Photometry of Two Total Lunar Eclipses

ABSTRACT

This paper summarizes disk-integrated brightness measurements of the moon during its May 16, 2022 and November 8, 2022 eclipses. The totally-eclipsed Moon had respective B- and V-filter brightness values of 0.29 and –1.83 magnitudes near greatest eclipse on May 16. On November 8, the Moon at greatest eclipse had respective J- and H-filter brightness values of –7.42 and –8.41 magnitudes. These appear to be the first J- and H-filter brightness measurements of the totally-eclipsed Moon. The eclipsed Moon did not darken nearly as much as it sank deeper into Earth's umbra for the J and H filters as for the B and V filters. Based on several total eclipses, the Moon is a little brighter than predicted for the V filter and significantly brighter than predicted for the B filter.

INTRODUCTION

Total lunar eclipses are an opportunity to measure how our upper atmosphere interacts with light. Furthermore, since lunar eclipses happen at different times, the atmosphere over different parts of the Earth affects the eclipsed-Moon's brightness (Karkoschka, 1996). Finally, since they happen in different years, they serve as a probe to measure atmospheric changes happening over multi-year periods of time (Di Giovanni, 2018), (Herald and Sinnott, 2014).

Barbier (1961) reviews lunar eclipse studies carried out before 1961. By that time, astronomers knew that the brightness of the totally eclipsed Moon changed from year to year and that it was 10-13 magnitudes dimmer than at a fully illuminated phase in visible light. They also knew the eclipsed moon darkened more in shorter visible wavelengths than at longer ones. Finally, they were aware that ozone absorption affected the color of the totally eclipsed Moon.

Since 1960, several amateur astronomers have estimated the eclipsed Moon's color and brightness using approximate (but useful) methods. For example, many have carried out color estimates of the totally eclipsed Moon on the Danjon index (Astronomical Almanac, 2021).

Others have carried out visual brightness estimates using the reverse-binocular method or some other similar technique (Schober and Schroll, 1973). These results have been reviewed elsewhere (Westfall, 1989), (Schmude, 2012), (Keen, 2018). Two trends confirmed in this early work include the relationship between the eclipsed-Moon's brightness and its Danjon index number, and that the brightness drop of the eclipsed Moon is larger after large volcanic eruptions. Brightness measurements with photoelectric photometers and similar devices yield more accurate brightness and color measurements of the eclipsed Moon as described in the next paragraph.

Schober and Schroll (1973), Ugolnikov et al. (2011), Hernitschek et al. (2008), Schmude et al. (2000), Schmidt (2022) and (Schmude (2004, 2022) have carried out brightness measurements of the eclipsed Moon using photoelectric photometers. These studies involved the measurement of the eclipsed-Moon's brightness in standard Johnson B and V passbands. They have yielded accurate quantitative brightness measurements in these two wavelength ranges. This has allowed for the comparison between experimental and theoretical work related to total lunar eclipses.

Mallama (2022) reports that the eclipsed-Moon's brightness depends on three characteristics of our atmosphere. These are refraction, absorption and focusing of sunlight. He goes on to produce a model that predicts the brightness of the eclipsed Moon based on these three factors. He predicts the brightness of the eclipsed Moon in blue, green, red, and infrared light based on the Johnson-Cousins BVRI system. He also predicts the Moon's brightness and B – V color index at mid-eclipse for the lunar eclipses between 2000 and 2050. Therefore, experimental measurements of the eclipsed Moon's brightness may be compared to predicted values.

Measuring the brightness of the eclipsed Moon at wavelengths above 1000 nm may give us new insights on how our atmosphere interacts with this kind of light. Schmude (2023) reports early whole-disk brightness measurements of the moon in the standard J and H photometric filters (Henden, 2002). These appear to be the first disk-integrated measurements of the Moon with these filters. The November 8, 2022 total lunar eclipse presented an opportunity for the writer to measure the eclipsed-Moon's brightness in the J and H filters.

The standard eclipse terms U2 and U3 are used in this report. The point U2 is when all of the Moon has just entered the Earth's umbra and U3 is the last instant that the Moon is in the Earth's umbra before beginning to move out of it. The time of greatest eclipse is when the Moon is closest to the center of Earth's umbra.

PURPOSE OF WORK

This paper reports accurate brightness values of the eclipsed Moon on May 16, 2022 (B and V filters) and November 8, 2022 (J and H filters). It is hoped that these results will help in better understanding how our atmosphere interacts with different wavelengths of light. Furthermore, eclipse modeling may help us better detect long-term changes in the stratosphere.

METHOD AND MATERIALS

The instruments and location are described in this paragraph and details on the two eclipses are given in the next two paragraphs. An SSP-3 Solid-State Photometer with a 2.0 mm aperture (Optec, 1997) along with a 0.024-meter lens with a focal length of 0.12 m was used in collecting the eclipse data on May 16. The entire system was transformed to the B and V system using the Two-Star Method (Hall and Genet, 1988). An SSP-4 Solid-State Infrared Photometer with a 1.0 mm aperture (Optec, 2005) along with a 0.01 m aperture lens with a focal length of 0.06 m was used in collecting the November 8 data. The entire system was transformed to the J and H system (Henden, 2002), (Schmude, 2016). All measurements for both eclipses were made from Barnesville, GA, USA at a latitude and longitude of 33.05° N and 84.15° W. Barnesville is at an elevation near 250 m.

Part of the difficulty of studying lunar eclipses is that the Moon's color changes at different stages in an eclipse. Essentially it grows redder as it approaches the deepest part of

Earth's umbra. Therefore, the transformation correction changes. An iterative approach was generally used for the May 16 results. Essentially, a B – V value was assumed, and transformation corrections were made. The resulting B – V value was compared to the assumed value and minor adjustments were made until the computed B – V value was within 0.01 magnitudes of the assumed B – V value. Extinction coefficients were measured during this eclipse. Secondary extinction coefficients of $k''_B = -0.03$ and $k''_V = 0.00$ were used (Hall and Genet, 1988).

The SSP-4 solid-state photometer was used in measurements of the Moon on November 8. Alpha Taurus was the comparison star, and its brightness values are from Henden (2002). Extinction coefficients were not measured on the morning of November 8 but were measured that evening. Values of $k_J = 0.0931$ and $k_H = 0.0795$ magnitudes/air mass were measured; these are close to the mean values for Barnesville, GA (Schmude, 2018). Transformation coefficients were measured using Jupiter (J – H = –0.50) and Alpha Taurus (J – H = 0.78) as comparison objects. The Two-Star Method was used (Hall and Genet, 1988) in measuring these coefficients. Transformation coefficients of 0.0359 and 0.0695 were measured for the J and H filters, respectively. Once again, an iterative approach similar to the one used for the May 16, 2022 eclipse, was used in applying transformation corrections. This is because the J – H value changed during the eclipse.

RESULTS

Table 1 lists brightness measurements of the Moon made during the May 16, 2022 eclipse. Clouds and hazes interfered for most the first half of this eclipse. The sky transparency improved afterwards. The B – V value of the full uneclipsed Moon is near 0.84 magnitudes (Lane and Irvine, 1973), (Schmude, 2017). During eclipse, the B – V value rose to 2.12 magnitudes near greatest eclipse and later dropped to 1.95 (4:38 UT) and 1.37 magnitudes (4:49:30 UT). At 4:54 UT the Moon reached U3 (Edgar, 2021), (Harvey, 2021), (Astronomical Almanac, 2021). Therefore, the B – V value dropped as the Moon went from greatest eclipse to the edge of Earth's umbra. This is consistent with previous measurements (Cuffey, 1952), (Schmude et al., 2000), (Schmude, 2022) and with theory (Mallama, 2022) (Karkoschka, 1996).

Table 1: Brightness measurements of the Moon during the total lunar eclipse on May 16, 2022. All brightness values are in magnitudes.

Time (UT)	**Filter**	**Brightness (magnitudes)**	**B – V (magnitudes)**
3:51	B	–0.20	(1.95) [A]
4:11	V	–1.83	---
4:14:30	B	0.29	2.12
4:34:30	V	–2.31	---
4:38	B	–0.35	1.95
4:41	V	–2.30	---
4:44:30	V	–2.63	---
4:49:30	B	–1.65	1.37
4:52:40	V	–3.40	---
4:52:50	V	–3.43	---
4:53	V	–3.46	---
4:53:10	V	–3.49	---
4:57	V	–4.61	---

[A] This B – V value is used in computing the color transformation correction factor; this value is selected because it was the measured B – V value 26.5 minutes after greatest eclipse which should be near the B – V value 20.5 minutes before greatest eclipse (Harvey, 2021).

How do the B- and V-filter measurements compare to predicted values? Mallama (2022) predicts a V-filter brightness of –0.5 magnitudes for the totally-eclipsed Moon on May 16, 2022. This value is for greatest eclipse. This is fainter than the observed (or measured) value in Table 1 (–1.83 magnitudes). The predicted B – V value is 4.0 magnitudes which is above the observed value of 2.12 magnitudes. Schmidt (2022) reports his measurements of the January 31, 2018 eclipse. He reports a "visual" mid-eclipse brightness of –2.8 magnitudes, which is 1.8 magnitudes brighter than the predicted brightness, = –1 magnitude (Mallama, 2022). Mallama (2022) states that the Moon drops to a V-filter magnitude of –3.5 when it has reached U2 or U3. The Moon reached point U3 at 4:45:11 UT on May 16 (Astronomical Almanac, 2021). A brightness of measurement of –3.49 magnitudes was made one minute before U3. Therefore, this is consistent with the prediction in Mallama (2022).

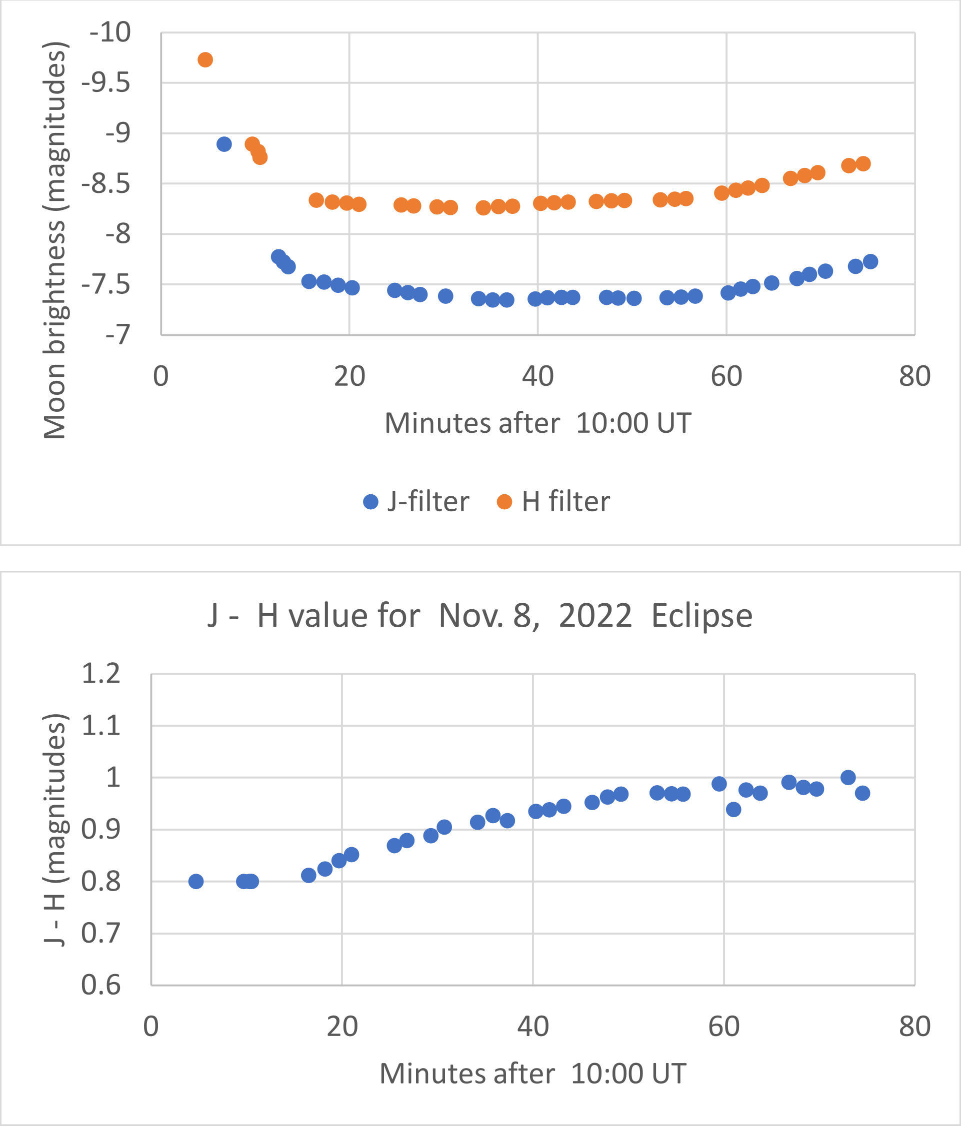
The brightness drop on May 16 may be estimated by computing the full Moon's without Earth's shadow. Our Moon had a phase angle of 1.0° at greatest eclipse while its Sun and Earth distances were 1.0134 and 0.002397 au, respectively (JPL Solar System Dynamics, 2022). Schmude (2018) reports a full-Moon brightness of -12.80 magnitudes when its respective phase angle, Sun distance and Earth distance are 3°, 1.000 au and 0.0025694 au. A mean opposition surge, when going from phase angles of 3.0° to 1.0° is 0.17 magnitudes (Kaydash et al. 2013). The distances on May 16, 2022 result in an additional brightness increase of 0.12 magnitudes. Therefore, the V-filter brightness of the Moon on May 16 would have been –12.80 – 0.17 – 0.12 magnitudes or –13.09 magnitudes without Earth's shadow. The B-filter brightness would have been –13.09 + 0.84 = –12.25 magnitudes at greatest eclipse without Earth's shadow. Therefore, brightness drops of V = 11.26 and B = 12.54 magnitudes occurred because of the eclipse.

Figure 1 shows the J- and H-filter brightness measurements of the totally-eclipsed Moon on November 8. The J- and H-filter brightness values at greatest eclipse are –7.42 and –8.41 magnitudes. These are much brighter than the corresponding values for the B- and V-filters on May 16. It is also apparent that there is smaller drop in brightness between U2 and the time of greatest eclipse for the H filter compared to the V filter. The corresponding brightness differences for the 2022 eclipses are V = 1.7 magnitudes (greatest eclipse to U3), and H = 0.07 magnitudes (U2 to greatest eclipse). This means the Moon does not get much darker as it approaches the center of Earth's umbra for the H filter.

One may compute the brightness drop of the eclipsed Moon on November 8 by comparing the brightness at greatest eclipse with what the Moon's brightness would have been without Earth's shadow. Essentially, the Moon at the time of greatest eclipse on November 8 had respective phase angle, observer, and sun distance values of 0.9°, 0.9934 au and 0.00260 au. Schmude (2023) reports a full-Moon brightness at respective phase angle, observer, and Sun distance values of 0.0°, 1.0000 au and 0.002570 au of J(1, 0) = –14.75 and H(1, 0) = –15.51 magnitudes. The Moon distances at greatest eclipse on November 8 results in a dimming of 0.01 magnitudes and the phase angle (0.9°) results in an additional dimming of 0.06 magnitudes (Kaydash, et al., 2013). This means the full Mon would have had brightness values of J = –14.68

and H = –15.44 magnitudes at greatest eclipse. Therefore, the Moon dropped by 7.26 and 7.03 magnitudes in the J and H filters, respectively. Consequently, the eclipsed Moon does not darken as much in the J and H passbands as in those for the B and V filters.

Figure 1: The Moon's J- and H-filter brightness during the November 8, 2022 eclipse (upper graph) and J – H value at the same time (lower graph).



There are no predictions for the Moon's brightness at U2 for the J and H filters. An H-filter brightness of 8.33 magnitudes was measured at 10:16:30 UT which is just a few seconds before the predicted time of U2 for the November 8, 2022 eclipse. This is a difference of 4.83

magnitudes (or a factor of ~86) from the corresponding predicted value for the V filter. Consequently, the Moon darkens more in the V filter than in the H filter when it just enters the Earth's umbra.

DISCUSSION

The brightness of the eclipsed Moon has been measured on at least nine different dates with photoelectric photometers. On eight of these, the brightness at greatest eclipse was measured in the V filter. These occurred in 1990, 2000, 2003, 2004, 2007, 2018, 2019 (Hernitschek et al., 2008; Schmude et al., 2000; Schmude, 2004, 20022 and Schmidt, 2022) and 2022 (current work). The mean value of the observed minus predicted brightness for these eclipses, at brightest eclipse, is –0.69 magnitudes or a factor of 1.9 (Mallama, 1996, 2022). In all cases, the measured brightness was greater than the predicted value. There are only three measured B – V values for the totally eclipsed Moon. These were on January 21, 2000, (Schmude et al., 2000), January 21, 2019 (Schmude, 2022) and May 16, 2022 (current work). In all three cases, the observed B – V value was lower than the predicted value. The mean observed minus predicted B – V value is 1.25 magnitudes. Since the mean V-filter brightness is 0.69 magnitudes brighter than what is predicted, the B-filter brightness is –0.69 – 1.25 = –1.94 magnitudes (or a factor of 6.0) brighter than what is predicted.

Both the B- and V-filter measurements are consistent with the eclipsed Moon being brighter than predicted. Mallama (2022) points out that the refraction of light is nearly independent of wavelength. Therefore, it is unlikely that refraction is the cause of the discrepancy. There is a chance that the atmosphere may absorb less blue light than what was previously thought. It is unlikely the Solar Corona is the cause of the excess brightening. The integrated brightness of the Corona is less than one-millionth the brightness of the Sun (Sytinkaya and Sharonov, 1963), (MacQueen et al., 2001). Therefore, the Corona will cause a brightening of less than 0.01 magnitudes to the eclipsed Moon.

How is it the eclipsed Moon does not darken much in the J and H filter as in the B and V filters? One explanation is that the atmosphere absorbs less near-infrared light than visible light. Mean extinction coefficients for seven different filters are summarized in Table 2. All of these were measured by the writer at locations near Barnesville, Georgia USA. One may see that our atmosphere absorbs more light in the V filter than in the H filter. This may be why the eclipsed Moon does not darken as much in the H filter as in the V filter.

Table 2: Mean extinction coefficients measured by the writer near Barnesville, GA.

Filter	**Extinction coefficient (magnitudes/air mass)**	**Source**
U	0.56	Schmude (2019)
B	0.38	Schmude (2008) p. 215
V	0.23	Schmude (2008) p. 215
R	0.16	Schmude (2008) p. 215
I	0.12	Schmude (2008) p. 215
J	0.088	Schmude (2018)
H	0.066	Schmude (2018)

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