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The ASTRA Spectrophotometer[1]

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Abstract. A CCD-based spectrophotometer for a new automated 0.5-m telescope at the Fairborn Observatory, Washington Camp, AZ, USA, altitude 1800 m should begin operations by Spring 2004. The Citadel ASTRA (Automated Spectrophotometric Telescope Research Associates) Telescope will permit observations of Vega the primary spectrophotometric standard, rapid measurements of the naked-eye stars, sufficient observing time to obtain photometric measurements of the nightly extinction, and still obtain high quality observations of stars of about 10.5 magnitude in an hour. This multiplexed cross-dispersed instrument should produce high-quality fluxes at least of $\lambda\lambda$3300-9000 with a resolution of 14 Å in first and 7 Å in second order and full wavelength coverage except for regions badly affected by telluric lines.

The telescope and spectrophotometer are optimally designed for efficient operations using input from astronomers and the experience of the design team. The CCD frames will be reduced to one-dimensional spectra using program CCDSPEC by Austin F. Gulliver & Graham Hill and photometrically calibrated using program SPECPHOTOCAL by Barry

Smalley that should correct for the effects of most telluric lines at airmasses ≤ 4.

Model atmospheres are the analytical link between the physical properties of stars (M, R, L, and composition) and the observed flux distributions and spectral line profiles. By comparing predictions of model atmospheres with spectrophotometric fluxes (and Balmer line profiles) effective temperatures, surface gravities, and metallicities can be found for a wide variety of stars. Comparisons for the same star between the best-fitting model atmospheres calculated from different codes will provide insight into how well each code reproduces these observations. High-quality elemental abundance studies will permit consistency checks. As the efficiency of convection can produce observable results in the energy distributions, it should be possible to check the results of different convection theories. Investigators will be able to synthesize a variety of indices which could be obtained by filter photometry.

The first major observing project will be the revision and extension of the bright secondary standards. The existing grid of good secondary standards will be increased several-fold and include those selected to be near variables of particular interest. Over the lifetime of the instrument, measurements of secondary stars for calibration and extinction will be used to improve the quality of the secondary standard fluxes. In less than a year of normal observing, all isolated stars with V $\leq$ 7.5 mag. and declinations between $+76°$ and $-35°$ can have their fluxes well measured.

Adelman, Gulliver, and Smalley in planning to deal with this potential flood of ASTRA data, realize that they will need help to make the best scientific uses of it. Thus they are interested in discussing possible collaborations. As many studies of variable stars will utilize local spectrophotometric standards, they plan to calibrate such stars as part of the initial effort.

1. Introduction

We are building a simple, efficient, and elegantly designed CCD spectrophotometer and an automated 0.5-m telescope at the Fairborn Observatory, Washington Camp, AZ. This unique multiplexed instrument should produce high quality fluxes through at least the $\lambda\lambda$3300-9000 region. Its data will have applications to a wide variety of astrophysical problems. With a resolution of 14 Å in first and 7 Å in second order, one could synthesize indices for most optical region filter photometric system and then perform studies using such indices. Spectrophotometric data reveals the details of the flux distributions in far greater detail, similar to classification spectroscopy, and considerable astrophysical information that will be studied is lost at filter photometric resolutions.

Almost all the rotating grating scanners used for spectrophotometry and to measure the absolute fluxes of Vega and the secondary standards were retired well over a decade ago. Most replacement instruments were not intended for stellar observations and lack the required accuracy and precision. The stellar fluxes from rotating grating scanners may contain systematic wavelength-dependent errors due to errors in the absolute calibration, extinction, bandpass centering, scattered light in the instrument, and other causes. Such data typically consists of 15 to 20 values covering $\lambda\lambda$3400-7100 with 20 to 50 Å wide bandpasses usually at spectral regions with minimal line blanketing. The extinction was based often on mean observatory values and the errors are rarely better than 1 %. Breger (1976a), Ardeberg & Virdefors (1980), and Adelman et al. (1989), in particular, compiled these observations. There are also 5-m Hale telescope measurements, based largely on rotating grating scanner calibrations, with now retired instruments: the multichannel spectrophotometer (Oke & Gunn 1983, Gunn & Stryker 1983) and the Double Spectrograph (Oke 1990 who provided standards for the Hubble Space Telescope) and satellite measurements of the optical ultraviolet (e.g., Code & Meade 1979). Many more stars had their ultraviolet fluxes measured to a reasonable accuracy and precision by the IUE satellite than by previous instruments in the optical region.

With optical region grating scanner (and ultraviolet flux) data and Balmer line profiles, astronomers derived reasonably good effective temperatures and surface gravities of normal single slowly rotating B, A, and F stars. These have been expressed in terms of filter photometric indices of various systems. For stars with significant non-solar compositions, such calibrations are not necessarily accurate as metallicity, microturbulence, macroturbulence, and/or magnetic fields affect the stellar fluxes in subtle, yet measurable ways (Adelman & Rayle 2000).

For stellar astrophysics, at the heart of our understanding the history and evolution of galaxies, this spectrophotometric instrument is critical for future advancements. Spectrophotometry can also be an important technique for the study of solar system objects, nebulae, star clusters, and galaxies. NEW DIRECTIONS IN SPECTROPHOTOMETRY (eds. Philip, Hayes & Adelman 1988) discusses additional uses.

We are not planning observations to improve the absolute flux calibration of Vega at this time. Although our instrument would prove to be superior to the rotating grating scanners for this research, a Fourier transform interferometer would be even better.

2. The ASTRA Telescope and Team

The 0.5-m Citadel ASTRA telescope will be at Washington Camp, AZ, just north of the US-Mexican border several kilometers east of Nogales, AZ. The spectrophotometer will be mounted at the f/16 Cassegrain focus. The science CCD is most likely to be an Apogee Instruments SPH5 or its possible successor with a three stage piezoelectric cooler with a liquid recirculation system. The spectrophotometer will be in an insulated box, which will be kept at a temperature of about 4° C. The CCD will be a Hammatsu 1024 x 128 with square 24 micron pixels or a Marconi 30-11 CCD with 1024 x 254 square 26 micron pixels.

Although the 0.5-m telescope will be the first of its type designed by Louis Boyd, it will incorporate many features used by the other small automated telescopes of Fairborn Observatory including control by ATIS (Automated Telescope Instruction Set whose documentation is available at www.fairobs.org), disk and roller drives on both axes, and a very short search and find interval between successive program stars of a few seconds on average. Don Epand has implemented many of the ATIS commands needed for spectrophotometric observations. We anticipate that flexure will not be a problem, but we will investigate this possibility during testing.

3. The Spectrophotometer

Using funding from the Institute for Space Observations, and advice from Dr. E. Harvey Richardson, his then masters student John Pazder produced the design which was optimized using the Code 5 optical design package. Frank Younger's mechanical design is intended to be rugged, to minimize time and cost in manufacture, and to minimize maintenance. We will use high quality components to reduce failures and will monitor the throughput to ascertain when the mirrors need to be realuminized that will be done if at all possible at the same time as the telescope optics. The total mass, including the front disk, optics, and detectors, should not exceed 14 kilograms.

The insulated case will be a box, rectangular in cross-section. The optical plate, made from 1.2-cm thick aluminum, will be attached to the telescope-mounting collar. The length overall will be roughly 38 cm, greatest width 28 cm, and height 14 cm. All electrical and fluid connections will be made through a panel attached to the optical plate. The case can be removed and/or opened to provide access to the instrument.

The optical parts will be mounted on goniometers, providing 2-axis rotation for alignment. The intersection of the rotational axes will coincide with the intersection of the principal ray of the system. With our slitless spectrophotometer, focusing will be done with the telescope. The initial optimal optics placement on the optical plate will use a pinhole at the design focus. The optics will be located empirically to provide instrumental alignment and focus. The grating rotation will be set at the initial alignment and, thereafter only moved when necessary. The second camera mirror rocking action will be accomplished piezoelectrically, providing both amplitude and frequency adjustment.

A prismatic cross disperser provides the necessary order separation to allow the spectrograph to cover 3000 Å to 10000 Å in a single exposure. The main dispersion element is a 300 gr/mm grating with a 8600 Å blaze. From diffraction grating efficiency data from Richards Grating Laboratory, the optimal order coverage was found to be 5500 Å to 10000 Å in the first and 3000 Å to 6000 Å in the second order. A 500 Å overlap between the orders allows the crossover wavelength to be fine tuned depending on the characteristics of the final grating.

A 1.0 arc second object is 2 pixels wide at the image, matching the image size to the Nyquist frequency of the CCD detector. The optical performance of the spectrograph at 80 % encircled energy is better than 17 microns (50 % in 8 microns) over the whole spectral range for a point source object. The 1.0 arc second image of the star, which would have a width of 30 microns for a perfect camera, will have an image size, at worst, of 35 microns. Table 1 contains additional information on the spot sizes. As both the spectrograph camera and collimator are off-axis systems the instrument has very low scattered light. Baffles can be introduced if necessary. As the smallest bandpasses can be two pixels wide, the resolution will be 14 Å in the first and 7 Å in the second order.

Table 1. Spot Sizes

First Order					
λ (nm)	550.	660.	775.	880.	1000.
50 % ee (microns)	7.2	7.1	7.6	7.2	7.6
80 % ee (microns)	14.6	12.5	11.5	11.6	13.1
RMS	13.4	10.3	9.6	9.4	10.1
Second Order					
λ (nm)	330.	400.	465.	530.	600.
50 % ee (microns)	7.4	6.4	6.5	6.7	7.6
80 % ee (microns)	13.3	12.2	11.7	11.2	15.8
RMS	12.8	11.7	10.5	9.6	13.9

To preserve the resolution as set by the stellar image in this slitless design and to find cosmic ray hits, the spectrum will be widened to 5 pixels by a very slight mechanical rocking of the last mirror by a piezoelectric actuator which can be turned off if desired. The separation of the two orders will be sufficient, at least forty pixels, so that during the rocking, the sky measurements of each order will not overlap. A hole in the 45° mirror used to acquire the star acts as a stop. As the CCD read noise will be of order 10 electrons per pixel, rocking the spectrum would increase the noise by some 20 electrons, if not compensated by the optimal extraction routine.

The guide and centering camera optics are both standard off-the-shelf achromatic doublets. For the guide camera the image scale is set to 3 pixels for a 1.0 arc second disc, and for the centering camera the image scale is 2 pixels for a 1.0 arc second disc. We will finalize the mechanical and optical design with measurements of the real optical components.

4. Data Reduction

We are writing our own computer codes to understand their details and include our experience with the site and the instrument, have the necessary flexibility to optimize them for our particular needs, and produce *rigorous error estimates.* We plan to perform suitable comparisons with other codes such as IRAF that can be used to reduce CCD exposures to help reveal any code errors.

Austin Gulliver & Graham Hill have written an optimal extraction computer program CCDSPEC to batch-reduce spectroscopic coudé CCD exposures that contain spectral data after being provided with the needed bias and flat exposures. It is relatively fast requiring less than 30 minutes to reduce a night of Dominion Astrophysical Observatory coudé spectroscopy on a DEC Alpha 3000 300X workstation. For the spectrophotometer it will reduce the first and second order spectra possibly on a faster computer.

Superior spectrophotometry requires measuring the instrumental profile and the scattered light that is found in pixels other than the one corresponding to its wavelength. We will apply our experience with the coudé spectrograph of the

DAO 1.2-m telescope to these tasks (Hill et al. 1996). We do not know of any spectrophotometric instrument that has included a scattered light correction in its reduction procedure. Although CCDs are usually very linear devices, their linearity and polarization properties must be checked. This is quite important in observing Vega, which is much brighter than the other standards.

Our initial wavelength scale will be the theoretical dispersion solution. We plan to confirm it using suitable exposures of spectral lamps made with a slit. Also we can use strong features in the stellar fluxes such as lines of the Balmer and Paschen series.

With our instrument's ability to multiplex measurements throughout its wavelength coverage, the time investment to make frequent nightly observations of standards will be minimal. To expose a 5 th magnitude A0 V star and read the CCD should take about 20 seconds to obtain at least a signal-to-noise ratio of 100 at all useful wavelengths. This estimate is based on the total system efficiencies given in Table 2 below, the Tüg et al. (1977) calibration of Vega, a 0.5 m telescope, and allowance for atmospheric extinction. (The major uncertainty in this exposure time estimate is the number of read electrons per pixel.) Even with observations of sufficient stars for extinction and calibration, 5 to 10 per hour, many bright stars can be observed each hour. In an observing time of less than an hour, our spectrophotometer should obtain data for stars brighter than at least 10.5 mag. to 1 % accuracy and will provide a considerable volume of data. Determining the faint limit as a function of error and spectral type is an important goal for our test period.

The limited dynamic range of the science CCD with a full well capacity of 300,000 electrons per pixel means that we will have to use neutral density filters for the stars brighter than about third magnitude and thus the instrument requires a filter wheel. The complicates the recalibration of the secondary stars making it a two-step process.

Table 2. Total System Efficiencies

1st order	λ(nm)	efficiency	2nd order	λ(nm)	efficiency
	550.	25 %		350.	18 %
	640.	37 %		400.	27 %
	730.	36 %		450.	33 %
	820.	25 %		500.	31 %
	910.	20 %		550.	29 %
	1000.	11 %		600.	24 %

The spectrograph will use two small CCD cameras for acquiring stars and for guiding. At the telescope focus, a flat mirror with a small hole will be placed in the light beam at a 45° angle. The light reflected from the mirror will be focused on a small CCD camera for target acquisition. As soon as the target star is found, the telescope control computer will move the telescope so that the light falls through the hole in the mirror, allowing the light to enter the spectrograph. The light from the zeroth order in the spectrograph will be focused onto a second small CCD camera. The center of the image will be kept at a particular pixel by use of an automated guider.

To obtain flat fields, the telescope will point to a semi-transparent screen placed in front of the telescope and illuminated by incandescent hot photoflood lamps. Our experience has shown that such a system will work well from the infrared through the Balmer jump region. To acquire sufficient signal below the Balmer jump while not saturating the most sensitive wavelengths may require the use of filters.

We are concerned about properly calibrating spectral regions containing the Balmer and Paschen lines and jumps and with large amounts of telluric contamination. Smalley's numerical simulations show that one can recover the flux to better than 1 % in all but the regions of most severe telluric contamination. Extinction modeling (see e.g., Hayes & Latham 1975) will improve as we gain knowledge of the variations with time, airmass, and wavelength at the observing site.

The raw data will be first run through Smalley's program SPECPHOTOCAL to perform an extinction correction using all the data from the night, assuming that the extinction was constant. If necessary the correction will be rerun with an appropriate time-interpolation scheme. Once this is satisfactorily accomplished, the data will be transformed to absolute fluxes and the error estimates will be made.

We want to obtain closure on the secondary standards by the end of the first year of observations and then concentrate on the other projects to demonstrate the quality of the data. We will make extensive comparisons with existing spectrophotometry.

Adelman has extensive experience with the Four College Automated Photoelectric Telescope (FCAPT) Consortium that has operated a 0.75-m telescope at Fairborn Observatory in southern Arizona for the past 12 years. The FCAPT demonstrated that APT's are capable of high photometric accuracy and stability. Over the last seven years APT precision has been better than 6 millimag. in the Johnson V filter and 5 millimag. in the Strömgren y filter for stars ninth magnitude and brighter. It is of one of several successful automated telescope efforts. Lessons learned will be applied in this new project. For example, it is very important is to have the data analysis tools working before the potential flood of data begins.

We will make our fluxes and the extinction coefficients available to the community after we have analyzed the data. Observations taken with this instrument will be archived at The Citadel by Adelman. When data sets from particular projects are published, they will also be made available via a central archiving facility such as the Astronomical Data Center at NASA's Goddard Space Flight Center.

5. Opportunities for Collaboration

The Fairborn Observatory site averages the equivalent of about 150 photometric nights per observing season, which runs from the middle of September to the beginning of July. Small automated telescopes built by Fairborn Observatory have declination limits between +75° and -35°. Our telescope might be able to do slightly better. The spectrophotometer should make several 10s of thousands of program star observations per year. Even using automated fitting routines, it is beyond the abilities of the three astronomers, Adelman, Gulliver, and Smalley, who will be planning the observing and reducing the data to a usable form, to successfully analyze more than a small fraction of the potential observations. As they realize that they will need help to make the best scientific uses of the ASTRA data, they are interested in discussing possible collaborations.

The two major projects which are discussed below are basic to other applications and are natural parts/products of the calibration effort. Our team can either do the auxiliary projects alone or in collaboration with others. The comparison of observations with model atmospheres requires the calculation of grids of model atmospheres as well as observations of Balmer line profiles. Observations of Hβ and Hγ, and perhaps other hydrogen lines at high dispersion will help us understand the usefulness of those at spectrophotometric resolution and vice versa. We plan to make the calculation of synthetic colors and line indices part of our data reduction stream. These calculations should be done for all current major systems. Line ratio determinations from the spectrophotometry may also be useful for some applications.

Beyond these projects are those on particular types of stars and investigations of particular kinds of stellar physics. Some examples are:

Fundamental Stars, Solar Type Stars, Eclipsing Binaries, Hydrodynamical Effects and Variability, and CP Stars

As many studies of variable stars will utilize local spectrophotometric standards, we prefer to calibrate such stars as part of the initial effort. Thus we are interested in arranging collaborations before the start of observations. ATIS has a relatively new feature, which permits the telescope to automatically obtain complete phase coverage of any periodic variable with a known period.

We are also very interested in analysis tools that will be useful for many different types of projects. Organizational tools for databases and data catalogs are also a concern.

Some basic terms for collaborations follow:

1. All collaborations will have Adelman, Gulliver, and/or Smalley as a team member(s) and as a coauthor(s) on all resulting papers. More than one of these astronomers may participate in a given project if they are particularly interested in the topic and contribute more than the data and an understanding of its properties.

2. All page charges, if any, will usually be the responsibility of their collaborators. (But, those relating to the two major projects will be negotiated.)

3. All papers will be part of an ASTRA paper series.

4. The spectrophotometric values will appear in a published catalog after a substantial usage of the data has been made. This catalog, coauthored by Adelman, Gulliver, and Smalley, will include references to papers in which the data was used.

5. The data will be analyzed and submitted for publication in a timely manner. To keep ASTRA operations funded requires the publication of useful results.

6. Projects

During the first two years of observing, we will begin two major projects:

1. *Revision and Extension of the Secondary Standards*: The fluxes must be reduced to a uniform system based on the absolute fluxes of Vega. Not all possible secondary standards are equally good for calibrating all wavelength regions. Taylor (1984) extended and made more uniform the existing bright star standards. For our instrument, they will have to be redetermined as its resolution is greater than what had been the usual practice, of order 25 Å. Standards for larger telescopes brighter than our faint limit will also be checked and extended (e.g., those by Stone (1977), Oke & Gunn (1983), and Oke (1990)). We will have a wider selection of stars than with a rotating grating scanner. Using as standards metal-poor stars such as the field-horizontal branch stars and the subdwarfs minimizes the sensitivity of fluxes to spectral lines moving into and out of bandpasses due to the Earth's rotation and orbital motions (see, e.g., Oke & Gunn (1983), Philip & Hayes (1983)). Adelman has shown the utility of Hipparcos satellite photometry to select non-variable stars and produced two lists of stars, which are the most constant (Adelman 2001, 2002). The stars from the above mentioned sources are our initial candidate secondary standards. The measurements of the secondary stars for calibration and extinction will also be used to improve the quality of our secondary standard fluxes.

2. *Sample Fluxes of Population I and II Stars*: This longer term project will enable population synthesis analyses which require high quality optical region fluxes of all known types of stars. We plan to observe all single stars in the Bright Star Catalog and its supplement and stars in clusters and associations, which pass within 45° of our telescope's zenith to empirically, define the zero age main sequence and calibrate the HR diagram.

Two important auxiliary projects are:

A. *Comparisons with Model Atmospheres*: Model atmospheres are the analytical link between the physical properties of stars (M, R, L, and composition) and the observed flux distribution and spectral line profiles. By comparing predictions of model atmospheres with spectrophotometric fluxes (and Balmer line profiles) effective temperatures and surface gravities can be found for a wide variety of stars. Our data should be far superior to existing data for this purpose. Comparisons between the best fitting model atmospheres calculated with different codes for the same star can be performed to give insight into how well each code reproduces these observables. By also deriving the elemental abundances, consistency checks can be made. Hill, Gulliver & Adelman (1996) developed a powerful fitting program STELLAR which now uses a four-dimensional grid of SYNTHE synthetic spectra (Kurucz & Avrett 1981) and continuous energy distributions from ATLAS9 model atmospheres (Kurucz 1993) to perform a simultaneous rms error fit to the observed metallic and hydrogen line spectra as well as the continuous flux distributions of stars. The input files include as variables: effective temperature, surface gravity, microturbulence, and scaled solar abundances. As a separate project we will continue obtaining Hβ and Hγ profiles of stars at the DAO's 1.2-m telescope.

For parts of the HR diagram for which codes other than ATLAS9 produce the best model atmospheres, we plan to work with their authors. We recognize the need to include effects of sphericity, NLTE, and velocity fields for some types of stars.

B. *Synthetic Colors and Line Indices from Spectrophotometry*: Breger (1976b) showed that by synthesizing colors from the spectrophotometry one can check for consistency with photometry and/or provide photometric indices for stars which lack such values. Systems of particular interest are Johnson UBV, Cousins RI, Strömgren, Geneva, and Vilnius. It is important to use representative filter transmission curves and high quality photometry of sufficient stars in each system to calculate magnitudes and color indices. That our instrument will produce data without major gaps in wavelength coverage will be a significant advantage over most previous scanner flux data for this purpose.

The strongest metal lines can be seen in continuous wavelength spectrophotometry at somewhat lower resolution (e.g. 20 Å by Fay et al. 1973). Hence one will be able to create many line strength measures. It should be possible to assess the metallicity of many stars using for example, the Ca II K-line. Further for cool stars, one could measure the dependence of strong spectral features as functions of surface, gravity, and [Fe/H] as have Burstein et al. (1986) and Gorgas et al. (1993) and use them to study Population II objects.

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