitor</td>
<td>22 µF</td>
</tr>
<tr>
<td>2</td>
<td>Capacitor</td>
<td>1000 µF</td>
</tr>
<tr>
<td>1</td>
<td>Inductor</td>
<td>680 µH</td>
</tr>
<tr>
<td>1</td>
<td>Resistor</td>
<td>10k Ω</td>
</tr>
<tr>
<td>2</td>
<td>Resistor</td>
<td>100k Ω</td>
</tr>
</tbody>
</table>

To save time and space, two separate voltage sources were built simultaneously on a single breadboard. A close up of the first channel’s source can be seen in Fig. 3.2.
3.3 Testing of Preliminary Apparatus

To determine the viability of the voltage source, tests were run for both the single and dual-channel systems. An Ocean Optics spectrometer was used to record the intensity, and the raw data was collected using the OceanView program. Fig. 3.3 displays the testing apparatus that was used for both tests as well as a close-up of the dual-channel voltage source with the positioning of the spectrometer. In order to minimize the interference from other light sources, the testing was conducted in a windowless workroom with all light
sources either switched off or covered.

Figure 3.3: Images of testing apparatus. (Left) Testing setup with the voltage source(s), spectrometer and computer for interface. (Right) Close-up of the dual-channel system and testing components.

The initial test attached three red LEDs in parallel to channel 1 to observe the change in intensity as the voltage was increased from 0 to 12V. Fig. 3.4 displays the intensity curves of the source as the voltage was increased. It can be seen that at 1V the curve is defined entirely by the background noise and not affected by the LEDs themselves. It was found that at 3V (Fig. 3.4a) the intensity of the LEDs first began to affect the curve but the interference from the background still played a large factor. As the voltage was increased, it can be seen that the intensity associated with the LEDs themselves overcame that of the background. This test revealed that channel 1 was working as expected so a second test of both channels was conducted.
For the second test, channel 2 which contained 3 blue LEDs was connected in parallel with channel 1. The total intensity profile was observed. Fig. 3.5a and 3.5b show that the intensity output of each channel is nearly identical when at the same voltage. This further demonstrated that each channel was providing the desired voltage. The buildup of background noise in comparison to the LED intensity as experienced in the testing of the single channel is once again visible, particularly in Fig. 3.5a which is at a lower voltage for each channel. Fig. 3.5c and 3.5d demonstrate that as the voltage of each channel is adjusted separately the resulting intensity curve adjusts as expected.
Figure 3.5: Dual channel intensity profiles. Intensity profile voltage source with red (channel 1) and blue LEDs (channel 2) at various voltages.

After successful testing of the apparatus with the low-powered LEDs preliminary tests of the high-powered LEDs could be conducted. However, due to the sensitivity of the voltage vs. current relationship of the high-powered LEDs, the consistency of the voltage source needed to be verified first.

3.4 Testing of High-Powered LED

When working with high-powered LEDs, it is paramount to verify that the voltage being supplied to the LED is regulated. This is because small changes in the voltage being supplied create large changes in the current running through the LED. Substantial current
changes greatly increase the risk of destroying the LED through overloading. By looking at Fig. 3.6, this relationship is clearly visible. It can be seen that a change from 2.8V to 3.2V results in a nearly 10 fold increase in the current flowing through the LED. In order to compensate for this relationship, the output voltage of each channel was measured.

![Figure 3.6: Voltage vs. Current plot for Roithner 450 nm LED [Roithner Lasertechnik, 2020]](image)

To test the output voltage, a voltmeter was used to measure the voltage output of each channel and compare it with the input voltage selected on the GUI. It was found that each source produced an output voltage that was slightly greater than the input. In particular, the percent difference between the two values for voltages ranging from 0 to 12V averaged 16% for the first channel and 14% for the second. It was also noted that the error range was much larger for smaller voltages and that a true value of 0V could not be reached for either source. These particular concerns will be discussed more in the following section.
Though there was a discrepancy between the input voltage and output voltage, the error was small enough that short tests of a single high-powered LED could be conducted. However, only if the input voltage was below the output voltage error margin. An LED of 450 nm was chosen for the initial test. It was soldered to a printed circuit board (PCB) in order to be more easily added to the circuit. The PCB used was produced by Roithner particularly for the LEDs in the SMB1N series. It allowed for proper cooling of the LED by means of a large heat sink; this made testing the LED possible as overheating is one of the largest concerns for LEDs operating at these power levels. The particular PCB did not have built in breadboard connections so alligator clips were used to connect it to the system.

For this test, the voltage of the power supply was fixed at 3V. This ensured that the maximum current of the LED was not exceeded. The LED was also only operated for short periods of time in order to maintain an operating temperature that was low enough not to increase the voltage. Fig. 3.7 shows the successful lighting of the 450 nm LED. It is evident from the image that the intensity is vastly greater than that of the 3 LEDs tested before.
Figure 3.7: Image of high powered LED test. Roithner SMB1N-D450 LED being powered by the voltage source operating at 3V.
Chapter 4: Discussion

After completing the software analysis, building and testing the apparatus, it has been shown that the preliminary apparatus is capable of powering a dual channel voltage source with each channel tunable from 0V to 12V. It has also been shown that the source is able to, for short times, safely run a single, high-powered, Roithner LED. It is now time that the limitations and scalability of the preliminary apparatus be examined and any changes needed for more safely controlling the high-powered LEDs be determined.

4.1 Increasing Channel Number and Number of LEDs

By better understanding the limitations on the voltage and current of the apparatus, its scaling ability can be determined. To begin this analysis, it is important to note that the original design documents advised not to provide any single channel with more than 0.6A of current. They reported that at currents higher than this the sag in the output voltage is no longer negligible. However, they also reported that the maximum sag was 0.2V, so it is possible that the sag in output voltage may not be enough to have a substantial effect on the intensity of the high-powered LEDs. Additional testing of the output voltage at increasingly large currents should be conducted next. In particular, currents up to 1A should be tested as that is the maximum current required for the higher wavelength Roithner LEDs. If the voltage sag has a negligible effect on the overall intensity of the LEDs, there will be an increase in the number of channels and LEDs per channel that can be run by the 65W/20V power supply. Once these tests have been conducted,
final decisions on the number of channels the power supply can control can be made.

Regardless of the results of this testing, it is necessary to increase the number of channels that can be interfaced with the Arduino and GUI. There are two options here, each with their own benefits and setbacks. The first is adjusting the software to enable the control of more channels and the second is using additional Arduinos with the dual channel software. The first allows for an increase in channel number while still utilizing a single GUI. The latter increases the processing power and number of GUI needed but eliminates the complexities that may come with adjusting the software. It is possible that both of these options may need to be utilized in order to reach the 16 channels needed for the final apparatus.

With an increase in channels also comes the option for an increase in the number of LEDs per channel. This brings about the question of what type of circuit, series or parallel, should be utilized for a multi-channel, multi-LED system. After evaluating the possibilities and researching other large scale, high-powered LED systems, it has been determined that it would be best to build a completed circuit with the voltage sources in parallel but the LEDs themselves in series. Fig. 4.1 displays the basic circuit diagram for this type of circuit with expandable channel numbers (N) and LEDs per channel (n).
By using a mixed circuit, the limitations of the power supply can be minimized. To best understand these minimizations, it is favorable to consider an idealized circuit. In this ideal case, the current will be split evenly between each channel and be constant over each LED in the channel. For example, if the preliminary apparatus was to be expanded to five channels, then the current being supplied to each would be 0.65A (one fifth of the 3.25A from the power supply). If this current is too large for the LEDs in the channel, it can be further dampened through the use of resistors. It should be noted that in this ideal case it has been assumed that the resistance of each channel is equal. Further calculations to compensate for the current difference in each channel caused by any variations in resistance of the non-ideal system must be completed before finalizing the full scale design.
Fig. 4.2 displays a possible arrangement of the up-scaled voltage source using the high-powered LEDs determined from the software analysis and the 65W/20V power supply.

Figure 4.2: Example circuit layout. Diagram of 5-channel, expanded circuit using the 65W/20V power supply.

Overall, the total channels can range from 1 to 10 depending on the desired individual channel current. This would allow for a channel current of 1.1A for a 3-channel system and 0.33A for the 10-channel system. This range of channel currents makes it possible to power some arrangement of all of the high-powered LEDs as the required current for them ranges from 0.3A to 1.0A. The number of LEDs per channel could also be maximized to include anywhere from three to five LEDs. These limits come from the maximum and minimum forward voltages of the LEDs with values of 3.8V and 2.2V, respectively. These channel and LED ranges allow for many circuit configurations using the
preliminary apparatus; however, an apparatus that utilizes all 166 LEDs over the full 16 channels will require some changes. The two largest being that the software will need to be adjusted to allow for voltages larger than 12V to be supplied and a larger power supply must be added.

4.2 The Fully Scaled Apparatus

To understand the requirements of a fully scaled apparatus, it is first necessary to determine the power requirements for each individual channel of LEDs. Table 4.1 displays the total power requirement for each channel based on the maximum current and forward voltage for each LED. The power for one LED can then be multiplied by the number of LEDs to find the total channel power. From these values it can be determined that the maximum power consumption of the LEDs is 236W. This total power consumption of the LEDs will differ from the minimum power requirement of the final supply. To determine the latter, the minimum current and voltage must be evaluated.
Table 4.1: Final apparatus channel power requirements. Table of the total power required for each type of LED.

<table>
<thead>
<tr>
<th>Company</th>
<th>Part Number</th>
<th>Power (W)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thor Labs</td>
<td>LED385L</td>
<td>2.1</td>
</tr>
<tr>
<td>Thor Labs</td>
<td>LED395L</td>
<td>2.1</td>
</tr>
<tr>
<td>Roithner</td>
<td>SMB1N-D450</td>
<td>7</td>
</tr>
<tr>
<td>Roithner</td>
<td>SMB1N-D470</td>
<td>6.65</td>
</tr>
<tr>
<td>Roithner</td>
<td>SMB1N-490H</td>
<td>6.65</td>
</tr>
<tr>
<td>Roithner</td>
<td>SMB1N-590</td>
<td>5.25</td>
</tr>
<tr>
<td>Roithner</td>
<td>SMB1N-620D</td>
<td>4.725</td>
</tr>
<tr>
<td>Roithner</td>
<td>SMB1N-670D</td>
<td>9</td>
</tr>
<tr>
<td>Roithner</td>
<td>SMB1N-680D</td>
<td>9</td>
</tr>
<tr>
<td>Roithner</td>
<td>SMB1N-720</td>
<td>11.76</td>
</tr>
<tr>
<td>Roithner</td>
<td>SMB1N-750</td>
<td>9.6</td>
</tr>
<tr>
<td>Roithner</td>
<td>SMB1N-760D</td>
<td>20</td>
</tr>
<tr>
<td>Roithner</td>
<td>SMB1N-780D</td>
<td>10.4</td>
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<td>Roithner</td>
<td>SMB1N-830N</td>
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<td>Roithner</td>
<td>SMB1N-880D</td>
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</tr>
<tr>
<td>Roithner</td>
<td>SMB1N-910D</td>
<td>45</td>
</tr>
</tbody>
</table>

To understand the minimum requirements for the current and voltage of the full system, we can refer back to the general diagram in Fig. 4.1. For an ideal expandable circuit of this design, it is important to note two things. The first is that the total current will be split evenly between each channel and the second is that the voltage supplied to the channel must be large enough to power each of the LEDs in the channel. This implies that the power supply must have a minimum current that is equal to the number of channels times the maximum current required. It also indicates that the supply must have a maximum voltage that is equal to the maximum voltage required to run the largest
channel. By determining each of these values, the minimum power of the final apparatus can be determined.

The minimum current draw of the final apparatus will be 16A. This is due to the necessary current being 1A for the largest wavelength infrared LED. This makes it necessary to supply the full 1A to each channel. Resistors can be used to reduce the current through each channel as necessary. For the minimum voltage needed, we will only be considering the voltages of the Roithner LEDs as the UV LEDs supplied through Thor will likely be switched out for higher powered LEDs. Making this adjustment will not effect the final power result as the needed intensity in the UV is substantially less than the rest of the spectrum. This means fewer LEDs will be needed and therefore the overall voltage will be smaller than that of the larger wavelengths. After making this adjustment, it can be seen that the largest channel voltage total comes from the the 830nm channel. This voltage is 55V and is what the minimum supply voltage to each channel must be. The voltage to each channel can later be regulated using their respective buck converters. These 16A and 55V minimums require that a minimum power supply of 880W be used for the final system if using a mixed parallel/series circuit as described in Fig. 4.1.

Since the difference between the maximum power consumption (236W) and the minimum power requirement (880W) of this type of supply is so large, there will be a substantial amount of power being supplied yet unused. This unused portion would cause large amounts of heat to build up in the system which would inevitably cause system failure. Compensating for this is fundamental to the final design and can be achieved in
various ways. The most advantageous solution is for the circuit layout to be reorganized in order to minimize the minimum power requirement. This reorganization would involve a similar layout to that of Fig. 4.1 with the larger wavelength channels having an additional nested parallel, series design rather than a single channel of LEDs in series. These types of layout modifications can compensate for heat buildup but additional analysis and testing is required before a final design can be reached.

4.3 Creating a Constant Current Source

As mentioned in the previous sections, the relationship between the voltage and current being supplied to any high-powered LED is quite sensitive (as seen in Fig. 3.6). That is, a very small change in the voltage (0.2-0.4V) can increase the current by an entire order of magnitude. These types of drastic current changes would result in failure of the LED and could cause a ripple effect in the complete circuit. The voltage source that has been built for the preliminary apparatus is a constant voltage source. That is, it supplies a consistent voltage to the system and theoretically also supplies a constant current. However, in reality small changes in the system over time (particularly thermal changes) can cause small increases in voltage that are sufficient enough that they must be compensated for. To accommodate for this, it is necessary to drive the high-powered LEDs with a constant current source instead.

The preliminary apparatus can be modified to serve as a constant current source. This can be accomplished by adjusting the constant voltage source so that it monitors the
current running through the channel rather than the voltage being supplied. This is most readily done by using a sense resistor that relates the voltage running through it to the current running across it. The circuit adjustments to achieve this can be seen in Fig. 4.3, where $V_{fb}$ is the voltage feedback from the original circuit and $V_{fb,new}$ is the new feedback voltage delivered to the OpAmp. This new feedback voltage will have been adjusted by a proportionality constant that will relate the voltage across the sense resistor to the current through it. This adjustment allows for the current to be monitored and adjusts the PWM of the PMOS accordingly. This enables the system to maintain a constant current.

![Figure 4.3: Constant Current Adjustments. Diagram of the circuit adjustments needed to create a constant current source.](image)

4.4 Additional Considerations

As mentioned in the previous section, the difference between the output voltage and input voltage was substantially larger for small voltage values. In particular, it was found that neither source would approach a 0V output when desired. Instead, the voltage output for each source was 1.6V for both a 0V and 1V input. These values skewed the overall
average difference. However, due to the fact that the required forward voltage for most LED’s is greater than 3V, these two initial values can be ignored. This brings the percent difference for each source to a more acceptable 6% and 4%, respectively.

Another issue that must be noted is the noise seen at the lower voltages of the tests for both the single and dual-channel systems. These noise levels were significant at voltages of 4V or less for both tests even though care was taken to eliminate background light interference. It is particularly important to note this noise at low voltages as all of the Roithner LEDs in the SMB1N series reach max intensity between 2.2V-4V. Though these voltages are within the range of increased background noise for preliminary testing, it is unlikely that the same significance will be observed with the high-powered LEDs. This is due to the fact that the intensity of the new LEDs is so much greater than the low-powered LEDs used in the preliminary testing that it will likely overpower the noise by a significant amount. This will need to be tested explicitly but it is partially confirmed by the lack of noise in the higher voltage (and therefore higher intensity) preliminary tests.
Chapter 5: Conclusions

ATM.ITT is a research project aimed at growing a better understanding of how the irradiation quality of an exoplanets host star can affect photosynthetic life on the planetary surface. Insight into this topic is necessary for determining which of these exoplanets are most suitable for life. One of the most important aspects of the ATM.ITT project is an irradiation source that can simulate the conditions of these various host stars. The ISEAS project has begun creating a second generation ATT.ITT project at Eastern Michigan University by building and testing a preliminary irradiation source.

Preliminary research was conducted using software that was created to evaluate the intensity profile of various combinations of LEDs. The intensity profile from the software was compared to that of a known M-dwarf star and visually aligned in order to determine the optimal LED combination. From the software, it was decided that a total of 166 high-powered LEDs over 16 separate channels would allow for sufficient simulation of the desired host stars. This information was then used to begin the design and construction of the irradiance source.

The preliminary apparatus served as a constant voltage source in which the voltage supplied to each of the two channels was tunable from 0V to 12V. The tunability of the apparatus was made possible by means of a buck converter which stepped down the incoming voltage by means of a PWM signal. Testing of this preliminary apparatus demonstrated that the preliminary source was capable of simultaneously powering two channels of low-powered LEDs within 6% output voltage accuracy. A preliminary test of a
single high-powered LED was also successful. Proof of the reliability of the preliminary voltage source leads to questions about the scalability of the power supply and the design of the final, fully scaled apparatus.
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