Examining the effects of on-orbit aging of SL-12 rocket bodies using visible band Spectra with the MMT Telescope

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ABSTRACT

The characterization of deep space debris has posed a significant challenge in the study of space objects. To be most effective, characterization must be performed quickly and under non-ideal operational conditions, generally using non-resolved techniques. Multi-color photometry and the resultant color indices offer the potential to rapidly discriminate between debris and intact space objects such as rocket bodies and satellites. However, these studies are not well informed by high resolution spectra of these same objects, due to the lack of prior measurements with large astronomical telescopes. We present a spectroscopic study of orbital debris aimed at characterizing changes over time in object properties, using ground-based spectroscopy of several similar rocket bodies in geosynchronous orbit, launched at different times. High and moderate resolution spectroscopy is not routinely collected by SSA resources. Nonetheless, several researchers have collected satellite spectra for research purposes. Several researchers have also noted the progressive reddening of spacecraft surfaces.

In this study, we have collected high resolution spectra of five Russian SL-12 rocket bodies in geosynchronous orbit. The spectra were collected with the Blue Channel Spectrograph on the 6.5 m MMT telescope at Mt. Hopkins. The measurements were taken using the 300-line grating, which is blazed for the red, and can cover a 520 nm range at dispersion 0.196 nm/pixel. The large collecting aperture of the MMT allowed the rapid collection of multiple high signal-to-noise spectra with only 2 minutes per exposure. This short exposure allowed us to have confidence the solar phase angle was near constant during each collection, but that the spectra were averaged over the rotation of the rocket body. These spectra allow analysis of both the variation in albedo over a large wavelength range, and searches for discrete absorption features. The SL-12 (also called the "Proton K") was a mainstay Russian four-stage to GEO launch vehicle that was used from 1974 to 2012. The SL-12 fourth stage rocket bodies (henceforth referred to as "SL-12 RB") offer a convenient ensemble of objects for which photometric techniques can be developed and tested. For this study, spectra of five SL-12s with a range of years-on-orbit (YOO) ranging from 23-35 years were collected, allowing a comparative study of the evolution of the spectra over a 12-year difference in age. Additionally, all these objects have been previously observed in the near-IR with the UKIRT WFCAM. The spectra are analyzed for evidence of the effects of on-orbit reddening and other changes over time.

1 INTRODUCTION

Since the launch of Sputnik in 1957, space surveillance has tracked and studied satellites and space debris with optical telescopes. The first attempts to use optical photometry to characterize satellites were published by the U.S and Russians in the late 1950s [1, 2]. The excellent historical review papers by Lambert [3] and Sukhov [4] summarize much of the history of photometric technique development in the US and Russia respectively. Multi-color photometric measurements offer the opportunity to quickly measure the bulk spectral characteristics of a space object. The concept of exploiting the color indices in the visible bands has been previously explored in SSA. For example, BVRI photometry with the Cerro Tololo Inter-American Observatory (CTIO) 0.9 m telescope has been used by Lederer et al. to compare measured color indices of 18 IDCSP (Initial Defense Communications Satellite Program) satellites with the predictions from laboratory measurements of solar cells [5]. Previously we performed a study considering the efficacy of 5-color photometry in the near-IR to rapidly characterize geosynchronous space objects with the modest goal of distinguishing classes of objects and identifying anomalous members of classes [6].

One of the challenges interpreting the results of these studies is differentiating the effects of aging from fundamental differences in the spacecraft themselves. Published results on the effects of aging on materials are conflicting. Despite the belief in the community that spacecraft materials generally redden with age, there is little supporting evidence of this from observations of objects on orbit. For example, aging has been noted on four GPS satellites by Fliegel using BVRI photometry [7]. Fliegel's observations detected significant evolution of spectra across the Johnson B, V, R, and I bands (429-804 nm). Guyote has also attempted to explain the reddening phenomenon physically with mixed results [8]. Cardona et. al. studied 13 objects including rocket bodies, debris, and four intact satellites with a range of age of nearly 35 years with BVRI photometry and found no obvious trend, although he acknowledged that one might not be expected given the wide variety of objects in his sample [9]. Firth and his team examined eight geosynchronous satellites based on Boeing HS-376 busses with years on orbit (YOO) ranging from 12 to 34 years with the UKIRT WFCAM [10]. In Firth's study, mean J-K and H-K colors were plotted as a function of YOO, and only a very weak reddening trend was apparent, especially with object SSN 12065 (cataloged as 1980-091A, SBS-1) is excluded.[1] Using a similar methodology to Firth *et. al.*, our 5-color study of SL-12 rocket bodies was inconclusive with respect to systematic changes in the color indices with age [6].

In contrast to these studies, the most unambiguous published data showing spectral evolution with age show a systematic reduction in reflectivity in the red ("blueing"). These studies have the advantage of using an ensemble of similar rocket bodies launched and discarded over a long period of time. Since they are rocket bodies, the predominant surfaces are structural and the design of the RB unchanging over time. In particular, using RBs avoids the complications of evolving solar panel technology that complicated Frith's analysis of HS-376 satellites. Jorgensen measured reflectance spectra over a range of YOO of 10-13 years of foreign discarded rocket bodies and noted significant decrease in relative reflectance above 750 nm with aging [11]. Other classes of RB measured by Jorgensen did not show significant evolution of the spectra with time, and we hypothesize that this is due to differences in the white paint used by the different countries that developed the launch systems.

We recently had the opportunity to measure five of the previously observed SL-12 RB with the MMT telescope Blue Channel Spectrograph. Consequently, we are now able to analyze near-IR photometric measurements in five bands, visible band high resolution spectroscopy, and visible band multi-color high-speed photometry on the same set of objects. Our intent is to use the high-resolution spectroscopy to provide detailed insight into the interpretation of both the near-IR and the visible band photometry. The five SL-12s measured have a range of YOO from 23 to 35 years, allowing a comparative study of the evolution of the spectra over a 12-year difference in age. In this paper, we present the MMT spectra collected and discuss the observable effects of aging on the observed spectra. In a later publication, the team intends to publish the consolidated results of the study, including MMT visible band spectra, visible band photometry, and near-IR photometry.

2 SL-12 Fourth Stage Rocket Body

For this study, targets were selected Russian SL-12 fourth stage rocket bodies. The SL-12 (also called the "Proton K") was a mainstay Russian four-stage to GEO launch vehicle that was used from 1974 to 1994 (see Fig. 1) [12, 13]. The SL-12 fourth stage rocket bodies (henceforth referred to as "SL-12 RB") offer a convenient ensemble of objects for which photometric techniques can be developed and tested. The rocket bodies are bright (11.5 mag in the Z band, or 12 m_v), and at least 25 such objects are available within the longitude range visible from Hawaii and Tucson, Arizona. This upper stage was used to insert the payload into GEO from its transfer orbit and was discarded in GEO without moving it to a graveyard orbit.

The SL-12 RB had at least three different versions. The Blok DM (1974) and Blok DM-2 (1982) were similar in structure and fuel but differed slightly in length. A third version (DM-2M) was developed specifically to support sea launches and is similar structurally to the DM-2. This upper stage was used to insert the payload into GEO from its transfer orbit and was discarded in GEO without moving it to a graveyard orbit. The SL-12 RB is large, measuring 3.7 m in diameter and approximately 6.2 m long (the DM-2 version). Reportedly the stage could impart a rotation rate of up to 1.5 rpm for spacecraft separation, although observed rotational spin rates of discarded SL-12 rocket bodies are typically significantly faster (5–12 rpm).

[1] As noted in [10], there is evidence that SSN 12065 is cross-tagged with another object. SSN 12065 is significantly brighter than all other HS-376 busses measured, and very different phase function and color indices compared to the other HS-376 objects in the sample.

Our previous near-IR survey included 55 separate data collections on 24 unique SL-12 RBs that were launched from 1977 to 2012. Examples of both major variants were included in the sample (12 DMs, 12 DM-2s). Our MMT spectral measurements included five of the previously observed SL-12 RB. Optical photometry adds time resolved signatures, and rotational rates to inform the interpretation of the WFCAM near-IR signatures and to confirm our expectation that the spectra from the MMT Blue Channel Spectrograph are indeed rotationally averaged.

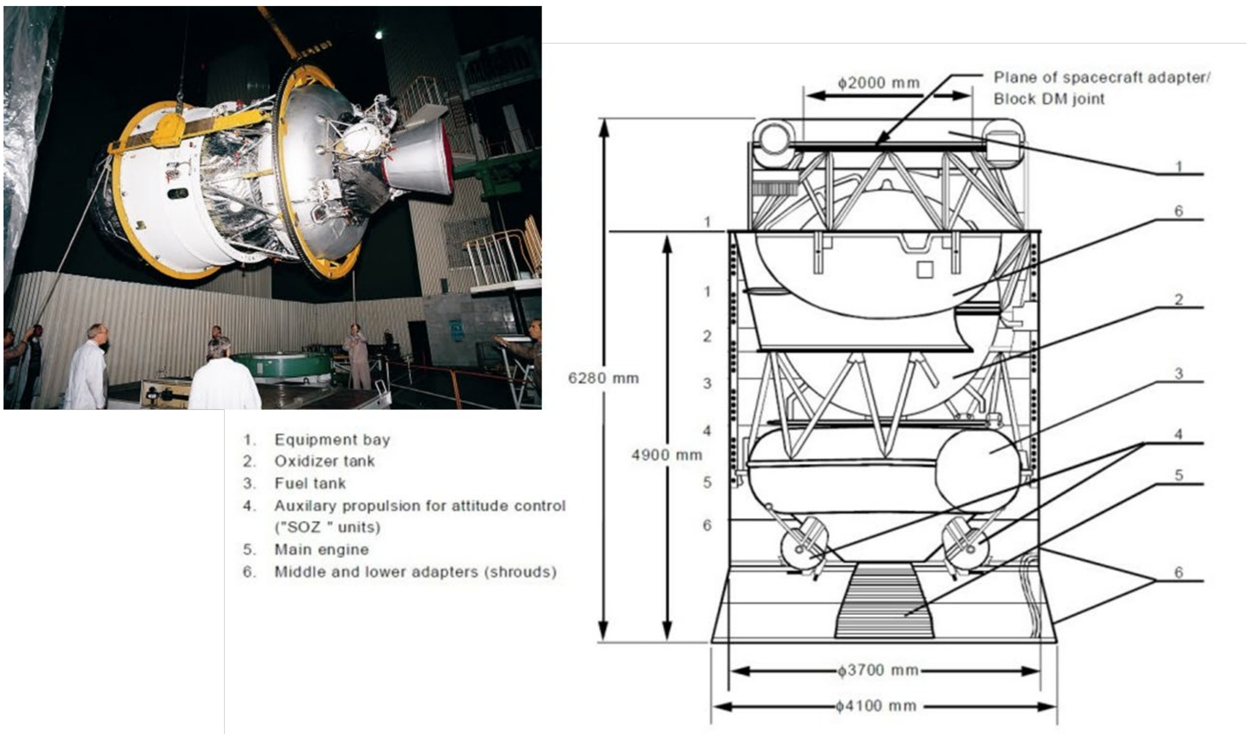

Fig. 1. Photograph and Line Drawing of the SL-12 Fourth Stage Rocket Body.

3 SUMMARY OF MEASUREMENT CAMPAIGN

The high-resolution spectra were taken with the 6.5 meter MMT telescope Blue Channel Spectrograph on a single night in January 2019. The supporting high-speed visible photometry was taken with the Chimera Photometer on the Steward Observatory 1.5 m telescope at Mt. Bigelow in 2018 and 2019.

High-resolution spectra taken on five of the SL-12 RB with the MMT 6.5 meter telescope and spectrograph on Mt. Hopkins. The MMT Spectrograph is a two-channel low-intermediate resolution echelle spectrograph originally commissioned with the MMT telescope in 1979 and later upgraded with new detectors [14, 15]. The original design paralleled the Hale Double Spectrograph's dual optical paths, one optimized for the blue end of the visible spectrum, and the other for red, reflecting the spectral response of detectors in the late 1970s. For our measurements, only the blue channel was available, providing a spectral coverage of 520 nm range at a dispersion of 0.196 nm/pixel.[2]

The SL-12 RB selected from the previous objects collected with UKIRT and which had an acceptable elevation between our time-critical collection program (see Tab. 1). The large collecting aperture of the MMT allowed the

[2]During these measurements, a high-speed EM-CCD camera was mounted at the normal location of the Red Channel Dewar and was performing time critical observations for another satellite observing program. Consequently, the phase angle and elevation of the SL-12 RB collections were opportunistic.

rapid collection of multiple high signal-to-noise spectra with short 2-minute exposures. These short exposures enabled the rapid collection of many high-quality spectra in the limited time available for the observations. Additionally, solar phase angle changes during the integration are minimal. Furthermore, since typical rotational periods of SL-12 RB are 5-15 s, the effects of rotation are averaged out. In addition to the SL-12 RB spectra reported here, the team was able to collect high-quality spectra of a Block 2F GPS, Galaxy 15, Galaxy 18, and NATO 3B.

Tab. 1. Summary Data Five SL-12 RB with both UKIRT WFCAM and MMT Spectral Data. Years on Orbit is from launch to the collection of the relevant data.

Int. Desg.	SSC	Payload	Type	Launch Date	Years on Orbit		Near-IR Color Indices			
					UKIRT (2016)	MMT (2019)	Z-Y	Y-J	J-H	H-K
1995-045D	23656	Kosmos 2319	DM-2	1995-08-30	21.22	23.37	0.26	1.34	0.51	0.57
1994-030D	23111	Gorizont 30	DM-2	1994-02-18	22.74	24.90	0.26	1.52	0.82	0.44
1984-041D	14943	Gorizont 9	DM	1984-04-22	32.57	34.72	0.11	0.50	0.52	0.25
1983-100F	14394	Ekran 11	DM	1983-09-29	33.13	35.29	0.24	0.46	0.58	0.35
1983-066F	15141	Gorizont 7	DM	1983-06-30	33.38	35.54	0.18	0.49	0.48	-0.03

4 SL-12 ROCKET BODY SPECTRA

There are few published spectra of satellites or debris on-orbit published in the open literature. Additionally, measurement of spectral evolution of satellites with age is inconsistent. Jorgensen measured reflectance spectra over a range of YOO of 10–13 years of foreign discarded rocket bodies and noted significant and systematic decrease in reflectance over time above 750 nm wavelength[3] [11]. These measurements were made with the SPICA spectrograph on the AMOS 1.6 m telescopes using the instrumentation and techniques described by Nishimoto [16]. Note that this evolution in the spectra is a general decrease in the redness of the object, and opposite of the commonly held expectation that reddening should be expected due to space weathering. Guyote *et al.* has also attempted to explain the phenomenon by adapting a space weathering model developed by B. Hapke for asteroids with mixed results and the presumption that surfaces redden with aging [8]. Understanding the physical processes and predicting the spectral evolution of objects on orbit is greatly complicated by a lack of high-quality data of similar objects over a range of years-on-orbit. In the open literature, despite the common belief that satellites become redder with age, there is little data to support this expectation as reviewed earlier in this paper.

We observed five SL-12 RB targets on 11 January 2019 with the MMT 6.5-m telescope on Mt. Hopkins, using the Blue Channel Spectrograph. The spectrograph used a 300-line/mm grating, allowing a coverage of 4000–9000 Å with a resolution of about 0.5 nm FWHM. The telescope tracked each object from its orbital elements. Several other satellites in geosynchronous orbit were also observed, and a spectrophotometric standard star was observed with the same setup on 12 January 2019. We obtained several exposures for each satellite of 40-180 sec depending on brightness. For calibration, spectra of a HeAr/Ne internal lamp was taken immediately after each satellite series, and an internal continuum lamp and twilight sky exposures were taken for flat fields.

Data reduction of the spectra followed standard astronomical procedures using the IRAF (Image Reduction and Analysis Facility) software[4] as described in Massey *et al.* [17]. Briefly, the long-slit spectral images are corrected for zero level, flatfield (pixel response), and the instrumental response in both the dispersion and spatial directions. The spectral trace (location) of the object is fit in each image and a flux spectrum is extracted. The trace is also used to extract a spectrum from the corresponding HeAr/Ne calibration lamp image. Emission lines are identified in the calibration spectrum and a low-order Chebyshev polynomial is used to fit the wavelength as a function of pixel number. This calibration is applied to produce a spectrum of flux as a function of wavelength.

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[3] Jorgensen *et. al.* did not identify the specific class of RB, although in other works, both the Russian SL-12 and U.S. IUS are studied.

[4] IRAF is distributed by NOAO, the National Optical Astronomical Observatory.

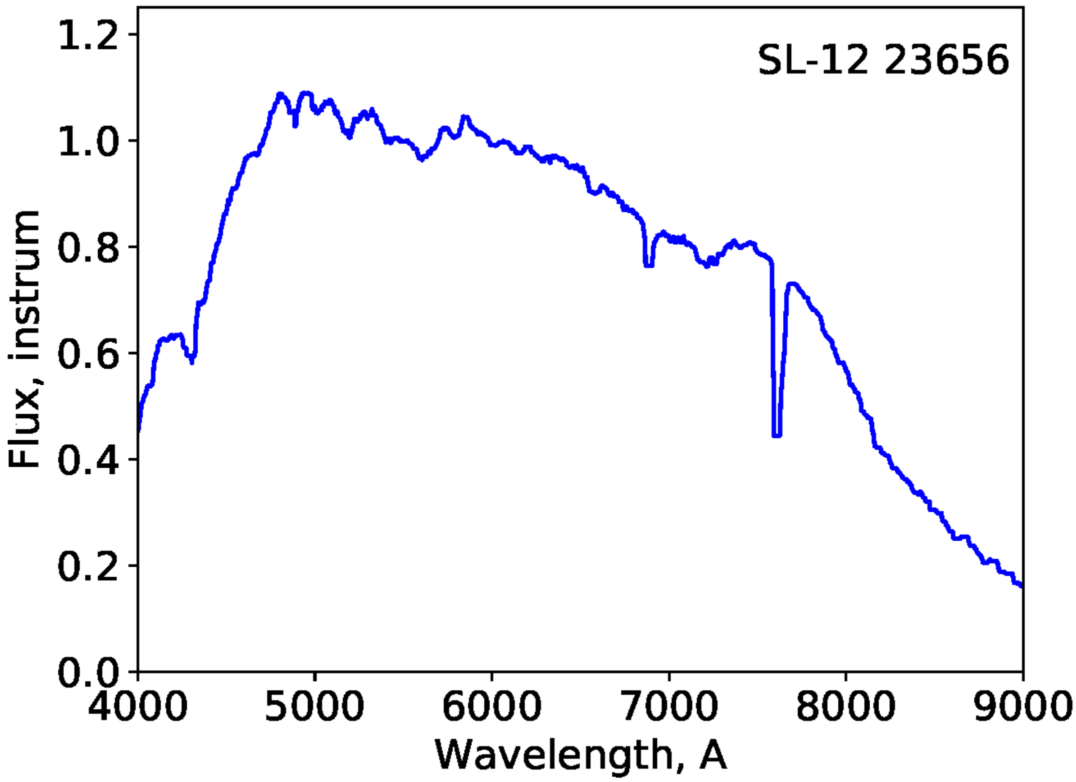

Fig. 2. Spectrum of 1995-045D (SSC 23656), the youngest SL-12 RB in the sample.

Fig. 2 shows the spectrum of 1995-045D, the youngest of the observed SL-12 RBs. The overall shape of this spectrum and many of the small-scale features are due to the incident solar spectrum, and the falloff of spectrograph sensitivity at blue and red ends of the spectrum. The absorption bands at 6800 and 7600 Å are atmospheric. Above 6600 Å, there is residual ringing in the spectrum with a period of approximately 30 Å due to fringing in the CCD that is not fully removed by our reduction.

Fig. 3 shows the spectra of the five SL-12 RBs normalized to the youngest, 1995-045D (23656), at 5500 Å. The curves are organized by age, and not SSN since RB 1983-066F was not cataloged until August 1984. Normalizing the spectra compensates for the solar illumination and response effects and allows a direct visualization of the evolution of the reflectance spectra with respect to the youngest SL-12 RB in our sample. Dividing the spectra causes larger fringing artifacts, so the normalized spectra have been smoothed by a 75 Å filter. The data from 7500 to 7700 Å have been omitted as they have large residuals from the atmospheric absorption. One object, 1984-041D (14943), has lower observed flux in the blue: this is an observational artifact caused by atmospheric extinction, as 1984-041D was observed at airmass 2.2 while the others were observed at airmass 1.3–1.6. There is a systematic trend that the older SL-12s have less reflectivity in the red; this is a real effect. Our sample of five RB span in age from 23.4 to 35.5 YOO, expanding considerably over the range of YOO observed by Jorgensen in [11].

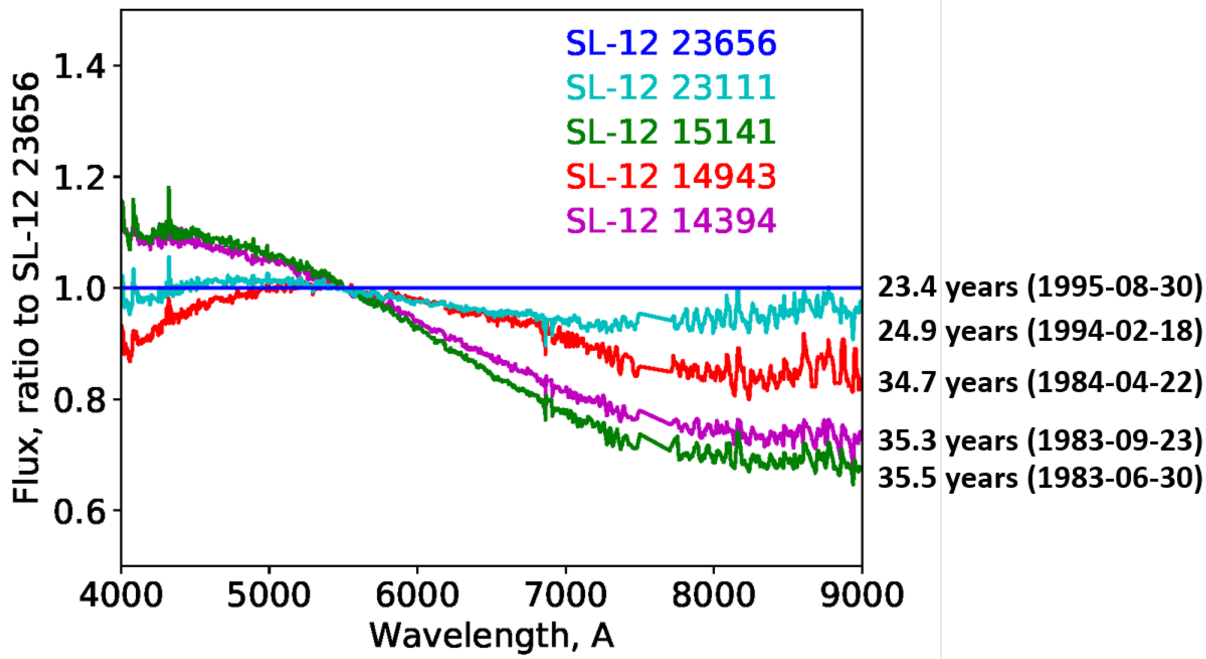

Fig. 3. Comparison of the spectra of the five SL-12 upper stage RBs. All spectra have been normalized to the youngest RB, 1995-045D (23656).

Fig. 4 shows the spectra of the five SL-12 RBs again, this time divided by the spectrum of a G2V solar type star, to measure the satellite albedo as a function of wavelength. The star Hipparcos 08194 was observed with the MMT and Blue Channel spectrograph on October 8 2019, using the same instrumental setup as our satellite observations. The star spectra were reduced in the same manner as the satellite spectra. Using this G2V star as a model for the solar spectrum incident on the RBs, the flux from the target divided by the solar flux incident on it yields the albedo. Because the absolute normalization is arbitrary, the divided spectra are normalized at 5500 A as before. The fringing in the red is amplified by the division and so we only present the albedo curves to 7100 A. We smooth the spectra by 30 A to reduce these artifacts.

These curves in Fig. 4 show the relative wavelength dependence of the albedo of the RBs. We note that the residuals at the locations of strong absorption features in the solar spectrum are small, showing that the G2V star is a good model of the incident solar spectrum, which gives confidence in the overall shape of the albedo curve. We do not find features in the albedo localized in wavelength. We do find that the shape of the albedo curve shows RBs have several times higher reflectivity in the red than in the blue. The shapes of the albedo curves blueward of 5000 A are fairly similar (apart from 1984-041D, 14943, which was affected by atmospheric extinction). In the red, the older RBs have noticeably lower relative albedo than the younger RBs. It seems unlikely that the albedo would increase with age in the blue, so we suggest that the evolution of the relative albedo is driven by a decrease in reflectivity at redder wavelengths.

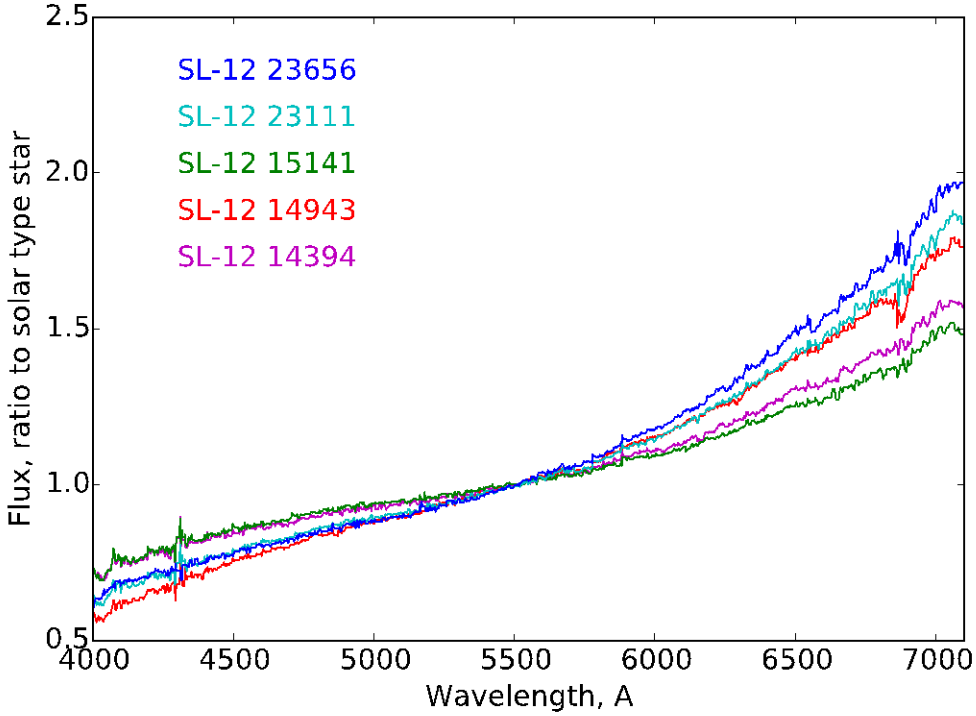

Fig. 4. Relative albedo from the spectra of the five SL-12 upper stage RBs, each divided by a spectrum of a G2V solar type star. The curves have been normalized at 5500 A.

5 DISCUSSION

Our MMT visible band spectra represent a unique data set in the community, measuring similar objects over an 18-year span of years-on-orbit and showing systematic bluing with age. Contrary to our expectations, the systematic bluing of the spectra appears to continue monotonically even after 35 years on orbit. In the future, we plan to survey a similar set of SL-12 RB over a range of age using the UKIRT 1–5 Micron Imager Spectrometer (UIST). With this instrument, we plan to create a similar data set to the MMT SL-12 RB spectra here that can be used to systematically study the effects of aging in those spectral bands and inform our interpretation of the near-IR color indices in that context. We also intend to develop and test new observational and processing techniques to use UKIRT in the future to take high-quality colors with WFCAM and to improve the phase angle coverage of the 5-color photometry for several different classes of objects, including the SL-12 RB.

Our spectral measurements with MMT show for the first time compelling evidence for spectral evolution and demonstrate that for this class of object, this effect results in a systematic decrease in reflectiveness in the red. Over the next year we plan to continue to refine our techniques, continuing to develop operational techniques for rapid object characterization while informing the development of those techniques with high resolution observations such as spectrometry.

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