Ultraviolet Imaging Probe (UIP)
for the Pan-STARRS-1 Telescope

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1. Introduction

The Pan-STARRS-1 telescope has been designed to operate with a filter set that is closely matched to the Sloan Digital Sky Survey (SDSS) g, r, i, and z filters. In addition, an even longer wavelength filter near the cutoff of Si CCDs, the y filter, will be used. However, a deliberate decision has been made not to include a filter covering ultraviolet wavelengths. The reasons for this are both scientific and technical.

For the main scientific mission of the Pan-STARRS project, the search for potentially hazardous asteroids, observations in the near ultraviolet offer only disadvantages over work at longer wavelengths, since both the reflectance of typical asteroid surfaces as well as the reflected solar spectrum peak at wavelengths much longer than ultraviolet. Many other core scientific projects planned with the Pan-STARRS data are focused on high-redshift objects, many of which are characterized by being undetectable at ultraviolet wavelengths. On the technical side, near-ultraviolet wavelengths pose many problems: The seeing is generally inferior to that at longer wavelengths, atmospheric dispersion is a much more limiting factor, and the difficulty of designing corrector optics increases rapidly. By ignoring the near-ultraviolet wavelengths, a system design with significantly better performance at longer wavelengths is possible: The Pan-STARRS CCD detectors (paper by J. Tonry, these proceedings) are optimized for longer optical wavelengths, relatively simple corrector optics can be built (J. Morgan, these proceedings), and the coatings both for the mirrors and the corrector lenses can be optimized for longer wavelengths.

While the decision not to include a near-ultraviolet bandpass in the Pan-STARRS filter set is both scientifically justified and technically sound, some projects could still benefit substantially from observations at these wavelengths. Therefore, we are working on a small additional sky probe dedicated to obtaining relatively shallow, but well calibrated, photometric data in the SDSS u-band.

2. Scientific Justification

Most photometric systems contain a filter bandpass in the near ultraviolet, between the terrestrial atmospheric cutoff defined by ozone absorption and the Balmer break in the spectra of hot stars. The reasons for this choice are that hot stars, spectral types O and B, emit most of their flux at these wavelengths. Fig. 1 shows a comparison of the Sloan Digital Sky Survey (SDSS) bandpasses and typical stellar spectra. For ground-based observations, the near-ultraviolet band (the u-band in case of the SDSS) is therefore the best tracer of these hot, and necessarily young stars.

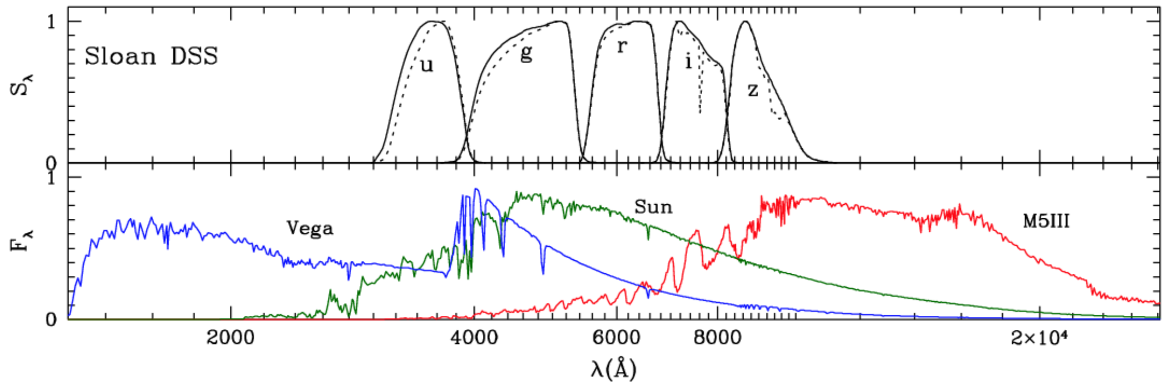

Fig. 1: The Sloan Digital Sky Survey (SDSS) bandpasses, compared to a range of stellar spectra [1].

Another important benefit of including a near-ultraviolet band is related to the problem of determining the effective temperature of a star and interstellar extinction towards it. The effective temperature can be used to determine the absolute magnitude of a main-sequence star. In combination with the interstellar absorption, this can then be used to determine the distance to the star from a comparison of absolute and apparent magnitude of that star. Interstellar extinction is wavelength dependent and therefore leads to a reddening of a star's colors, an effect that is difficult to distinguish from a lower temperature of a star if only two wavelengths and therefore one color are used. The method usually employed to break the degeneracy of temperature and interstellar extinction is the use of color-color diagrams, where two colors (magnitude differences) are plotted against each other. The main sequence of ordinary, hydrogen burning stars usually forms a well-defined locus in these diagrams. Fig. 2, from [2], shows three examples of such color-color diagrams based on Sloan Digital Sky Survey data obtained in bandpasses similar to those of Pan-STARRS-1. Once a unique combination of interstellar absorption and temperature has been established, the star can be placed in a color/absolute-magnitude diagram.

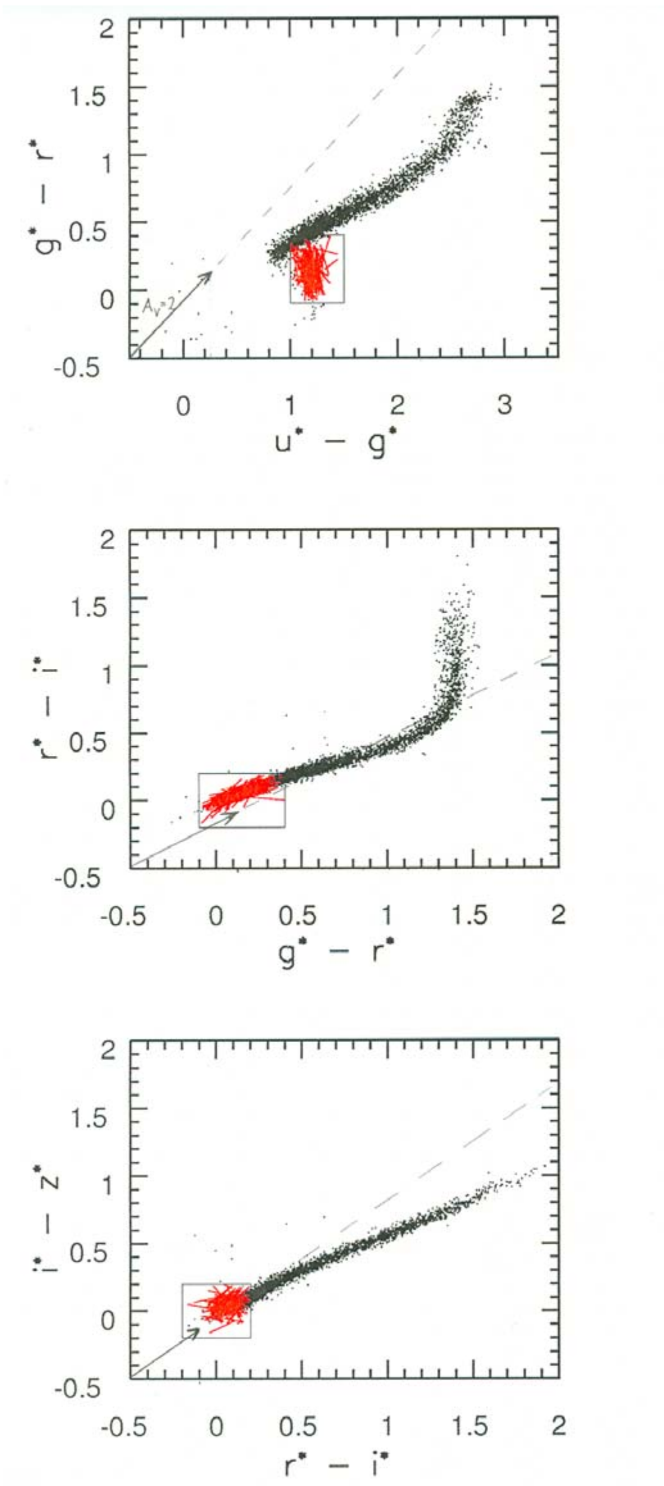

Fig. 2

Three color-color diagrams based on the SDSS filter set. The grey near the left end of each diagram represent RR Lyrae stars. The dots represent the locus of main sequence stars. The arrow is the reddening vector for an interstellar absorption A_V=2 mag. The comparison of these diagrams shows that multiple color-color diagrams are required to obtain a unique solution for star color (basically effective temperature) and interstellar absorption.

Included in these diagrams is an arrow representing the reddening vector corresponding to an interstellar extinction of Av=2 magnitudes based on the A_λ/A_V values for the SDSS filters [1]. The absorption in the Johnson V filter is commonly used as a standardized measure of interstellar extinction, even if the actual photometry is done in a different photometric system.

As can be seen from this figure, the interstellar reddening vector often lies parallel to the distribution of stellar colors. In these cases, the degeneracy of stellar color (or temperature) and interstellar reddening (and therefore interstellar absorption) cannot be resolved.

The center panel is the (g-r)/(r-i) color-color diagram, combining the shortest bandpasses that Pan-STARRS will provide. The red colored data points represent RR-Lyrae stars that are not of concern in the context discussed here. To the left side of all color-color diagrams, early spectral type stars (B and A) are plotted, the right end of each diagram represents stars of spectral type M. The central panel of Fig. 2 illustrates that both for early spectral types, as well as for intermediate spectral types (around K type), the reddening vector lies parallel or tangential to the locus of the main sequence. This means that with these data points alone, it is impossible to compute a unique solution of intrinsic stellar color and interstellar reddening.

The longer wavelength (r-i)/(r-z) color-color diagram shows a reddening vector that is not parallel to the main sequence locus for all but the earliest spectral types. It therefore resolves the intrinsic color and interstellar reddening degeneracy for most stars.

The top panel shows the (u-g) and (g-r) color-color diagram, combining the three shortest bandpasses used by SDSS. Of the three diagrams shown inthis has the largest angle between the locus of the main sequence and the reddening vector, and therefore offers the best opportunity to determine intrinsic color and interstellar reddening separately for early-type stars.

In combination, these diagrams illustrate that, in order to arrive at a unique solution of intrinsic stellar color and interstellar reddening, all three color-color diagrams are required, and that the inclusion of the u-band enables the determination of these parameters for hot stars.

Beyond this particular scientific example, the benefits of obtaining even a shallow ¾ -of the sky survey in the u-band is the establishment of a sufficiently dense grid of stars of known u-band flux so that any project that requires u-band data can simply calibrate their deeper images using these known secondary calibration stars. The Pan-STARRS astrometric and photometric survey will cover a larger area of sky than the SDSS. A u-band imaging probe that works in parallel to PS1 and gets it data reduced in the same data reduction pipeline as the Pan-STARRS ISP will fully benefit from the careful characterization of the photometric quality of each night that PS1 will perform for the AP survey. It is therefore reasonable to expect that the photometric calibration of all PS1 AP bands, including the ISP and the UIP data, will be superior to that of the SDSS.

The latest work on design reference mission for the AP survey suggests that each area of the ¾ of the sky will be visited 72 times for 30 seconds over the course of the 3 year duration of the survey. Therefore, the u-band survey can be expected to be both quite deep and photometrically precise. Assuming a reasonably good throughput, which will be discussed in more detail below, we expect to achieve a similar depth in the accumulated data as the SDSS. With this large number of images, some image quality can be recovered by sub-sampling the 5 arcsec pixels of each image. In the medium deep fields, there will be about 800,000 s of total integration time over the 3 years and the limiting magnitude should substantially exceed the SDSS.

3. Survey Concept

As desirable as a 3/4 –sky u-band survey may be, conducting a sky survey, reducing the data, and making them available in a data base is a formidable task. As a stand-alone project, such a survey has never been undertaken. However, as an add-on to the Pan-STARRS-1 AP survey, such a survey is easily feasible, since the Pan-STARRS ISP will conduct shallow sky surveys in the Pan-STARRS g, r, i, z, and y bands. Therefore, the integration of such a sky probe into the PS1 system, software control of the sky probe, readout of the CCD, pipeline reduction of the data, and preparation of the accumulated, distortion-corrected sky images will all be largely in place and can be used for UIP. It is only in this environment of PS1 that the UIP survey can be conducted at little marginal cost.

4. Hardware Concept

The hardware of UIP is relatively simple and cheap. The UIP is expected to use an Apogee CCD camera, the same camera originally used for the ISP, if and when ISP will be upgraded to a deep depletion orthogonal transfer array. The apogee CCD camera is a 2k×2k thinned CCD with 13.5μm pixels. It is the largest thermoelectrically cooled high quantum efficiency CCD camera that is commercially available. To match the field of view of the PS1 telescope, the UIP needs to have a focal length of 500mm, the same as the ISP.

We have evaluated several options for the optical system used for UIP. The starting point was the Nikkon lens used by the ISP (B. Granett, these proceedings). The problem with this commercial, all refractive system was the large total thickness of glass used and the marginal optical quality. In combination, the likelihood of this system working well in the near-ultraviolet were low.
We have evaluated a simple, corrector-less Schmidt telescope design. The advantage of such a custom-design would have been that all optical parameters would have been completely controllable. However, the f-ratio achievable with good optical quality was low, and the cost even for such a simple custom system was high. A search of the market for amateur astronomy astrographs resulted in the selection of the new Takahashi Epsilon 180 astrograph as the optical system for UIP. This astrograph has the required focal length of 500mm, has a clear aperture of 180mm and offers excellent image quality at optical wavelengths. The design uses a hyperboloid primary mirror, a flat Newtonian secondary, and a doublet corrector lens made from extremely low dispersion glasses. Unfortunately, we could not obtain throughput and image quality data in the u-band from the manufacturer. The image quality in the blue, however, is much better than we require, and the collecting area of the astrograph is large, so that we can achieve acceptable performance even in the face of reduced image quality and throughput in the u-band. Of all commercial optical systems available on the market, the Takahashi E 180 offers the best mix of characteristics for use as the UIP optical system. Multiple examples of high-quality astronomical images taken with the E 180 at optical wavelengths by amateur astronomers exist and demonstrate the system is optically and mechanically of good quality.

We will adapt the E 180 for use in the UIP by motorizing the focusing mechanism, using much of the same hardware and software solutions that were used for the ISP.

The UIP will be equipped with a single fixed u-band filter. We intend to purchase a filter that nominally reproduces the bandpass of the SDSS, but avoids the red leak problem that SDSS has encountered with their filters. Also, as SDSS has found out, even nominally identical filters will have slightly different bandpasses when used in ambient conditions (as in UIP) compared to use in vacuum as in the SDSS camera.

Fig. 3: The Takahashi E 180 optical tube assembly

Fig. 4: The E 180 focusing mechanism

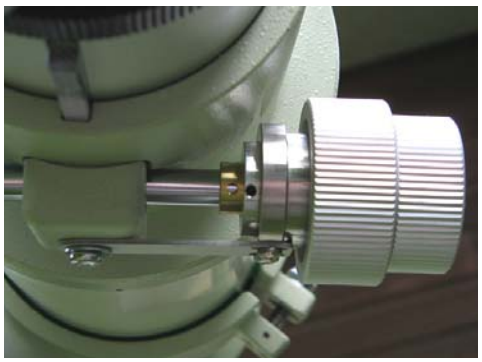

Fig. 5: The micro-focusing gear unit planned for UIP

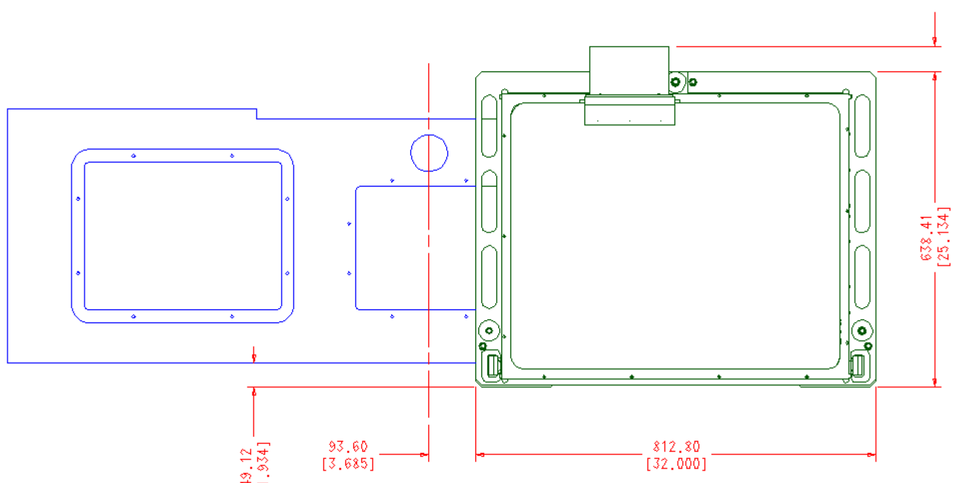

Fig. 6: Drawing of the central box of the PS1 telescope. Indicated in green is the ISP. The spectroscopic sky probe will be of identical dimensions and will be mounted symmetrically on the left side. Between those two instruments, the UIP will be mounted.

References:

[1] Girardi, L, Grebel, E. K., Odenkirchen, M., and Chiosi, C, Theoretical Isochrones in several Photometric systems, 2004, A&A, 422, 205

[2] Ivezic, Z. et al., Candidate RR Lyrae stars found in Sloan Digital Sky Survey commissioning data, 2000, AJ, 120, 963