Contrib. Astron. Obs. Skalnaté Pleso **43**, 518 – 522, (2014)

The APASS all-sky, multi-epoch BVgri photometric survey

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Received: November 18, 2013; Accepted: January 19, 2014

Abstract. The APASS photometric survey covers the whole sky, from Pole to Pole, and has measured in Landolt B, V and Sloan g',r',i' bands all stars in the range $10.0 \leq V \leq 17.0$ over about four distinct epochs between 2009 and 2013. The photometry is accurate to 0.02 mag and the astrometry to 0.17 arcsec. At the time of writing 8 incremental Data Releases have been issued covering ≥ 50 million stars. The final survey products will be ready by the end of 2014 and will include 100 million stars. Extension to brighter stars ($7.5 \leq V \leq 10.0$) and additional bands (u', z' and Y) is underway.

Key words: Surveys – Catalogs – Techniques: photometric

1. The project

In the 7th to 17th magnitude range, no accurate photometric catalog exists that covers the entire sky in the optical part of the spectrum.

The photometric errors in the Tycho-2 catalog (Hoeg, et al., 2000) for objects at 10th magnitude are already at the 0.05 to 0.07 magnitude level and increase to 0.1 to 0.2 magnitudes at 11th magnitude, significantly worse than can easily be achieved by small amateur telescopes. The Sloan Digital Sky Survey (York, et al., 2000; hereafter SDSS) has very good precision but saturates brighter than 14th magnitude and covers only about 25% of the sky. The photometric calibration of the USNO-B catalog based on digitized photographic plates suffers from the intrinsic inaccuracies and inhomogeneities of such plates (Monet, et al., 2003), with typically 0.2mag errors. Even after projects like Pan-STARRS and LSST calibrate the sky at 14th magnitude and fainter, there will still be a gap from 10th to 14th magnitude where some 13 million (Kharchenko, et al. 1997) objects of astrophysical interest lie, and where all running or planned major spectroscopic stellar surveys of (at least) this decade will operate (like RAVE, ESO-Gaia, HERMES-GALAH). This gap means that fundamental astrometric and photometric support data will be missing for such surveys.

Observers involved in follow-ups of optical transients currently calibrate fields individually, leading to inefficient use of telescopes worldwide and slow response to alerts. The use of large and small telescope open-shutter time to calibrate target fields using all-sky standards is a major impact on research

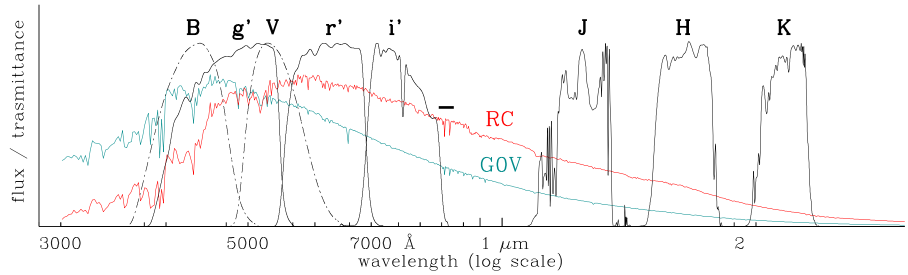

Figure 1. The spectral energy distributions of a G0 main sequence and of a Red Clump star (the typical field stars in any magnitude limited sky survey), overplotted with the transmission profiles of Landolt BV and Sloan $g'r'i'$ bands adopted by APASS. The infrared 2MASS JHK bands (including telluric absorptions) are also plotted. The thick horizontal dash at 8600 Å marks the wavelength range covered by RAVE and *Gaia* spectra.

productivity. In fact, proper photometric calibration against Landolt and SDSS equatorial standards requires the best nights of an observing run, and often uses 15-30% of the available time.

To address and solve these issues, we have assembled a team of researchers from various Institutes, including AAVSO, Southwest Research Institute and Lowell Observatory with expertise in photometric/astrometric surveys and robotic observatories, aiming to design and carry out an astrometric/photometric survey of the sky at optical wavelengths in the 10th to 17th mag range. The AAVSO Photometric All-Sky Survey, or APASS, is producing an accurate, homogeneous catalog in five filters (Johnson B,V and Sloan g',r',i') of some 100 million objects covering the entire sky from 10th to 17th magnitude, with an external accuracy of 0.02 magnitudes or better up to 15th magnitude and astrometric positions accurate to 0.15 arcsec. We choose these filters to bridge the transition from the widely used Johnson system, with its enormous database of historical observations and better diagnostic capability, to the SDSS system, which is becoming the new standard for all-sky survey photometry.

In addition to filling in a wide magnitude gap in the photometric coverage of the sky not to be addressed by future surveys, APASS is also filling in the time gap with Pan-STARRS and LSST from which data will not be available for probably another decade. Scientific exploitation of APASS data has already begun, examples being: derivation of photometric temperatures for the half-million stars observed by the RAVE Galactic Archeology spectroscopic survey (Kordopatis et al. 2013, Munari et al. 2014a), discovery and characterization of RR Lyr members of the newly found Aquarius stream - the tail of a disrupting globular cluster (Munari et al. 2014b), and the input catalog for the HERMES-GALAH spectroscopic galactic survey with the 400 fiber positioner at the prime focus of the AAO 4m telescope at Siding Spring. USNO is now including APASS

DR6 (50 million stars, about half of the final APASS catalog and about half of the expected quality) as part of their UCAC-4 data release (Zacharias et al. 2013).

We released Data Release 7 in May 2013 (http://www.aavso.org/apass). DR7 contains 50 million stars in 98% of the sky. Each data release includes all previous stars, but with improved results based on additional observations plus new processing. This will be a dynamic catalog until the final global solution is completed.

2. The hardware

APASS is constructed from commercially available off-the-shelf hardware, so that the major effort (as always) is software. We are using many standardized packages for controlling and scheduling the telescope, IRAF for data processing, MySQL/Postgres for database storage, etc. so that the amount of custom software is minimized, and the main effort is devoted to deriving the best possible photometry. This innovative approach has many desirable aspects: it is easy to maintain and to get operational; the equipment is easily duplicated or even transported to other sites for all-sky coverage; the equipment is inexpensive.

We installed APASS-North at Dark Ridge Observatory (altitude 2164m) in central New Mexico in October 2009, and APASS-South was installed in October 2010 at the Cerro Tololo Inter-American Observatory (2215m), in the PROMPT6 dome. At both sites, a pair of twin remotely controlled, small telescopes obtain simultaneous CCD observations during dark- and grey-Moon time over five optical bands: B, V (tied to the equatorial standards of Landolt 2009) and g',r',i' bands (tied to the 158 primary standards given by Smith et al. 2002, that define the Sloan photometric system). The telescopes are 20cm f/3.6 astrographs feeding Apogee U16m cameras (4096$\times$4096 array, 9 μm pixels), that cover a field 2.9 deg wide with a 2.6 arcsec/pix plate factor. The photometric filters are of the dielectric multi-layer type and are produced by Astrodon. Transmission curves and photometric performances of Astrodon filters are discussed and compared to more conventional types of photometric filters in Munari et al. (2012) and Munari & Moretti (2012). On average 70 fields are observed per night at each APASS location, 20 of them being standard fields (Landolt, Sloan).

3. Operation

We have divided the night sky into two sets of 5200 field centers, spaced on a 2.8$\times$2.8 degree grid, providing a 5% overlap between fields. The second set of field centers is offset a half-width in both RA and DEC, so that it becomes a center-to-edge overlap set with the first set. Each set is measured on two different nights, so that every point in the sky has a minimum of four visits in all 5 filters. By using four separate nights for each target, we average extinction and other random nightly errors, improving the mean photometry. For each field, two 180-second exposures are made with one telescope/camera at B and g'; and three 90-second exposures are made simultaneously with the other telescope/camera at V,r',i', resulting in the coverage of 8 fields per hour and roughly 70 unique fields per night, so that about 500 square degrees of sky plus standard fields are covered per photometric night.

Every photometric night, visits to 20 Landolt equatorial and +45 or −50 degree fields (Landolt 1983, 1992, 2009, 2013) are made. Several fields are observed off the meridian to provide extinction measures over a wide airmass range. With the large field of view, hundreds of Landolt standards are measured every night. Note that the primary SDSS standard fields are usually centered on Landolt standards (Smith et al. 2002), so both BV as well as gri standards are observed nightly and used for transformations from the instantaneous local photoemtric system to the standard system. Only the following data reduction reveals if any given night was indeed really photometric, or not. The data from good photometric nights are currently used in the incremental data releases, where new data are combined with pre-existing ones to improve the average values listed for all stars in the survey. Data from non-photometric nights will be used during the preparation of the final catalog and the release of epoch photometry.

In theory, the entire 41,253 square degrees of sky could be covered once in 82 nights in this fashion; the 4-night coverage would take about 330 photometric nights. The total APASS data volume would be a minimum of 3.25 TB, not counting calibration frames, revisits, the bright extension described later, and all non-photometric observing. As with every ground-based survey, there are many sources of lost nights (moon avoidance, clouds, equipment, etc.) and we are surveying from both a northern and a southern hemisphere site to complete the survey. However, the data-collection phase of the main survey is nearly complete, with only a few remaining fields.

4. Bright star extension

For the vast majority of bright stars, we still lack homogeneous and accurate optical photometry. The only available source common to all bright stars is the B_T,V_T,H_p photometric catalog built from data of the Hipparcos-Tycho space mission. While the Tycho B_T and V_T bands are reasonably close to Johnson's corresponding bands and their transformation onto the B,V bands of Cousins southern E-regions is sufficiently well established for star of normal colors (Bessell 2000), the Hipparcos H_p adds little to the photometric characterization, being equivalent to a white light sum of the B_T and V_T bandpasses. What is almost completely lacking is homogeneous photometry at the shortest optical wavelengths (like the U band) and at the reddest ones (like the R and I bands). The largest available database to date of UBV photometric measurements of these bright stars only contains 92,000 objects, variously assembled from a heterogeneous literature, and has been published by Mermilliod and Mermilliod (1994).

An extention of the APASS survey will cover the stars brighter than the current saturation level (about 10 mag), and we will include u', z' and Y imaging for those stars. These will take advantage of the bright Moon time unscheduled for the current survey on fainter stars. Exposures will be shortened to 20sec/10sec pairs to accurately measure stars as bright as V=7.5 during those nights or periods of nights where the sky brightness does not permit the longer, normal survey exposures. During the latter stages of the survey, the bright extension will be the predominant operational mode to make effective use of the nights where only a handful of deep survey fields need to be imaged.

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