Georgia Journal of Science

Volume 71 *No. 2 Scholarly Contributions from the Membership and Others*

Article 4

2013

Full-Disk Wideband Photometry of the Moon: R and I filter Measurements

Richard W. Schmude Jr.
Gordon State College, schmude@gordonstate.edu

Recommended Citation
Schmude, Richard W. Jr. (2013) "Full-Disk Wideband Photometry of the Moon: R and I filter Measurements," *Georgia Journal of Science*, Vol. 71, No. 2, Article 4.
Available at: http://digitalcommons.gaacademy.org/gjs/vol71/iss2/4

FULL-DISK WIDEBAND PHOTOMETRY OF THE MOON: R AND I FILTER MEASUREMENTS

Richard W. Schmude, Jr.
Gordon State College
419 College Dr.
Barnesville, GA 30204
Schmude@gordonstate.edu
678-359-5832 (Office)
770-358-0728 (Home)

ABSTRACT

A total of 42 full-disk brightness measurements of our Moon are reported. These measurements include the entire lunar disk including the Earthlit portion. All measurements were made on the Johnson R (red) and I (infrared) system and were fitted to cubic equations. The results are summarized in this report. The selected normalized magnitudes of the Moon are R(1,0) = -0.70 ± 0.10 and I(1,0) = -1.12 ± 0.06. The selected geometric albedo is 0.18 ± 0.01 for the Johnson R and I system.

Key words: Moon, Moon photometry, geometric albedo

INTRODUCTION

Since 2007, astronomers have undertaken a new series of lunar studies. Several countries have launched space probes to our Moon (1). In spite of this whole-disk brightness measurements in recent years are scarce.

Lots of good whole-disk photometric work of the Moon was carried out in the twentieth century. Harris summarizes brightness measurements done up to about 1960. He reports an equation which expresses the Moon's brightness at different solar phase angles in visible light (2). He also reports albedos and normalized magnitudes for the Johnson R and I system (3). Minnaert gives an integrated phase curve of the Moon which lists the relative brightness in terms of phase (4). Lane and Irvine (5) report results of a multi-wavelength photometric study of the Moon covering wavelengths between 0.36 and 1.06 μm in 1964-1965. Their measurements cover solar phase angles of between 6° and 120°. The solar phase angle (α) is measured from the Moon's center to the Sun's center at the observer's location. Lane and Irvine (5) also review geometric albedo measurements of the Moon. Schmude (6) reports measurements made in the Johnson B and V system. His measurements cover solar phase angles of between 4° and 150°. In spite of these studies, nobody has undertaken a whole-disk brightness study of our Moon at different solar phase angles in the Johnson R and I system.

The purpose of this work is to summarize whole-disk brightness measurements of the Moon in the Johnson R and I system. These are used to determine equations that express the R and I filter brightness for solar phase angles between 2° and 159°. The Moon's geometric albedo is also reported.

MATERIALS AND METHODS

An SSP-3 solid-state photometer, R and I filters and a 0.03 m telescope were used in recording all brightness measurements. This is the same equipment used earlier (6). The equipment was transformed to the Johnson R and I system. The telescope aperture was reduced for the Moon measurements because of its extreme brightness. The same calibrated masks used in Schmude (6) were used here. The lens and photometer yielded a circular field of view having an angular diameter of 55.6 ± 0.7 arcminutes. Light from the sky was subtracted from all Moon and comparison object measurements.

The size of the Earth affects the perceived brightness of the Moon. For example, the Moon appears a bit smaller and fainter than it does when crossing the meridian. For example, on January 28, 2012 at 1:00 U.T. an observer in Boston saw the Moon 0.04 magnitudes dimmer in the V filter than an observer in Los Angeles assuming identical scope, filter, detector and sky conditions. The different distances and solar phase angles for the two cities are the reasons for the brightness difference. For Venus or Mars, the brightness difference is at least 100 times smaller. Differences of 0.04 magnitudes cannot be neglected. It is for this reason that the JPL Ephemeris (7) was used to compute the Macon, Georgia to center of Moon distance rather than the center of Earth to center of Moon distance. All brightness measurements were made approximately 60 km from Macon.

Table I summarizes the resulting brightness measurements. These were corrected for atmospheric extinction and color transformation. Only measurements of the waxing phase are considered here.

Table I: Brightness measurements of the Moon

R Filter			**I Filter**		
Date	**Solar phase angle (degrees)**	**Brightness (magnitudes)**	**Date**	**Solar phase angle (degrees)**	**Brightness (magnitudes)**
Jan. 6.166, 2001	50.9	-12.22 ± 0.06 [a]	Jan. 6.166, 2001	50.9	-12.79 ± 0.06 [a]
Jan. 7.207, 2001	37.2	-12.62 ± 0.06 [a]	Jan. 7.207, 2001	37.2	-13.17 ± 0.06 [a]
Jan. 9.133, 2001	9.8	-13.57 ± 0.06 [a]	Jan. 9.133, 2001	9.8	-14.01 ± 0.06 [a]
Jan. 29.045, 2001	131.5	-9.015 ± 0.08 [b]	Apr. 26.052, 2001	151	-7.84 ± 0.10 [a]
Mar. 25.055, 2001	155.4	-6.35 ± 0.09 [c]	Apr. 27.065, 2001	138	-9.07 ± 0.07 [a]

Table I: *Continued*

Apr. 26.052, 2001	151	-7.23 ± 0.09 [a]	Apr. 28.065, 2001	125.1	-10.02 ± 0.06 [a]
Apr. 27.065, 2001	138	-8.44 ± 0.08 [a]	May 3.094, 2001	58.4	-12.62 ± 0.06 [d]
Apr. 28.065, 2001	125.1	-9.43 ± 0.06 [a]	May 4.094, 2001	45	-12.87 ± 0.06 [d]
May 3.094, 2001	58.4	-12.18 ± 0.06 [d]	Mar. 13.047, 2005	146.2	-8.31 ± 0.08 [a]
May 4.094, 2001	45	-12.47 ± 0.06 [d]	Apr. 15.173, 2005	106.2	-10.81 ± 0.07 [d]
Mar. 12.034, 2005	158.9	-6.00 ± 0.12 [a]	Apr. 17.192, 2005	83.7	-11.69 ± 0.06 [d]
Mar. 13.047, 2005	146.2	-7.70 ± 0.08 [a]	Apr. 19.131, 2005	62.4	-12.38 ± 0.06 [d]
Apr. 15.173, 2005	106.2	-10.29 ± 0.07 [d]	Apr. 24.315, 2005	2.3	-14.07 ± 0.05 [e]
Apr. 17.192, 2005	83.7	-11.19 ± 0.06 [d]	Nov. 6.147, 2011	51.6	-12.73 ± 0.05 [e]
Apr. 19.131, 2005	62.4	-11.91 ± 0.06 [d]	Dec. 3.095, 2011	82.8	-11.86 ± 0.05 [e]
Apr. 24.315, 2005	2.3	-13.65 ± 0.05 [e]	Dec. 31.039, 2011	103.9	-11.08 ± 0.05 [e]
Nov. 5.122, 2011	62.8	-11.92 ± 0.05 [e]	Jan. 1.017, 2012	92.6	11.48 ± 0.05 [e]
Nov. 8.197, 2011	29.3	-12.64 ± 0.05 [e]	Jan. 28.067, 2012	124.5	10.02 ± 0.07 [e]
Dec. 2.117, 2011	93.9	-11.06 ± 0.07 [e]			
Dec. 3.063, 2011	83.1	-11.31 ± 0.05 [e]			
Dec. 30.031, 2011	115.3	-10.08 ± 0.05 [e]			
Dec. 31.013, 2011	104.1	-10.55 ± 0.05 [e]			
Jan. 1.042, 2012	92.7	-10.98 ± 0.05 [e]			
Jan. 28.030, 2012	124.8	-9.50 ± 0.05 [e]			

[a] The comparison object is α-CMa.

[b] The comparison object is α-Ari.

[c] I have lost the original record of this measurement when the value was recorded, I did not record the comparison object.

[d] The comparison object is α-Boo.

[e] The comparison object is Jupiter.

Before April of 2005, I used a bright star in the sky as the comparison object. The problems with this were: 1) the B – V value of the star was often much lower than the corresponding value for our Moon leading to large color transformation corrections and 2) the stars used were dim compared to the Moon and, hence, scattered light from the Moon was a problem. In recent measurements, Jupiter was used as the comparison object because it has a similar color as our Moon and it is brighter than the brightest night-time stars. The use of Jupiter reduced errors from scattered moonlight and color transformation. Jupiter's brightness was measured before the Moon measurements using a comparison star. With this, Jupiter's brightness was corrected to the Jupiter-Sun and Jupiter-Earth distances on the night of the Moon measurement. The writer has measured Jupiter's brightness in the Johnson V(8) and I(9) systems as it rotated. It had a nearly constant brightness during the dates of measurements. Therefore, any brightness change from rotation is believed to be lower than 0.03 magnitudes.

Table II summarizes several sources of random error. Each is described.

Table II: Estimated errors in the brightness measurements of the Moon. All estimated errors are given in units of stellar magnitudes.

		Comparison Object		
Error Description	**Symbol**	**Jupiter**	**α-CMa**	**α-Ari and α-Boo**
Comparison object brightness	U_c	0.03	0.01	0.01
Scattered light from Moon	U_s	0.01	0.02	0.03
Color transformation	U_{ct}	0.01	0.04	0.03
Mask correction	U_m	0.02	0.02	0.02
Atmospheric extinction	U_a	*	*	*
Random measurement error	U_r	0.02	0.02	0.02

*This varies with the altitude of the Moon. The lower the Moon's altitude, the higher will be the uncertainty from atmospheric extinction.

Uncertainties in the comparison object (U_c) brightness are reported to be around 0.02 magnitudes when α-CMa, α-Ari or α-Boo was used (10) and 0.03 magnitudes when Jupiter was used.

Scattered moonlight introduces uncertainty. Measurements were usually made when the comparison object was at least 20° from the Moon. This reduced the problem of scattered light. The large distance, however, introduced a larger extinction uncertainty which is described later. A smaller uncertainty

(U_s) for scattered light is selected for measurements based on Jupiter as a comparison object since it is brighter than any nighttime star.

Color transformation is another source of uncertainty. This occurs because each telescope-detector-filter combination has a different sensitivity to each wavelength of light. As a result each telescope-detector-filter combination is transformed to the Johnson R and I system. The color transformation depends on the difference in the B – V value between our Moon and the comparison object (11). Since Jupiter has almost the same B – V value as our Moon, the uncertainty is lower. On the other hand, Sirius is a blue-white star and, hence, it is bluer than our Moon. Consequently, a larger uncertainty for color transformation is selected. The color transformation uncertainty is designated as U_{ct}.

The mask correction factor uncertainty is estimated as 0.02 magnitudes. Its uncertainty is designated as U_m.

In many cases, the largest source of uncertainty is atmospheric extinction (U_a). Estimated extinction uncertainties of up to 0.10 magnitudes are selected based on the Moon's altitude at the time of measurement. The higher the altitude, the lower is the estimated extinction uncertainty.

The final source of uncertainty is random fluctuation in the measurements and in detector response (U_r). This is estimated to be 0.02 magnitudes.

The total uncertainty (U_T) for each measurement is computed from:

$$U_T = [(U_c)^2 + (U_s)^2 + (U_{ct})^2 + (U_m)^2 + (U_a)^2 + (U_r)^2]^{0.5} \quad (1)$$

The uncertainty for each measurement is listed in Table I.

The normalized magnitudes, $R(1,\alpha)$ and $I(1,\alpha)$ are computed from:

$$R(1,\alpha) = R - 5.0\mathrm{Log}(r \times \Delta) \quad (2)$$
$$I(1,\alpha) = I - 5.0\mathrm{Log}(r \times \Delta) \quad (3).$$

In these equations r is the Moon-Sun distance; Δ is the Moon-Macon, Georgia distance. Both r and Δ are in astronomical units. The resulting $R(1,\alpha)$ and $I(1,\alpha)$ values are plotted in Figure 1.

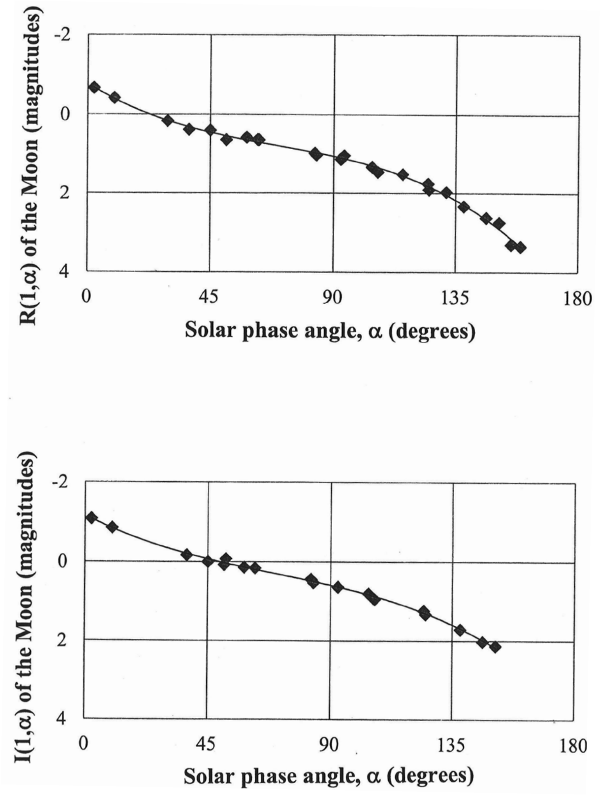

Figure 1. Normalized magnitudes R(1,α) and I(1,α) for the Moon. These were computed from the measurements in Table I and equations 2 and 3. The best fit cubic curve is drawn through the points. Equations for each curve are listed in Table III and are of the same form as equations 5.

Table III: Polynomial fits to equations 4 and 5.

Equation	Filter	a	b	c	d	R
4	R	-0.77	0.0422	-0.000429	0.00000205	0.9975
5	R	-0.84	0.0515	-0.000558	0.000003401	0.9990
4	I	-1.16	0.0347	-0.000297	0.00000141	0.9986
5	I	-1.19	0.0405	-0.000361	0.00000245	0.9996

RESULTS

The R filter measurements were fit to two different equations:

$$R_m = a + b\alpha + c\alpha^2 + d\alpha^3 + 5\log[r \times \Delta] - 2.5\log[k] \quad (4)$$
$$R_m = a + b\alpha + c\alpha^2 + d\alpha^3 + 5\log[r \times \Delta] \quad (5).$$

In both equations, Rm is the measured R filter brightness; a, b, c and d are coefficients to be determined and α is the solar phase angle. In equation 4, k is the fraction of the Moon's disk which is illuminated as seen from Macon, Georgia and r and Δ are defined previously. The resulting least squares fits are listed in Table III for both equations. The I filter measurements were analyzed in the same way.

The correlation coefficients (R) are listed in Table III. The closer these are to 1.00, the better is the fit. The correlation coefficients indicate equation 5 is a better fit than equation 4. Therefore, equation 4 is not considered further.

The standard errors for the equation 5 fits are 0.096 and 0.049 stellar magnitudes for the R and I filters, respectively. The standard errors (s) were computed from:

$$s = [(\Sigma(Y - Y_o)^2)/(n - 1)]^{0.5} \quad (6)$$

where Y is the measured magnitude, Y_o is the magnitude predicted from the appropriate equation in Table III and n is the number of brightness measurements. The standard errors are consistent with the estimated uncertainties of the measurements but are higher than those for models of bright planets (12-17). Two reasons for the larger standard errors here are: 1) larger uncertainties from extinction corrections and 2) larger uncertainties from scattered light.

DISCUSSION

The normalized magnitude at a solar phase angle of 0°, R(1,0) and I(1,0), may be computed from the equations in Table III or from measurements of the Moon when it is nearly at opposition. The values in Table III are consistent with values of R(1,0) = -0.84 and I(1,0) = -1.19 based on Equation 5. One may also compute normalized magnitudes from the measurements made on April 24, 2005 when the Moon's solar phase angle (α) was 2.3°. The normalized magnitudes at α = 2.3° are R = -0.67 and I = -1.08. Based on the results in Table III, the corrections from α = 2.3° to α = 0° are -0.12 and -0.09 magnitudes for the R and I values, respectively. After adding these factors, the normalized magnitudes for April 24, 2005 become: R(1,0) = -0.79 and I(1,0) = -1.17. These values are dimmer than those in Table III. Values of the normalized magnitudes of our Moon are summarized in Table IV. The same procedure in Mallama and Schmude (15) is used in computing the geometric albedos. Magnitudes and color indexes of the Sun are from Livingston (18) and the lunar diameter, 3,474.8 km, is from (19). The selected normalized magnitudes and geometric albedos of the Moon are listed in Table IV. They are based on the weighting scheme in the table.

Table IV: Normalized magnitudes and geometric albedos of the Moon.

R(1,0)	I(1,0)	Geometric albedo		Weight	Reference
		R	I	t	
-0.59	-1.05	0.16	0.17	2	(3)
-0.79	-1.17	0.19	0.19	1	April 24, 2005 measurements
-0.84	-1.19	0.19	0.20	1	Extrapolated value in Table III
-0.70 ± 0.10	*-1.12 ± 0.06*	*0.18 ± .01*	*0.18 ± .01*		*Selected values*

ACKNOWLEDGEMENTS

The writer is grateful to John George and Alan Fuller for their advice on statistics.

REFERENCES

1. Schmude RW Jr: “Artificial Satellites and How to Observe Them.” New York: Springer Science + Business Media, p39, 2012.
2. Harris DL: Photometry and Colorimetry of Planets and Satellites. In Planets and Satellites (Kuiper and Middlehurst, Eds) Chicago: The University of Chicago Press, p289, 1961.
3. ibid p310.
4. Minnaert M: Photometry of the Moon. In Planets and Satellites (Kuiper and Middlehurst, Eds) Chicago: The University of Chicago Press, p214, 1961.
5. Lane AP, Irvine WM: Monochromatic phase curve and albedos for the lunar disk. Astronomical Journal 78: 267-277, 1973.
6. Schmude RW Jr: Full-Disc Wideband Photoelectric Photometry of the Moon. Journal of the Royal Astronomical Society of Canada 95: 17-23, 2001.
7. http://ssd.jpl.nasa.gov/horizons.cgi
8. Schmude RW Jr: Jupiter Observations During the 2010-2011 Apparition. Journal of the Association of Lunar and Planetary Observers 54 (No. 3): 34-52, 2012.
9. Schmude RW Jr: Unpublished light curve collected during November 8-10, 2012.
10. Iriarte B, Johnson HL, Mitchell RI, Wisniewski WK: Five-Color Photometry of Bright Stars, Sky and Telescope 30 (July): 21-31, 1965.
11. Hall, DS, Genet RM: “Photoelectric Photometry of Variable Stars.” second ed, Richmond: Willmann-Bell, Inc., Chapter 13, 1988.

12. Mallama A, Wang D, Howard RA: Photometry of Mercury from SOHO/LASCO and Earth: The phase function from 2° to 170°. Icarus 155: 253-264, 2002.
13. Mallama A, Wang D, Howard RA: Venus phase function and forward scattering from H2SO4. Icarus 182: 10-22, 2006.
14. Mallama A: The magnitude and albedo of Mars. Icarus 192: 404-416, 2007.
15. Mallama A, Schmude RW Jr: Cloud band variations and the integrated luminosity of Jupiter. Icarus 220: 211-215, 2012.
16. Schmude RW Jr: The magnitude and color of the Saturn system. Icarus 211: 732-739, 2011.
17. Mallama A: Improved luminosity model and albedo for Saturn. Icarus 218 (1): 56-59, 2012.
18. Livingston WC: Sun. in Allen's Astrophysical Quantities, fourth edn, (Cox ed) New York: Springer, p341, 2000.
19. The Astronomical Almanac for the year 2012, Washington DC: US Govt. Printing Office, pF3, 2011.