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Memorie della

Parameterization of stars

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Abstract. Stellar and Galactic astronomy will be revolutionized by the massive surveys now taking place, or in the planning stages. These surveys include ground-based projects (Pan-STARRS, RAVE, SDSS/SEGUE, etc.) and space-based (*Gaia*), but all have a common theme, to collect data that will enable the determination of the physical parameters of stars with the goal of unravelling the structure and evolution of the Galaxy. The ideal survey would be capable of determining the physical parameters of stars in every part of the HR diagram, but in reality compromises are necessary. In this contribution, I will argue that the most versitile scheme to approach this ideal is to combine multi-band photometry with spectroscopy. The choice of the photometric system and the spectroscopic region and resolution are critical, and I will review the advantages and disadvantages of the different schemes employed in various surveys.

1. Introduction

The massive stellar surveys now underway or in the planning stages, such as Pan-STARRS, RAVE, SDSS/SEGUE and *Gaia*, promise to revolutionize both stellar astronomy and our understanding of the origin, structure and evolution of our Galaxy. To untangle the complex history of the Galaxy, these surveys must be able to identify disparate populations of stars, and the key to that is to determine, to high precision, the positions, velocities and physical parameters of vast numbers of individual stars. Each of the above mentioned surveys adopt different strategies to accomplish that goal; some have more limited ambitions than others. Ideally, a survey should be capable of determining the physical parameters of stars in all parts of the HR diagram, but the wide range of stellar parameters and physical phenomena involved means that all surveys (and all possible surveys!) fall short of the ideal; compromises must be made. These compromises lead to strategies that necessarily limit the ability of a survey to parameterize stars all across the HR diagram. What are the advantages and disadvantages of the different strategies employed in these surveys?

2. The Determination of Stellar Parameters: Strategies

2.1. Parameters from Photometry only

A well designed multi-color photometric system can be very successful in characterizing stars over large parts of the HR diagram. Historically, the Strömgren *uvbyβ* system probably takes the prize for elegant simplicity; it has been used successfully in studies of B through G-type stars. The now superceded photometric system designed for the *Gaia* spacecraft consisted of 5 broad and 14 medium passbands. While complex, this sys-

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tem showed genius in its design and in its versatility in characterizing stars over much of the HR diagram (Jordi et al. 2006). This system has now been replaced with low-resolution prism spectra. It appears, at first glance, that the use of these very low resolution (30 – 300Å) spectra will result in some degradation of the ability of *Gaia* to parameterize stars in certain parts of the HR diagram (for instance, in the G-type stars), but there are some interesting opportunities that this change brings. I will attempt to explore some of these later in this paper.

There are basically three strategies for deriving stellar parameters from photometry. One strategy, which is now being used quite extensively in the literature, is to convert all available photometric magnitudes for a star into fluxes and so construct at least part of the stellar energy distribution (SED). The next step is to then find the best-fitting Kurucz flux model for this SED. Sometimes constraints are introduced (for instance a metallicity may be assumed, or, more commonly, the microturbulent velocity is fixed), but quite often the fitting procedure is allowed the freedom of the entire Kurucz flux library. The resulting temperatures can be fairly reasonable, and where the goal is simply to, say, predict fluxes in the infrared, perfectly adequate, even though the typical errors are on the order of a few hundred Kelvin. But often the other parameters derived using this technique, especially the metallicity, can be completely spurious. The reason for this is easy to understand. Not all parts of the spectrum are equally sensitive to the physical parameters, and so performing an unweighted fit to a SED dilutes the astrophysically rich information from the sensitive regions, giving a poor result. For instance, in the A-type stars the Balmer jump region is very sensitive to $T_{\rm eff}$ and $\log g$, while the J, H and K IR bands are quite insensitive to $T_{\rm eff}$. A change of 500 or even 1000K in $T_{\rm eff}$ might barely affect the fit at J, H and K, and so if these regions are weighted equally with the Balmer jump region, photometric errors at J, H and K can dominate the fit and lead to a less than optimal solution.

If one has only photometry at hand, a much better strategy to use is to determine as many parameters ($T_{\rm eff}$, $\log g$, [M/H], interstellar reddening) as possible using careful calibrations of the photometric indices. There are a number of such calibrations in the literature, including $T_{\rm eff}$ calibrations by Alonso et al. (1996, 1999) for Strömgren and $B-V$ photometry, based on the IRFM method of Blackwell & Lynas–Gray (1994), who themselves supplied a $T_{\rm eff}$ calibration of the $V-K$ index, the reddening calibration of Olsen (1988), the calibrations of Schuster & Nissen (1989) for [Fe/H] in terms of Strömgren photometry (or the recent revisions by Nordström et al. 2004), etc. The careful and judicious application of such calibrations can yield very high quality stellar parameters; an outstanding example of this is the recent Geneva-Copenhagen survey of the solar neighborhood (Nordström et al. 2004). While I have concentrated here on the more "classical" photometric systems, such calibrations are possible and are being derived and used for newer systems, such as the Sloan $u'g'r'i'z'$ photometric system, 2MASS JHK photometry, etc. Of course, these calibrations generally have very strict limits of validity, which can be a problem and complication for their application in surveys dealing with stars ranging over much of the HR diagram. For instance, the Geneva-Copenhagen survey dealt primarily with F and G main sequence stars, and most of the calibrations they used are invalid outside of that spectral-type range.

For more complex photometric systems or for surveys or studies that will need to address stars over a much broader parameter space than, for instance, the Geneva-Copenhagen survey, an altogether different approach may be required to derive stellar parameters. One could, of course, adopt the calibration technique described in the previous paragraph, although with the need to cover a large portion of the HR diagram, this would quickly become unmanageable. A better method, now being explored by Bailer-Jones and colleagues (Bailer-Jones 2005a) is to use artificial intelligence, perhaps in the form of a neural network, to extract astrophysical parameters from the observations. What such a system does, of course, is essentially map the observation space onto the physical parameter space: it is, in a sense, a "super" calibration. Such an AI system will need to be cleverly designed to deal with difficult and nearly intractable problems: any photometric system, no matter how intelligently designed, is subject to local and global degeneracies. A good example is the classic global degeneracy between $T_{\rm eff}$ and $A_{\rm v}$ (interstellar extinction) made more difficult by the likelihood that the extinction law varies from place to place in the Galaxy.

These are important and complex problems that will need to be addressed with any AI system devised to interpret the massive amounts of photometry from any of the upcoming surveys. It is not entirely clear that an AI system can be devised that will be capable of extracting all the information from a given photometric system. One fundamental problem is that such an AI system will have to be trained, at least initially, with photometric indices derived from synthetic spectra. There are two dangers inherent in this: first, in some parts of the HR diagram, synthetic spectra do not adequately reproduce the actual stellar spectra in any wavelength region, and there are some spectral regions for which spectral synthesis is inadequate for even the most mundane stars. For instance, the likelihood is that the synthetic spectra used in the training process will not include chromospheres (see, for instance, Munari et al. 2005a). This means that an important set of phenomena in the G and K type stars, the prime targets of many of these surveys will not be included in the training process. The second danger lies in the fact that if we train an AI system with what we know, it will have difficulty in recognizing what we do not know – i.e. truly unusual and astrophysically interesting objects. Since the new surveys will typically observe millions to hundreds of millions of objects, we can be guaranteed that we will run across classes of stars that we have not yet encountered.

Even though the *Gaia* spacecraft design has abandoned its multi-color photometric system and replaced it with low-resolution prism spectra, many of the above statements apply directly to stellar parameterization by *Gaia*. *Gaia* will now obtain low-resolution spectra (from 330 – 1000 nm) for each target star spanning, on the average, about 60 pixels. How these stellar energy distributions (SEDs) will be used to extract physical parameters for the stars has not been completely worked out. Of course, as I emphasized earlier, the wrong way to proceed would be to carry out unweighted fits to Kurucz models.

One way of proceeding, of course, is to perform numerical photometry on these SEDs, and attempt to reproduce the 19-band *Gaia* photometric system. I expect that with only 60 pixels in each SED, and non-uniform resolution across the spectrum, reproducing this photometric system will not be possible, but the basic idea of giving greater weight to spectral regions that contain the most astrophysical information is the key. One innovative idea that might be pursued was investigated by Bailer-Jones (2005b). Bailer-Jones examined the problem of optimally sampling stellar spectra to best determine the astrophysical parameters of a wide range of stars. He did this by considering the filter system as a set of free parameters that could be determined by optimizing how well the filter system discriminates between stellar types and avoids degeneracies. Surprisingly, the resulting filter systems had broad, overlapping bands. These broad bands might be more compatible with the low-resolution SEDs to be obtained by *Gaia*. One might even extend this concept by designing optimal passbands or weightings for different stellar types. For instance, the analysis pipeline might first determine a rough stellar type and then apply the passbands optimized for that particular stellar type to determine the physical parameters. This technique might be capable of overcoming many of the degeneracies a traditional fixed photometric system is subject to. Such a procedure could be implemented by a two-stage AI technique.

2.2. Parameters from Photometry and Spectroscopy

Even though such innovative techniques might be capable of going a long way toward eliminating photometric degeneracies, even the best designed photometric system will still be subject to regions of degeneracy, where stellar types with quite different physical parameters overlap in the various color-color diagrams. In my opinion, the most effective and probably the most versatile strategy to overcome this fundamental problem is to combine a well-designed photometric system with spectra observed in a carefully chosen spectral region, obtained with sufficient resolution and S/N to aid in the discrimination of stellar types.

Spectra, of course, can be used to characterize stars over the entire HR diagram; the success of the MK system attests to this, and adding spectra to photometry is a smart move for a survey that must deal with many stellar types. Adding spectra can also enable the survey to collect information on other types of stellar phenomena, such as chromospheric activity, detect and measure chemical peculiarities, and even recognize truly new classes of stars, something that photometry (see above) is ill equipped to do.

This is the strategy we have adopted in the Nearby Stars (NStars) program in which we are characterizing all of the dwarf and giant stars earlier than M0 within 40 parsecs of the sun. Our earliest star is a B3 dwarf. The basic photometric system we use is the Strömgren *uvby* system, augmented where necessary (and possible) with ultraviolet IUE or TD1 (Thompson et al 1978) fluxes for the hotter stars, and Johnson-Cousins *RI* photometry for the cooler stars. But we combine these photometric fluxes with classification-resolution (2 – 4Å) spectra obtained in the blue-violet spectral region. We use the blue-violet, not only because we are also providing new, precise spectral types for our stars and measurements of chromospheric activity from the Ca II H & K lines, but because this spectral region has the advantage that it contains temperature and gravity sensitive features useable from O to M-type stars, and spectral features that enable the detection of a vast array of peculiar types. To determine stellar parameters, we simultaneously fit synthetic spectra and fluxes to the blue-violet spectra and fluxes from the photometric sources mentioned above (see Figure 1 and Gray et al. 2003, 2006). With care, this strategy leads to well-constrained fits over a wide range of effective temperatures, gravities and metallicities. We could, possibly, have achieved just as satisfactory fits from the spectra alone, just as these spectra can be used alone for precise MK spectral classification which, likewise, places the star accurately in the HR diagram. But we found, after extensive experimentation, that the parameters could be more precisely determined, and with fewer spurious solutions, when both photometric fluxes and spectra were used in the solution simultaneously.

Of course, in the NStars program, we do not have to worry about reddening, and so blue-violet spectra are easily obtained for all our stars. This is not the case for most of the surveys mentioned above, especially if the Galactic plane is included in the survey. The need to deal with large extinctions requires the choice of a spectral region in the red or infrared, and two of the surveys, *Gaia*, and RAVE have chosen the 840 – 880 nm window. This spectral region is a good choice for many reasons. First, it is remarkably free from telluric absorption, a very important consideration for ground-based surveys such as RAVE. Second, this spectral region contains a high density of astrophysically important lines, including the higher Paschen series lines of hydrogen, the Ca II infrared triplet, and a multitude of lines largely due to α-elements such as calcium, silicon and magnesium, but also a number of strong lines of iron. In the cool stars, the region also includes lines of TiO and CN. The region also conveniently contains a diffuse interstellar band which will aid in the determination of extinctions. The Ca II triplet in the late-type stars shows good sensitivity to both temperature and gravity, with the added bonus that it is a good indicator of chromospheric activity. Both surveys primarily use this region for the determination of radial velocities, but the features mentioned above lend considerable potential for using this region to determine physical parameters.

While the 840 – 880 nm region is suitable for the stars that are of principal interest to both the *Gaia* and the RAVE surveys, namely the F, G and K-type stars, it is much less desirable for earlier stars. It is almost useless for spectral classification earlier than a spec-

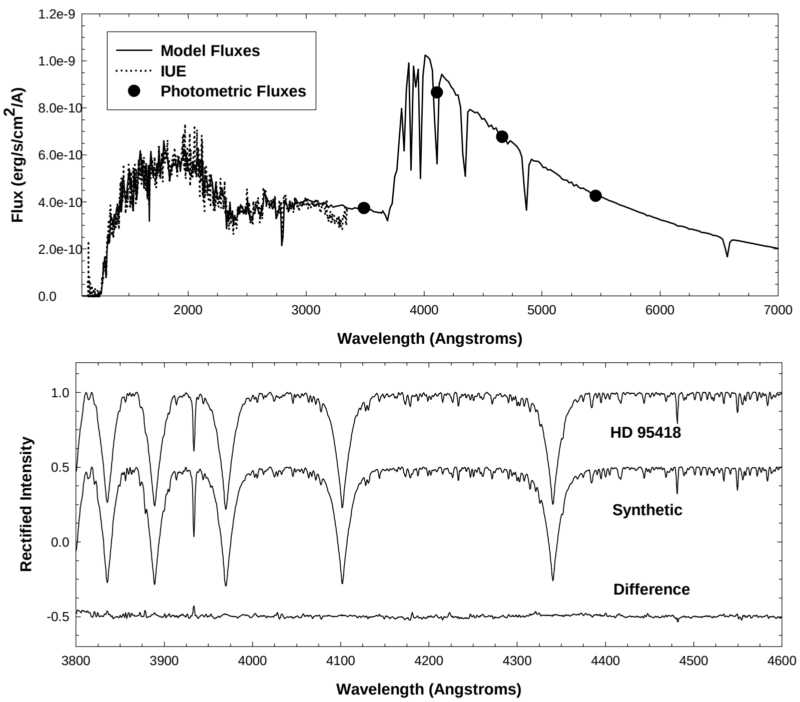

Fig. 1. The NStars program uses both photometric fluxes and blue-violet spectra to determine the basic physical parameters for a star. Here the Strömgren *uvby* fluxes are augmented with ultraviolet fluxes from the IUE. Synthetic spectra were calculated with SPECTRUM (Gray & Corbally 1994) using Kurucz (1993) models without convective overshooting.

tral type of B3, and its usefulness for parameterization and radial velocities is compromised even as late as F0 by the fact that the higher Paschen lines dominate this region. In the A and B-type dwarfs, the overlapping wings of these higher Paschen lines contribute a strong pseudo-continuous opacity, which results in the ability to discriminate between dwarfs and giants being much reduced in this region over the classical blue-violet. However, the supergiant classes are very distinct. Even in the late F-type stars, from F5 to early G, and from dwarf to giant, the spectral features in this region give a much poorer discrimination of the temperature and luminosity classes than in the blue violet. The SED information produced by *Gaia* should help with the discrimination in this spectral region, but without complementary information, it turns out that this region has some fundamental *spectroscopic* degeneracies which limit its usefulness for parameter determination.

RAVE is primarily a radial velocity survey which uses the 841 − 880 nm region (at $R \sim 8500$) to measure radial velocities. It also plans to use this region for stellar parameterization, but currently is not using any photometric information in this parameterization (Munari et al. 2005b). The problem with this is that, as mentioned above, there are some fundamental spectroscopic degeneracies in this spectral region. One of the most important degeneracies is found in the F5 to early G spectral-type range. In this range, among dwarfs and even giants, the spectral features (meaning individual line strengths and the profiles of the lines

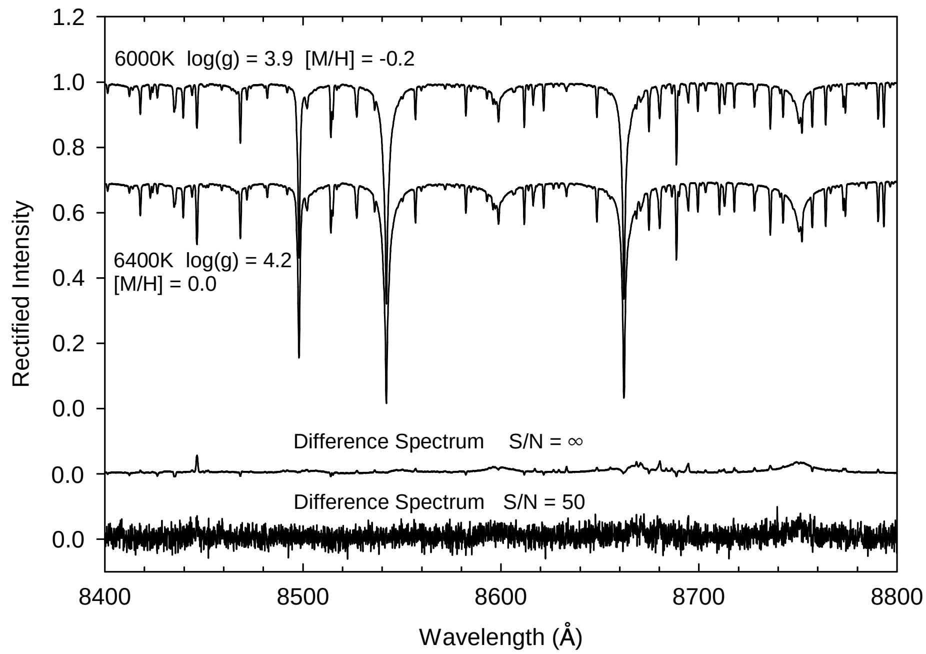

Fig. 2. An illustration of the $T_{\rm eff}$, [M/H], $\log g$ degeneracy in the 840 – 880 nm spectral region. Here two synthetic spectra ($R \sim 12000$) with $\Delta T_{\rm eff} = 400$K, $\Delta \log g = 0.3$ and Δ[M/H] = 0.20 are compared. The difference spectrum is constant to within 2 – 3% (except for the O I feature at 8446Å). If one spectrum is "observed" at S/N = 50 (the average S/N for the RAVE survey is 30) and differenced with the other as a template, the bottom difference spectrum is obtained. No recognizable and useable features remain in this difference spectrum.

of the Ca II infrared triplet) are only slowly changing functions of temperature. This, coupled with the fact that in this spectral region a slightly metal-weak early G subgiant looks remarkably like a normal mid F-type star (with differences only on the order of a few percent), means that there is a fundamental $T_{\rm eff}$–[M/H]–$\log g$ degeneracy, which can lead to unavoidable errors in the $T_{\rm eff}$ determination as high as 400K, $\sim$ 0.3 in [M/H] and on the order of 0.3 or more in $\log g$. This degeneracy is illustrated in Figure 2 using synthetic spectra. The blue-violet has an advantage over this spectral region, as the Balmer lines may be used as late as K0 in both classification and parameterization as metallicity-independent temperature discriminants. The Paschen lines in the 840 – 880 nm region fade, in the dwarfs, to broad, low contrast features (with depths a few percent below the continuum) by F5, and can exert little or no leverage as temperature indicators.

Before concluding, let me list a few other points about this spectral region.

1) One advantage of the 840 – 880 nm region for the later-type stars is the abundance of lines of α-elements, such as silicon, calcium and magnesium. This will make possible the determination of the enhancement of the α/Fe ratio in metal-weak stars.

2) It is unfortunate that this region lacks measureable lines of s-process elements such as barium and strontium, or any of the rare earths. This will make it difficult to explore chemical

peculiarities seen in G and K giants, such as the Barium stars, and certainly difficult to pick up some types of chemically peculiar A and F-type stars.
3) Silicon Ap stars will be easy to pick up, but Ap stars with enhancements of europium (or any other rare earth), strontium or chromium will not show up in this region.
4) There are a large number of CN lines in this spectral region and so stars with carbon enhancements such as the carbon stars should be very easy to pick up. However, the density of CN lines in this region may pose a problem for abundance analysis in K giants; starting at about K0 in the giants, lines of CN become strong enough and numerous enough that there begin to be significant problems with blending with atomic lines at the resolution *Gaia* and RAVE will be working at ($\sim 0.7 - 1.1$Å).

3. Conclusions

The determination of stellar parameters across the HR diagram using results from the current and future surveys will be a challenging problem. I have argued that, given a well-designed photometric system, this goal can be achieved, but that such a system alone may fail to recognize truly new stellar types. A well-designed photometric system combined with spectroscopy in a carefully chosen region of the spectrum is the ideal solution, and opens the survey to measuring much more than the basic physical parameters of stars; spectra and photometric systems work in complimentary ways, and one can make up for the weaknesses of the other. A survey based only on spectroscopy may fail or give unsatisfactory results if the spectral region chosen is prone to spectroscopic degeneracies.

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