The Sloan Digital Sky Survey Reverberation Mapping Project: Photometric g and i Light Curves

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ABSTRACT

The Sloan Digital Sky Survey Reverberation Mapping (SDSS-RM) program monitors 849 active galactic nuclei (AGN) both spectroscopically and photometrically. The photometric observations used in this work span over four years and provide an excellent baseline for variability studies of these objects. We present the photometric light curves from 2014 to 2017 obtained by the Steward Observatory’s Bok telescope and the CFHT telescope with MegaCam. We provide details on the data acquisition and processing of the data from each telescope, the difference imaging photometry used to produce the light curves, and the calculation of a variability index to quantify each AGN’s variability. We find that the Welch-Stetson J-index provides a useful characterization of AGN variability and can be used to select AGNs for further study.
1. INTRODUCTION

The variability of active galactic nuclei (AGN; hereafter synonymously used with “quasar”) is one of the most powerful tools available to explore the physical processes in these objects and to determine their role in the evolution of galaxies (e.g., Ulrich et al. 1997; Vanden Berk et al. 2004; MacLeod et al. 2010). Various aspects of quasar variability touch on a wide range of physical processes (Kozłowski et al. 2010), and studies span a wide breadth of topics, ranging from continuum variability and the exploration of quasar accretion processes (e.g., Krolik et al. 1991; Clavel et al. 1991; Czerny et al. 1999; Kelly et al. 2011), to emission-line variability and the broad-line region (e.g., Peterson et al. 2004; Blazhko et al. 2015), to the study of so-called “changing-look” AGN (e.g., Tohline & Osterbrock 1976; Cohen et al. 1986; Clavel et al. 1989; Denney et al. 2014; Shappee et al. 2014; LaMassa et al. 2015; MacLeod et al. 2016), and to studies of absorption line variability (e.g., Smith & Penston 1988; Turnshek et al. 1988; Barlow 1993; Lundgren et al. 2007; Filiz Ak et al. 2013). AGN variability/monitoring programs provide important insights into the nature of the inner regions of quasars on a variety of scales, leading to better understanding of their role in the evolution of AGN and galaxies. There are many time-series datasets that focus on AGN over a variety of scales. Most spectroscopic monitoring projects, by necessity, have focused either on small numbers of AGN at high cadence or large numbers of AGN at very low cadence. While there are science goals that can be accomplished by both types of datasets, statistical interpretations are limited by the small sample sizes in the first case, and detailed investigations are limited by the small numbers of epochs in the second case. Recently, however, large surveys that use multi-object spectrographs have begun to target statistically significant samples of representative quasar populations for much higher cadence, long-duration studies (e.g., King et al. 2015).

The Sloan Digital Sky Survey Reverberation Mapping (SDSS-RM) project (Shen et al. 2015a) is an ongoing program that monitors 849 broad-line quasars/AGNs. The project is based on a spectroscopic campaign using the Baryon Oscillation Spectroscopic Survey (BOSS) spectrographs (Smee et al. 2013) that began at the end of the SDSS-III survey and continues through the SDSS-IV survey (Blanton et al. 2017). As of summer 2019, the program has accumulated 6 years of SDSS spectroscopic data. To complement the spectroscopic data, the SDSS-RM field has been photometrically monitored at the Canada-France-Hawaii (CFHT) and Steward Observatory Bok telescopes. The SDSS-RM field was observed in the SDSS g and i bandpasses with the CFHT from 2014 to 2016, and with the Bok from 2014 through 2017. In addition, the field was monitored photometrically as a part of the Pan-STARRS1 MD07 program during 2010-2013, which extends the total time baseline to 9 years. This program will continue to be observed through 2020, and monitoring of this field will continue as a part of the SDSS-V Black Hole Mapper project (BHM; Kollmeier et al. 2017).

Reverberation mapping (RM; Blandford & McKee 1982; Peterson et al. 2004) is the primary objective of the SDSS-RM program. RM uses the time delays between the variability of emission from different regions within the AGN. For example, optical continuum variations are echoed by emission lines from the broad-line region (BLR), but with a time delay corresponding to the time it takes for light to travel to the BLR from the continuum-emitting region. This information yields a characteristic radius of the BLR gas, which can be combined with an orbital velocity estimate from the width of the broad emission lines to estimate the black hole mass.

The main goals of SDSS-RM are to obtain reverberation mapping BLR time-lag measurements and to estimate black hole masses for hundreds of quasars. Technically, these goals require only spectroscopic monitoring. However, the cadence of the SDSS-RM spectroscopy, while higher than any previous study of such a large sample, is by itself inadequate. Supplemental photometric monitoring of the SDSS-RM field is critical, as the additional photometry can better sample the continuum light curves, led by improved sensitivity to shorter time lags and improved accuracy for longer lags. In addition, the photometry can be used to improve the spectrophotometric calibration of the spectroscopy. Simulations and real data analyses thus far indicate that the additional photometry will allow us to nearly double the number of lag determinations compared to only using the spectroscopic data (Shen et al. 2015a, 2016b; Grier et al. 2017).

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The SDSS-RM program has reported $\sim 100$ additional broad-line lag measurements (Shen et al. 2016a; Grier et al. 2017; Grier et al. 2019). In addition, the SDSS-RM collaboration has produced a wide variety of results using the first 1–4 years of data, including studies of broad absorption-line variability, host-galaxy properties, emission line velocity shifts, and quasar variability (Shen et al. 2015b; Grier et al. 2015; Sun et al. 2015; Matsuoka et al. 2015; Shen et al. 2016a,b; Denney et al. 2016a,b; Li et al. 2017; Grier et al. 2017; Sun et al. 2018; Yue et al. 2018; Hemler et al. 2019; Wang et al. 2019). However, there will be many other scientific applications for a dataset containing more than 70 spectroscopic epochs over a period of several years with more than 100 epochs of accompanying photometric observations of a sample of 849 quasars that span a wide range in redshift ($0.1 < z < 4.5$), and were chosen to span a wide range quasar properties (see Shen et al. 2019).

In this work, we present the details of the photometric data from the CFHT and Bok telescopes obtained during the first four years of the SDSS-RM program. Details of the telescopes and the strategy for data collection at both facilities are described in Section 2. The datasets were individually pre-processed by their respective facilities’ pipelines (see the subsections in Section 2). The light curves were produced using the ISIS difference imaging packages (Alard 2000) described in Section 3. We present in Section 4 the light curves for all 849 SDSS-RM targets and an additional 365 AGNs that were also monitored as a part of the program by the Bok telescope. In Section 5 we calculate a variability index to quantify the variability of each object and to identify which objects have a highly variable continuum. We conclude this paper in Section 6 with a summary of our work and provide a synopsis of future studies.

2. DATA COLLECTION

2.1. CFHT Observations

The CFHT/MegaCam (Aune et al. 2003) is a wide-field optical imager with a pixel scale of 0.′′187. Its field of view (FoV) was expanded from 1 deg$^2$ (36 CCDs) to 1.1 deg$^2$ (40 CCDs) in 2015. All MegaCam observations were made in Queued Service Observations (QSO) mode, and a log of the observations is presented in Table 1. Each semester’s observations at the CFHT are discussed in the appropriate section below. Raw and calibrated CFHT/MegaCam images can be retrieved from the Canadian Astronomy Data Centre using the proposal IDs given below.$^1$

2.1.1. CFHT pointings layout

The SDSS-RM field overlaps with the W3 wide-field and the D3 deep-field of the Canada-France-Hawaii Telescope Legacy Survey (Semboloni et al. 2006)$^2$. To cover the footprint of the 7$^2$ SDSS-RM field, we used a total of nine slightly overlapping pointings labeled A through I with two dither positions at each pointing to fill in the CCD gaps. The sky coordinates of the centers of the 18 different dither positions (labeled A1 through I2) are given in Table 2. The layout of the fields is shown in Figure 1a for 2014A-2015A (36 unvignetted CCDs) and in Figure 1b for 2016A-2017A (40 unvignetted CCDs). Two exposures were taken at each dither position. The first was a fixed 30 (40) s short exposure in $g$ ($i$) for bright RM targets. The second had an exposure time determined dynamically to achieve a desired point-source S/N of 25 at $i = 22$ and $g = 22.25$, given the seeing and transparency at the time of the observation. At CFHT, this procedure is known as SNR-QSO mode. The average dynamic exposure lengths in 2014A were 55 s in $g$ and 77 s in $i$.

2.1.2. Observing Semester 2014A (Proposal 14AC02)

A total of 81.4 hours was awarded from Canada, France and China, and 52.2 hours of data were obtained. The observations were made using the CFHT filters $g$,MP9401 and $i$,MP9702.$^3$ In each MegaCam run, the $g$ and $i$ observations were executed in Observation Groups (OGs). Completion of the $g$ observation group triggered, via a relational execution link (REEL), an $i$ observation group to be executed within 12 hours (24 hours in Dec/Jan and Jun/Jul). On most occasions, the $g$ and $i$ OGs were executed on the same night. If no $i$ epoch was obtained within 24 hours of a $g$ epoch, the $i$ epoch was skipped in favor of a new $g$ epoch two nights later. Under poor weather conditions, the requested cadence increased to nightly near the end of a MegaCam run to try to obtain a minimum of 4 epochs.

2.1.3. Observing Semester 2015A (Proposal 15AS02)

1 http://www.cadc-ccda.hia-iha.nrc-cnrc.gc.ca/en/cfht/

2 See http://www.cfht.hawaii.edu/Science/CFHTLS/T0007/T0007-docsu10.html

3 See http://www.cfht.hawaii.edu/Instruments/Filters/megaprime.html
A total of 20.4 hours was awarded from Canada, France, and China, and 15.5 hours of data were obtained. At the beginning of 2015A, Megacam was upgraded from 36 to 40 CCDs. New filters that allowed unvignetted observations of the entire FoV were also installed. For our observations, however, we wished to avoid any changes in photometry due to bandpass differences; thus, we continued to use the same filters as in 2014A. In this semester, we tried to obtain two $g$-band epochs per MegaCam run, separated by 4 to 10 days. Additional $g$-band epochs could be added to a run if the time allocated for our observations in previous MegaCam runs had gone unused. An $i$-band epoch was requested to occur either within 15 hours after a $g$-band epoch or not at all.

2.1.4. Observing Semester 2016A (Proposal 16AC12)

A total of 20.4 hours was awarded from Canada, France and China, and 15.8 hours of data were obtained. Beginning with semester 2016A, we used the new filters (CFHT filters g.MP9402 and i.MP9703) for an unvignetted view of the upgraded focal plane with 40 CCDs. However, we have not yet processed the photometric measurements of the target quasars using images from the 4 new CCDs. We used the same scheduling pattern as in semester 2015A.

2.1.5. Observing Semester 2017A (Proposals 17AC12 + 17AF13)

A total of 16 hours was awarded from Canada and France, and 12 hours of data were obtained. Due to a smaller time allocation in 2017A, we chose to request only $g$-band observations. After the entire field was observed, at least 72 hours were required to elapse before it could be observed again. Results incorporating these data will be presented at a future date.

2.2. Bok Observations

Monitoring of the SDSS-RM field with Steward Observatory’s 2.3m Bok telescope commenced in December 2013 and is ongoing. The SDSS-RM observations were allocated time through the regular proposal process and observing nights were often shared with other programs to maximize time coverage and observing efficiency. SDSS-RM data are collected with the 90Prime instrument (Williams et al. 2004), a ∼ 1° field of view. As with the CFHT observations, Bok data are collected in the SDSS $g$ and $i$ bandpasses. To complement the CFHT dark time observations and provide the continuous photometric coverage, the Bok observations were typically obtained during bright lunar phases, including full Moon. The sky background is thus quite high, which degrades the overall sensitivity. Each Bok pointing has a design exposure time of 300s, but this time was sometimes divided into multiple exposures to keep the bright sky background well below saturation limits.

The 90Prime FoV covers the SDSS-RM field in 9 total pointings. To better cover CCD gaps and to compensate the high backgrounds, these pointings are divided into two exposures (typically 150s, as above) that are dithered by a few arcminutes, leading to a total of 18 pointings per epoch. Usually only one bandpass is used per night and filter changes occur on adjacent nights. An exception is the three nights around full Moon, where only the $i$ band is used due to the high background at shorter wavelengths. Collecting all 18 pointings takes roughly two hours with overhead for focus and pointing alignment. The pointing sequence is repeated through the night as time permits. Given the overlap between pointings as well as the repeated passes, an individual quasar receives anywhere from one to ∼10 observations in a single night, allowing for analyses of short-timescale variability. The observation pattern is presented in Figure 2, demonstrating that regions within the SDSS-RM field received between ∼ 200 and ∼1000 observations over the three year period beginning with the 2014 campaign, obtained from over 5000 individual exposures. Table 3 provides the log of the Bok observations over the four years.

2.2.1. Bok Data Reductions

Bok 90Prime data were processed using standard optical image processing techniques implemented in a python-based pipeline developed by our group. The pipeline organizes data by observing night and automatically identifies the calibration frames taken for each night. Bias and dome flat correction frames are produced by a stacked median of ∼10 calibration frames. The science frames are sorted by filter and associated with the calibration frames that are nearest in time. The overscan region of each science image is collapsed to one dimension using a median, followed by a 17-pixel wide median filter to smooth the overscan pattern. The resulting vector is subtracted from the image. The two-dimensional bias frame is then subtracted, and the dome flat is applied to the images.

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4 See http://www.cfht.hawaii.edu/Instruments/Filtersmegaprime.html
5 https://github.com/imcgreer/idmrm and https://github.com/legacysurvey/rapala
The four 90Prime CCDs each have four readout channels with independent amplifiers. The next step is to combine the 16 image channels into a single, 4-CCD mosaic with the necessary gain corrections. We found that there are small gain variations over the course of a night and that tracking these variations is necessary to obtain a uniform sky background. To remove sensitivity to illumination gradients, we selected small windows of pixels along the borders of adjacent images, then fit for the multiplicative factor needed to balance the sky levels of the associated amplifiers. Once the four amplifiers in each CCD were balanced to a common level, we used a similar procedure to fit the sky levels near the center of the field in order to match the CCD sky levels.

The dome screen illumination pattern is quite different than the night sky illumination, so the science images from each night are combined into a filter specific illumination correction. This correction is obtained by scaling each image to a common sky background level and stacking with a clipped mean. The image is binned by a factor of 8 along each axis using a median to remove small objects (stars and galaxies). A smooth 2D spline is then iteratively fit to this rebinned image, removing outlier pixels. The final result is applied to the science images and results in a highly uniform sky background.

For the $i$-band images, we also create a fringe pattern image. The median sky level is removed from each image, and the images are stacked to produce the fringe master. The sky-subtracted images are divided by the fringe master to determine the scaling of the pattern that matches the fringe amplitudes in each frame. Then, the scaled fringe master image is subtracted from the original science frame (prior to removing the median sky level).

A final, high signal-to-noise ratio sky flat is constructed from the science frames by median combining the images scaled by the sky background after masking bright objects identified using Source Extractor (Bertin & Arnouts 1996). This sky flat is usually composed of images from a single observing run, unless there are too few ($\leq 100$), in which case they are combined over multiple runs. Although the corrections in the sky flats are small (few per cent), there are notable patterns remaining after the previous processing steps that the sky flat is able to correct.

The final detrending step is to remove a low-level variable gradient in the sky by fitting a linear two-dimensional spline to the sky background of each image after masking objects. Only the gradient is subtracted – the mean sky level of each image is preserved. Object catalogs are generated using SExtractor and then Scamp (Bertin 2006) is used for astrometric registration. A catalog of astrometric references for the field was initially constructed from SDSS, and later updated to use Gaia DR1 positions (Lindegren et al. 2016). The resulting RMS in star positions is $\sim 0.05\arcsec$.

The pipeline utilizes multiprocessing to run processing steps in parallel. On a typical multi-core desktop machine, the entire set of $>5000$ images can be processed in roughly one day.

### 2.2.2. Photometric Analysis

Although the primary source of photometry for SDSS-RM is the difference imaging catalogs, we also performed aperture photometry on the Bok images. Locations of both reference stars from SDSS and the RM quasar targets were identified using the WCS solutions from the processing pipeline. A set of apertures from 0\".9 to 10\".1 were placed at each target location and counts within the apertures were obtained with sep. We primarily focus on the 2\".3 and 6\".8 apertures, which provide roughly optimal and total light apertures for typical Bok seeing.

We construct light curves for all targets. The reference stars are treated as constant sources and are a valuable cross-check on processing errors or poor quality imaging that leads to photometric outliers. For each reference star, we determine a median magnitude and RMS scatter, and then flag measurements that are $>5\sigma$ outliers. If a single image contains a large number of outliers, we examine it by eye. Most of these cases are images affected by strong scattered light from the bright Moon during the Bok observations, and they are removed from our analysis. Once the data set is cleaned of bad epochs, we determine photometric zero points and color terms relative to the SDSS $g$ and $i$ band photometry of the field using bright ($g < 17, i < 19$ mag) stars.

After removing outliers, we find that the internal accuracy of the Bok photometry reaches $\sim 10$ mmag for bright stars (17 mag), and $\sim 30$ mmag at $g=19$. This suggests we have met our goal for photometric accuracy and that the Bok photometry will be suitable for tracking quasar variability.

### 3. DIFFERENCE IMAGING

For the analysis of the data sets collected at the CFHT and Bok telescopes, we used the ISIS difference imaging package (Alard & Lupton 1999; Alard 2000). To produce the differential flux light curves, the reduced data were

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6 https://github.com/kbarbary/sep

7 The software can be downloaded from http://www2.iap.fr/users/alard/package.html
parsed into separate FITS files, separated by field, CCD, and bandpass. The CFHT data had 9 fields while the Bok data had 18. The CFHT and Bok data sets were processed with ISIS separately.

The images for each subfield are first interpolated to a common frame. Next, a reference image is constructed using the images with the best seeing, lower sky backgrounds, and high transparencies. For each individual image, the reference image is convolved to match its PSF structure, and the individual image is scaled and subtracted from that convolved reference image to create a difference image on the flux scale of the reference image. Negative values in a difference image indicates that a source is brighter than on the reference image. Details of the convolution matrix and their applications are described in Alard & Lupton (1998) and Alard (2000).

The RM targets and a selection of standard stars were identified on the reference image, and PSF photometry was performed at those positions. Using the midpoint of the image observation (in terms of Modified Julian Date) as our time index, light curves were constructed with the differential flux values from ISIS. In this paper, we present the differential flux light curves for each SDSS-RM quasar from each field in which it appears on that field’s reference image. Grier et al. (2017) describe how for their analysis, they merged these differential light curves from the different datasets and corrected the uncertainties reported by ISIS using the standard star observations.

3.1. CFHT Processing

For the CFHT data spanning 2014 to 2016, the raw data were detrended with the Elixir pipeline. With the detrended data, we separated the multi-extension FITS files into the individual CCD images (36 for the 2014 data set and 40 for the subsequent years). Processing was systematically performed per field, per pointing (1 or 2), per filter (g− or i−band), and per CCD. Source Extractor (Bertin & Arnouts 1996) was used to identify the best subset of the images to create the reference image, based on the sky background and the median FWHM. The number of images selected to construct the reference image ranged between 4 and 10. For some subfields, a bright foreground star would dominate and inflate the sky background. In such problematic subfields, fewer images could be included in the construction of a robust reference image.

Each CCD has a small field of view and typically contained 2 to 8 AGNs. We selected ~100 reference stars in each subfield along with the AGNs. We used the standard stars’ light curves to rescale the uncertainties and correct for any offsets between the years (e.g., due to the filter change - see Section 2.1).

Once the image quality had been assessed and all the targets identified in the fields, we began the ISIS difference imaging processing by doing an interpolation of the images, reference image creation, image subtraction of the convolved images to the reference image, and finally PSF photometry of the residual images.

3.2. Bok Processing

The dataset from the Bok 90′′ telescope spanned the observational season of the SDSS-RM field from 2014 to 2017. The field was observed in mostly bright time, which allowed coverage of the variability during the times when the field was not observed by SDSS or CFHT. The bulk of the data were primarily taken during 2014, and it is this dataset that serves as the baseline for the difference imaging processing of the subsequent years of Bok data.

The Bok data from 2014 were processed with ISIS mostly using the same procedures as for the CFHT 2014 data, but with a few changes. One extra step in the preparatory work done to the Bok images was to add back in the sky background value, as this information was removed from the reduced images from the Bok pipeline. Without this sky background information, ISIS had difficulty producing a useful reference image as well as convolving the rest of the images because ISIS assumes the sky is included. This particular step was done only for the 2014 dataset. In the 2015-2017 data reduction, the sky background was retained. Next, the image with the best FWHM and lowest sky background was identified, and the other images were interpolated to its reference frame. This reference image (which was based on primarily 2014 images) was the basis for the later, incorporated Bok data sets. Since the Bok fields had a larger field of view, more reference stars were available and processed per field. The standard stars were used to rescale the uncertainties in the flux measurements of the SDSS-RM AGNs (see Grier et al. 2017).

In addition to the original 849 RM targets from Shen et al. (2015a), 365 objects were also identified as possible AGN in the Bok fields. These extra 365 targets currently lack spectroscopic data and only have Bok time-series photometry spanning the four years. These AGN are in the CFHT data, but at the time of the ISIS processing, the information for these extra objects were not available, and thus they were not processed.

4. RM TARGET LIGHT CURVES
For the photometric light curves, we include with this paper the ISIS output from its phot module of the ISIS software. The output photometry files are provided as online data and are archived as a multi-extension FITS file. The columns in the output photometry files are as follows:

**Column 1:** Midpoint of the observation in Modified Julian Date (days).

**Column 2 and 4:** Differential fluxes

**Column 3 and 5:** Respective uncertainties in the differential flux measurement of Column 2 and 4

**Column 6 and 7:** Sky background measurements

**Column 8:** The local average sky value over Nsky pixels.

**Column 9:** The local median sky value over Nsky pixels.

**Column 10:** Nsky pixels used in Column 8 and 9.

**Column 11:** The aperture flux measured over N pixels.

**Column 12:** The number of pixels, N

The fluxes are in units of counts but are all on the flux scale of their reference image. Two differential flux values are calculated, which are based on two different PSF weighting schemes for extracting the fluxes. Any significant difference between these fluxes is an indication of subtraction problems usually due to a nearby bright source, clouds, or other systematic problems. ISIS itself assumes clean subtractions, in which case the “sky” on a subtracted image is consistent with zero. However, clouds can produce a local, variable “sky” in the subtracted images, and we use a modified code which attempts to correct for a local sky. For our analysis we used the flux and uncertainty values of Columns 2 and 3. The actual photometric noise may be larger, by up to a factor of 2, compared to what is reported in Columns 3 and 5. The crude aperture flux value in Column 11 can be used as a sanity check against the flux values determined in Columns 2 and 4. In the ISIS convention, a negative flux on the subtracted image means the source is brighter than on the reference image. To convert the differential flux to a magnitude, the flux of the object from the reference image must be subtracted to the differential flux. These differential flux values are all with respect to the reference images used in the processing. We intend to provide the reference flux values of the QSOs in a later paper after incorporating additional datasets that are being collected now.

Since the field of view of both the CFHT and Bok data sets are relatively large, we can see variable cloud cover in the frames. The differential flux scalings are affected by this cloud cover, and by the halos of bright, foreground stars. In both cases, the sky background values can be non-zero, and can be checked with the values in Column 6 and 7 of the ISIS output files. A number of targets found close to the edge of a CCD may have fewer epochs due to the object occasionally falling off the edge of the image. Due to the dithering, the edges of the reference image are some 20 pixels inward from the nominal chip edge. The software would discard flux measurements of targets from these edge regions due to problems such as poor PSF profiles. In some cases, these edge targets have fluxes measured from an adjacent subfield, so the light curves can still be constructed.

### 5. MEASURING AGN VARIATIONS

The photometric dataset we present here provides an excellent opportunity to apply a variability index, which can be used to select interesting targets for further study. We characterized the variability with the Welch-Stetson J-index, which was originally developed for identifying pulsating variable stars (Welch & Stetson 1993; Stetson 1996). We calculated the J-index using both the Bok and CFHT datasets; however, the Bok dataset has the advantage of having more epochs, which yielded a more robust variability index. The description of the Welch-Stetson J-index construction is provided in the appendix. For a more thorough description of this analysis tool, we direct the reader to Stetson (1996).
5.1. Application of the variability index

We calculated the variability index for all 849 SDSS-RM objects using both the Bok and CFHT $g$ and $i$ data. We also calculated the Welch-Stetson J index for the additional 365 AGN (Shen et al. 2019) with the Bok data. These additional AGN were not processed in the CFHT datasets, since at the time of the differential flux processing, the positions of those objects were not available. Subsequent ISIS processing of the CFHT dataset is planned to include these additional AGNs. The Bok dataset has more epochs and a longer time baseline. Thus, the Bok variability index should be more accurate and better reflect the variable nature of the AGN. We find that the J-index values calculated from the CFHT dataset are consistent with the values based on the Bok datasets. We provide the J variability index for each SDSS-RM AGN in Table 4. In Figure 3, we present histograms of the J-index with respect to filter and telescope. Our calculation of the J-index took into account of the case where an AGN was observed over different subfields due to the dithering of the field. Separate J-indices were determined for the table, and we averaged those values.

Grier et al. (2017) examined 220 AGNs of the SDSS-RM sample for RM lags between the continuum and the $H\beta$ line. To select AGN that were variable, they used a measurement of the RMS scatter about the mean to quantify the variability. Their method differs from the formulation of the Welch-Stetson index; however, a visual inspection of the light curves indicates that both measurements track AGN variability well.

We note that there were several differences in the treatment of the light curves before these variability measurements were made. For example, Grier et al. (2017) merged the light curves from the different datasets and corrected the flux uncertainties from the original ISIS fluxes. In our work, we adopted the differential flux values without any correction. Thus, a direct comparison between our J-index and their RMS variability measure is not feasible.

Determining what level of variability measurement constitutes “significant” variability is somewhat subjective. Our visual inspection of the 220 AGN sample suggests that the J-index is well correlated with the actual variability (both in the short and long-term). In Figure 4, the light curves of two AGNs with similar $g$-magnitudes show how the J-index can be used to pick out highly variable objects. RM 275 has a larger J-index value compared to RM 481, and their light curves exhibit their levels of variation reflecting their different variability indices. We provide here the J variability index as a guide for readers to select interesting objects for future projects. An example of a large variability index indicating activity in an AGN is RM 17, which is described as a hypervariable quasar by Dexter et al. (2019).

Figure 5 presents the variability index with respect to the $g$ and $i$ magnitude of the SDSS-RM objects. We show in this Figure the distribution of the indices from the Bok datasets and the CFHT datasets. At brighter magnitudes, larger variability indices are seen, but at fainter magnitudes, we find fewer objects with such a level of variability. This result could be due to an observational bias in the sample, but in general, objects with large variations at brighter magnitudes are more readily identified in a sample.

To check this conclusion, we plot the J-index against redshifts from Shen et al. (2015a). Figure 6 shows the distribution of the variability index with redshift. There remains a trend of larger variation in nearby AGN, but this level of large variation is visible through the whole range of redshift. One of the goals of the SDSS-RM project is to study the AGN activity for a wide range of redshifts. The presence of different levels of variation across all redshifts in the SDSS-RM sample confirms that reverberation mapping should be feasible over this range with no pre-selection on quasar variable properties.

To understand the J-index calculated from data taken at two different telescopes, we plot the indices from the $g$– and $i$–band data in Figure 7. There is no one-to-one correlation between the J-indices calculated from the Bok and CFHT data. The reason for the typically larger J-index for Bok data could be due to the differing S/N of the individual images from each telescope. The uncertainties of the flux measurements are folded into the J-index calculation (see Appendix for more details), and the $g$–band uncertainties are smaller per Bok exposure. Thus, the Bok J-index values will appear to have a larger variation compared to the J-index based on the CFHT datasets, for both $g$– and $i$– bandpasses. As mentioned above, the Bok dataset has more epochs and a longer time baseline than the CFHT dataset. Variability will be more likely to be detected in the Bok data than with the CFHT data.

Further, we compared separately the J-index calculated based by telescope. In Figure 8, we compare the J-index based on $g$– and $i$–band data, and again, we do not see a clear one-to-one correlation. In this case, the $g$–band J-index shows a higher variability value than the $i$–band based data. The variability in amplitudes are generally larger in shorter wavelengths (e.g., MacLeod et al. 2010). This is likely due to a combination of local accretion disk temperature changes being more evident with shorter wavelength and effective disk areas being smaller with shorter wavelength, the latter leading to shorter-wavelength flux more closely tracking variations in illuminating flux from the
innermost regions of the accretion flow. In Figure 8, we added the one-to-one trend line to help guide the eye, and to emphasize how it is clearly not one-to-one.

6. SUMMARY

We present the photometric datasets for the SDSS-RM AGNs obtained at the CFHT and Bok telescopes over a span of 4 years (2014-2017). We applied ISIS, a differential flux photometry technique, to the time-series data, and we calculated a variability measure, the Welch-Stetson J-index. The variability index can be used to select interesting AGN for further study. We find that many of the variable AGN in this sample have long-term variability (i.e., the variation occurs over years rather than days). We were able to identify objects with low levels of variability that appear to be significant and above the noise level. Almost all the objects in this study appear to have some level of variation in their continuum flux over the course of the observations.

There are many projects currently underway using these photometric data. The SDSS-RM team has been merging the Bok and CFHT datasets with the SDSS BOSS spectra to analyze the various lags seen in the AGN (see Grier et al. 2017 and Grier et al. 2019). The photometry is also being used to measure inter-band continuum lags in quasars to learn about the accretion disk size (Homayouni et al. 2019). Over 200 AGNs from the original SDSS-RM sample have merged Bok and CFHT light curves that have been published by Grier et al. (2017), and more are expected to be merged and analyzed for future projects (e.g., Grier et al. 2019, Homayouni et al. 2019, and Homayouni et al. 2020).

Based in part on observations obtained with MegaPrime/MegaCam, a joint project of CFHT and CEA/DAPNIA, at the Canada-France-Hawaii Telescope (CFHT) which is operated by the National Research Council (NRC) of Canada, the Institut National des Sciences de l’Universe of the Centre National de la Recherche Scientifique of France, and the University of Hawaii.

The authors wish to recognize and acknowledge the very significant cultural role and reverence that the summit of Maunakea has always had within the indigenous Hawaiian community. We are most fortunate to have the opportunity to conduct observations from this mountain.

We thank the CFHT staff who supported our program, including Nadine Manset, Todd Burdullis, Simon Prunet, and Andreea Petric.

We thank the anonymous referee for the helpful comments to this paper.

PH acknowledges the support of the Natural Sciences and Engineering Research Council of Canada (NSERC), funding reference number 2017-05983. CJG, WNB, and DPS acknowledge support from NSF grant AST-1517113. YS acknowledges support from an Alfred P. Sloan Research Fellowship and NSF grant AST-1715579. LCH acknowledges the National Key R&D Program of China (2016YFA0400702) and the National Science Foundation of China (11721303, 11991052). JVHS and KH acknowledge support from a STFC grant ST/R000824/1. CSK is supported by NSF grants AST-1814440 and AST-1908570.

APPENDIX

A. THE WELCH-STETSON J VARIABILITY INDEX

The Welch-Stetson J-index (or simply the J-index) has many features that best incorporate the SDSS-RM photometric datasets to produce a robust quantification of the AGN variation. The J-index takes advantage of the observing cadence, specifically if there were paired epochs close in time. For the Bok data, two observations were taken of each subfield, depending on the sky conditions. We can also calculate the J-index for unpaired, single epochs. This feature allows us to use all of the observations rather than tossing out unpaired epochs. To define a “pair” of observations from a night’s dataset, we selected a minimum time interval between observations of 0.005 days (7 minutes). Any two observations taken within this interval were considered to be a “pair”; any observation taken outside of this interval was considered to be part of another (subsequent) observation or pair. If an observation does not have a closely-timed observation, it was considered to be a “single” observation of that subfield. In our datasets, we assume the second of a pair of observations was collected within 7 minutes after the collection of the first observation. This time interval can be adjusted to define “paired” observations for a specific dataset.

Another strength of the J-index is that it uses information from two different bandpasses. For variable stars, the variation is often correlated with color due to the nature of the stellar pulsation. However, for AGNs, the observed variability in the light curve does not necessarily correlate in $g$ and $i$ at the same moment in time as time delays
between the $g$ and $i$-band continuum fluxes have been observed (e.g., Shappee et al. (2014), Fausnaugh et al. (2016, 2018), Homayouni et al. (2019), and Cackett et al. (2020)). Thus, we chose not to combine the $g$ and $i$ datasets in the construction of the J-index.

The J-index is composed of the relative error ($\delta$), normalized residuals of a pair of observations ($P_k$), and a weighting factor ($w_k$). Stetson (1996) defines the relative error as the residual from a mean magnitude, weighted by the measurement’s uncertainty and the number of observations, $n$, as

$$\delta_i = \frac{f_i - \bar{f}}{\sigma_{f,i}} \sqrt{\frac{n}{n-1}} \quad (A1)$$

In the case of our dataset, we do not use magnitudes, but differential flux values from ISIS, thus in Equation A1, instead of using Stetson (1996)’s “$v$ magnitude”, we are using “$f$” for the differential flux.

As described in Stetson (1987) and Stetson (1996), we follow the prescription to obtain a robust weighted mean flux value through iteration. When the initial weighted mean flux value has been determined from Equation A1, we recalculate the weight by its residual error. This weight of an observation is defined as

$$w_i = \left[ 1 + \left( \left| \frac{\delta_i}{2} \right| \right) \right]^{-1} \quad (A2)$$

The following equation is used for the calculation for the weighted mean flux from Welch & Stetson (1993) (their equation 1 and 2, computed in terms of flux):

$$\bar{f} = \frac{\sum_{i=1}^{n} f_i \sigma_{f,i}^{-2}}{\sum_{i=1}^{n} \frac{1}{\sigma_{f,i}^2}} \quad (A3)$$

For our weighted mean flux, $\bar{f}$, we iterated five times to reach a stable value and to minimize the effects of any large outliers in the light curve data. We found that increasing the number of iterations did not change the value of the mean flux significantly. A quick visual inspection revealed that some of the light curves did show a real, large outlier from the photometry. To help aid in the robustness of our variability index, we removed any large, obvious outliers that were $3\sigma$ from our weighted mean flux. In some cases, a single outlier did influence the calculation of the variability index, and with $3\sigma$ clipping, we have a more robust index value.

For a pair of closely timed data points, the product of the residual errors can be constructed from the $i$-th and $j$-th observations. This product is identified as the normalized residuals of the $k$-th pair

$$P_k = \delta_i \delta_j \quad (A4)$$

The normalized residual for a single observation can be simplified to

$$P_k = \delta_i^2 - 1 \quad (A5)$$

The J-index is calculated from Equation A6. The $\text{sgn}$ function simply returns the sign of the expression, whether it is positive or negative. The subscript $k$ refers to the paired observation. We use the weighting factor determined from Equation A2 here for the J variability index. In this weighting factor, we use the residual error of the pair or single observation and does not require iteration used with the weighted mean flux.

$$J = \frac{\sum_{k=1}^{n} w_k \text{sgn}(P_k) \sqrt{|P_k|}}{\sum_{k=1}^{n} w_k} \quad (A6)$$

The advantage of using paired observations compared to single observations is that the $P_k$ quantity will be positive in most cases. The individual residual errors will be positive for fluxes far above the weighted mean or negative for fluxes far below. A quasar with strong variability can have $P_k$ values ranging from small to large values, but the sum will produce a large J index value.

In a few cases, Equation A6 yielded a negative value. Stetson (1996) describes how cosmetic defects or problems with the data processing can produce this negative value. We identified four AGN with a negative J-values in the Bok
dataset, and upon inspection of the reference frame, all of these objects are found near the edge of a CCD where the PSF photometry can fail.

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Figure 1. RM field pointing layout. The magenta circle is the SDSS-BOSS spectrograph FoV. The SDSS-RM field is contained within the CFHTLS W3 (wide) field, and partially overlaps the CFHTLS D3 (deep) field, indicated by the cyan square labeled “D3”. The letters denote the positions of each of the 9 pointings, and the order in which they are observed. The blue and red outlines are the two dithered exposures at each pointing. Each pointing overlaps the next by $\geq 16.5''$ in RA and $\geq 88.5''$ in DEC. The left panel shows the imaged areas of the FoV for semesters 2014A and 2015A, when 36 CCDs were unvignetted. The right panel shows imaged areas of the FoV for semesters 2016A and 2017A, when 40 CCDs were unvignetted. Both are approximate, in that they do not account for the small change in the extent RA of the MegaCam field of view over the range in DEC shown.
Figure 2. Number of observations of individual standard stars in the Bok observations of the SDSS-RM field, including data obtained during 2014-2016. The patterns due to the pointing sequence are clearly visible: dark blue regions are observed only once during a pointing sequence, and light blue regions are observed twice due to the overlap in dithered frames at each of the 9 primary pointing centers. Green regions are overlaps between the 9 pointing centers, resulting in twice as many observations per star. Finally, the yellow/red regions near the center are where 4 or more pointings overlap. Holes are regions around bright stars. Over the three year period, individual stars received anywhere from $\sim 200$ to $\gtrsim 1000$ photometric measurements.
Figure 3. Distribution of the J variability indices for the SDSS-RM AGNs. Upper plots are for the J variability indices calculated from the Bok datasets. Lower plots are for the J indices calculated from the CFHT datasets. The left plots are for $g$-band data and the right plots are for $i$-band data.
Figure 4. (Upper) Light curve of RM 275, which has a large, long-term variation. RM 275 has a calculated variability index of $J = 48.22$. RM 275 has a $g$-band magnitude of 20.73. The photometric error bars are negligible with respect to the range in flux presented here. In the ISIS convention, a negative differential flux means the source is mostly brighter than on the reference image. (Lower) Photometric light curve of RM 481, which appears to have a relatively small variation between 2014 and 2017. This AGN has a $g$-band magnitude of 20.74 and a variability index of $J = 3.09$. 
Figure 5. (Upper) Bok $g-$ and $i-$band variability indices as a function of magnitude for the SDSS-RM AGNs. (Lower) CFHT $g-$ and $i-$band J-indices as a function of magnitude.
Figure 6. Distribution of J-indices, constructed from $g$- and $i$-band data, as a function of redshift, $z$. (Upper) J-indices were calculated from Bok datasets while (lower) plots have J-indices based from the CFHT datasets.
Figure 7. Comparison of the Welch-Stetson J-index constructed from Bok and CFHT data. The upper panel is the comparison of J-index based on the $g$–band data. The lower panel is for the J-index based on the $i$–band data.
Figure 8. Comparison of the J-indices constructed from $g$- and $i$-band data. A one-to-one line is provided to show that the quasars are more variable at shorter wavelengths. Upper panel: J-index based on Bok data. Lower panel: J-index based on CFHT data.
Table 1. Log of CFHT Observation

| MJD  | UT Date  | Filter | Avg Seeing | Weather  | Comment                   |
|------|----------|--------|------------|----------|---------------------------|
|      |          |        |            |          |                           |
| 2014A|          |        |            |          |                           |
| 56712| 20140224 | g,i    | 0.7        | photometric |                           |
| 56715| 20140227 | g,i    | 1.0        | photometric |                           |
| 56721| 20140305 | g      | 1.2        | photometric | partial coverage          |
| 56722| 20140306 | g,i    | 0.7        | photometric |                           |
| 56723| 20140307 | g,i    | 0.6        | thin cirrus |                           |
| 56741| 20140325 | g,i    | 1.0        | thin cirrus |                           |
| 56743| 20140327 | g      | 0.8        | photometric | partial coverage          |
| 56744| 20140328 | g,i    | 0.7        | photometric |                           |
| 56751| 20140404 | g,i    | 0.7        | photometric |                           |
| 56772| 20140425 | g      | 0.9        | thin cirrus |                           |
| 56776| 20140429 | g,i    | 0.6        | photometric |                           |
| 56778| 20140501 | g,i    | 0.7        | photometric |                           |
| 56780| 20140503 | g,i    | 0.4        | thin cirrus |                           |
| 56781| 20140504 | g,i    | 0.5        | thin cirrus | partial coverage in i     |
| 56783| 20140506 | g,i    | 0.5        | partly cloudy | partial coverage in i   |
| 56798| 20140521 | g,i    | 0.6        | photometric |                           |
| 56801| 20140524 | g,i    | 0.8        | photometric |                           |
| 56803| 20140526 | g      | 0.9        | thin cirrus |                           |
| 56805| 20140528 | g,i    | 0.7        | photometric |                           |
| 56807| 20140530 | g,i    | 0.8        | photometric |                           |
| 56809| 20140601 | g      | 0.8        | photometric |                           |
| 56811| 20140603 | g,i    | 0.5        | photometric |                           |
| 56829| 20140621 | g,i    | 0.6        | photometric | partial coverage (CFHTLS D3) |
| 56831| 20140623 | g,i    | 0.5        | photometric |                           |
| 56833| 20140625 | g,i    | 0.6        | photometric |                           |
| 56835| 20140627 | g,i    | 0.6        | photometric |                           |
| 56837| 20140629 | g,i    | 0.6        | photometric |                           |
| 56839| 20140701 | g,i    | 0.8        | photometric | partial coverage in i     |
| 56841| 20140703 | g,i    | 0.6        | thin cirrus |                           |
| 56865| 20140727 | g,i    | 0.8        | photometric | partial coverage (CFHTLS D3) |
| 2015A|          |        |            |          |                           |
| 57078| 20150225 | g      | 1.0        | photometric |                           |
| 57104| 20150323 | g      | 0.6        | partly cloudy |                       |
| 57105| 20150324 | g      | 0.8        | photometric | short exposures only      |
| 57123| 20150411 | g      | 0.8        | thin cirrus |                           |
| 57133| 20150421 | g      | 0.8        | photometric | partial coverage          |
| 57134| 20150422 | g      | 1.0        | thin cirrus | partial coverage          |

Table 1 continued on next page
| MJD UT Date | Filter | Avg Seeing | Weather | Comment |
|------------|--------|------------|---------|---------|
| (days)     | (arcsec) |            |         |         |
| 57157      | 20150515 g,i | 1.0 | photometric |         |
| 57160      | 20150518 g,i | 0.8 | thin cirrus | partial coverage in i |
| 57166      | 20150524 g | 0.7 | photometric |         |
| 57185      | 20150612 g | 1.0 | photometric |         |
| 57191      | 20150618 g | 1.0 | photometric |         |
| 57213      | 20150710 g,i | 1.0 | photometric | partial coverage in i |
| 57216      | 20150713 g,i | 1.0 | photometric | partial coverage in i |
| 57217      | 20150714 i | 0.9 | photometric |         |
| 57220      | 20150717 g,i | 1.0 | thin cirrus | partial coverage in i |
| 57221      | 20150718 i | 0.5 | photometric |         |
| 57223      | 20150720 g,i | 0.8 | photometric |         |
| 57420      | 20160202 g,i | 0.9 | photometric |         |
| 57433      | 20160215 g,i | 0.6 | photometric |         |
| 57479      | 20160401 g,i | 0.6 | photometric |         |
| 57492      | 20160414 g,i | 1.1 | photometric |         |
| 57508      | 20160430 g,i | 0.9 | photometric |         |
| 57520      | 20160512 g,i | 0.6 | thin cirrus |         |
| 57542      | 20160603 g | 0.8 | photometric |         |
| 57543      | 20160604 i | 0.6 | photometric |         |
| 57547      | 20160608 g | 0.6 | photometric |         |
| 57567      | 20160628 g | 0.9 | partly cloudy |         |
| 57568      | 20160629 i | 0.9 | thin cirrus | partial coverage |
| 57806      | 20170222 g | 1.0 | photometric | partial coverage |
| 57807      | 20170223 g | 1.0 | photometric |         |
| 57833      | 20170321 g | 0.9 | photometric |         |
| 57840      | 20170328 g | 0.8 | photometric |         |
| 57843      | 20170331 g | 0.7 | photometric |         |
| 57846      | 20170403 g | 0.8 | photometric |         |
| 57862      | 20170419 g | 0.8 | photometric |         |
| 57868      | 20170425 g | 0.9 | partly cloudy |         |
| 57871      | 20170428 g | 0.7 | photometric |         |
| 57875      | 20170502 g | 1.1 | thin cirrus |         |
| 57877      | 20170504 g | 0.8 | photometric |         |
| 57890      | 20170517 g | 0.7 | photometric |         |
| 57894      | 20170521 g | 0.6 | thin cirrus |         |
| 57903      | 20170530 g | 0.6 | thin cirrus |         |
| 57924      | 20170620 g | 1.0 | photometric |         |
| 57950      | 20170716 g | 0.8 | thin cirrus |         |

*Table 1 continued on next page*
### Table 1 (continued)

| MJD  | UT Date   | Filter | Avg Seeing | Weather  | Comment     |
|------|-----------|--------|------------|----------|-------------|
|      | (days)    | (arcsec) |            |          |             |
| 57964| 20170730  | g      | 0.8        | photometric |             |

**Note**—“Partial coverage” indicates not all RM pointings were imaged that epoch. Epochs MJD=56829 and 56865 were pointings to observe additional calibration sources in the CFHT-LS D3 field, which partially covers the RM field. The Weather column refers to the weather status during our observations that night and are taken from the searchable CFHT QSO Night Reports and Program Status available at [http://www.cfht.hawaii.edu/en/science/QSO/#nr](http://www.cfht.hawaii.edu/en/science/QSO/#nr), where more than one weather condition is noted during our observations, we cite the worst condition reported.
| Position | RA          | DEC          |
|----------|-------------|--------------|
| A1       | 14:14:47.17 | +53:05:46.0  |
| A2       | 14:14:50.83 | +53:03:31.0  |
| B1       | 14:14:47.19 | +52:07:00.5  |
| B2       | 14:14:50.81 | +52:04:45.5  |
| C1       | 14:08:43.77 | +52:09:50.0  |
| C2       | 14:08:47.54 | +52:07:35.0  |
| D1       | 14:08:15.56 | +53:05:46.0  |
| D2       | 14:08:19.40 | +53:03:31.0  |
| E1       | 14:08:35.77 | +54:01:42.0  |
| E2       | 14:08:39.63 | +53:59:27.0  |
| F1       | 14:14:47.15 | +54:04:31.5  |
| F2       | 14:14:50.85 | +54:02:16.5  |
| G1       | 14:20:58.53 | +54:01:42.0  |
| G2       | 14:21:02.07 | +53:59:27.0  |
| H1       | 14:21:18.77 | +53:05:46.0  |
| H2       | 14:21:22.26 | +53:03:31.0  |
| I1       | 14:20:50.61 | +52:09:50.0  |
| I2       | 14:20:54.08 | +52:07:35.0  |
Table 3. Log of Bok Observations

| MJD  | UT Date   | Filter(s) | Ave. Seeing | Comment                      |
|------|-----------|-----------|-------------|------------------------------|
| (days)| (arcsec)  |           |             |                              |
| 56648| 20131222  | g         | 3.0         | partial coverage             |
| 56671| 20140114  | g         | 1.5         |                              |
| 56672| 20140115  | i         | 1.7         |                              |
| 56673| 20140116  | i         | 1.7         |                              |
| 56674| 20140117  | i         | 1.4         |                              |
| 56675| 20140118  | g         | 1.4         |                              |
| 56677| 20140120  | g         | 1.5         | partial coverage, partly cloudy|
| 56678| 20140121  | g,i       | 1.2         |                              |
| 56680| 20140123  | g,i       | 1.7         | thin clouds                  |
| 56683| 20140126  | g,i       | 1.4         |                              |
| 56685| 20140128  | g         | 1.5         |                              |
| 56686| 20140129  | i         | 1.3         | cloudy                       |
| 56701| 20140213  | g         | 1.7         | thin clouds                  |
| 56702| 20140214  | i         | 1.5         | thin clouds                  |
| 56703| 20140215  | i         | 1.4         |                              |
| 56705| 20140217  | g         | 1.4         | partial coverage, cloudy     |
| 56706| 20140218  | g         | 1.6         |                              |
| 56707| 20140219  | i         | 1.8         | partly cloudy                |
| 56728| 20140312  | g         | 1.5         |                              |
| 56729| 20140313  | i         | 1.2         | thin clouds                  |
| 56730| 20140314  | g         | 2.0         | cloudy                       |
| 56731| 20140315  | i         | 1.3         |                              |
| 56732| 20140316  | i         | 2.5         | windy                        |
| 56733| 20140317  | i         | 1.4         |                              |
| 56734| 20140318  | g         | 1.5         |                              |
| 56760| 20140413  | g         | 2.2         | partly cloudy with wind      |
| 56761| 20140414  | i         | 1.4         | partly cloudy with wind      |
| 56762| 20140415  | g,i       | 1.8         |                              |
| 56763| 20140416  | i         | 1.0         |                              |
| 56764| 20140417  | g         | 1.9         |                              |
| 56771| 20140424  | g         | 1.6         | partly cloudy                |
| 56772| 20140425  | i         | 1.2         |                              |
| 56773| 20140426  | g         | 1.9         | partial coverage, cloudy     |
| 56774| 20140427  | g         | 1.7         |                              |
| 56775| 20140428  | i         | 1.5         |                              |
| 56789| 20140512  | g         | 2.2         |                              |
| 56790| 20140513  | g         | 2.1         |                              |

Table 3 continued on next page
| MJD (days) | UT Date (mm/dd/yyyy) | Filter(s) | Ave. Seeing (arcsec) | Comment |
|-----------|----------------------|-----------|----------------------|---------|
| 56791     | 20140514             | i         | 2.0                  |         |
| 56792     | 20140515             | i         | 1.3                  |         |
| 56793     | 20140516             | g         | 1.6                  | thin clouds |
| 56794     | 20140517             | g         | 1.3                  | thin clouds |
| 56795     | 20140518             | g,i       | 1.4                  | thin clouds with wind |
| 56817     | 20140609             | g         | 1.4                  |         |
| 56818     | 20140610             | g         | 1.4                  |         |
| 56819     | 20140611             | g,i       | 1.9                  |         |
| 56820     | 20140612             | i         | 1.1                  | partly cloudy |
| 56821     | 20140613             | i         | 1.7                  |         |
| 56838     | 20140630             | g         | 1.5                  |         |
| 56839     | 20140701             | i         | 1.3                  |         |
| 56840     | 20140702             | g         | 1.5                  |         |
| 56855     | 20140717             | i         | 1.3                  | partly cloudy |
| 56856     | 20140718             | g         | 1.9                  |         |
| 2015A     | 20150109             | g         | 1.7                  | partly cloudy |
| 57032     | 20150110             | g         | 2.1                  |         |
| 57057     | 20150204             | g         | 1.5                  |         |
| 57058     | 20150205             | i         | 1.5                  |         |
| 57062     | 20150209             | g         | 1.5                  |         |
| 57063     | 20150210             | i         | 1.3                  |         |
| 57087     | 20150306             | g         | 2.5                  |         |
| 57088     | 20150307             | i         | 1.7                  |         |
| 57116     | 20150404             | g,i       | 1.5                  | partial coverage in g, cloudy |
| 57117     | 20150405             | g,i       | 1.8                  | partly cloudy |
| 57148     | 20150506             | i         | 1.6                  | partly cloudy |
| 57149     | 20150507             | g         | 2.2                  | partial coverage, cloudy |
| 57150     | 20150508             | i         | 2.1                  |         |
| 57170     | 20150528             | g,i       | 1.5                  |         |
| 57171     | 20150529             | g,i       | 1.9                  | partial coverage in g |
| 57211     | 20150708             | g,i       | 1.9                  | partial coverage in i |
| 57212     | 20150709             | i         | 1.4                  | partial coverage |
| 2016A     | 20160130             | g,i       | 1.6                  | partly cloudy |
| 57435     | 20160217             | g         | 3.0                  |         |
| 57451     | 20160304             | g         | 1.1                  | partial coverage, cloudy |
| 57467     | 20160320             | g,i       | 1.3                  | cloudy |
| 57480     | 20160402             | g         | 1.7                  | partial coverage |
| 57481     | 20160403             | g         | 1.7                  | partial coverage, cloudy |

*Table 3 continued on next page*
| MJD (days) | UT Date | Filter(s) | Ave. Seeing (arcsec) | Comment |
|-----------|---------|-----------|----------------------|---------|
| 57494     | 20160416 | g         | 3.1                  | partial coverage |
| 57509     | 20160501 | g         | 2.0                  | partial coverage |
| 57522     | 20160514 | g         | 1.8                  | partly cloudy |
| 57523     | 20160515 | i         | 2.6                  | cloudy |
| 57535     | 20160527 | g         | 1.4                  |         |
| 57551     | 20160612 | g         | 1.4                  |         |
| 57578     | 20160709 | g,i       | 2.3                  | partial coverage in g |
| 57579     | 20160710 | g         | 2.2                  | partial coverage, cloudy |
| 57788     | 20170204 | g         | 1.5                  | partial coverage, cloudy |
| 57798     | 20170214 | i         | 1.6                  | partial coverage |
| 57806     | 20170222 | g         | 1.4                  | partial coverage |
| 57818     | 20170306 | g         | 2.1                  | cloudy |
| 57830     | 20170318 | i         | 1.2                  | partial coverage |
| 57831     | 20170319 | g,i       | 1.2                  | partial coverage in i, partly cloudy |
| 57847     | 20170404 | g         | 2.3                  |         |
| 57848     | 20170405 | i         | 1.4                  |         |
| 57855     | 20170412 | g,i       | 1.5                  |         |
| 57895     | 20170522 | g         | 1.8                  |         |
| 57904     | 20170531 | g         | 1.3                  | partial coverage, cloudy |
| 57905     | 20170601 | g         | 2.1                  | cloudy |
| 57907     | 20170603 | g         | 1.6                  |         |
| 57920     | 20170616 | g         | 1.7                  |         |
| 57921     | 20170617 | i         | 1.5                  |         |
| 57960     | 20170726 | g         | 1.9                  | partly cloudy |
| RM ID | $\alpha$ (J2000.0) | $\delta$ (J2000.0) | $z$ (kpc) | $g$ mag | $i$ mag | Bok $g$ Var Idx | CFHT $g$ Var Idx | Bok $i$ Var Idx | CFHT $i$ Var Idx | $g$ mag | $i$ mag |
|-------|---------------------|---------------------|-----------|--------|--------|-----------------|------------------|----------------|----------------|--------|--------|
| 0     | 213.697906          | 53.065586           | 1.4819    | 22.388 | 21.641 | 7.946           | 9.484           | 2.111          |                  |        |        |
| 1     | 213.654312          | 53.073048           | 1.4628    | 21.250 | 20.837 | 9.161           | 1.527           | 3.309          | 1.370          |        |        |
| 2     | 213.774719          | 53.060932           | 1.2880    | 21.060 | 20.669 | 5.440           | 2.411           | 4.163          |                |        |        |
| 3     | 213.673996          | 53.149841           | 2.2371    | 22.271 | 21.730 | 5.686           | 3.034           | 2.882          | 1.220          |        |        |
| 4     | 213.756454          | 53.016392           | 1.7572    | 21.926 | 21.629 | 6.438           | 1.450           | 5.666          | 1.692          |        |        |
| 5     | 213.814209          | 53.116009           | 0.7585    | 20.638 | 20.262 | ...             | ...             | 3.426          | 2.671          |        |        |
| 6     | 213.664200          | 53.008118           | 1.2851    | 20.275 | 19.324 | 7.954           | 4.804           | 7.097          | 3.796          |        |        |
| 7     | 213.785721          | 53.005531           | 2.7656    | 21.356 | 21.254 | 12.253          | 2.905           | 3.026          | 1.288          |        |        |
| 8     | 213.826141          | 53.147217           | 1.8474    | 22.581 | 21.796 | 3.912           | 7.003           | 2.517          | 4.005          |        |        |
| 9     | 213.723190          | 53.180897           | 1.3278    | 22.179 | 21.662 | 6.740           | 2.799           | 7.635          | 2.777          |        |        |

Note—This table is published in its entirety in the electronic version of this paper and is available in a machine readable form. A portion is provided here to guide in its form and content.