Narrowband Photometry of Solar Analogs in the Near Ultraviolet

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1 Introduction

The observations presented here are part of a narrowband photometry program to determine the chemical composition of different comets. This long-duration program was begun in 1976 by R. Millis (Lowell Obs.) and M. A'Hearn (Univ. Maryland), and has undergone several phases. Most recently, new filters were designed and manufactured, and are presently being calibrated for use. These new filters were prompted by the appearance of Comet Hale-Bopp and will replace the deteriorating International Halley Watch filters.

The narrowband filters are designed to isolate the emission bands of various neutral gas species (OH, NH, CN, C_3, C_2), and from cometary ions (CO^+ and H_2O^+), as well as the reflected solar continuum from dust grains. In order to measure the fluxes from the emission bands, accurate subtraction of the solar continuum at each wavelength is required. Solar analogs are used to represent the solar spectrum, so the calibration process requires that observations of the solar analogs be made in each of the narrowband filters.

Since four of the filters are located in the near-UV where atmospheric extinction is relatively high (especially for the OH filter at 3080 Å), accurate extinction coefficients are measured nightly for reducing the observations. Due to the narrow filter bandpasses, no color terms are needed in the reductions, a major advantage over UBV measurements. Therefore, while these filters are not optimized for stellar studies, they can provide a nearly-unique data set for solar analogs in the near-UV.

2 The Hale-Bopp Narrowband Comet Filters

The new narrowband comet filter set (designated the "Hale-Bopp (H-B) set") consists of 11 filters that isolate the neutral gas, ions or continuum in a comet's spectrum. The specifications for each filter are listed in Table 1 and the transmission curves are plotted in Figure 1 along with the transmission curves for the IHW filters and a spectrum of Comet P/Tuttle (courtesy of S. Larson).

Knowledge gained from the IHW filter set was used to improve the characteristics of the new filters, including a reduction in contamination of the continuum filter from gas emissions. Also, advancements in the manufacturing process produced higher transmissions, squarer profiles and more robust, longer-lived UV filters.

Table 1. Filter Specifications

ID / Species	Central Wavelength	FWHM	Typical Peak Trans.
OH	3090 Å	62 Å	60%
NH	3362	58	77
UV Cont.	3448	84	61
CN	3870	62	83
C_3	4062	62	68
CO^+	4266	64	69
Blue Cont.	4450	67	82
C_2	5141	118	87
Green Cont.	5260	56	75
H_2O^+	7020	170	74
Red Cont.	7128	58	73

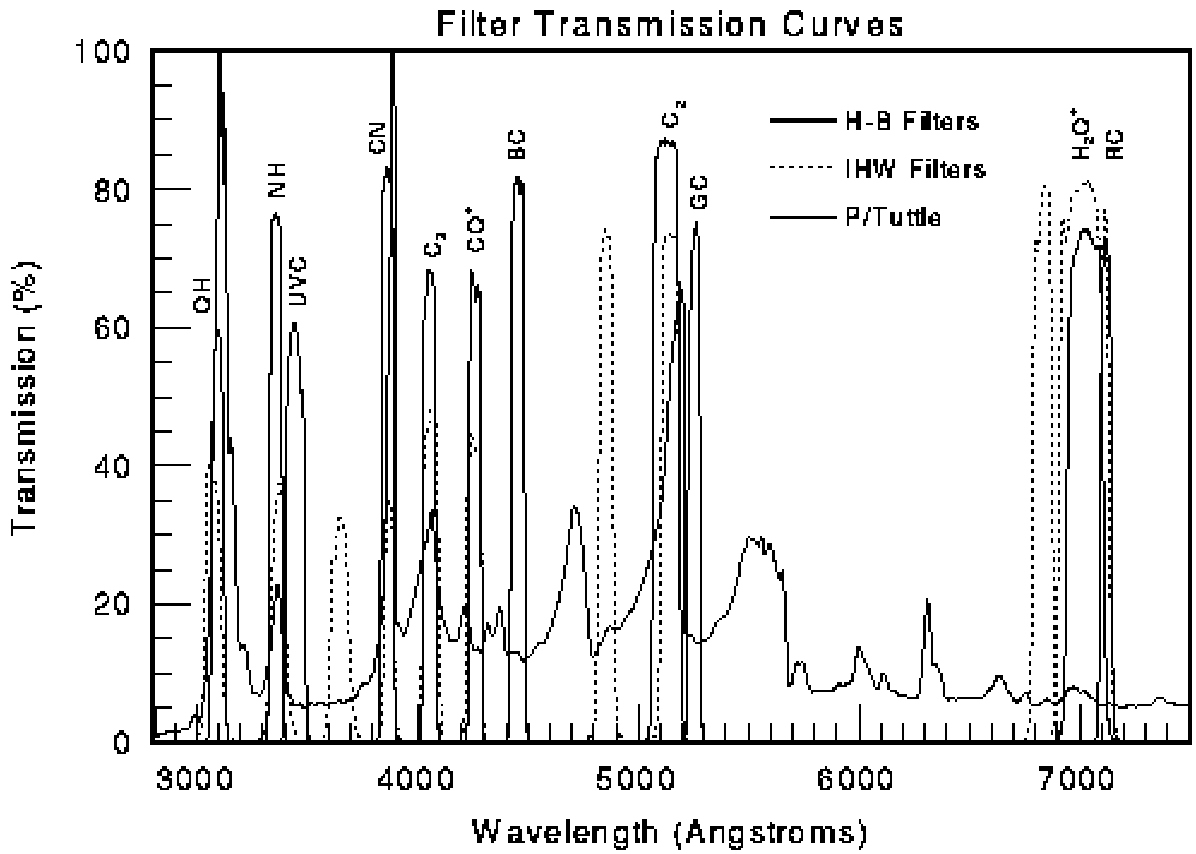

Figure 1: Transmission curves for the narrowband filters (heavy lines). For comparison, the IHW filters (dotted line) and a spectrum of Comet P/Tuttle (thin solid line) are also shown.

3 Solar Analog Candidates

Because there is no as-yet-agreed to solar twin, the choice of which solar analogs to include in the observations was based on the principle that they should be photometrically as close as possible to the sun. Several parameters were used for comparison to the Sun, and in general, stars were chosen so that their values would bracket the Sun's value. In this manner, the ensemble of all stars should represent a close approximation to the sun.

The parameters that were used to guide the selection process include, in approximate order of importance:

- Spectral Type
- Effective Temperature
- B-V Color
- Metallicity
- Chromospheric Activity
- Surface Gravity
- Bolometric Magnitude

Further criteria were that each star must be accessible to our telescopes (i.e. not too far south) and to our instruments (not too bright or faint), and that the total number of objects should be sufficient but not overwhelming for our observational program. A list of the candidate solar analogs is given in Table 2, with its value for each of these parameters. The Sun is also listed, with the target values that were adopted for comparison. A question mark is shown if a value is not known and any information that will help to fill in these gaps would be appreciated.

Table 2. Solar Analog Candidates

HD	Name	PPM	SAO	V	B-V	U-B	Sp.	T_{eff}	[Fe/H]	log g	Mbol	Activ.
	SUN			-26.74	0.64	?	G2	5777	0.00	4.44	4.75	weak
11131		210682	148033	6.77	0.62	0.12	dG1	5820	-0.09	4.37	4.71	high
25680		93234	76438	5.90	0.62	0.12	G5	5794	-0.03	4.30	4.63	high
81809		192396	136872	5.36	0.64	0.12	G2	?	?	?	?	weak
146233	18 Sco	199464	141066	5.49	0.65	0.18	G2	5789	+0.05	4.45	4.53	weak
186408	16 Cyg A	37671	31898	5.96	0.64	0.20	G1.5	5780	+0.06	4.29	4.06	weak
29461	VB 106	120102	94049	7.96	0.67	0.21	G5	?	?	?	?	high
186427	16 Cyg B	37673	31899	6.20	0.66	0.20	G2.5	5765	+0.05	4.30	4.30	weak
191854		59420	49262	7.42	0.66	0.22	G5	?	?	?	?	weak
28099	VB 64	119900	93936	8.12	0.66	0.20	G2	5777	+0.16	4.50	4.80	high
30246	VB 142	120238	94114	8.33	0.67	0.21	G5	?	?	?	?	high
76151		191823	136389	6.01	0.65	0.21	G3	5727	+0.07	4.50	4.65	med
217014	51 Peg	114985	90896	5.47	0.67	0.20?	G2.5	5755	+0.06	4.18	4.73	weak

4 Solar Analog Results

Preliminary colors for twelve solar analogs and Jupiter's moon Ganymede were measured at Lowell Observatory using a conventional photoelectric photometer. Results from nine of the eleven filters are presented here. (CCD data from the two longest wavelength filters have not been reduced, and so are not shown.)

Figure 2 shows solar analog colors normalized to the 4450 Å filter. To enhance the differences between stars, the colors are shown relative to the star 16 Cyg B. The data used in this plot are given in Table 3, with the three lines for each star representing the relative color, the formal sigma and the number of measurements included in each value. Measurements of Jupiter's moon Ganymede are also included, as it has sometimes been used as an effective solar analog.

In Figure 2, the Y-axis for each individual star is shifted vertically by 0.05 mag to provide a clear depiction of each star's relative colors. The stars' order from top to bottom is based on the changes from one spectrum to another, which corresponds fairly well to the U-B color and to the effective temperature.

There are several interesting aspects of these stars visible on these plots. All of the analogs have very similar colors at wavelengths between 4000 and 5300 Å. At shorter wavelengths, the following differences are apparent:

- Three stars (HD 11131, HD 25680, HD 81809) stand out as much brighter in the UV than 16 Cyg B, with deviations as high as 0.21 magnitudes at 3870 Å.
- Two stars (HD 76151, 51 Peg) are fainter in the UV, though the difference is only 0.07 mag at its greatest.
- A group of three stars (VB 64, VB 106, VB 142) have the same shapes (including oscillations from filter-to-filter) in their colors at the shorter wavelengths, although they have somewhat different overall slopes.
- One star (HD 191854) is a very close match to 16 Cyg B at all wavelengths.

The choice of 16 Cyg B as the comparison star is somewhat arbitrary, and comparisons to other stars are equally legitimate. For example, a popular favorite solar analog at present is 18 Sco, for which the closest match is 16 Cyg A.

Another item that should be noted is the apparent large sensitivity to stellar temperature of the measurements in the 3870 Å filter. Values at this wavelength can exhibit large variations, even though the overall color trend in the UV is not as large.

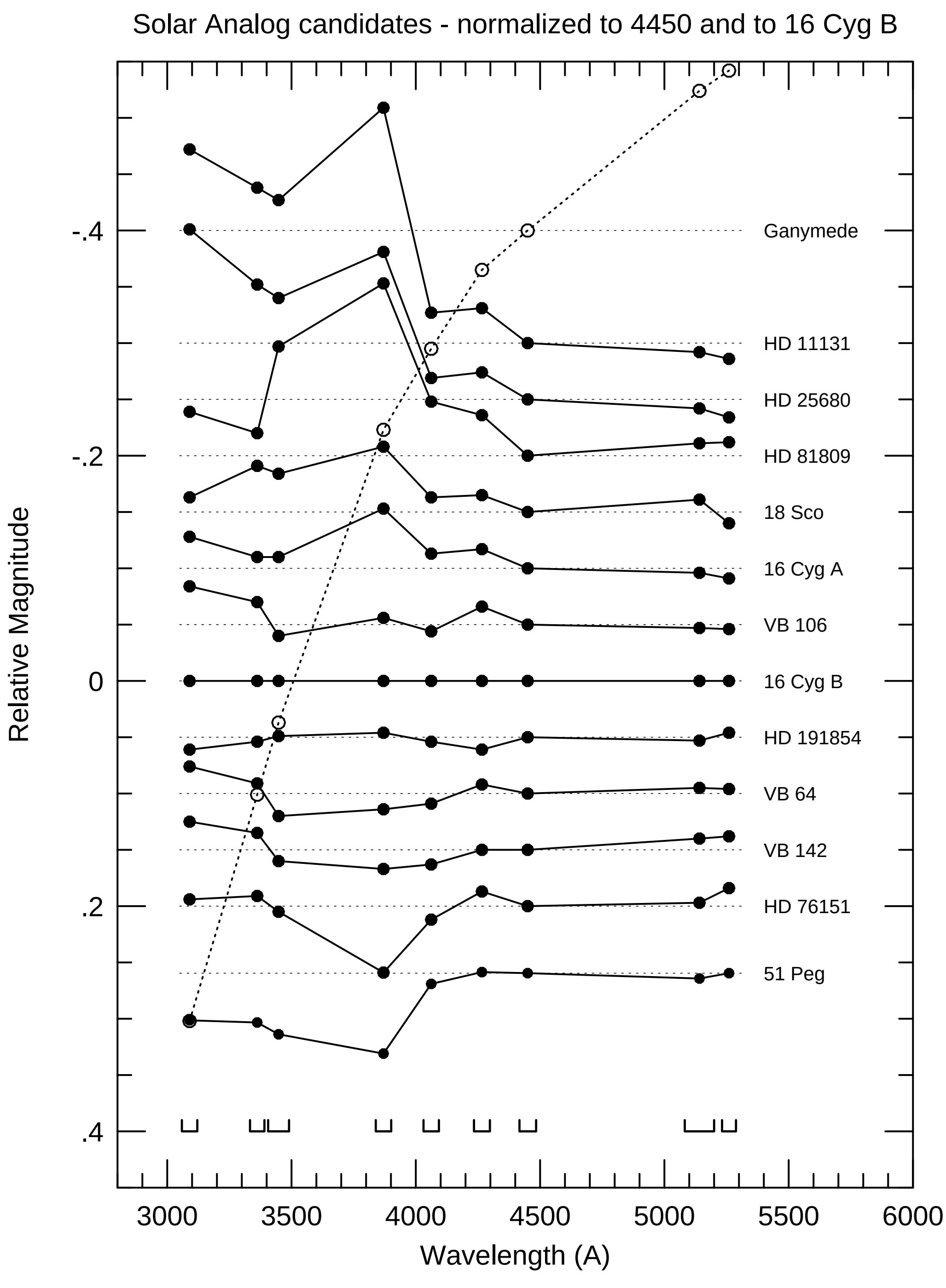

Figure 2: Colors of the solar analog candidates, normalized to 4450 Åand to 16 Cyg B. Each star is offset by 0.05 mag for clarity. The colors of Ganymede are shown as the dotted line. Bars at the bottom denote the filter bandpasses.

Table 3. Solar Analog Colors Relative to 16 Cyg B

Star	3090	3362	3448	3870	4062	4266	4450	5141	5260
HD 11131	-0.172	-0.138	-0.127	-0.209	-0.027	-0.031	0.000	0.008	0.014
	0.002	0.008	0.006	0.004	0.004	0.006	0.000	0.005	0.007
	4	4	6	6	6	6	6	6	6
HD 25680	-0.151	-0.102	-0.090	-0.131	-0.019	-0.024	0.000	0.008	0.016
	0.010	0.005	0.009	0.009	0.004	0.005	0.000	0.003	0.003
	7	8	11	12	12	8	12	12	12
HD 81809	-0.039	-0.020	-0.097	-0.153	-0.048	-0.036	0.000	-0.011	-0.012
	—	—	0.000	—	0.004	—	0.000	0.003	0.007
	1	1	2	1	4	1	4	4	4
18 Sco	-0.013	-0.041	-0.034	-0.058	-0.013	-0.015	0.000	-0.011	0.010
	—	—	—	—	—	—	—	—	—
	1	1	1	1	1	1	1	1	1
16 Cyg A	-0.028	-0.010	-0.010	-0.053	-0.013	-0.017	0.000	0.004	0.009
	0.008	0.007	0.008	0.005	0.004	0.003	0.000	0.005	0.005
	8	7	9	9	9	7	9	9	9
VB 106	-0.034	-0.020	0.010	-0.006	0.006	-0.016	0.000	0.003	0.004
	0.012	0.011	0.010	0.007	0.003	0.006	0.000	0.006	0.005
	5	4	6	6	7	5	7	7	7
16 Cyg B	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
	0.012	0.008	0.006	0.005	0.004	0.006	0.000	0.005	0.006
	8	7	9	9	9	7	9	9	9
HD 191854	0.011	0.004	-0.001	-0.004	0.004	0.011	0.000	0.003	-0.004
	0.013	0.005	0.004	0.007	0.002	0.003	0.000	0.006	0.005
	6	6	7	7	7	6	7	6	7
VB 64	-0.024	-0.009	0.020	0.014	0.009	-0.008	0.000	-0.005	-0.004
	0.011	0.008	0.007	0.008	0.007	0.002	0.000	0.005	0.003
	3	3	5	5	8	4	8	8	8
VB 142	-0.025	-0.015	0.010	0.017	0.013	0.000	0.000	-0.010	-0.012
	0.019	0.005	0.003	0.007	0.007	0.007	0.000	0.006	0.003
	4	4	6	5	5	5	6	5	4
HD 76151	-0.006	-0.009	0.005	0.059	0.012	-0.013	0.000	-0.003	-0.016
	—	—	—	0.006	0.002	—	0.000	—	0.015
	1	1	1	2	2	1	3	1	3
51 Peg	0.044	0.046	0.057	0.075	0.010	-0.001	0.000	0.005	0.000
	0.010	0.006	0.005	0.006	0.003	0.004	0.000	0.005	0.004
	8	9	9	9	9	9	9	9	9

5 Conclusions

As can be seen, the near-UV is an excellent wavelength regime to distinguish subtle stellar properties for solar analog candidates. Unlike the far-UV, where variations among stars may be due to each star's position in its respective "solar" cycle, differences between stars of the magnitude seen here must be caused by differences in more fundamental properties.