Satellite Characterization with *uvbyCaHβ* Photometry

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We propose using the extended Strömgren photoelectric system, *uvbyCaHβ*, for artificial satellite characterization. The *uvby* filters are dominated by the solar continuum, and the *Ca* and Hβ filters by solar absorption lines where an intrinsic blackbody contribution from the satellite itself could be detected.

1. THE ADVANTAGE OF PHOTOMETRY

Photometric systems were developed to quantitatively estimate stellar temperatures and metallicities as an alternative to spectroscopy. Instead of a grating or prism to reveal the full spectrum of starlight, filters were used to select only specific regions of the visual spectrum. In the era of photomultiplier tubes, these systems used the broad bandpasses of the filters to advantage. Since the bandpasses have less resolution than spectroscopy, photometry offers faster detection of a star, and/or at fainter magnitudes. It is better for surveys in crowded fields, where objective prism spectroscopy would give overlapping images. Unusual results from photometry motivate further investigation using spectroscopic methods.

The Sun, with its abundance of photons, has been a fascinating exemplar star for analysis of its spectrum at the highest resolution possible. At the resolution of photometric systems, it is a well-understood baseline for our analysis.

2. THE EXTENDED STRÖMGREN PHOTOMETRIC SYSTEM

There are hundreds of different photometric systems. Some are motivated by astrophysical theory, while others are pragmatic, where a missing filter on the first night of an observing run inspires a new standard system. Established photometric systems are revised, by the replacement of a well-worn filter, by the predominance of the filter sets at national observatories, or extended by the addition of more filters in the suite. Despite this proliferation, the icons of photometry remain the UBV system [1] and the *uvby* system [2]. Newer systems are generally extensions of these two, with data reduced to be correlated to one of the two systems, and the two basic systems are related to each other (via the *v* and V filters).

The choice of the *uvbyCaHβ* photometric system for this study, out of the many, is based on the well-established nature of the *uvby* filters, and the placement of narrow *Ca* and *Hβ* filters on significant absorption features in the solar spectrum. This is a measurable way, with respect to the *uvby* filters, to remove solar radiation and detect a satellite's radiation in those filters.

The *uvby* system uses the differences between measurements to create a color index and two color-difference indices, sensitive in the range of A2 to G2 type stars:

1) $b - y$, relatively insensitive to chemical composition,
2) $c_1 = (u - v) - (v - b)$, a measure of the Balmer discontinuity, and
3) $m_1 = (v - b) - (b - y)$, a measure of the total intensity of the metal absorption lines in the v band.

The intent was that some correlation between these indices could mimic the spectroscopically-derived Hertzsprung-Russell diagram of luminosity vs. temperature, or other some other astrophysically interesting feature. As it happens, the most fruitful is c_1 against m_1, which is evocative of the H-R diagram [3].

The next index, *Hβ,* evolved from spectrophotometry on objective-prism plates into a photoelectric measurement using two interference filters [4]. The two filters, narrow and wide band, centered on the Balmer series hydrogen β absorption line. The relative strength of the wide to the narrow photometric filter measurements, as established in Crawford and Mander [5], provided better discrimination between early type B, A, and F type stars. Crawford [4] used the *Hβ* index in conjunction with UBV, since it stands independent of the other filters in the system.

Strömgren [3] pointed out that while m_1 and c_1 can give coarse two-dimensional classification, adding *Hβ* gave excellent and unambiguous classification. The resultant extension, the *uvbyHβ* system, has such utility that extensive catalogs of standards and secondary standards have been made (see [6] and [7]). Recent CCD studies of clusters have added extensively to the list, including a series by Anthony-Twarog and Twarog [8, 9].

The third paper in that series on clusters [10] introduced a new index, *hk*, using a new filter, *Ca*, encompassing the Fraunhofer H and K lines of Ca II. (Strömgren [3] had proposed a filter centered on the K line).The *Ca* filter replaces the *v* filter in the calculation for m_1, for metallicity for cool stars:

$$hk = (Ca - b) - (b - y)$$

The break point for usefulness of m_1 for hot stars vs. *hk* for cool stars is at about spectral type G0, slightly warmer than the solar spectral type of G2V.

The *Ca* filter had been developed and defined in a series of papers starting with Anthony-Twarog et al. [11], for low-metallicity stars. Anthony-Twarog et al. have published an extensive series on *uvbyCaHβ* CCD photometry of low-metallicity open clusters, most recently Twarog et al. [12].

While not widely used, the *Ca* filter has a substantial catalog of observations. Added to the *uvbyHβ system*, this provides a well-motivated photometric system. What we are particularly interested in are the absorption features in the *Ca* and *Hβ* filters, in comparison to the continuum features in *uvby* (though the Balmer series Hδ absorption line appears in the *v* filter.) The *uvby*, *Ca*, and *Hβ* filter central wavelengths and their FWHM (full-width half maximum) values are presented in Table 1 below. All but the *Ca* filter are commercially available.

Table 1. Extended Strömgren System Filters, Central Wavelength and Full Width Half Maximum Bandpass

Filter	Central Wavelength (Å)	FWHM (Å)	Central Wavelength (nm)	FWHM (nm)	Notes
u	3500	300	350	30	
Ca	3950	90	395	9	Ca II H&K, Hε
v	4110	190	411	19	Hδ
b	4670	180	467	18	
Hβ wide	4850	129	485	13	
Hβ narrow	4858	29	486	3	
y	5470	230	547	23	

The data are shown in both the traditional Ångstrom units (10^{-10} cm) and the modern nanometer units (10^{-9} cm) that will be used later in this study.

For the purpose of this investigation, what is important is not the ability to distinguish a B-type star from an M-type star using photometry, but to consistently characterize the solar spectrum as it is reflected from a satellite at various angular altitudes from the terrestrial observing platform, during continuous tracking as long as the satellite is in the field of view.

3. SIMULTANEOUS OBSERVATIONS

Photometry can detect a star faster than spectroscopy, but its accuracy depends on an exacting and tedious serial methodology. The original type of sensor, the photomultiplier, has a field of view that encompasses the star and a small portion of sky around the star, which has its own brightness. A measurement of the sky is taken, to be subtracted away from the star measurement. This has to be done for each filter. Measurements of standard stars, again in each filter and with nearby sky measurements, need to be taken. Meanwhile, the altitude of the star is changing, giving varying values of atmospheric refraction and extinction. The photometric condition of the sky can also be changing over the course of observation of a single star when using this method, which can make the data useless.

More recent use of CCDs for photometry offer a wide field of view, so that the sky and even possibly standard star measurements can be taken from the same image, but its response is less sensitive than photomultiplier tubes, and again, images need to be taken in each filter. Crawford and Mander [15] explained the observing procedure for *Hβ*: two narrow filter measurements on the star, two wide, two narrow, then narrow and wide on sky. The sky conditions need to be consistent, but not highly photometric, during these measurements. Crawford and Mander pointed out "…the freedom from extinction and color effects (both filters have nearly the same effective wavelength) greatly aids the system establishment and keeps errors low."

One advantage to extending an already-established system was noted by Twarog and Anthony-Twarog [13]. For the establishment of a new system, an extensive standard star catalogue that spans the sky is needed. Thousands of stars had been observed in the *uvby* system, and to re-observe nearly 2,000 stars in all five *uvbyCa* filters would have been prohibitive. It was sufficient to observe the stars in only three filters, *Caby*, to add the *Ca* filter to the set. Photometry of a single star requires multiple observations. Besides the obvious observation of the star itself, empty sky, and reference stars must be observed – and in each of the filters. For this study, they observed *y, b, Ca, Ca, b, y,* and sky, for each star. Integration times were increased for the *Ca* filter observations; in each case, the photometer recorded at least 10,000 counts above sky.

The advantage of simultaneous observations in different colors can be exploited in instrumentation. Making parallel, or simultaneous, photometric observations compensates for the shortcomings of serial photometry. Simultaneous observations have the advantage of identical atmospheric conditions for accuracy in calculating the indices.

BUSCA, the Bonn University Simultaneous Camera, can accommodate four filters. Reif et al. [14] examined BUSCA's color indices during fluctuating photometric conditions (e.g., thin clouds) to determine correction factors. While standard CCD photometry would have given "nonsensical results," the color indices for simultaneous photometry during changing conditions were largely constant, and small transmission changes had "negligible effect." More recent instrumentation includes the triple-beam ULTRACAM, with filters for the Sloan g′ band and a narrow-band Na I for observing ultracool dwarf stars [15] and X-ray transients [16]. MITSuME has three CCD cameras on each focal plane of two telescopes for simultaneous $g'R_cI_c$ photometry [17].

4. THE SOLAR SPECTRUM

We use the solar irradiance spectrum that Thuillier et al. [18] obtained with the SOLSPEC instrument in low Earth orbit. It has three separate spectrometer channels, in ultraviolet, visible, and infrared, covering the spectrum from 180nm to 3000nm. SOLSPEC was flown on several STS missions from 1983 to 1994, including the free-flying EURECA mission, gathering data from August 1992 through June 1993. The data were calibrated with laboratory blackbody data for up to 3300 K [19]. The altitudes of the space shuttle orbits ranged from 300 to 470 km; the EURECA mission was retrieved at 470 km.

For comparison of the actual solar spectrum with the spectral irradiance of a blackbody of temperature T (in degrees Kelvin), and at wavelength λ, we use the Planck function, which will give B, the amount of energy emitted per unit wavelength:

$$B_\lambda(T) = \frac{2hc^2 / \lambda^5}{e^{hc/\lambda kT} - 1}$$

where h is Planck's constant, c is the speed of light, and k is Boltzmann's constant. The SOLSPEC data is the solar spectral irradiance at zero air mass at Earth, in units of microWatts per cm^2 per unit wavelength.

The values of solar spectral irradiance, at the center wavelength of the *uvbyCaHβ* filters, are presented in Table 2.

Table 2. Solar Spectral Irradiance at Filter and Absorption Feature Central Wavelengths.

Filter or Absorption Line	Central Wavelength (nm)	Solar Spectral Irradiance (μW/cm^2/nm)	Blackbody Spectral Irradiance (μW/cm^2/nm)	Difference Calc - Obs (μW/cm^2/nm)
u	350	102.185	125.609	23.424
Ca II H line	394	85.583	153.901	68.318
Ca	395	114.660	154.418	39.758
Ca II K line	397	92.379	155.433	63.054
v	411	161.305	161.897	0.592
b	467	198.159	177.160	-20.999
Hβ narrow	486	177.278	178.961	1.683
y	547	187.408	176.227	-11.181

The Ca II H and K lines are shown separately in Table 2, in addition to the central wavelength of the *Ca* filter which, with a FWHM bandpass of 9 nm, includes both of these absorption lines. The spectral irradiance of a blackbody at 5780 K at a distance of 1 Astronomical Unit – were the Sun a blackbody emitter – is shown as well. The final column in the table demonstrates the extent to which the solar absorption features deviate from blackbody radiation.

5. SATELLITE BLACKBODY SPECTRAL IRRADIANCE

Wien's law gives the peak wavelength of blackbody radiation as

$$\lambda_{\text{max}} = 2.9 \text{ x } 10^7 / T$$

where λ is in Ångstroms and T is the temperature in degrees Kelvin. For a solar temperature of 5800 K, and a satellite temperature of 120 C or 394 K, we have

$$\lambda_{\text{max, Sun}} = 5000 \text{ Å}$$

$$\lambda_{\text{max, sat}} = 73{,}600 \text{ Å}$$

which, considered alone, would be overwhelming in favor of the Sun for its detection in the visual portion of the electromagnetic spectrum. However, all blackbodies radiate at all wavelengths. We need to consider as well the relative flux of the reflection of the sunlight from the satellite to the satellite's blackbody radiation, in the *Ca* and *Hβ* filters, where the solar contribution is reduced because of the presence of absorption lines.

We will use the Planck function, as before, to calculate spectral irradiance of the satellite at various temperatures T. Normally T would be about 120 C (394 K), were there no intrinsic characteristics of the satellite that might increase the temperature or change the emissivity. Also, we wish to see at what temperature a noticeable contribution, relative to the solar contribution, might occur.

Tables 2 and 4 have the observed spectral irradiance for the Sun and the calculated spectral irradiances for a satellite at various temperatures, in μW/cm^2/nm. Table 2 has the region affected by the *Ca* filter, 386nm to 404 nm, and Table 4 has the region affected by the *Hβ* filter, 480nm to 490nm.

In Tables 3 and 5, we apply the respective filters; Tr is the transmission of the filter, and Ir, the spectral irradiances, are in μW/cm^2/nm. The filtered values are simply multiplied, at each wavelength, by the transmission.

Table 3. *Ca* Filter Region Solar Spectral Irradiance (Ir) and Satellite Spectral Irradiance at Several Blackbody Temperatures, in μW/cm^2/nm.

Ca Filter Wavelength (nm)	Solar Ir 5780 K	Sat Ir 2000 K	Sat Ir 1600 K	Sat Ir 1200 K	Sat Ir 800 K	Sat Ir 400 K
387	106.132	7.874E-4	7.550E-6	3.267E-9	6.119E-16	4.020E-36
389	112.017	8.443E-4	8.291E-6	3.734E-9	7.573E-16	6.318E-36
391	130.574	9.046E-4	9.096E-6	4.261E-9	9.351E-16	9.882E-36
393	86.698	9.683E-4	9.968E-6	4.855E-9	1.152E-15	1.538E-35
395	114.660	1.036E-4	1.091E-6	5.524E-9	1.416E-15	2.384E-35
397	92.379	1.107E-3	1.193E-5	6.276E-9	1.737E-15	3.678E-35
399	164.211	1.182E-3	1.304E-5	7.121E-9	2.125E-15	5.648E-35
401	179.951	1.261E-3	1.423E-5	8.068E-9	2.595E-15	8.636E-35
403	184.100	1.345E-3	1.551E-5	9.129E-9	3.162E-15	1.315E-34

Table 4. *Ca* Filter Response, with Percentage Transmission (Tr) to Solar Spectral Irradiance (Ir), and to Satellite Spectral Irradiance at Several Blackbody Temperatures, in μW/cm^2/nm

Ca Filter Wavelength (nm)	Tr (%)	Solar Ir 5780 K filtered	Sat Ir 2000 K filtered	Sat Ir 1600 K filtered	Sat Ir 1200 K filtered	Sat Ir 800 K filtered	Sat Ir 400 K filtered
387	1.0	1.0613	7.874E-6	7.550E-8	3.267E-11	6.119E-18	4.020E-38
389	7.0	7.8412	5.910E-5	5.804E-7	2.614E-10	5.301E-17	4.422E-37
391	26.0	33.949	2.352E-4	2.365E-6	1.108E-9	2.431E-16	2.569E-36
393	36.0	31.211	3.486E-4	3.588E-6	1.748E-9	4.147E-16	5.538E-36
395	39.0	44.717	4.039E-4	4.256E-6	2.154E-9	5.522E-16	9.298E-36
397	39.0	36.028	4.317E-4	4.654E-6	2.448E-9	6.772E-16	1.434E-35
399	25.0	41.053	2.955E-4	3.259E-6	1.780E-9	5.313E-16	1.412E-35
401	7.0	12.597	8.830E-5	9.958E-7	5.684E-10	1.817E-16	6.045E-36
403	2.0	3.682	2.690E-5	3.102E-7	1.826E-10	6.325E-17	2.629E-36

Table 5. *Hβ* Filter Region Solar Spectral Irradiance (Ir) and Satellite Spectral Irradiance at Several Blackbody Temperatures, in μW/cm^2/nm.

Hβ Narrow Wavelength (nm)	Solar Ir 5780 K	Sat Ir 2000 K	Sat Ir 1600 K	Sat Ir 1200 K	Sat Ir 800 K	Sat Ir 400 K
480	209.462	9.833E-3	2.320E-4	4.502E-7	1.696E-12	9.063E-29
481	209.389	1.004E-2	2.387E-4	4.693E-7	1.814E-12	1.048E-28
482	208.899	1.025E-2	2.456E-4	4.891E-7	1.940E-12	1.211E-28
483	206.238	1.046E-2	2.562E-4	5.097E-7	2.075E-12	1.399E-28
484	203.296	1.068E-2	2.598E-4	5.310E-7	2.218E-12	1.615E-28
485	193.735	1.090E-2	2.672E-4	5.531E-7	2.370E-12	1.863E-28
486	177.278	1.112E-2	2.747E-4	5.760E-7	2.531E-12	2.148E-28
487	177.282	1.134E-2	2.825E-4	5.997E-7	2.703E-12	2.475E-28
488	191.606	1.157E-2	2.904E-4	6.243E-7	2.886E-12	2.850E-28
489	195.220	1.181E-2	2.984E-4	6.498E-7	3.080E-12	3.280E-28
490	202.604	1.204E-2	3.067E-4	6.762E-7	3.286E-12	3.773E-28

Table 6. *Hβ* Filter Response, with Percentage Transmission (Tr) to Solar Spectral Irradiance (Ir), and to Satellite Spectral Irradiance at Several BlackbodyTemperatures, in µW/cm^2/nm.

Hβ Narrow Wavelength (nm)	Tr (%)	Solar Ir 5780 K filtered	Sat Ir 2000 K filtered	Sat Ir 1600 K filtered	Sat Ir 1200 K filtered	Sat Ir 800 K filtered	Sat Ir 400 K filtered
480	0.9	1.885	8.850E-5	2.088E-6	4.052E-9	1.526E-14	8.157E-31
481	2.0	4.188	2.008E-4	4.774E-6	9.387E-9	3.629E-14	2.096E-30
482	5.3	11.072	5.432E-4	1.302E-5	2.592E-8	1.028E-13	6.421E-30
483	19.6	40.423	2.050E-3	4.951E-5	9.990E-8	4.066E-13	2.743E-29
484	42.8	87.011	4.570E-3	1.112E-4	2.273E-7	9.491E-13	6.913E-29
485	89.3	173.005	9.730E-3	2.386E-4	4.939E-7	2.116E-12	1.664E-28
486	93.3	165.400	1.037E-2	2.563E-4	5.374E-7	2.362E-12	2.004E-28
487	63.0	111.688	7.147E-3	1.780E-4	3.778E-7	1.703E-12	1.559E-28
488	24.0	45.985	2.778E-3	6.969E-5	1.498E-7	6.926E-13	6.841E-29
489	19.6	38.26	2.314E-3	5.850E-5	1.274E-7	6.037E-13	6.429E-29
490	2.4	4.862	2.890E-4	7.361E-6	1.623E-8	7.887E-14	9.055E-30

For each blackbody temperature, Tables 3 and 5 show the spectral irradiance increasing with wavelength, while the solar spectral irradiance shows the effect of the absorption features. For the filtered blackbody spectral irradiances, the increase with temperature shows as asymmetry in the filter response, especially in the wings of the filter. This is more noticeable with as the blackbody temperature decreases. However, since we are doing photometry, the photometer will not be sensitive to the asymmetry. The contribution of the satellite in either the *Ca* or the *Hβ* filters appears to be similar; the solar Ca II H and K absorption features are stronger, but the satellite blackbody contribution weaker at that wavelength region.

6. CONCLUSION

Characterization of satellites by *uvbyCaHβ* photometry could be achievable for several reasons.

a. The Haleakala telescope can simultaneously collect photometry in multiple filters, so that atmospheric extinction effects can be removed from the observations, with sky and dark measurements done before and after the satellite observations, and not during;
b. The extended Strömgren standard stars can be used to calibrate the program;
c. The absorption line filters isolate the solar absorption line wavelengths, where the solar contribution relative to the satellite contribution is reduced;
d. It requires the addition of one filter to a standard set of Strömgren *uvbyHβ* filters, a relatively inexpensive acquisition;
e. Rigorous data processing overcomes signal-to-noise.

More detailed development of this method entails knowledge of the characteristics of the available photometric instrumentation at Haleakala, particularly sensitivity, modifications to the photometric reduction software, and calibration of the extended Strömgren system at Haleakala.

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