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Near-Infrared Brightness of Saturn

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ABSTRACT

An SSP-4 photometer and filters transformed to the Mauna Kea J and H system were used in measuring the brightness of Saturn + rings (hereafter "Saturn") in 2014 and 2015. The selected normalized magnitudes extrapolated to a solar phase angle of 0° are J(1,0) = –10.67 ± 0.05 and H(1,0) = –10.40 ± 0.05 in 2014 and J(1,0) = –10.76 ± 0.03 and H(1,0) = –10.51 ± 0.03 in 2015. These appear to be the first published J and H magnitude values for Saturn.

Keywords: Saturn, J – H color index, near-infrared photometry

INTRODUCTION

Over the past 60 years, near-infrared studies of the planets have increased. Harris (1961) reported that Kuiper carried out a study of the energy distribution of the bright planets at wavelengths of between 1.0 and 2.5 μm. He also reports intensity ratios for the bright planets. Even at this early stage, it was evident that the ratio of Jupiter's albedo at a wavelength 2 μm compared to 1 μm is depressed compared to Saturn's. Irvine et al. (1968a,b) report near-ultraviolet to near-infrared brightness measurements of Saturn. Binder and McCarthy (1973) report albedos of the belts and zones on Saturn. Their results are based on spectrophotometer readings made with ten filters sensitive to wavelengths of between 0.6 and 2.0 μm. Two of their filters have band passes centered at 1.240 μm (filter 7) and 1.554 μm (filter 9). These are like the J and H filters except that band passes are narrower. A band pass describes the range of wavelengths of light that pass through the filter. Binder and McCarthy (1973) report geometric albedos consistent with mean values of 0.37 (filter 7) and 0.5 (filter 9) for Saturn's northern hemisphere. Although filters 7 and 9 are sensitive to some wavelengths in the J and H filters, albedos cannot be compared because of differences in filter band passes. Fountain (1972) published a photograph of Saturn taken with light having a wavelength of 1-2 μm. The rings are brighter than the globe. Clark and McCord (1979) report near-infrared reflectance spectra of Jupiter and Saturn. The spectra for both planets show large absorption features at 1.0, 1.17, 1.4, and 1.75 μm. Clark and McCord (1980) report the near-infrared reflectance spectra of Saturn's rings. The data are also presented at http://speclab.cr.usgs.gov/planetary.spectra/planetary-sp.html. More recently, Baines et al. (2005) report near-infrared spectra of Saturn's globe from Cassini data. They report atmospheric depths "at which the gas opacity reaches unity for a two-way nadir path" for different wavelengths (Baines et al. 2005). Most of the band pass of the J filter and half of that of the H filter reach to the haze layer near 1.0 bar. The remainder of the light reaches to the methane clouds near 0.01 bars. Nicholson et al. (2008) report Cassini near-infrared spectra of Saturn's rings. Schmude (2011) and Mallama (2012) report photometric models of Saturn in visible and near-infrared light.

The Johnson/Glass JHKLMN system was an early attempt to introduce standard infrared band passes (Bessell 2005). The problem with this system is that the filters often had band passes that exceeded the atmospheric windows and, hence, the atmosphere would sometimes influence the wavelength cut-off. Simons and Tokunaga (2002) were aware of this problem and as a result define "Mauna Kea band passes" in the wavelength range of 1.0 to 5.0 μm. They report that water vapor has a minimal effect on these. Tokunaga et al. (2002) present a technical description of J, H, K, L, and M filters. These are designed to reduce noise, allow better color transformation, and be suitable for adaptive optics situations. This group also reports extinction data for near-infrared wavelengths at Mauna Kea. Tokunaga and Vacca (2005) present isophotal wavelengths, flux densities, and magnitudes for the standard A0 star Vega (alpha Lyrae). Henden (2002) published a list of standard star magnitude values for J and H filter photometry. To the best of my knowledge there are no published J or H filter brightness measurements of Saturn.

The purpose of this report is to summarize new J and H filter brightness measurements of Saturn made in 2014–2015. These measurements have not been carried out before and, hence, I believe would be of scientific value. These values may aid in studies of extrasolar planets. This is because the J – H values of several of these planets have been measured (Kuzuhara et al. 2013). Furthermore, ammonia has an absorption feature at 1.51 μm (Clark and McCord 1979) which is within the range of the H filter. If the ammonia abundance were to increase, the absorption at 1.51 mm would increase leading to a fainter H filter brightness and a more negative J – H value. Therefore, the J – H value may serve as a probe for ammonia abundances on Saturn. Furthermore, J and H filter brightness measurements may place constraints on models of Saturn's great white storms (Sanchez-Lavega et al. 2012).

MATERIALS & METHOD

Brightness measurements reported here are based on readings made with an SSP-4 photometer and filters transformed to the Mauna Kea J and H system. The SSP-4 photometer has a model G5851 detector manufactured by Hamamatsu Corporation. It is an InGaAs-PIN photodiode. The detector is operated in a cooled state usually at –25 °C with a two stage thermoelectrically Peltier cooler. It is sensitive to light with wavelengths of between 1.05 and 1.85 μm (Optec 2005). The circular aperture over the detector is 1.0 mm across. This along with the telescope gives a detector field of view of 420 arcsec (Optec 1995). This field should ensure that almost all of the light from Saturn and the comparison star reach the detector. Mallama et al. (2006) reported that small fields of view may have been a problem in some of the Venus measurements. The J and H filters have band passes centered at 1.250 ± 0.042 μm and 1.650 ± 0.045 μm, respectively. The band pass widths are 0.200 ± 0.040 μm (J) and 0.300 ± 0.060 μm (H) (Optec 2005).

The sequence usually used for brightness measurements was SCS STS SCS STS SCS STS SCS where the first S is three 10-s sky readings near the comparison star, C is three 10-s comparison star + sky readings, and the next S is three 10-s star readings near the comparison star. In the next set, S is three 10-s sky readings near the target, T is three 10-s target readings and the next S is three 10-s sky readings near the target. This process continued for the comparison star and target until the fourth set of comparison star readings was made. It was often necessary to make sky readings before and after the C and T readings because the detector offset oftentimes changed. Occasionally, check star readings were also made.

Atmospheric extinction coefficients for the J and H filters were usually measured. In cases when they were not, mean extinction coefficients (magnitudes/air mass) of 0.124 ± 0.008 and 0.085 ± 0.007 were used. Uncertainties are standard errors of the mean. These values are based on measurements made between April 26, 2014 and August 29, 2014. These coefficients were measured from Barnesville, Georgia, at an elevation of 0.25 km and are close to those reported in Henden (2002).

Transformation coefficients were measured using the "star pair" method described in Hall and Genet (1988) except that the J – H value replaced the B – V value. The color-dependent extinction coefficient, k", term was assumed to equal zero for both filters. Transformation coefficients were computed mostly from measurements of Arcturus and Vega. The selected values were $\varepsilon_J = 0.0443$ and $\varepsilon_H = 0.0151$ for 2014 and $\varepsilon_J = 0.107$ and $\varepsilon_H = 0.055$ for 2015. A plastic rope-tote was blown off my car and onto the photometer in February 2015. This may have caused a shift in transformation coefficients.

In several measurements Vega was a check star. Mean values of J = 0.01 ± 0.02 and H = –0.01 ± 0.02 were measured for this star in 2014. These are close to those in Henden (2002).

There are several sources of uncertainty in the measurements. Four of these are from the following: 1) comparison star magnitudes, 2) atmospheric changes, 3) transformation uncertainty, and 4) random error. Each source is discussed.

All comparison star magnitudes are from Henden (2002). An estimated error of 0.02 magnitudes (U_c) is assumed for comparison star magnitudes.

In all Saturn measurements, the comparison star was over 20° from Saturn. Because of this, extinction corrections were made. The extinction coefficients were usually measured for one portion of the sky. Essentially, they were measured in the same way as in Hall and Genet (1988). Extinction corrections of ~0.1 to ~0.2 magnitudes were usually made. Estimated uncertainties for extinction corrections (U_e) of 0.04 and 0.03 magnitudes are assigned to the J and H magnitude values, respectively.

A third source of uncertainty is color transformation. The problem is that Saturn's spectrum differs from that of its comparison star, alpha-Bootes. The J – H value for this star is 0.69; however, the corresponding value for Saturn is approximately –0.3. Transformation corrections of 0.1 (J) and 0.05 (H) magnitudes were made in 2015. Smaller corrections were made a year earlier. The estimated transformation uncertainty (U_{tr}) for the J and H filter measurements is 0.03 and 0.015 magnitudes, respectively.

A final source of uncertainty (U_r) is the result of random fluctuations in the signal. This source also includes small changes in b, the ring tilt, during 2014 and 2015. This is estimated to be 0.015 magnitudes for both filters.

The total uncertainty (U) is the square root of the sum of the squares of each source which is:

$$U = (U_c^2 + U_e^2 + U_{tr}^2 + U_r^2)^{0.5} \quad (1).$$

The total uncertainties are 0.06 and 0.04 magnitudes for each J and H filter measurement, respectively.

RESULTS

The measured J and H brightness measurements for Saturn are listed in Tables I (2014) and II (2015). All measurements are corrected for atmospheric extinction and color transformation. The ring tilt angle changed about 0.4° during each year. It has the symbol b and is the square root of the product of the subsolar and sub-Earth latitude (Schmude 2011). Ring tilt angles are from the Astronomical Almanac (2013, 2014). In 2014, b was 22° and in 2015 it was 24.5°.

Before photometric constants were determined, it should be established whether any brightness changes occurred from rotation. Saturn rotates once every 10 to 11 hours. Therefore, different sides will face Earth on two consecutive nights. Measurements were made in 2014 on May 5 and 6; 16 and 17; 20 and 21; July 27–30, and August 27–29. The data were usually consistent with changes of less than 0.05 magnitudes. Therefore, brightness changes from rotation are assumed to be small.

In both years, measurements covered solar phase angles from less than 0.5° to almost 6°; therefore, it was possible to measure both the solar phase angle coefficients and the opposition surge.

Equation 2 is a general photometric equation for Saturn.

$$J = J(1, 0) + c_J\alpha + 5 \text{ Log } [r\ \Delta] \qquad (2).$$

In this equation, J is the measured J-filter magnitude, c_J is a constant, α is the solar phase angle (the angle between the Earth and Sun measured from Saturn) and will be positive here, J(1, 0) is the normalized magnitude extrapolated to $\alpha = 0°$ when the Saturn-Sun (r) and Saturn-Earth (Δ) distances = 1.0 au. Equation 2 is rearranged as:

$$J - 5 \text{ Log } [r\ \Delta] = J(1, 0) + c_J\alpha \qquad (3).$$

Values of $J - 5$ Log $[r\ \Delta]$ were computed from Table I and the r and Δ values predicted in the JPL Ephemeris (2016) at www.alpo-astronomy.org. These are plotted against α. See Figure 1. Since Saturn has a large, nonlinear brightening when $\alpha < 1.5°$ only those values for $\alpha \geq 1.5°$ were included in this plot. The slope of the best fit line equals c_J and the y-intercept equals J(1, 0). The same procedure was used for the H filter. The measurements in Table II were used in computing the corresponding values for 2015. See Figure 2 and Table III.

Saturn has a nonlinear brightening for $\alpha < 1.5°$ which is the opposition surge. The rings are probably the cause. Values of the opposition surge for both filters and years are summarized in Table III.

Some statistical information is evident in Figures 1 and 2. The individual correlation coefficients are 0.772 (J – 2014), 0.827 (H – 2014), 0.645 (J – 2015), and 0.863 (H – 2015). At the 95% confidence level, the correlation in all four graphs is significant (Larson and Farber 2006). Values of the standard error of estimate are summarized in Table III. These are consistent with estimated uncertainties. The uncertainties for the J(1,0), H(1,0), c_J, and c_H values are at the 95% confidence level and were computed from the procedure outlined in Morrison (2014).

DISCUSSION

The V – J and J – H color indexes for our Sun are 1.11 and 0.31 (Cox 2000; Roddier et al. 2000). The corresponding values for Saturn are about 0.95 and –0.30. Therefore, that planet's albedo drops in the J and H filter compared to the V filter. The J – H value is consistent with the results in Binder and McCarthy (1973).

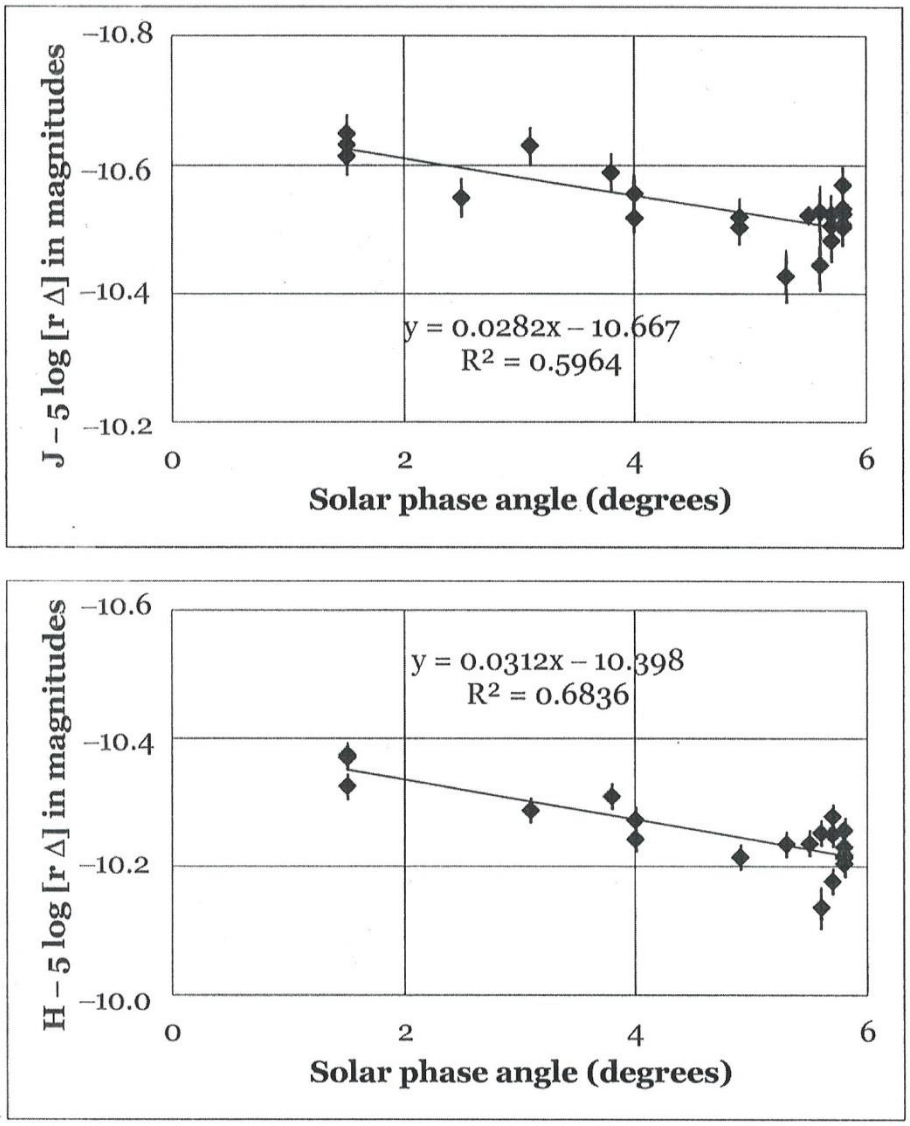

Figure 1. Graphs of J – 5 log [r Δ] and H – 5 log [r Δ] plotted against the solar phase angle of Saturn for 2014. In these equations J and H are the J and H filter magnitudes as listed in Tables I and II, r is the Saturn-Sun distance, and Δ is the Saturn-Earth distance. Both r and Δ are in astronomical units. The best-fit linear equations with values of the square of the correlation coefficient (R^2) are shown. Uncertainties are drawn as vertical lines and are usually 0.06 and 0.04 magnitudes for each J and H point, respectively.

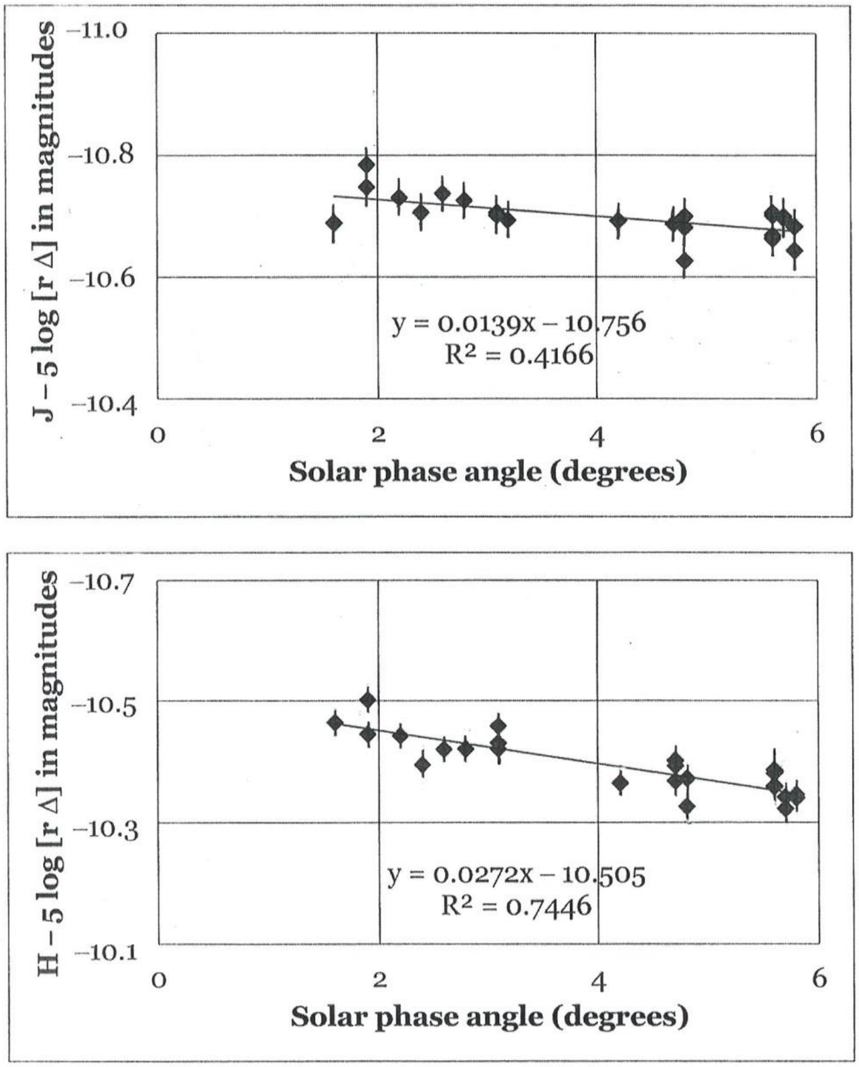

Figure 2. Graphs of the normalized magnitude J – 5 log [r Δ] and H – 5 log [r Δ] plotted against the solar phase angle of Saturn for 2015. In these equations J and H are the J and H filter magnitudes as listed in Tables I and II, r is the Saturn-Sun distance, and Δ is the Saturn-Earth distance. Both r and Δ are in astronomical units. The best-fit linear equations with values of the square of the correlation coefficient (R^2) are shown. Uncertainties are the same as in Figure 1.

Table I. Brightness measurements of Saturn + rings made with the J and H filter and an SSP-4 photometer in 2014. For all measurements, Alpha-Bootes (Arcturus) was the comparison star.

Date (2014)	**Filter**	**Magnitude**	**Date**	**Filter**	**Magnitude**
April 26.265	H	–0.59	June 4.144	J	–0.80
April 26.281	J	–0.88	June 10.099	J	–0.87
April 26.299	H	–0.64	June 10.115	H	–0.53
April 26.322	J	–0.91	June 18.180	J	–0.81
April 26.352	J	–0.90	June 18.201	H	–0.53
April 26.399	H	–0.64	June 21.151	J	–0.73
May 5.278	J	–0.93	June 21.164	H	–0.46
May 5.293	H	–0.70	June 21.210	J	–0.77
May 5.308	J	–0.95	June 21.225	H	–0.49
May 5.320	H	–0.69	July 5.166	J	–0.70[a]
May 5.334	J	–0.88	July 6.096	H	–0.38
May 5.349	H	–0.68	July 6.125	J	–0.67
May 6.247	J	–0.93	July 24.123	J	–0.61
May 6.264	H	–0.69	July 24.145	H	–0.35
May 6.281	J	–0.95	July 27.133	J	–0.58
May 6.301	H	–0.67	July 27.148	H	–0.37
May 6.318	J	–0.95	July 29.128	J	–0.62
May 6.333	H	–0.71	July 29.142	H	–0.29
May 8.165	J	–1.01	July 26.163	J	–0.66
May 8.178	H	–0.76	July 29.175	H	–0.30
May 16.250	J	–0.91	July 30.118	J	–0.59
May 16.263	H	–0.67	July 30.133	H	–0.31
May 16.279	J	–0.91	July 30.150	J	–0.59
May 16.293	H	–0.68	July 30.164	H	–0.34
May 16.309	J	-0.92	Aug. 17.080	H	–0.23
May 16.324	H	–0.70	Aug. 17.093	J	–0.54
May 17.167	J	–0.93	Aug. 23.075	J	–0.52
May 17.183	H	–0.70	Aug. 23.090	H	–0.17
May 17.200	J	–0.92	Aug. 27.095	J	–0.43[b]
May 17.215	H	–0.69	Aug. 27.108	H	–0.12[b]
May 20.170	J	–0.90	Aug. 28.080	H	–0.23
May 20.185	H	–0.67	Aug. 28.097	J	–0.51[b,c]
May 21.156	J	–0.95	Aug. 29.030	H	–0.21
May 21.176	H	–0.63	Aug. 29.042	J	–0.50
May 24.183	J	–0.85	Sept. 6.030	H	–0.19
May 24.197	H	–0.59	Sept. 6.043	J	–0.38[c]

[a]Assume J – H = -0.27
[b]Saturn is less than 19.5 degrees above the horizon.
[c]Large scatter in the data

Table II. Brightness measurements of Saturn + rings made with the J and H filter and an SSP-4 photometer in 2015. For all measurements, Alpha-Bootes (Arcturus) was the comparison star.

Date (2015)	**Filter**	**Magnitude**	**Date**	**Filter**	**Magnitude**
Feb. 14.474	J	–0.70	May 23.173	J	–1.17
Feb. 14.487	H	–0.38[a]	May 23.191	J	–1.16
Feb. 27.420	J	–0.74	May 23.205	H	–0.93
Feb. 27.439	H	–0.38	May 23.252	J	–1.16
Feb. 27.469	J	–0.74	May 23.274	H	–0.91
Mar. 7.417	H	–0.45	May 30.353	J	–1.03
Mar. 7.433	J	–0.77	May 30.367	H	–0.79
Mar. 28.389	J	–0.84	June 7.133	J	–0.92
Mar. 28.410	H	–0.51	June 7.148	H	–0.70
Mar. 28.435	J	–0.82	June 16.093	J	–0.93
Mar. 31.372	H	–0.52	June 16.113	H	–0.62
Mar. 31.389	J	–0.84	June 18.120	J	–0.95
Mar. 31.408	H	–0.55	June 18.145	H	–0.64
Mar. 31.424	H	–0.54	June 20.092	J	–0.94
Apr. 21.309	J	–0.90	June 20.118	H	–0.63
Apr. 21.323	H	–0.63	July 7.098	J	–0.87
Apr. 21.349	H	–0.64	July 7.113	H	–0.54
Apr. 21.378	J	–0.91	July 16.100	H	–0.77
Apr. 21.402	H	–0.67	July 16.114	H	–0.47
Apr. 21.419	J	–0.91	Aug. 5.114	J	–0.74
May 1.390	J	–0.96	Aug. 5.127	H	–0.44
May 1.401	H	–0.67	Aug. 5.137	J	–0.74
May 4.299	J	–1.01	Aug. 5.153	H	–0.43
May 4.315	H	–0.73	Aug. 13.056	J	–0.73
May 4.339	J	–0.98	Aug. 13.068	H	–0.39
May 4.352	H	–0.67	Aug. 13.101	J	–0.73
May 11.326	J	–1.01	Aug. 13.121	H	–0.39[b]
May 11.345	H	–0.74	Aug. 28.045	J	–0.64
May 23.156	H	–0.94	Sept. 1.081	H	–0.30

[a]Used k_J = 0.103 and k_H = 0.082 mag./air mass
[b]Large scatter in the data

The rings have a large impact on Saturn's color and brightness (Schmude 2011; Mallama 2012). For example, in the V filter for b = 22°, Saturn's V(1,0) value is –9.739 whereas at a ring tilt angle of 0° it is –8.914. This is a difference of 0.825 magnitudes or a factor of 2.14 (Mallama 2012). Therefore, at b = 22° the rings contribute over 50% of Saturn's light at a wavelength of 0.54 μm. A similar situation may occur for the J and H filters. The brightness of Saturn + rings drops ~0.1 to 0.2 magnitude as α rises from 1.5° to 6°. Clark and McCord (1980) report reflectance spectra of Saturn's A and B rings combined. Their data were recorded between April 21, 1976 and February 21, 1978.

During this time the phase angles ranged from 0.10° and 6.33° and the ring tilt angles, b, ranged from 11.5° and 21.2°. Because of this, the rings changed brightness during the 22 months in which data were recorded. Their spectrum is normalized to 1.0 at a wavelength of 1.02 μm, and, hence absolute ring albedos are not reported. One broad absorption feature is between 1.45 and 1.7 μm. Water absorption is believed to be the cause. This feature also lies within the spectral range of the H filter. There is no similar absorption feature for the J filter. More measurements are needed to determine how the J – H color index changes with the ring tilt angle.

There are at least three reasons why more data were not collected in 2014 and 2015. One reason was the weather. Most of the summer nights were either cloudy or had a transparency gradient. Since measurements are made with a photometer instead of with a camera clear skies are essential for reliable measurements. A second reason as to why more data were not collected was because the writer wanted to collect measurements of the other bright planets (Jupiter, Mars, Venus, and Mercury). A final reason was time. A single J filter measurement required about 20 to 25 min.

Table III. Photometric constants for Saturn based on measurements made in 2014 and 2015

Parameter	**Saturn 2014**	**Saturn 2015**
J(1,0) (magnitudes)	–10.67 ± 0.05[a]	–10.76 ± 0.03[a]
H(1,0) (magnitudes)	–10.40 ± 0.05[a]	–10.51 ± 0.03[a]
c_J (magnitude/degree)	0.028 ± 0.010[b]	0.014 ± 0.007[b]
c_H (magnitude/degree)	0.031 ± 0.010[b]	0.027 ± 0.007[b]
Standard error of estimate (magnitudes) – J	0.037[c]	0.026[c]
Standard error of estimate (magnitudes) – H	0.034[c]	0.024[c]
Mean J – H $\alpha \geq 1.5°$ (magnitudes)	–0.29	–0.30
Mean V – J $\alpha \geq 1.5°$ (magnitudes)	0.92	0.98
Opposition surge J filter (magnitudes)	0.09[d]	0.17[e]
Opposition surge H filter (magnitudes)	0.11[d]	0.19[e]

[a]The uncertainty is for the 95% confidence level and is computed as twice the standard deviation of the y-intercept as described by Morrison (2014).

[b]The uncertainty is for the 95% confidence level and is computed as twice the standard deviation of the slope as described by Morrison (2014).

[c]This is for a ≥ 1.5°

[d]These values are for $\alpha = 0.4°$ and b = 22°.

[e]These values are for $\alpha = 0.22°$ and b = 24.5°.

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