

Spectral Classification: The First Step in Quantitative Spectral Analysis

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Abstract Classification lies at the foundation of many sciences, and that is true for Astronomy as well. However, many stellar spectroscopists neglect this vital first step when carrying out a spectral analysis. This chapter discusses and illustrates the ways that spectral classification can contribute to spectroscopic analysis at every step of the process.

Keywords Methods: data analysis · Techniques: spectroscopic · Stars: fundamental parameters · Stars: abundances

1 Introduction

Morgan et al. (1943) introduced MK Spectral Classification seventy years ago and that system has a long list of important contributions to astronomy. Some of the highlights include the first demonstration that the Milky Way Galaxy is a spiral (Morgan et al. 1953); the identification of the critical link between stellar populations, kinematics, and elemental abundances (Roman 1950, 1952, 1954), which opened the door to modern theories of the chemical evolution of the Galaxy; the discovery and systemization of chemical peculiarities in the A- and B-type stars (see Titus and Morgan 1940); the discovery of the Humphreys-Davidson luminosity limit for the most massive stars (Humphreys and Davidson 1979); the identification of the most massive (O₂) main-sequence stars (Walborn et al. 2002); and, more recently, the discovery and characterization of the L- and T-type dwarfs (see Kirkpatrick et al. 1993, 1999; Burgasser et al. 1999; Geballe et al. 2002).

Classification is an essential activity of science, and serves as the beginning point for deeper analysis, and as such should not be neglected. It would be remiss, for

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instance, for a biologist to carry out a DNA study of a particular organism without first classifying it to the level of species, or to embark on a study of an ecosystem without identifying all of the associated organisms. Classification in both of those cases makes possible a more detailed study.

In stellar astronomy, spectral classification can play a similar role of laying the foundation for a more quantitative analysis of the stellar spectrum. Modern stellar astronomers unfortunately, often skip this step, but there are many reasons to classify before you analyse.

2 The Role of Classification in Spectral Analysis

The MK Spectral type is a *fundamental datum* of Astronomy if and only if (1) the spectral type is obtained solely through comparison with the MK spectral standards, and (2) theory and external sources of information are not used in the determination of the spectral type. By adhering to those two rules, the spectral type can serve as a starting point for further research. Why should the spectral type be independent of external sources of information? An simple example can help explain this: let us suppose that we admit photometric information into our determination of the spectral type (amazingly, I just recently had a referee who insisted that I should do exactly that), and so bias our spectral type to be in better accord with the observed colour of the star. If we do that, and then go on to use the spectral type to determine the interstellar reddening, our results will be unreliable. On the other hand, a spectral type derived solely through comparison with the MK standards will serve you at every point in your analysis; it can provide beginning points for stellar parameters, it can suggest interesting lines of inquiry, and at the end will provide a “reality check” for your results.

MK spectral classification has two goals that are of importance to spectral analysis. First, MK classification seeks to locate a star within the context of the broad population of stars—i.e. its location in the H-R diagram. Second, MK classification is extraordinarily good at identifying peculiar and therefore astrophysically interesting stars.

This means that spectral classification can be very useful in the early stages of spectral analysis. The first step in spectral analysis is the estimation of the basic physical parameters, T_{eff} , $\log g$, and $[M/H]$. The spectral type, via calibrations, gives reddening-free estimates for those parameters, including the microturbulent velocity (c.f. Gray et al. 2001). In addition, in conjunction with photometry, spectral classification can help determine the interstellar reddening in a way that does not depend on a reddening model.

Spectral classification can identify peculiar and astrophysically interesting stars, and thus help in the selection of stars worthy of further analysis. Knowledge that a star is peculiar in some way can be of vital importance in spectral analysis. In addition to suggesting lines of inquiry, it is important to realize that some types of peculiar stars (for instance some Ap and Am stars) can have atmospheric structures

that deviate strongly from standard model atmospheres. If the researcher is unaware of this, either time will be wasted or incorrect results published.

At the end of your spectral analysis, the spectral type serves as a useful reference and check on your results. Is the spectral type in reasonable accord with your results? If not, then why not? Have you missed something important? Have you followed up all lines of inquiry suggested by your spectral type?

3 How are Spectral Types Determined?

3.1 Standard Stars

Spectral types are determined by direct comparison of the unknown with MK standard stars. The spectral criteria used in spectral classification were originally confined to the blue-violet part of the spectrum, but that is no longer the case, and spectral classification can be successfully carried out from the ultraviolet to the infrared. More details on spectral classification in general and the spectral criteria employed in that process can be found in *Stellar Spectral Classification* (Gray and Corbally 2009).

Standard stars are best observed with the same telescope/instrument combination used for obtaining the spectra of your program stars. Obtain spectra of enough standards to ensure that they bracket the range of possible spectral types of your program stars. Unfortunately, many telescope time allocation committees are reluctant to schedule adequate time to obtain observations of standards, and so in that case an alternative must be found. Published spectral libraries provide spectra that may be manipulated to conform to the spectral resolution (linespread function) of your program spectra. The web-based compilation *Librerias de espectros estelares* maintained by Daniel Montes at <http://pendientedemigracion.ucm.es/info/Astrof/invest/actividad/spectra.html> is an excellent source, but beware of the spectral types assigned in some of those libraries—they are often inaccurate or of uncertain provenance. Using only recognized MK standards is important in avoiding systematic errors in your spectral types. A number of tables of MK standards may be found in *Stellar Spectral Classification*. Another possibility is to ask a colleague who has the appropriate instrumentation to observe your star and a set of MK standards at typical MK resolutions (1–4 Å per two pixels, that is $R = 1,000 - 4,000$).

Then, classify your star *before* you begin your spectral analysis, not as an afterthought!

3.2 An Example of How to Classify a Star

There is not enough space to give examples of classification over the entire H-R diagram, but one example will illustrate the general principles. The book *Stellar Spectral*

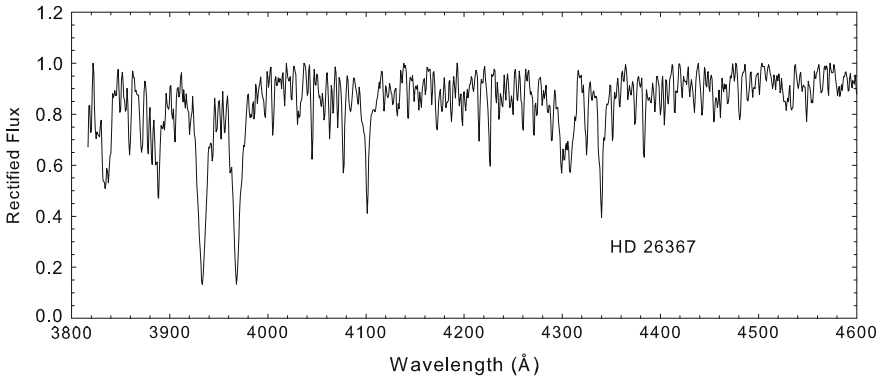


Fig. 1 The blue-violet spectrum of the peculiar F-dwarf, HD 26367. This spectrum has a resolution of 1.8 \AA (per two pixels)

Classification is a useful general resource. Spectral classification on the MK System is two-dimensional, and so the spectral type of a normal star consists of a temperature type (say, A0), and a luminosity type (say, V), and is written A0V. However, many spectral “peculiarities”, such as non-solar metallicities, can be handled within the framework of the MK System.

As an example, consider the peculiar F dwarf, HD 26367 (see Fig. 1, Gray and Griffin 2007). Spectral classification begins with a rough estimate of the spectral type, often before detailed comparison with the standards takes place. This, of course, can take experience, but comparison of your program star with the spectral sequences in *Stellar Spectral Classification* can be helpful. This initial assessment suggests that HD 26367 is a late F-type (\sim F8) dwarf with possible chemical peculiarities. The procedure is to first refine the temperature type (F8) by comparison with the spectra of MK standards of dwarfs of adjacent temperature types (Fig. 2), and then to refine the luminosity type by comparing with a sequence of standards (with the temperature type just determined) in the luminosity dimension. The process is iterated to convergence. The spectral features marked in Fig. 2 are useful in the temperature classification of late-type F dwarfs, and consist of the hydrogen lines (which weaken as the temperature decreases), the metallic-line spectrum in general, including the marked strong lines of Fe I and Ca I (which strengthen as the temperature decreases), and the G-band (which also strengthens as the temperature decreases).

It is important to keep in mind that the star might be metal-weak or metal-rich, in which case criteria based on the strength of the metallic-line spectrum or the G-band would lead to systematic errors in the spectral type. The classifier thus first concentrates on metallicity-independent temperature criteria. These consist of (1) the hydrogen lines, and (2) ratios of lines of different excitation energies of the iron-peak elements. A careful comparison of the strengths and profiles of the hydrogen lines of HD 26367 with the adjacent standards confirms a spectral type in the range

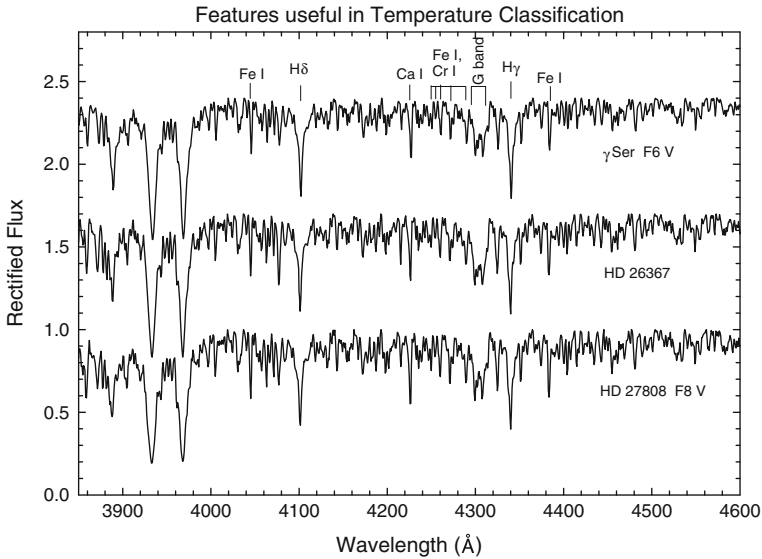


Fig. 2 The spectrum of HD 26367 is shown with the spectra of two adjacent MK standard dwarf spectra, γ Ser (F6 V) and HD 27808 (F8 V). Spectra criteria useful in the temperature classification of F- and G-type stars are marked on the top spectrum

F6–F8, but it is not possible to be more precise. Figure 3 indicates line ratios useful in temperature classification that are essentially independent of metallicity because they are based on iron-peak elements (which tend to have consistent abundance ratios). Fe I 4271 Å is a relatively low-excitation line (1.5 eV); it grows more rapidly with declining temperature than the adjacent higher excitation (2.4 eV) Fe I line at 4260 Å. Another ratio involving Fe I, Fe II 4233 Å and Fe I 4236 Å illustrated in the figure may also be used in the late F-type dwarfs. Caution, however, is required, as that ratio is also somewhat sensitive to gravity (luminosity) differences. For HD 26367 these two ratios give an average spectral type of F7. In the same region, a Cr I resonance line (4254 Å) may be rationed with Fe I 4260 Å to give a criterion that is very sensitive to the temperature in the G- and early K-type stars. It likewise is metallicity independent.

We now consider the metal-hydrogen ratios (Fe I 4046 Å/H δ , Ca I 4226 Å/H δ , Fe I 4383 Å/H γ —Fig. 4). These are very sensitive discriminants of the temperature type in the late-F and G-type stars, but of course can be biased if the overall metallicity is not near solar. Those ratios indicate a temperature type of F7 for HD 26367, as they appear precisely intermediate to the ratios in γ Ser (F6) and HD 27808 (F8).

The overall strength of the metallic-line spectrum also places HD 26367 (assuming a ‘V’ luminosity type) intermediate to the F6 and F8 standards, and therefore at F7.

Thus the metallicity-independent temperature criteria (hydrogen-line strengths and the iron-peak line ratios) are in excellent agreement with the metallicity-dependent criteria (metal-hydrogen ratios and the overall strength of the metallic-line spectrum). This agreement indicates that HD 26367 has an overall metallicity that is

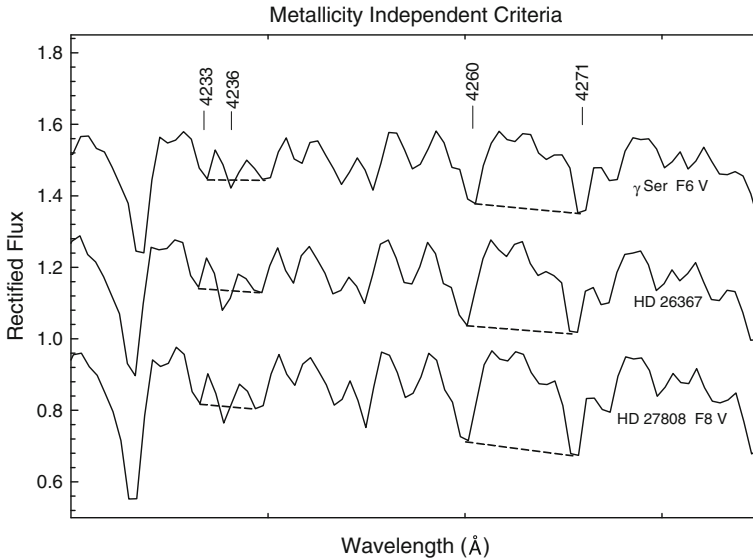


Fig. 3 The spectral lines marked in the figure may be used to estimate the spectral type independent of the metallicity of the star. Fe I 4271 Å is a low-excitation (1.5 eV) line which grows rapidly with declining temperature. It may be compared in ratio with Fe I 4260 Å, which has a higher excitation energy (2.4 eV) and so grows more slowly. The *dashed lines* joining the cores of the lines are meant to guide the eye; in this case, the ratio in HD 26367 agrees better with that in the F6 standard. The 4233 Å/4236 Å ratio may be used similarly but with some caution. The 4233 Å line is a blend of an Fe II and an Fe I line; the Fe II line fades while the Fe I line grows with declining temperature, yielding a blend that is nearly independent of temperature in the late F-type dwarfs. The 4236 Å line, however, is dominated by Fe I, and so grows with declining temperature. The ratio in HD 26367 suggests F8. The average spectral type based on these criteria is, therefore, F7

very nearly solar. If there is disagreement, then the temperature type is determined using only the metallicity-independent criteria.

The result, assuming that the luminosity class is ‘V’, is that the spectral type is firmly at F7. However, we have not yet considered the G-band, which is also a good temperature criterion in the F- and G-type stars. That comparison (see Fig. 5) indicates something is amiss—the G-band of HD 26367 is clearly stronger than the G-bands of both the F6 and the F8 V standards. This suggests that HD 26367 is carbon-rich, as the G-band is a molecular feature arising from CH.

We must now refine the luminosity class for HD 26367. Figure 6 shows a luminosity sequence of F8 standards (ideally we would use F7 standards for this purpose, but none exist, as F7 is not a “full” MK type). Lines of singly-ionized species, in particular Sr II, Fe II, and Ti II, in ratio with lines of neutral species (for instance the strong Fe I and Ca I lines marked in Fig. 2) make useful luminosity-sensitive criteria, with only a weak temperature sensitivity. The ratio Sr II 4077 Å/Fe I 4046 Å and especially the Sr II 4216 Å/Ca I 4226 Å ratio indicate a luminosity type between III and II (giant to bright giant), in gross disagreement with our original estimate of a

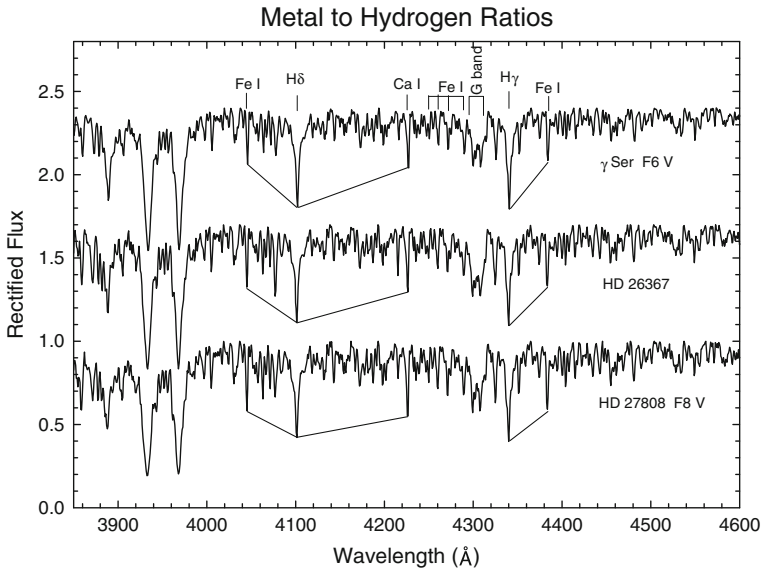


Fig. 4 The metal-to-hydrogen ratios shown in this figure may also be used to estimate the temperature type of the star, although these ratios are not reliable if the metallicity of the star is not nearly solar. Disagreement between the temperature type so determined and the metallicity-independent criteria described in the text will indicate that the star is either metal-weak or metal-rich. The lines drawn in the figure are to guide the eye only, and are not used in the actual determination of the temperature type

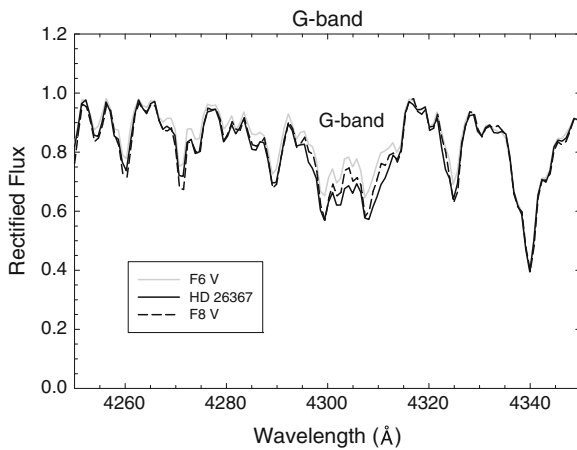


Fig. 5 The G-band strength of HD 26367 (*black*) in comparison with those of the F6 V standard (*grey*) and the F8 V standard (*dashed*). Note that the G-band of HD 26367 is stronger than either standard, indicating a possible carbon abundance enhancement

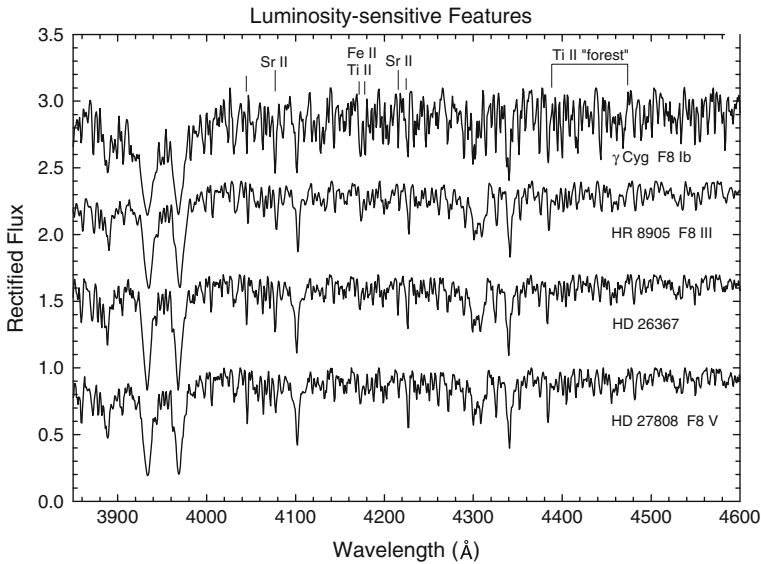


Fig. 6 Luminosity classification is carried out by comparing HD 26367 with dwarf, giant, and Ib supergiant F8 standards. Lines of ionized species such as Sr II, Fe II, and Ti II, usually in ratio with lines of neutral species constitute the luminosity criteria in F- and G-type stars. Here the Sr II lines give a discrepant luminosity class compared to the Fe II and Ti II lines, suggesting a strontium abundance anomaly

dwarf type. However, criteria based on Fe II and Ti II lines (for instance Fe II, Ti II 4172-78 Å in ratio with other nearby metallic-line blends, as well as the morphology of the so-called “Ti II forest” between 4400 and 4500 Å) places the luminosity class firmly at V (dwarf). This discrepancy in luminosity class suggests a strontium peculiarity; the significance of this abundance peculiarity will be explained below.

Thus, despite the strontium peculiarity, the conclusion is that HD 26367 is indeed a dwarf, consistent with the original assumption. If it had turned out that HD 26367 were a giant (III) or even a subgiant (IV), it would have been necessary to go back and redo the temperature classification with the appropriate standards and then iterate until consistency was obtained.

In conclusion, the final spectral type for HD 26367 is F7 V Sr CH+0.4. The CH+0.4 reflects the observation that the G-band is too strong for the spectral type; the index 0.4 is determined from the spectral type difference F9 – F7, where F9 is the spectral type with G-band strength in best agreement with the G-band of HD 26367. The formula used in the calculation of this index is

$$CH_{\text{index}} = 0.25\Delta,$$

where Δ is the spectral-type difference, in this case taken as +1.5, as F7 is a “half” spectral type. The index is rounded to the nearest tenth. Details on the calculation of abundance indices may be found in *Stellar Spectral Classification*.

The observation of a strontium and carbon over-abundance suggests that HD 26367 belongs to the group of “Barium Dwarfs” (see North et al. 1994). The leading theory explaining these abundance anomalies is that a barium dwarf was once in a close orbit with an AGB (carbon) star, and mass transfer from that star onto the present barium dwarf accounts for those anomalies. That AGB star is now a white dwarf. So, is HD 26367 a binary star? Yes, both Hipparcos and radial velocity measurements indicate the presence of an unseen companion with $M \sim 0.6M_{\odot}$ (Gray and Griffin 2007), exactly what we would expect for a white dwarf arising from an AGB star. Indeed, GALEX photometry indicates a slight far-UV excess (Gray et al. 2011), which presumably arises from that hot companion.

4 Conclusions

The exercise classifying HD 26367 illustrates many of the points made in this discussion. HD 26367 was first identified as an interesting star via spectral classification in the Nearby Stars Project (Gray et al. 2003, 2006). That classification suggested HD 26367 was a new, bright member of the barium dwarfs, and that led to a radial-velocity program to determine its status as a binary, and high-resolution spectroscopic observations which revealed not only that strontium and carbon are overabundant, but that the s-process elements in general are overabundant. When we were satisfied that HD 26367 was indeed a barium dwarf and a binary, its brightness encouraged us to apply for time on the GALEX space telescope, and so obtained observations that constituted the first direct detection, via ultraviolet excesses, of the white-dwarf companion of a barium dwarf. The important point here is that experience shows that much of what you will ultimately learn about your star via detailed spectral analysis can be *anticipated* through spectral classification, and that that spectral type can therefore serve as a useful guide for your analysis from beginning to end. In conclusion, *classify before you analyze!* That may be the most important lesson you learn in this workshop!

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