Setting the scene for Gaia and LAMOST
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Strömgren-Crawford $uvby\beta$ all sky survey - towards understanding of the Galaxy

Wei Wang[1], **Gang Zhao**[1], **Yuqin Chen**[1], **and Yujuan Liu**[1]

[1]Key Laboratory of Optical Astronomy, National Astronomical Observatories, Chinese Academy of Sciences, Beijing 100012, China
email: wangw@nao.cas.cn

Abstract. The Strömgren-Crawford (SC) intermediate-band photometric system is a very powerful and efficient one for the detailed study of stars, and therefore the Milky Way and local universe. However, due to the narrow bandwidth, low efficiency of detectors and serious atmospheric extinction in u band, and high photometric accuracy required, there was only one all sky survey in this system finished a decade ago, which is restricted to stars brighter than 8.3 mag in y (equal to V) in the solar neighborhood. In this context, it is the right time to carry out an all sky survey to a completeness depth of ∼19 mag, equivalent to a volume-completed distance 4 kpc for solar-type stars. For stars brighter than 15 mag in V, the expected photometric accuracies are ∼0.01mag. With these stars, high precision 3D extinction map can be obtained thanks to the β index. Stellar atmospheric parameters can be determined with accuracies comparable to those from high-resolution spectroscopy. Fundamental parameters like stellar luminosities and distances can be reliably estimated as well. We propose to use the Nanshan 1m telescope to start the survey in early 2014 in the Northern sky. There are several 1-m class telescopes in Chile which can be used to perform the Southern sky survey. This entire survey, when finished, will greatly improve our knowledge on stars and the Galaxy, and will provide us the first 6D map of the Milky Way together with the LAMOST survey and the Gaia mission.

Keywords. surveys – Stars: abundances, fundamental parameters – Galaxy: evolution, formation, structure

1. Introduction

Due to the narrow band and specific definition in u band, the Strömgren-Crawford (SC) system (Strömgren 1963, 1964; Crawford *et al.* 1970) provides a reliable method to determine stellar parameters for stars with a wide range of spectral types (e.g., early or late type stars, metal-poor stars). In particular, this photometric system can accurately identify stars at various evolutionary stages (Strömgren 1963, Árnadóttir *et al.* 2010). A recent evaluation of the importance of the capacity of the $uvby\beta$ photometric system was presented by Bessell (2005). The main characteristics of this system are presented in Table 1. Several photometric indices are defined: $(b-y)$, which measures the continuum slope and is sensitive to stellar temperatures for B, A, F and G stars; the metallicity index $m_1 = (v-b) - (b-y)$, a color difference designed to measure the blanketing due to metal lines near 4100Å; $c_1 = (u-v) - (v-b)$, a color designed to measure the strength of the Balmer discontinuity, and $\beta = \beta_{\rm w} - \beta_{\rm n}$, an index measuring the strength of the Hydrogen β line, which is also sensitive to stellar temperature for B, A and F and early G stars, and is free of interstellar extinction and reddening. The y magnitude is defined to be essentially the same as V for non-M stars. The dependence of stellar atmospheric parameters (APs) on these color indices can be easily inferred in Fig. 1, where the transmission curves of the SC system are shown in blue, those of the Johnson system in black, along with spectra of various types of stars.

The determination of interstellar extinction is a pre-request for precise determinations of stellar APs. Benefiting from the β and $(b-y)$ indices, we are able to obtain an intrinsic-color calibration and to estimate the amount of interstellar extinction, with accuracies down to < 0.01 mag (Karataş & Schuster 2010). The state-of-art accuracies are 60 K, 0.12 dex, 0.13 dex for effective temperatures T_{eff}, metallicities Z and gravities log g, respectively. The reliable measurements of log g allows distance determination with accuracy of 13% (Nordström *et al.* 2004). We emphasis here that such high accuracies of APs require the photometric uncertainties to be $<$0.05 mag, and better to be $\sim$0.01 mag. The uncertainties of APs are much smaller than those obtained with SSPP using SDSS DR9 spectra (Ahn *et al.* 2012), and is comparable to or better than those obtained with Gaia spectrophotometer (Liu *et al.* 2012).

Presently, there is only one SC survey, i.e., the Geneva-Copenhagen survey (GCS, Nordström *et al.* 2004), which is volume complete to a distance of 40 pc down to $V \sim 8.5$ mag. The HM catalog (Hauck & Mermilliod, 1998) collected all measurements in these systems, which include merely $\sim$66,000 stars in total. Therefore, the observations done in this system are highly deficient, which is mainly due to the fact that it requires much more integration time in the narrow and medium band photometry, especially in the u and β_n-bands.

The development of CCD photometry has seen the possibility to scan the whole sky in a reasonable time scale, to determine the properties of stars, and to infer the properties of the Milky Way from these measurements, including its stellar populations, and structures. For broad-band photometry, this approach has been very successful, e.g., the discovery of the thick disk (Gilmore & Reid 1983) using an I-band survey, the discovery of Sagittarius stellar streams(Newberg *et al.* 2002) based on the Sloan Digital Sky Survey (SDSS)(York *et al.* 2000).

Nowadays, given a much better sensitivity in the blue of CCD detectors, and a number of small aperture telescopes that are not as busy as before, it is the right time to carry out an all sky *uvbyβ* survey, with the purpose to obtain a much better understanding of the Galaxy.

Table 1. The characteristics of the standard SC *uvbyβ* photometric system.

	u	v	b	y	β_{n}	β_{w}
Central λ(Å)	3425	4100	4675	5480	4858	4850
FWHM(Å)	300	180	180	240	29	136

2. The survey design

We propose to carry out an all sky SC *uvbyβ* survey. The survey will be down to $V = 19$ mag with uncertainties of 0.1 mag (corresponding to a distance limit of 4kpc for solar type stars), and down to $V = 15$ mag with uncertainties of $\sim$0.01 mag. In the Milky Way, there are $\sim$0.75 million stars brighter than $V = 15$, for which high precision APs are expected to be produced with our survey. We emphasis again that the AP accuracies expected for the Gaia spectrophotometer is similar with or worse than those of our SC survey for 15 mag stars.

For our survey, the first step is to use a wide field 1m telescope at Nanshan site in Xinjiang. The site has an altitude of 2080 m, longitude of $87° : 10' : 38''$, and latitude of

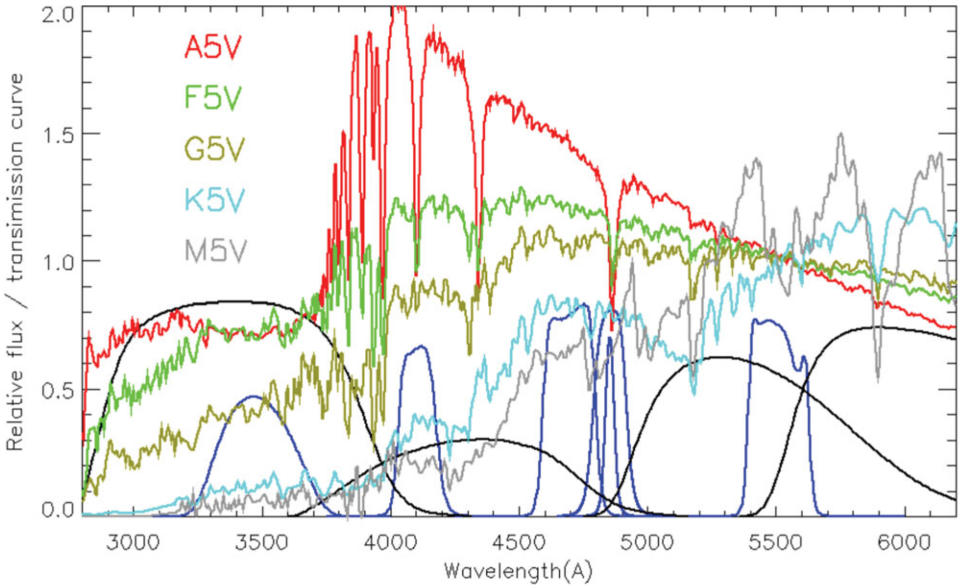

Figure 1. The transmission curves of the SC $uvby\beta$ photometric systems (blue curves) and the Johnson system (black curves), along with theoretical spectra of various types of stars.

$43^\circ : 16' : 44$". According to a two-year monitoring of the weather conditions, there are about 200–220 clear nights per year, the median seeing is $\sim$1.7", and sky background in V is about 21 mag/arcsec^2 in grey nights and can be as good as 22 mag/arcsec^2 in dark nights. The 1-m telescope is a simple prime-focus Alt-Az telescope, with effective field-of-view (FOV) of $1.3\times1.3\,\mathrm{deg}^2$, equipped with a 4K x 4K UV-enhanced back-illuminated E2V CCD chip. The pixel scale is $\sim$1.1 arcsec/pixel, which is in the regime of slightly under sampling. The CCD is currently cooled with Liquid nitrogen, but will be replaced by an electric cooling system. The high quality $uvby\beta$ filters for the 1-m telescope are being manufactured by the Scientific Customs company currently, and are to be delivered in September 2013.

From our calculations, based on typical condition at Nanshan, typical exposure times for vby and H_β wide filters will be $\sim$1 min, and those for u and H_β wide filters 5 min, to reach the depth we proposed. As the survey should be an magnitude-limited survey, we will slightly change the integration time, exposure by exposure, according to the airmass and seeing condition in the last frame. For each FOV, the total time will be around 15 min, including overheads. To ensure high precision flux calibration, a common region of $0.3\times0.3^\circ$ will be observed in RA and DEC direction, respectively. Basically, the sky will be scanned in 2.3°-wide stripes in RA direction. With this configuration, the telescope naturally keep pointing around the meridian. We will observe all the sky area north of DEC$=-5^\circ$, and the total area is $\sim 22065\,\mathrm{deg}^2$. It will take about 5 years to finish the Northern survey.

Test observations are being conducted on the Nanshan 1-m telescope with Johnson filters, in order to get familiar with the telescope and instrument, and to improve the mechanical systems, the electric systems, the ambient monitoring systems, and to stabilize the entire system. Test observations with SC photometry will be started as soon as the filters are installed. In the meantime, we are preparing the software for batch and remote observations, online-reduction package, real-time refinement control, offline-reduction packages, and archiving systems.

We are looking for an appropriate telescope in the South, mainly among those small aperture telescope located in Chile. We currently have three candidate telescopes, the MPG/ESO 2.2m telescope at La Silla, the Yale 1m telescope at CTIO, and a 0.7-m Maksutov telescope of the University of Chile at Pulkovo Observatory. The starting time of Southern survey will possibly be later than the Northern survey by $\sim$1 year, but given the much better site conditions in Chile, the finishing time will not be much later.

3. Flux calibrations and AP calibrations

For a high precision photometric survey, flux calibrations, including relative calibrations and absolute calibrations, are extremely crucial. We will have two kinds of standard star observations, one is to observe SC $uvby\beta$ secondary standard fields/stars several times each night, to aid the flux calibration and atmospheric extinction correction. The other is to observe HST spectrophotometric standard stars (Bohlin 2007, 2010) and spectrophometric Landolt standard stars (Stritzinger *et al.* 2005), whenever possible. In addition, adjacent fields have common regions, which allows accurate relative flux calibration. To check error propagation in the relative flux calibration, and to ensure the error propagation is insignificant, tens of 2.3°-wide stripes in the DEC direction will finally be observed. In Nanshan site, there will be an 25-cm telescope which can be used to monitor the sky background and and help to correct for telluric extinction simultaneously.

In the literature there are a lot of AP calibrations available, which can transform the color indices into APs, e.g., calibrations of all the four APs by Holmberg *et al.*(2007), and independent metallicity calibration by Twarog *et al.*(2007), intrinsic color E$(b-y)$ calibration by Nissen (1994). We will do AP calibrations in two ways. The first method is simple but less reliable. We translate our $uvby\beta$ indices to those indices in other works, which have well defined AP calibration formulas. It might be a better choice to do our own calibration when enough survey data have been collected, directly to high-precision APs (except $T_{\rm eff}$) from high resolution spectroscopy either from literature, or observed in the near future. $T_{\rm eff}$ will be calibrated using the infrared flux technique (see e.g. Ramírez & Meléndez 2005).

4. Science with $uvby\beta$ survey

The all sky survey is expected to be completed in 4–5 years, and will result in a catalogue including 0.3 billion stars with $V < 19$ mag and uncertainties <0.1 mag, and more importantly a catalogue including 0.75 million stars with $V < 15$ mag and uncertainties <0.01 mag. This corresponds to a volume complete distance of $\sim$1kpc for G dwarf stars, and $\sim$10 kpc for giant stars. For the later catalogue, accurate APs can be reliably determined, as well as fundamental parameters (FPs), like stellar ages, luminosities, distance, and extinction.

This will be the largest sample of stars, with accurate APs and FPs, with which important science subjects could be studied in detail, as listed below:

(*a*) A high-accuracy distance-dependent extinction map (3D map), deduced from the $(b-y)-\beta$ calibration. The extinction can be derived for every B, A, F and early G stars individually, and the measurement uncertainty of E$(b-y)$ is < 0.01 mag.

(*b*) As the spectral type, the metallicities, stellar distances, and stellar number densities have been determined, it will help a lot to study the structure of Milky Way, including its spiral arms, the thin and thick disk and the halo. The disk structures are not well studied previously, due to lack of survey data. For example, SDSS only observes high galactic latitude region, i.e., the halo and other galaxies. Open clusters in the disk and globular clusters in the halo, will be studied as well.

(*c*) To measure metallicity distribution and age-metallicity relationship, in order to understand chemical evolution and formation of the Galaxy.

(*d*) To discover and classify blue stars in the solar vicinity, including WDs, sdBs and HBs, which are not optimized in the blue in previous surveys.

(*e*) To search for and study metal-poor and extremely metal-poor stars.

(*f*) The β index can be used for the study for emission line nebulae, like planetary nebulae and H II regions, medium-redshifted quasars and AGNs.

(*g*) Combining our $uvby\beta$ photometric data, with LAMOST spectra to determine radial velocity, and with Gaia mission for good estimates of proper motions, a 6D map of the Galaxy will be produced, which will greatly enhance our understanding of the Galaxy.

5. conclusion

We are proposing to conduct an all sky SC $uvby\beta$ survey, in order to determine stellar atmospheric parameters and fundamental parameters to an accuracy comparable to high resolution spectroscopy, for all the $\sim$0.75 million stars with $V < 15$ mag. When the survey is successfully finished, we will be able to have a more detailed understanding of the Milky Way and its components.

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