
Stellar Astrophysics with Undergraduate Students

Saul J. Adelman

Department of Physics, The Citadel, 171 Moultrie Street, Charleston, SC 29409, USA, E-mail: adelmans@citadel.edu

I describe some of my research activities involving photometry, spectrophotometry, and high dispersion spectroscopy and indicate how working with undergraduates has led to scientific progress. One has to mentor students to help them understand how research can be done. The results depend on the abilities, the knowledge, the interests, and the interaction of the professor and of the student as well as the materials to be studied. Sometimes great progress can be made, but this is not always the case.

Introduction

Since I became an Assistant Professor in 1974, I have involved undergraduates with aspects of my research. My mode of research is to work on several projects or subprojects at the same time. I find areas that students can learn about the science and make a contribution. These problems have been selected in the expectation that the student contribution will most likely at least result in the progress that I would have made on my own in the same time.

The problems I choose to investigate change in response to the data available. My major research interest is investigating the properties of the stars with atmospheres and envelopes where radiation transports the energy outward from the core to the surface. In these layers of hot gas, local thermodynamic equilibrium (LTE) occurs. The radiation emitted is determined by both the local values of the gas temperature and density. Since radiation is lost to space, LTE is assumed to apply in stellar atmospheres where strict thermodynamic equilibrium does not hold.

Hipparcos Satellite Photometry

About 20 years ago I applied to study data of the members of the nearest star cluster, the Ursa Major Stream, from the Hipparcos Satellite, which primarily measured the distances to stars and also made photometry (light) measurements. I worked with several collaborators. I obtained high dispersion spectra at the coude spectrograph of the 1.22-m telescope of the Dominion Astrophysical Observatory in Victoria, BC, Canada. The observations were used to obtain the stellar motions along the line of sight as well as the apparent stellar rotational velocities [1].

Further, I obtained access to the photometry of all of the stars observed by Hipparcos [2]. Its single bandpass was large enough for most of the light in the optical window to be counted. As it observed from space, many of the problems of observing from the Earth's surface were eliminated, for example, atmospheric extinction.

At that time four colleagues and I were a few years into operating our Four College Automated Photometric Telescope (FCAPT). We were performing differential photometry of variable stars with an automated telescope which is now at Fairborn Observatory, Washington Camp, AZ. The brightness of each was compared with that of two supposedly constant stars, the comparison star and the check star that were close on the sky to the variable star. I picked these based on the experience of other astronomers and knowledge of the variability with stellar spectral type. This was not a perfect technique. My thought was to use the Hipparcos photometry as a tool to identify the most constant stars.

Stars with apparent low variability tend to be constant. The errors in the measurement process add noise to their values. Further each star's variability can change with time. I determined how the stellar statistics varied with stellar brightness. Then I obtained information on variability from the header of the computer file introducing each star's photometry and made it into a useful table. I extracted from this table information on the most variable and most constant stars. Some of my previous choices of check and comparison stars had to be replaced. This exercise improved the quality of my differential photometry data (see, e.g., [3]).

To go further I involved my introductory astronomy class of 18 students. I had them find the spectral classes of all of the 9110 bright stars which can be seen in the course of a year with the naked eye at dark sky sites from the computerized version of The Bright Star Catalogue [4]. We learned about the average variability of the stars in this compilation as a function of their Harvard spectral class. By combining our individual studies of different types of stars we found the variability for most single kinds of stars. Some spectral types of Supergiant stars were unexpectedly constant. This work was published as a series of papers with my students as co-authors ([5] and references therein).

Photometry from the Four College Automated Photometric Telescope

I have worked with students on data from the 0.75-m FCAPT.

This data takes more effort than the Hipparcos data to reduce and to interpret. This facility is now in its 22nd year of operation. Its photometer uses a photomultiplier tube as a detector. Automating the telescope operations means my partners and I share data obtained during approximately 140-200 clear nights per year without the need for a human observer. For Hipparcos photometry there was just a value describing the entire optical region while for the FCAPT we had a choice of filters. For studies of stars hotter than the Sun, I use the four intermediate width (250 Angstrom wide) filters of the well-defined Stromgren system. Observations are taken in the ultraviolet (*u*), violet (*v*), blue (*b*), and yellow (*y*). For cool K, S, and M stars, photometry was done using the B and V filters of the Johnson system and the R and I filters of the Cousins system (see, e.g, [6]).

I used much of my observing time to obtain data of the magnetic Chemically Peculiar (mCP) stars. Their light, magnetic, and spectra variations are usually accepted as being the result of observing spotted rotating stars. Their large scale primarily dipolar magnetic fields are variable over the photospheres and produce changes in the local chemistry by means of hydrodynamical processes including diffusion and gravitational settling. They in turn effect the radiated energy distribution. In the mCP stars, the spots have elemental abundances greater from than the background star. This causes energy to be moved from the ultraviolet region to the optical by enhanced line blanketing making their spectral energy distributions different from their background star. Shore & Adelman [7] who studied the changes in the line profiles of the mCP star 56 Ari at a given phase interpreted these results as due to variations produced by the precession of the magnetic axis, most likely due to a difference in the moment of inertia between the magnetic axis relative to its two perpendicular directions. In their photometry one should see a second period of several years in addition to the shorter rotational period. This is how a top behaves. If rotation is the dominant perturbation, an analogue of the Chandler wobble results [8] (see also, [9] concerning the variability of CU Vir). There are at least five mCP stars for which there is evidence of a second period in their light curves [8]. The best studied is 56 Ari [10] whose magnetic axis has a precessional period of 5 years. The rotational periods of mCP range from 0.5 to over 25+ years. For both CU Vir and 56 Ari there is definite evidence for their rotational periods increasing. For the latter star the rate is 2 s per century. One mCP star HR 7224 had an episode where it showed substantial changes in its light curve after which it slowly returned to its pre-episodic variability ([11] and additional observations).

As the star rotates, a distant observer can detect light variability that can be used to deduce the rotational period of the star. The technique is similar to a Fourier analysis. But in this case one is working with data which is not evenly spaced due to weather, different observing programs of the collaborators running for a few days to two months or more, and the revolution of the Earth about the Sun slowly changing the part of the sky which is observable. The weather at the Fairborn Observatory is suitable for observing from the end of

September through about July 4. During the summer there are thunderstorms and rain. The telescope has to be turned off to protect its electronics from lightning.

Most of my studies with students involved data from four stars, many of which were mCP stars. At the start of the analyses, I obtained typically about 75 sets of photometric measurements per star. Such an amount of data was obtained in about a week of clear weather with the FCAPT. Now I am obtaining longer data sets for certain stars. The analysis yields the period of the star, which has to be the same in the observations through the four filters, and the shapes of the light curves especially the amplitudes and the number of light maxima and minima. The first paper of this type on mCP stars with a student coauthor was [12].

I also worked with students on a paper which also assessed the quality of the comparison of comparison and check stars I was then using [13]. Adelman & Lovelace [14] investigated fast rotation B stars which show emission lines in addition to the usual absorption lines in their spectra. This data was often difficult to interpret due to phenomena occurring with different periods. A paper investigating both mCP and non-magnetic CP stars is [15]

Adelman & Woodrow [16] examined the photometric results of the then 70 mCP stars analyzed. They found virtually all the stars were variable. The rest might be. With periods between 0.5 days and greater than 20 years and after determining that these stars were a non-biased collection of stars, they concluded that all the stars of this class were variable and were likely behaving like tops.

FCAPT photometry has also been used to show that statistically the non-magnetic CP stars are not variable. I also investigated some supergiants whose variability is difficult to characterize as the periods seen in the data can change. For some peculiar S stars the challenge was due to their rotational periods being of order a year.

Spectrophotometry

Spectrophotometric fluxes are spectroscopic data obtained using photometric observation methods. Most of the best measurements of this kind were obtained using rotating grating scanners at objective prism or spectral classification resolution (25 to 50 Å), S/N > 100, and 15 to 20 bandpasses. The last of the rotating grating scanners was retired well over a decade ago. They were replaced with instruments lacking the required accuracy and precision or were not designed to produce photometric quality data. Thus a new generation of spectrophotometric instruments is needed.

With the older scanners, I found that certain broad features in the energy distributions were signatures of the mCP stars and the mercury-manganese stars, a kind of non-Magnetic CP star.

Both classes have a greater percentage of elements other than H and He in the Sun. One student project [17] investigated if these features were due to bound-free discontinuities. Another looked at the spectrophotometry of Chemical Peculiar stars to determine the effective temperatures and surface gravities [18]. Two Citadel cadets contributed to a similar investigation of the normal B and A-spectral type stars [19].

There are two basic problems in optical region spectrophotometry from the surface of the Earth. The first is the absolute calibration measurements while the second is the differential calibration of other stars relative to the standards. The rotating grating scanners and special instruments (e.g. J. B. Oke's 2" instrument for observing Vega) were used for absolute calibration measurements. One compared the fluxes of standard stars with those from calibration sources, e.g., blackbodies, and made allowances for atmospheric extinction and for absorption between the source and the telescope. It is not simple to obtain these important measurements. At best Vega the primary standard star has fluxes known to 1% in the optical region [20].

A group of astronomers mainly in the extended Baltimore, MD Area [21] are working to improve the absolute calibration (Program ACCESS). A major problem is that predicted fluxes from certain white dwarfs disagree with observed data. Project ACCESS will perform the new calibrations using a telescope flown in a few balloon flights.

My interest was to create an instrument to perform the differential calibration of stars relative to a grid of standard stars. Before designing a new instrument, my team and I studied the problems with the scanners. One needs to reduce the observation time by multiplexing. Hence we considered a CCD as the science detector. Our attempt to measure simultaneously data from the 1st and 2nd grating orders will work for certain spectral types. Scanners took typically 6-9 standards/night and required about 10 minutes for each scan. Astronomers who make absolute photometric measurements have told me that they spend 10 minutes/hour observing standards. Thus using this rule-of-thumb we should get over 50 standard star measurements per clear night. These observations will permit us to better determine the nightly extinction and any changes in it as a function of wavelength which is a major source of error. If more time is needed to properly calibrate the data, then my colleagues and I will take the time to do so. This instrument and plans for the data reduction are respectively described in [22] and [23].

The instrument has been completed. Our test observations indicate that it behaves within our planned criteria. What remains is to complete the top of the automated telescope, the device to flat field the CCD detector, and the programs to obtain and to reduce the data.

To derive the two important parameters of a star, its temperature and its surface gravity, one must obtain both its

fluxes (the amount of energy emitted as a function of wavelength) and the profile of one of its strong hydrogen lines, which I have chosen to be H β , which is centered at 4861 Angstroms, at moderately high dispersion. The observed quantities are compared with the predictions of model atmospheres to get these key parameters. In anticipation of the new spectrophotometer working in the foreseeable future, I have begun obtaining for the most likely stars to be observed near the start of scientific observations the profile of the H β line using the short camera of the 1.22-m Telescope Dominion Astrophysical Observatory's coude spectrograph.

The first major projects planned are 1) the revision and extension of secondary standards (my colleagues and I have selected these stars), and 2) sample fluxes of stars in the Solar Neighborhood and of the older population of stars in the Milky Way with the auxiliary projects a) comparison of fluxes with the results of modern model atmospheres codes, b) using spectrophotometry to derive synthetic colors of the most important photometric systems and line indices, and c) the determination of the stellar reddening mainly from the spectrophotometry.

When scientific data begins to arrive and the analysis codes are completed, I plan to use student help to speed the data reductions as well as to help in preparing the observing requests. A wide variety of calculations and data comparisons will need to be done in the analysis process. Students can participate in these activities.

When better absolute calibrations of the optical region fluxes become available, the discrepancies with the current best values can be straight-forwardly be accounted for. We hope to reduce the errors in effective temperature and in surface gravity to less than one-half of their current values. This will result in an improved understanding of the chemical evolution of our Milky Way Galaxy beginning with the Solar Neighborhood.

High Dispersion High Signal-to-Noise Spectroscopy

I am an expert in the high dispersion spectroscopy of B, A, and F type stars whose surface temperatures are between 1.2 and 4 times hotter than that of the Sun. My interests include the relationships among the normal and non-magnetic Chemically Peculiar stars. Since 1984, I have been a Guest Investigator at the Dominion Astrophysical Observatory (Victoria, BC, Canada). The detectors initially were photographic plates, later Reticon devices, and now CCDs similar to those in electronic cameras. I have worked with a number of students. The techniques have become more sophisticated with time. When I started with this work using data from coude spectrograph of the 2.5-m Mt. Wilson Observatory Telescope in the Los Angeles Area when I was a graduate student, I used chart recorders to output the digitization of photographic spectra (see, e.g., [24]) and did

the analysis by measuring the output charts. Later when I starting using the Dominion Astrophysical Observatory, I digitized spectra and coadded them in a computer and measured the spectra graphically with the aid of a computer screen. Even later Reticons and CCDs replaced the photographic plates (see, e.g., [25]). With the electronic detectors one could get higher signal-to-noise ratios (S/N). My colleagues and I strive for at least 200 compared with 25-30 for single photographic plates and 80 for coadded sets of typically 10 photographic plates. Our highest S/N for Vega is over 3500.

As part of this effort I have had to select the atomic data used in the analysis or organize it. At times I have involved students in organizing the line data for specific atomic ions into multiplet tables. A multiplet is a group of lines in an atom that differ slightly in energy where there are differing relative orientations either of the electronic spin and orbital angular momenta, giving different values of the quantum number J (in the case of fine structure) (see, e.g., [26]).

For 20 years I have been working with Dr. Austin Gulliver (Brandon University, Brandon, MB, Canada) and Dr. Graham Hill (New Zealand) to substantially reduce the errors in stellar elemental abundances which are canonically taken to be a factor of 2. Those of normal stars provide information on the evolution of abundances in the previous generation of stars. Differences in such abundances provide information on the homogeneity of the underlying processes. Discrepancies of the non-magnetic Chemically Peculiar star abundances tell us about the operation of the processes in their atmospheres that produce their somewhat different abundances.

The technique that has been used for the elemental abundance analysis for many years is known as "fine analysis". It integrates the amount of energy which is expected to be removed from the stellar atmosphere by a line and compares it with that seen to be removed on a high dispersion spectra. One adjusts the elemental abundance until the amount predicted agrees with observation. Some of my undergraduates have participated in fine analysis studies. An example of a fine analysis paper coauthored with a student is [27] which examined 4 normal stars. Students have also participated in new analyses of my published material [28]. Such studies have shown that the newer analyses usually yield results very similar to older ones. My students have also participated in comparing results of similar spectral type stars or of normal and peculiar stars with similar effective temperatures (e.g., normal A and metallic lined A stars [29]).

Fine analysis is now being replaced by spectrum synthesis analysis where the observed and predicted spectra are made to agree by adjusting the abundances. Spectrum synthesis graphically matches the line profiles which is more sensitive than just matching the amounts of energy each line removes. This technique is more sensitive to a range of parameters and better accounts for lines produced by more than one atomic line. Its power increases as the signal-to-noise ratio of the spectrum increases.

Last academic year Andrew J. Farr, now a Senior Physics major, helped me with a fine analysis of the ultrasharp-lined B3 IV star ι Her. We also began a spectrum synthesis

analysis. This data had a S/N > 500. It is now possible to use some blended lines in the analysis especially if both lines are produced by the same element and have similar atomic physics properties. We found some discrepancies in the two analyses, most of which were due to those of the atomic data. Using spectrum synthesis on a group of stars which have exceptional quality spectra, it should be able to catalog which lines of an element have systematically different results and this would make it possible to remove such problems. A paper [30] is in preparation.

Conclusions

I have involved undergraduate students in many aspects of my research. Some of the projects have been at a simple level while other work is more complex. To learn about how research is done, participation is far superior to reading about the process. Although the process in one area of a science can be somewhat different from that in other areas or other scientific activities, there is still much which can be transferred to future research.

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