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Dynamics of Sky Brightness during a Hybrid Solar Eclipse using SQM

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Abstract

This study aims to analyze sky brightness dynamics during a hybrid solar eclipse using the Sky Quality Meter (SQM). Strategic observation sites were selected along the eclipse path, and continuous data collection was conducted using the SQM-LU-DL, telescopes, weather stations, and GPS for accurate location and atmospheric data. Measurements began several days before the eclipse and continued throughout and after the event. Data collected included sky brightness, visual documentation, and atmospheric conditions, which were analyzed using GnuPlot to detect trends and patterns in brightness changes. The study revealed significant fluctuations in temperature and light frequency, with a sharp decrease at the eclipse's peak, followed by a return to normal levels. These findings emphasize the eclipse's impact on natural light intensity and highlight the importance of addressing light pollution. The study contributes to understanding astronomical phenomena's effects on the environment and human health, aiding in the development of effective light pollution mitigation strategies.

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A. Introduction

A hybrid solar eclipse is a rare and exceptional celestial phenomenon involving a transition between a total eclipse and an annular eclipse in one pass [1]. This phenomenon occurs due to the difference in distance between the Moon, Earth, and Sun, which makes the appearance of the eclipse vary at various locations along the eclipse path [2]. Elmhamdi et al. [3] stated that observing eclipse dynamics can offer an opportunity to understand atmospheric phenomena and their influence on sky brightness. One tool used to measure sky brightness is the Sky Quality Meter (SQM), which allows researchers to collect accurate and detailed data about changes in sky brightness during an eclipse [4].

Sky Quality Meter (SQM) is a tool designed to measure the night sky's brightness in units of magnitude per square second of arc [5]. Amateur and professional astronomers commonly use this tool to assess sky quality in various locations, especially in the context of light pollution [6]. However, Levin et al. [7] claim that the use of SQM is not limited to nighttime; SQM can also be used to measure changes in sky brightness during the day, including during astronomical phenomena such as solar

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eclipses. In the context of a hybrid solar eclipse, SQM can provide essential data on variations in sky brightness before, during, and after the eclipse's peak and help understand how the eclipse affects local atmospheric conditions [8].

Research on the dynamics of sky brightness during hybrid solar eclipses is a novel and exciting field of study. This research has several main objectives. First, it aims to characterize changes in sky brightness that occur during an eclipse. These changes can provide information about the interaction between sunlight and the Earth's atmosphere, including how light is scattered and absorbed by particles in the atmosphere [9][10][11]. Second, this research can help identify factors that influence variations in brightness, such as weather conditions, the height of the sun in the sky, and the path of the eclipse. Third, by using SQM, researchers can compare data from various locations along the eclipse path, providing a more comprehensive picture of this phenomenon. The novelty of this research lies in its focus on a specific and rare astronomical event, and its potential to contribute to our understanding of atmospheric dynamics and light pollution.

Hybrid solar eclipses occurring in the coming years offer a rare opportunity to conduct this research. As amateur and professional astronomers, atmospheric scientists, and researchers, your direct observations and measurements using SQM can begin several days before the eclipse to obtain baseline data on sky brightness at the selected location. During an eclipse, measurements are made continuously to capture changes in brightness with high time resolution [12]. After the eclipse, measurements were continued to ensure complete data on the recovery of sky brightness to normal conditions [13]. The data obtained is then analyzed to identify patterns of changes in brightness and relate them to the phases of the eclipse and the atmospheric conditions observed. Your contributions to this research are invaluable and can help us gain a comprehensive understanding of the dynamics of sky brightness during hybrid solar eclipses.

Understanding the dynamics of sky brightness during hybrid solar eclipses is not only relevant for astronomy and atmospheric sciences but also has practical implications [14] [15] [16]. For example, knowledge of how eclipses affect sky brightness can help in planning other astronomical observations that may be disrupted by sudden changes in lighting conditions [17]. In addition, these data can be used to improve atmospheric models used in various scientific and technical applications [18]. In a broader context, this research may also contribute to global efforts to understand and reduce the impacts of light pollution, which is an increasingly important concern in the scientific community and the general public [19].

Research on the dynamics of sky brightness during hybrid solar eclipses also requires collaboration and coordination between various parties, including scientists, amateur astronomers, and local communities in the areas traversed by the eclipse path [20]. The participation of these multiple parties is essential to ensure broad and diverse data collection and to maximize the benefits of this research. For example, amateur astronomers spread across various locations can provide additional data that helps complement observations from the primary scientific team. Local communities can also play a role in supporting logistics and access to optimal observation locations.

This research is very relevant in Indonesia, which is often one of the locations traversed by solar eclipses [21]. Indonesia has geographic and atmospheric diversity that can provide valuable data about variations in sky brightness in various environmental conditions [22]. In addition, public participation in observing solar eclipses has become a strong tradition, which can be used to support scientific research [23]. Collaboration between research institutions, universities, and local astronomical communities could be a model for other countries in the eclipse path [24].

Overall, research on sky brightness dynamics during hybrid solar eclipses using SQM is a vital effort to deepen our understanding of this natural phenomenon. By combining modern measurement technology, collaboration between various parties, and taking advantage of rare moments of solar eclipses, this research is expected to contribute significantly to science and society. The results of this research will not only enrich our knowledge about eclipses and sky brightness but also open new opportunities for future scientific research and applications. So, from this background, this research aims to determine the dynamics of sky brightness during a hybrid solar eclipse using SQM.

B. Method

This research was carried out in several critical stages, which included preparation, data collection, data analysis, and interpretation of results. The initial stage involved selecting strategic observation locations along the eclipse path to ensure optimal data collection. The chosen locations should cover several points along the eclipse path to obtain representative data variations. The primary tool used in this research was the Sky Quality Meter (SQM), which measures sky brightness in units of magnitude per square arc second.

The specific SQM model used in this research was the SQM-LU-DL, protected using a solar filter (Figure 1). This filter shields the SQM from direct sunlight, rainwater, and other weather influences. The SQM faces the sky at the highest possible position, ensuring no obstructions block the observation. Data was collected at 30-second intervals. The SQM connects to a computer via a USB cable, providing power and data transmission.

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Figure 1. Installation of SQM in the peak direction

The data collection stage began several days before the eclipse to obtain baseline sky brightness data at the selected locations. Sky brightness measurements were carried out continuously using the SQM before, during, and after the eclipse peak. These measurements included collecting sky brightness data several minutes before first contact, during all eclipse phases, and after final contact. Visual documentation and atmospheric conditions were also recorded using telescopes and weather stations to complement the brightness data obtained from the SQM.

After data collection, the analysis stage involved processing the data using GnuPlot. Data from the SQM and other tools was downloaded to a computer and analyzed using statistical methods to identify patterns and trends in changes in sky brightness. Atmospheric modeling was also conducted to understand the eclipse's effect on sky brightness. Interpretation of the results involved correlating changes in sky brightness with the eclipse phases observed atmospheric conditions and making inferences about the dynamics of sky brightness during hybrid solar eclipses. The complete research flow is presented in Figure 2.

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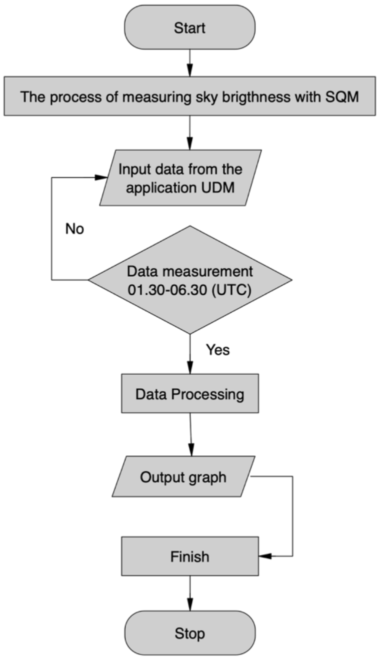

Figure 2. Research Flow

A quantitative research approach will be used to collect information regarding sky brightness levels using the Sky Quality Meter (SQM). Statistical analysis will be applied to interpret the data obtained. Equation 1 will be used to evaluate the performance of Unihedron Device Manager by utilizing relative frequencies to calculate sky brightness values based on the collected data [25].

$$p_i = \frac{n_i}{N} \quad (1)$$

Meanwhile, n is the number of frequencies of occurrence of sky brightness levels during all phases of a hybrid solar eclipse, and N is the number of frequencies of occurrence of sky brightness levels at interval I throughout the eclipse phase. The probability distribution graph can be processed by collecting sky brightness level data to identify the characteristics of light pollution as x,h. The value of the sky brightness level can be expressed as a function of the area of the class interval and density according to Equation 2 [26].

$$f(x) = \frac{n_i}{hN} \quad (2)$$

Eclipse phase data with the Maumere location is presented in Table 1.

Table 1. Eclipse Phases

Eclipse Phase	WITA	UTC
Initial Contact	10.38	02.38
Partial Eclipse Peak	12.11	04.11
Last Contact	13.46	05.46

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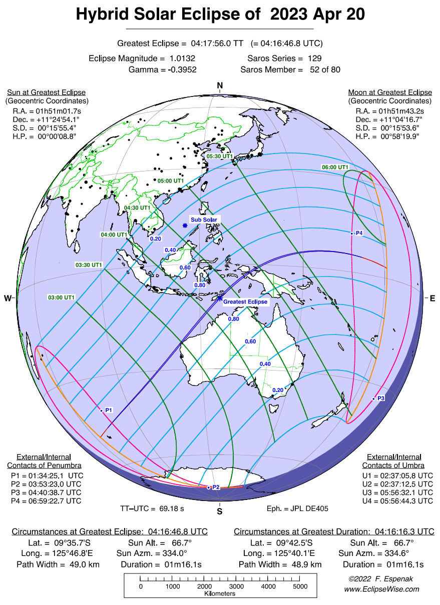
C. Results and Discussion

1. Hybrid Solar Eclipse Process

The first solar eclipse in 2023 is a rare phenomenon known as a hybrid or annular-total eclipse. It is a unique type of eclipse in which part of the path is visible as a ring (annular) while the other part is visible as a total. This duality occurs because the central point of the Moon's umbral shadow penetrates the Earth's surface in some places but does not reach the planet in other parts of its path. This unusual geometry is caused by the curvature of the Earth's surface, which results in some geographic locations being in the umbral shadow while others are in the antumbra instead of the umbra. In general, the middle path of a hybrid eclipse starts with a ring shape, changes to a total in the middle, and returns to a ring at the end of the path. However, there are cases where the central path starts as annular and ends as total, or vice versa. Because this event occurs near the top of the Moon's umbral shadow or antumbra, its central path is usually very narrow.



Adapted from *21st Century Canon of Solar Eclipses,* Fred Espenak, 2016.

Figure 3. Hybrid Solar Eclipse

The 2023 hybrid eclipse is visible within a thin corridor crossing the Eastern Hemisphere (Figure 3). The path of the Moon's shadow begins in the southern Indian Ocean near the Kerguelen Islands, moves northeast, almost touching the western part of Australia, crosses Indonesia, and ends in the Pacific Ocean about 3000 kilometers southeast of the Hawaiian Islands. The partial eclipse will be visible in the broader path of the Moon's

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penumbral shadow, covering Australia, Indonesia, northern New Zealand, and much of the western Pacific region, with the central eclipse path starting at 02:37 (UTC).

The eclipse begins when First Contact occurs, when the disk of the Moon, visible as a gray circle, begins to cover the disk of the Sun. As time goes by, the eclipsed part of the Sun's disk will get bigger until the entire Sun's disk is finally covered by the Moon, which is called the Second Contact. This process ends when the Moon's disk last covers the Sun's disk, referred to as the Third Contact.

The period between Second Contact and Third Contact is known as the Total Duration or Total Phase. This duration varies from one location to another, highlighting the unique experience of witnessing a solar eclipse. For instance, the longest total duration in the center of an Indonesian city for the April 20 2023 hybrid solar eclipse (GMH) occurred in Biak, Papua, lasting 1 minute 1.9 seconds with an eclipse magnitude of 1.004. Meanwhile, the longest total duration on the earth's surface, called the Greatest Duration (GD), occurred in the Timor Sea at coordinates (09°35'24" S 125°48'24" E), with a total duration of 1 minute 16 seconds and a magnitude eclipse of 1,013. Other cities in Indonesia experienced shorter total duration and magnitude of the eclipse.

During the total phase at these locations, the sky's brightness will dim until it resembles dawn or dusk, with the peak of dimness occurring at the Eclipse Peak, which is the midpoint of this total phase. After the Third Contact, the eclipsed disk of the Sun will become smaller until the Moon finally covers the Sun's disk, called the Fourth Contact. The time between First Contact and Fourth Contact is called the Eclipse Duration, which also varies from location to location. The most extended eclipse duration in Indonesia at GMH 2023 occurred in Tiakur, Maluku, 3 hours 10 minutes 32 seconds. Figure 4 shows an observation image of a partial solar eclipse in the Maumere region, NTT in time (WITA).

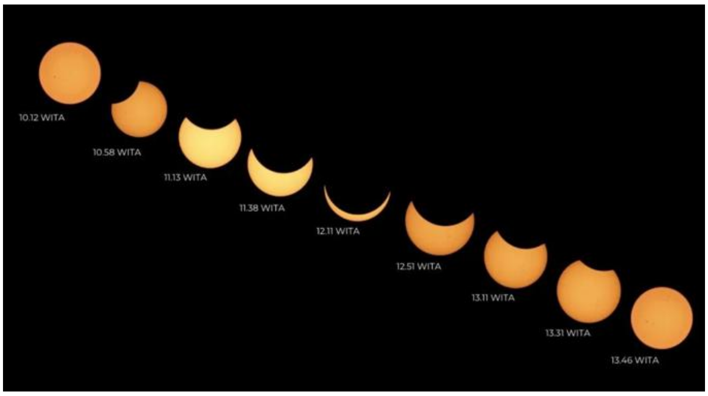

Figure 4. Image of the Hybrid Solar Eclipse in Maumere in WITA time

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2. SQM Measurement

The data provided results from monitoring light pollution using the SQM-LU-DL-R1 device at the Rooftop location of the Ahmad Dahlan Building, Muhammadiyah University, Maumere. This location has geographic coordinates -8.63106 latitude, 122.24228 longitude, and a height of about 40 meters above sea level. This data is issued under an ODbL 1.0 license and is available via the URL darksky.org/measurements. Measurements were carried out in the Asia/Makassar time zone, and the device used was in a static position with a fixed viewing direction.

Data includes measurements using a single channel without a specific filter, with additional details such as SQM device serial number, hardware identity, firmware version, and SQM masking offset value. Additional information includes test results of SQM readings for various parameters such as temperature (30.9°C), frequency (292Hz), and calibration values. This data also records the time difference with the reference and the last data collection time in UTC on April 20, 2023, at 01:49:24.026. This data is recorded continuously every 30 seconds with a threshold of 0 mesas, according to UDM (User Defined Metadata) version 1.0.0.332 settings.

In Figure 5, it can be seen that the temperature starts to increase from around 01:30 (UTC), reaching a peak around 03:00 (UTC) with a value close to 38°C. After reaching the peak, the temperature decreases drastically until it reaches its lowest point around 04:30 (UTC) with a value close to 28°C. After that, the temperature gradually increased until it reached a value close to 37°C at around 06:30 (UTC). These significant temperature fluctuations indicate major environmental changes during the observed period. The drastic drop in temperature around 04:30 (UTC) was caused by a specific natural event, namely a hybrid solar eclipse, where the influence of the moon's shadow caused a rapid drop in temperature. The rising temperature after the eclipse passes indicates a return to normal environmental conditions.

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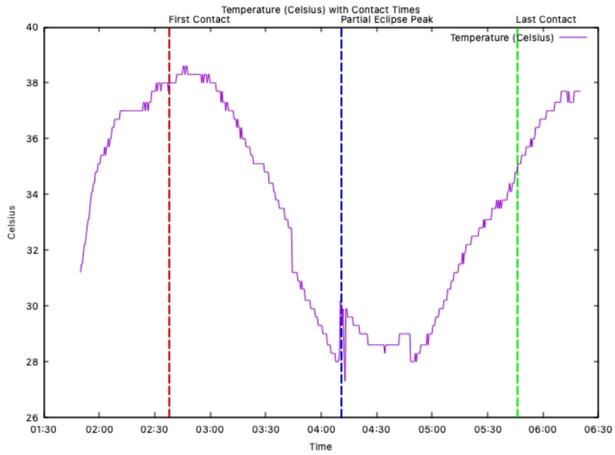

Figure 5. Temperature graph at each contact time

Figure 6 shows the results of measurements using the Sky Quality Meter (SQM) during the hybrid solar eclipse. Measurements were carried out in the time range from 02:00 (UTC) to 06:30 (UTC), showing changes in light frequency over time. At the beginning of the measurement, around 02:00 (UTC), the light frequency was recorded at approximately 292 Hz. Next, the frequency decreases gradually and reaches a peak of roughly 50-40 Hz around 04:10 (UTC), coinciding with the peak phase of the eclipse. After the eclipse's peak, the frequency increases gradually until the measurements end at around 06:30 (UTC).

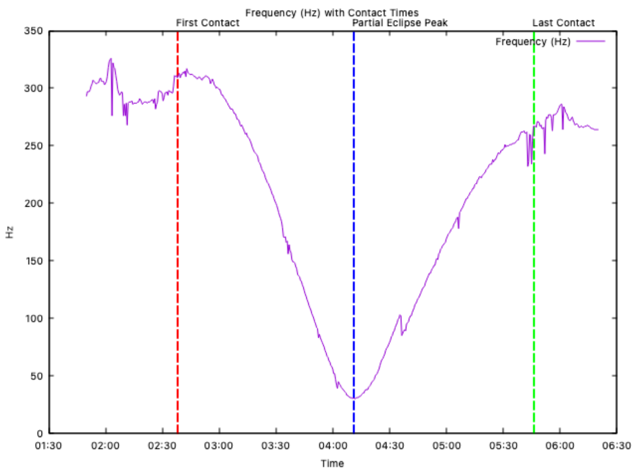

Figure 6. Frequency graph for each contact time

This data reveals a clear pattern of increasing light frequency from the start to the midpoint of the measurement, followed by a decrease after the eclipse's peak. This pattern mirrors the changes in light intensity during a hybrid solar eclipse. The significant reduction in sunlight reaching the Earth's surface during the eclipse's peak is evident, as is the subsequent

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increase after the eclipse concludes. This understanding of the eclipse's impact on light intensity is a crucial outcome of our research.

Figure 7 is a graph that shows changes in brightness in magnitude per arc second squared (mag/arcsec²) versus time. The x-axis shows the time from 01:30 (UTC) to 06:30 (UTC), while the y-axis shows the brightness in units of mag/arcsec². The graph shows that the brightness begins to increase around 02:30 (UTC), reaching a peak around 04:00 (UTC) with a maximum value close to 15.5 mag/arcsec². After the eclipse's peak, the brightness gradually decreases again until it reaches a more stable value around 06:00 (UTC).

This data shows a significant increase in brightness. Small fluctuations seen at the beginning and end of the graph indicate variations in brightness that may be caused by environmental factors or measuring instruments. Importantly, these graphs are designed to provide a clear and easily understandable picture of the pattern of changes in sky brightness during a hybrid eclipse in the indicated time span.

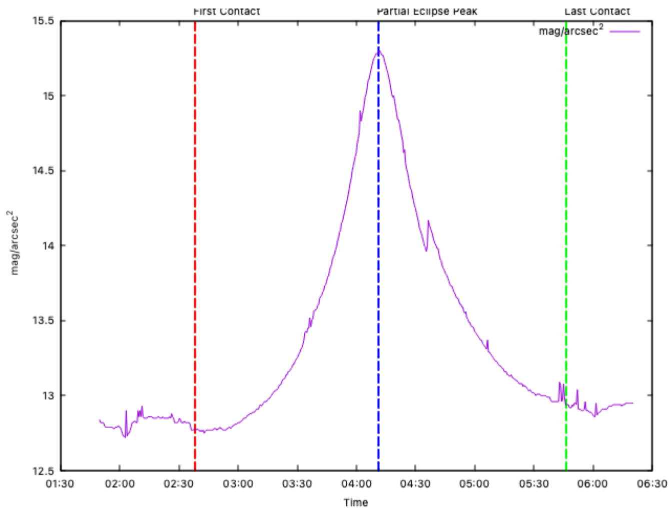

Figure 7. Brightness graph at each contact time

Comparison data using Phyphox (Figure 8) shows that the illuminance starts from a high value of around 1750 lux and then decreases gradually, reaching a low point below 250 lux. After that, the illuminance increases slowly until it approaches the initial value at around 16000 seconds. This measurement was carried out using the Phyphox application during a hybrid solar eclipse. Phyphox is an application that allows users to conduct various physics experiments using smartphone sensors. In this context, Phyphox measures illuminance or changing light levels during hybrid solar eclipses. The graph shows a pattern of significant changes in illuminance, with a sharp decrease followed by a gradual increase. This pattern reflects the process of a solar eclipse, in which the moon's shadow covers part or all of the sun, causing a drastic reduction in lighting levels. After the eclipse's peak, when the sun reappears from the moon's shadow, the illuminance increases again until it reaches normal conditions.

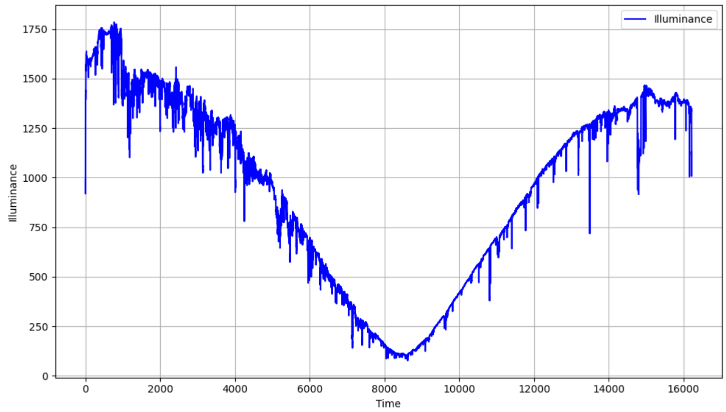

Figure 8. Illumination graphic during a hybrid solar eclipse

The data provided results from monitoring light pollution using the SQM-LU-DL-R1 device at the Rooftop location of the Ahmad Dahlan Building, Muhammadiyah University, Maumere. This location has geographic coordinates -8.63106 latitude, 122.24228 longitude, and a height of about 40 meters above sea level. This data is issued under an ODbL 1.0 license and is available via the URL darksky.org/measurements. Measurements were carried out in the Asia/Makassar time zone, and the device used was in a static position with a fixed viewing direction. Data includes measurements using a single channel without a specific filter, with additional details such as SQM device serial number, hardware identity, firmware version, and SQM masking offset value. Additional information includes test results of SQM readings for various parameters such as temperature (30.9°C), frequency (292Hz), and calibration values. This data also records the time difference with the reference and the last data collection time in UTC on April 20, 2023, at 01:49:24.026. This data is recorded continuously every 30 seconds with a threshold of 0 mpsas, according to UDM (User Defined Metadata) version 1.0.0.332 settings.

This research is fundamental in the context of monitoring and mitigating light pollution as well understanding of the phenomenon of hybrid solar eclipses. The data collected shows that changes in temperature and light intensity during the eclipse significantly impact the local environment. The temperature experienced large fluctuations, starting with an increase in temperature until it peaked at around 03:00 (UTC) and then decreased drastically during the peak of the eclipse at 04:30 (UTC). Solar eclipses can significantly influence local

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temperatures, impacting various aspects of local ecosystems and human activities. The return of temperatures after the eclipse indicates a recovery of the environment to customary conditions, highlighting the importance of understanding the short-term impacts of this astronomical phenomenon.

Cimoli et al. [27] revealed that the results of light frequency measurements during a solar eclipse will show apparent changes in light intensity. Bernhard et al. [28] claim that light frequency fluctuations will increase gradually until they peak at the eclipse's peak and then decrease again after the eclipse ends. This trend reflects the influence of the moon's shadow, which reduces the amount of sunlight that reaches the Earth's surface [29]. This information is invaluable for understanding how solar eclipses can affect the quality of light in urban and rural environments and the implications for astronomical observations.

Information showing changes in brightness in magnitudes per arc second squared (mag/arcsec^2) provides additional insight into the impact of a solar eclipse on sky brightness. The significant increase in brightness during the eclipse's peak indicates that the moon's shadow effectively reduces the amount of light scattered in the atmosphere, making the sky darker [30]. After the eclipse's peak, the brightness again decreases to a more stable level, reflecting the return of normal light conditions [31]. Small fluctuations in brightness may be caused by environmental factors or variability of measuring instruments. Still, the overall trend provides strong evidence of the effect of a solar eclipse on sky conditions [32].

The urgency of this research lies in the importance of understanding and managing light pollution and its impact on the environment and society. Light pollution has become an increasingly pressing environmental problem, with far-reaching implications for human health, ecosystems, and astronomy. This research provides important empirical data for developing effective light pollution mitigation strategies. By understanding how solar eclipses affect light intensity and sky brightness, we can design more adaptive and environmentally friendly lighting systems that reduce the negative impacts of light pollution while still meeting human lighting needs.

Furthermore, this research has practical implications for the astronomy community. Astronomical observations are often disrupted by light pollution, which reduces the visibility of celestial objects and the quality of astronomical data. Data from this research can be used to identify optimal time periods and environmental conditions for astronomical observations, allowing astronomers to plan their observations more effectively. Moreover, it can guide the design of more efficient observatory facilities by considering influential environmental factors, thereby directly benefiting the astronomy community.

Importantly, this research has significant implications for human health. Light pollution has been linked to a variety of health problems, including sleep disorders, circadian rhythm disruption, and an increased risk of chronic disease. By understanding how changes in light intensity during astronomical phenomena such as solar eclipses affect the light environment, we can develop better recommendations for lighting design that supports human health and well-being. This includes lighting that is more natural and in line with circadian rhythms, which can help reduce the negative impacts of light pollution on health.

Additionally, this research provides important insights into the impact of climate change on local light intensity and temperature. Significant temperature fluctuations during the eclipse indicate that climate change may affect atmospheric phenomena and microclimates in certain regions. This data can be used to model and predict the impact of climate change on local environmental conditions, which can help design more effective adaptation strategies.

Overall, this research highlights the importance of monitoring light pollution and understanding astronomical phenomena in the context of environmental change and human health. With accurate data and in-depth analysis, we can develop better policies and strategies to manage light pollution, protect the environment, support human health, and improve the quality of astronomical observations. The urgency of this research must be considered, considering its broad and significant impact on various aspects of our lives.

It is important to continue researching and monitoring light pollution continuously. Tracking technologies such as SQM and applications such as Phyphox provide practical tools for collecting the data required for in-depth analysis. By leveraging this technology, we can identify long-term trends, measure the effectiveness of interventions, and make more informed decisions to protect our environment. This research also emphasizes the importance of collaboration between scientists, policymakers, and the general public in addressing the problem of light pollution and its impacts.

D. Conclusion

Light pollution monitoring research using the SQM-LU-DL-R1 device on the Rooftop of the UNIMOF AD Building revealed the significant impact of the hybrid solar eclipse on local light intensity and temperature. The data collected shows temperature fluctuations and changes in light frequency that reflect the influence of the moon's shadow during the eclipse, where the temperature drops drastically, and the brightness of the sky decreases during the peak of the eclipse, then returns to normal after the eclipse ends. This research highlights the urgency of understanding and managing light pollution, which has broad implications for human health, ecosystems, and the quality of astronomical observations. More effective light pollution mitigation strategies can be developed with the empirical data obtained, including adaptive lighting designs that support circadian rhythms and human health. Additionally, insights into the impact of climate change on local light intensity can help design better environmental adaptation strategies. This research also emphasizes the importance of collaboration between scientists, policymakers, and society in addressing the problem of light pollution and the need for ongoing research using advanced monitoring technologies. With a holistic, data-driven approach, we can protect the environment, support public health, and ensure optimal quality of astronomical observations.

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