The Indo-U.S. Library of Coudé Feed Stellar Spectra

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ABSTRACT

We have obtained spectra for 1273 stars using the 0.9m Coudé Feed telescope at Kitt Peak National Observatory. This telescope feeds the coudé spectrograph of the 2.1m telescope. The spectra have been obtained with the #5 camera of the coudé spectrograph and a Loral 3K X 1K CCD. Two gratings have been used to provide spectral coverage from 3460 Å to 9464 Å, at a resolution of ∼1Å FWHM and at an original dispersion of 0.44 Å/pixel. For 885 stars we have complete spectra over the entire 3460 Å to 9464 Å wavelength region (neglecting

small gaps of < 50 Å), and partial spectral coverage for the remaining stars. The 1273 stars have been selected to provide broad coverage of the atmospheric parameters T_{eff}, log g, and [Fe/H], as well as spectral type. The goal of the project is to provide a comprehensive library of stellar spectra for use in the automated classification of stellar and galaxy spectra and in galaxy population synthesis. In this paper we discuss the characteristics of the spectral library, viz., details of the observations, data reduction procedures, and selection of stars. We also present a few illustrations of the quality and information available in the spectra. The first version of the complete spectral library is now publicly available from the National Optical Astronomy Observatory (NOAO) via FTP and HTTP.

Subject headings: astronomical data bases:miscellaneous—atlases—stars:fundamental parameters—stars:atmospheres

1. Introduction

The need for a comprehensive database of digital stellar spectra covering a large range in T_{eff}, log g, and [Fe/H] at moderate (1-2 Å FWHM) spectral resolution has increased considerably in the past decade. The uses of such a spectral library are wide ranging. To begin with, synthetic stellar spectra generated from model atmospheres now incorporate such extensive line lists (e.g., Kurucz 1993, 1994; Bell & Gustaffson 1978, 1989; Tripicco & Bell 1992, 1995) that the synthetic spectra can be compared to empirical spectra at increasingly high spectral resolution. Once the basic accuracy of the synthetic spectra has been established, the synthetic spectrum technique can then be utilized to explore areas of atmospheric parameter space that are not adequately represented in Solar Neighborhood stars. For example, recent results from galaxy population synthesis studies (e.g., Kuntschner et al. 2002; Terlevich & Forbes 2002; Trager et al. 2000 and references therein) indicate that the integrated spectra of most early-type galaxies are dominated by metal-rich stars with non-solar abundance ratios that are not found in the Solar Neighborhood. Second, with the advent of large databases of both stellar and galaxy spectra, generated by multi-fiber and multi-aperture spectrographs, methods for the automated parametrization of spectra in a fast and reliable manner are becoming essential. Indeed, various researchers have been exploring the application of Artificial Neural Networks to the automated parametrization of stellar spectra (e.g., Singh, Bailer-Jones, & Gupta 2002). In addition, Katz et al. (1998) have developed the TGMET software, which establishes the best match between a target spectrum and a library of reference spectra. For these techniques to be applied, a comprehensive set

of reference spectra with known atmospheric parameters is essential. Finally, in the field of spectral synthesis of the integrated light of galaxies, the need to resolve individual features in galaxy spectra, to effectively resolve the problems of non-uniqueness in extracting mean age and metallicity information from integrated spectra, has become increasingly evident (Worthey 1994; Vazdekis & Arimoto 1999). To carry out the modeling of the composite spectra of galaxies of different ages and metallicities requires a spectral database that covers all areas in the HR diagram sampled by theoretical isochrones.

Despite the clear necessity for a comprehensive spectral library, there is surprisingly little existing material to select from. In fact, until recently the existing spectral libraries have primarily consisted of low resolution (5 - 20 Å FWHM) spectrophotometry of typically ∼100 stars, covering a range in spectral type, but largely restricted to solar chemical composition (Pickles 1998 and references therein). This traditional emphasis on accurate spectrophotometry with broad wavelength coverage at low resolution has likely reflected both the low number of pixels in spectroscopic detectors until recently, coupled with the low resolution approach to spectral synthesis studies of stars and galaxies that supplied the chief driver for the libraries. However, the advent of large format CCD detectors in spectroscopy, along with the above-mentioned trends toward higher resolution modeling of the spectra of stars and of galaxies in integrated light, is now leading to the production of several extensive libraries of stellar spectra at higher spectral resolution. In particular, Jones (1999, see also Leitherer et al. 1996) completed a spectral database of 684 stars at 2 Å resolution (FWHM) using the Coudé Feed telescope at the Kitt Peak National Observatory (KPNO). Due to the small format of the existing CCD detector at that time, coverage is restricted to two ∼700 Å spectral regions. More recently, Prugniel & Soubiran (2001) published a spectral library, based on the ELODIE echelle spectrograph at the Observatoire de Haute-Provence, that covers the wavelength interval λλ4100-6800 Å at a resolution of R=42000 for 708 stars that cover a large range in atmospheric parameters. Finally, Cenarro et al. (2001) have observed 706 stars in the wavelength region λλ8350-9020 Å at 1.5 Å resolution, to characterize the behavior of the near-IR Ca II triplet for galaxy population synthesis.

In this paper we describe a new database of stellar spectra, encompassing more than 1000 stars, and covering the spectral region λλ3400–9500 Å at a resolution of ∼1 Å FWHM. The primary emphasis of this new spectral library is on broad wavelength coverage, particularly well into the blue, at a resolution sufficient to resolve numerous diagnostic spectral features that can be used in the automated parametrization of spectra and in the population synthesis of galaxies. We have also emphasized coverage in atmospheric parameter space, particularly at lower metallicity. The purpose of this paper is to provide a guide to the new spectral library, which is now publicly available from the National Optical Astronomy Observatory (NOAO) via ftp and http. The paper presents technical information about the observations

and the sample of stars observed to make the database readily useful to the astronomical community. In §2 we describe the observational procedures used in creating the library, and in §3 we describe how the sample of stars was selected. In §4 the data reduction procedures are described. In §5 we describe the actual format of the archived spectral database as well as the tables which summarize the key information about the stars. Finally, in §6 we show examples of the stellar spectra, some of which are meant to illustrate the challenges facing the automated parametrization of stellar spectra.

2.   Observations

All observations for the spectral library have been obtained with the Coudé Feed telescope at KPNO. The coudé feed is an auxiliary telescope (a 60" flat reflects the sky onto a 36" parabolic mirror which directs a converging beam into the 2.1-m telescope coudé optical train) which feeds a stellar image onto the slit of the coudé spectrograph of the 2.1-m telescope. Two spectrograph combinations were optimized for the red and blue portions of the spectra. For the blue the KPC10A grating (316 lines/mm) and blue corrector were used while for the red the B&L181 grating (316 lines/mm) and red corrector were used. In common were the #5 camera, the small collimator, and the 3K x 1K Loral CCD detector (F3KB). These combinations produce a fairly uniform dispersion of 0.44 Å/pixel yielding ~1300 Å coverage along the 3K dimension of the the CCD. The orientation of the CCD is such that spectra are dispersed as nearly parallel to the serial direction as possible. Any CTE problems then only affect the spectral profile and not the spectral resolution.

Consequently, the entire spectral region $\lambda\lambda$3400–9500 Å can be covered with 5 grating settings, albeit with only a little overlap between settings. With a slit width of 200 μm, or 1.4″, the focus is typically ~3 pixels FWHM, or ~1.2 Å. A slit length of 9.77 mm, or 70.6″, provides 100 pixels for source and sky. While we focussed the spectrograph to obtain roughly constant focus across the spectrum, inevitably there are small focus variations across specific 1300 Å grating settings, as well as small variations from night to night, despite the relatively stable environment in the Coudé Feed room. However, we anticipate that maximum use of the spectral database will be at typically 2 Å resolution, hence the slight focus variations along the spectrum will not be a major problem.

Exposure times at the various grating settings were adjusted to target a S/N ratio of better than 100:1 per 0.44 Å/pixel. However, when the seeing was poor, in regions of low flux and detector DQE, and for the faintest stars (B>10) such a high S/N ratio was not achievable. For the faintest stars we simply used a maximum exposure time of 20 minutes. The practical limit for the library is B=12.

Given that the coudé slit cannot be easily rotated to the parallactic angle or tracked with the field rotation inherent in the feed arrangement, and that a narrow (1.4″) slit is required to maintain spectral resolution, obtaining accurate spectrophotometry for the survey was not feasible. The problem is further exacerbated by the fact that the 60" feed mirror is particularly subject to wind shake. We typically acquire observations of three spectrophotometric standard stars during the night, to achieve approximate spectrophotometry. Radial velocity accuracy is also not an important consideration. The procedure while observing is to take a series of arc lamp exposures before twilight to build up a master arc exposure, then shorter exposures are obtained approximately on an hourly basis during the night. Given that the spectrograph is off the telescope in a thermally stable environment, the zero point shift is independent of the RA and DEC of the observation.

Altogether 6917 individual spectra of 1273 stars have been obtained during the time period from June 1995 through April 2003. The project has been a part-time effort over many years with changes in personnel and goals. As a consequence, on several observing runs, grating settings were used that do not provide full overlap with adjacent settings, leaving a considerable number of final spectra with small (<50 Å) gaps. The project has involved the participation of many present and former undergraduate and graduate students at the University of North Carolina, which has greatly aided in its completion.

3. Selection of Stars

The primary emphasis for the spectral database is on obtaining stellar spectra covering a wide range in T_{eff}, log g, and [Fe/H]. Naturally, it is important to select stars whose atmospheric parameters are well-determined from a fundamental (i.e., high dispersion) analysis, and preferably part of a large homogeneous sample. A prototypical example of a uniform sample of high-quality data is the Edvardsson et al. (1993) study, in which a high dispersion abundance analysis has been conducted for 189 F and early G stars. Our first priority has been on working with samples such as the Edvardsson et al. (1993) one, in which a number of stars have been subjected to a well-defined analysis that includes elemental abundance ratios, and thus are placed on a highly reliable relative scale. Furthermore, if subsequent work indicates that the effective temperature scale used in the analysis requires revision, the prescription is available to readily redefine both T_{eff} and [Fe/H] values for the entire sample. Abundance studies that fit these criteria and from which we have observed stars for our spectral database are Castro et al. (1997), Chen et al. (2000), Edvardsson et al. (1993), Feltzing & Gustafsson (1998), Luck & Challener (1995), Nissen & Schuster (1997), Tautvaisiene (1997), and Tautvaisiene et al. (2001). The individual samples are further summarized in

§5.2.

A second type of sample regards large compilations, homogeneous in quality, but for which the atmospheric parameter information is less extensive and/or fundamental than for the samples mentioned above. An example is the Dickow et al. (1970) multi-passband photometric survey of giants, for which atmospheric parameters have been extracted by Hansen & Kjaergaard (1971). A second example is the work of Brown et al. (1989), also for giants, for which the T_{eff} information has been taken from the DDO photometry of McClure & Forrester (1982), and [Fe/H] extracted from high-resolution spectroscopy over a very limited wavelength region (thus precluding a detailed elemental abundance analysis). Similarly, the atmospheric parameters for many of the metal-poor stars in the database are taken from Carney et al. (1994), where results are based on the combination of a photometric effective temperature and [Fe/H] from low S/N ratio high dispersion spectra in the Mg I triplet region. Another example is the previously mentioned Prugniel & Soubiran (2001) survey of 709 stars. While high dispersion spectra have been obtained for all stars, the atmospheric parameters are indirectly obtained from comparison of the star's spectrum with various template spectra. Further descriptions are given in §5.2.

A third category of stars in our database are those for which atmospheric parameters have been obtained for just one or a few stars, hence the literature values are subject to the additional systematic uncertainties associated with such targeted studies. For the most part, stars in this category have been included because they help to define regions of atmospheric parameter space which are otherwise sparsely represented in our database, such as F and G supergiants. The atmospheric parameter data for the majority of these stars have been taken from the monumental compilation of Cayrel de Strobel, Soubiran, & Ralite (2001) and, in some cases, from Cayrel de Strobel et al. (1997).

Finally, there are a number of stars in the database for which well-determined atmospheric parameters are lacking. These are primarily stars used to cover areas of parameter space which are under-represented. For example, we have observed a number of stars with supergiant spectral classifications, but without atmospheric parameter determinations, in order to enhance our sample of low-gravity stars. Likewise, we have observed a number of stars with early-type spectral classifications, but no additional information, to have some coverage of hot stars. In addition, we have observed a number of stars from Rose (1985) that are found to be strong-lined G dwarfs and are believed to be metal-rich, similar in fact to stars in the Cayrel de Strobe, Soubiran, & Ralite (2001) compendium that have [Fe/H]$\sim$+0.3. However, no fundamental abundance analysis has been carried out for these stars. For these latter stars we have assigned a log g of 4.0, and [Fe/H]=+0.3, but these parameters must be considered highly provisional at this point. In addition, many of the metal-poor dwarfs

studied by Carney et al. (1994) do not have a determination of log g. We have set log g = 4.0 for these stars.

In assigning atmospheric parameters to the stars in our sample, we used the following algorithm. We first checked both the Cayrel de Strobel et al. (1997) catalog of [Fe/H] determinations for all stars and the Cayrel de Strobel, Soubiran, & Ralite (2001) catalog of [Fe/H] determinations for F,G, and K stars. If values are given for the star in Cayrel de Strobel, Soubiran, & Ralite (2001), we used those over the 1997 catalog. In the Cayrel de Strobel et al. catalogs the atmospheric parameters from all determinations for a given star are listed in chronological order. We first check to see whether the star has values reported from Edvardsson et al. (1993), Luck & Challener (1995), Castro et al. (1997), Feltzing & Gustafsson (1998), or Chen et al. (2000). If any of these sources are available, we default to those values, since they represent homogeneous compendiums. If the star is contained in more than one of these references, we select in the order given above, i.e., Edvardsson et al. (1993) has highest priority. If the star has not been covered by any of the above five references, then we default to the most recent atmospheric parameters listed in Cayrel de Strobel, Soubiran, & Ralite (2001) which have complete information for all three parameters and also do not have a "quality" flag indicating lower quality data.

Overall, we have obtained good coverage over a large region of parameter space in T_{eff}, log g, and [Fe/H]. However, there are some areas with relatively low representation. First, it has been difficult to find an adequate sample of moderately metal-poor giants with -0.6≥[Fe/H]≥-1.2. Due to the modest aperture of the Coudé Feed system and the goal of a large library, we are restricted to a magnitude limit of B=12, which precludes observing giant branches in clusters with this intermediate metallicity (e.g., M71). As well, there is a danger in relying on stars selected from the metal-weak tail of a large photometric sample of nearby giants, since the tail of the distribution could be contaminated by stars with larger photometric errors. Second, coverage is sparse both for supergiants and for F and early G giants, especially those with well-determined atmospheric parameters. Third, there is limited coverage at high metallicity, i.e., [Fe/H]>+0.2, especially given the ongoing debate concerning the existence of super metal-rich stars (e.g., Taylor 2002 and references therein). Finally, we have only provided sparse coverage of O, B, and A stars. The number of such stars with well-determined atmospheric parameters at low gravity and below solar metallicity is very limited. Furthermore, there is the problem of emission contamination and peculiar chemical abundances in many of these stars. In addition, some of the early-type stars may be rapid rotators, thereby limiting the resultant spectral resolution.

The coverage of atmospheric parameter space by our Coudé Feed spectral library is shown in Fig. 1. As mentioned above, coverage is generally quite extensive for T_{eff} below

$\sim$6300 K (log T_{eff}<3.8), but rapidly thins out at higher temperature, and at [Fe/H]>+0.2.

4. Reductions and Calibrations

The first stage of instrumental calibration is performed at the telescope. All exposures are automatically corrected for amplifier bias levels using the overscan region and then trimmed of the overscan and bad edge columns and lines. Sequences of bias exposures at the beginning of the night's observations and quartz lamp flat fields at the beginning and end of the night, typically 20 in a sequence, are obtained. The bias sequence is averaged into a master bias which is then automatically applied to all subsequent calibration and stellar exposures. The flat fields, corrected by the master bias, are combined into master flat fields, though these are not applied at the telescope. A sequence of typically five comparison lamp exposures are combined. During the night the stellar and comparison lamp exposures are automatically bias calibrated and trimmed. The individual calibration exposures and the raw stellar exposures are not kept except in the observatory's failsafe tape archive.

The bias calibrated data, including the master flat fields and arc comparisons, are processed by a pipeline built using the IRAF[1] system and tasks. At the highest level the stages of the reductions are 2D flat field calibration, extraction into 1D spectra, dispersion calibration, telluric removal, heliocentric and radial velocity corrections, continuum calibration, linear dispersion resampling, and stacking and splicing of all exposures for a single star. Documentation and header standardization is also performed along the way.

The 2D flat field calibration involves normalizing the master flat field by a smooth curve approximately representing the quartz lamp spectrum. Because we later apply a continuum calibration, the actual detailed shape of the quartz lamp normalization is not critical. The normalized flat field provides calibration of the relative pixel responses, the slit function, and the fringing which occurs in the redder wavelength exposures.

The 2D flat field is applied to each 2D stellar exposure. Sometimes there is only one master flat field, but when there are two, obtained at the beginning and end of the night, the one nearest in time to the stellar exposure is used. This minimizes effects caused by flexure of the CCD relative to the rest of the spectrograph during the night as the dewar weight changes.

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[1]IRAF is distributed by the National Optical Astronomy Observatories, which are operated by the Association of Universities for Research in Astronomy, Inc., under cooperative agreement with the National Science Foundation.

The extraction of the stellar spectra from the 2D long slit format to the 1D format is performed using the `kpnoslit.doslit` IRAF task, in itself a type of pipeline. In this stage the position of the star in the image is determined. An extraction window is defined, centered on the peak of the profile, with a width set to the full width of the profile at 5% of the maximum. This adjusts automatically for seeing and guiding variations. Two regions on either side of the profile window are used to define and subtract a linear interpolation for the background in the extraction window.

The extraction to a 1D spectrum consists of summing the background subtracted pixel values along each column within the extraction window. The primary sum is weighted by estimates of the variance in each pixel, and pixel values that deviate by many sigma from the expected profile determined from nearby wavelengths are rejected. This is an implementation of the "optimal variance-weighted algorithm" (see Horne 1986). Since most of the sources are fairly bright the main effect of this method is to greatly reduce contamination from cosmic rays. For reference, the full extracted data set also includes the simple sum without weighting or rejection, the background, and an estimate of the uncertainty in the extracted value derived from the uncertainties in the summed pixels.

After extraction the nearest comparison lamp exposures are extracted over the same pixels and a dispersion function is fit to the line positions versus laboratory wavelengths. The dispersion function assigned to the stellar exposure is the average of the two weighted by the proximity in time.

The telluric corrections are applied next. Note that this is done prior to radial velocity corrections because telluric features are fixed in the observed frame of reference. For each program star a suitable telluric observation (same night observation of a star from a list of telluric "standards") is selected; the telluric standards are all rapidly rotating B stars. The telluric star is continuum normalized with a cubic spline of 5 pieces fit to non-telluric regions, where the telluric regions to be scaled and removed are specified in Table 1. After the continuum fitting, the non-telluric regions are set to 1 so that that those regions do not modify the matching regions in the program star. The telluric features are removed by scaling and dividing the template telluric regions into the stellar data. The scaling and any small wavelength shift are determined by minimization of the root mean square in the corrected spectra over the telluric regions. Hence, in effect, the telluric regions in the telluric stars are continuum normalized from nearby regions and only those regions are used to correct the program stars. For the program stars, data outside the telluric regions is not modified by this procedure.

To enhance the ease of use of the spectral library, we have adjusted all of the final spectra to heliocentric rest wavelength. For all but 128 stars in the library, radial velocities

are available from the literature, and are taken from SIMBAD. For the remaining 128 stars we use the `fxcor` routine in IRAF to determine radial velocities. For 125 of these we use the F8V star HD30562 as a radial velocity template. For the remaining 3 stars, HD24398, HD24760, and HD87344, which are B stars, we use the B star templates HD3360 and HD225132. The radial velocities have been obtained using the spectral region $\lambda\lambda 4000$ - 4700 Å.

As noted earlier, the combination of narrow slit, field rotation, observations taken in non-photometric conditions, and limitations in setting the slit to the parallactic angle makes flux calibration of our data problematic. Therefore, to smoothly join the different grating settings taken over many years and to provide a continuum shape suitable for automatic classifications algorithms, we fit each observation to a spectral energy distribution standard with a close match in spectral type. This requires a library of flux-calibrated spectra that covers both a large range in spectral type and the 3400 - 9500 Å wavelength range of our spectra.

Unfortunately, there is no available library of spectrophotometry that covers our extended wavelength region as well as providing full coverage of the stellar atmospheric parameter space. In fact, the existing spectrophotometric libraries primarily cover MK spectral types and luminosity classes, thus do not incorporate metal-poor stars. We have chosen the Pickles (1998) compilation as our spectrophotometric database. Note that this library is normalized to unity at 5550 Å and, hence, our library is also normalized to this point. Note that this normalization does not actually locate a "true" continuum at 5550 Å, since many faint spectral features at the location of the normalization point prevent the location of a true continuum there.

In order to handle the 14 cases for which there is no library spectral energy distribution (SED), such as for the C and S spectral types, or no known spectral type, such as some of the fainter metal-poor stars, we added a dummy SED with unit continuum everywhere. This SED is in the same format as the rest of the library so that the continuum matching is performed in the same way for all stars.

The continuum matching is carried out by integrating the SED standard and the observation into adjacent 10 Å bins. Bins that cover strong spectral features and/or telluric features are excluded. (The complete set of bins used may be found at *The Indo-U.S. Library of Coudé Feed Stellar Spectra* home page at `http://www.noao.edu/cflib/`.) A smooth transformation function, specifically, a 10th order Chebyshev (with iterative rejection to remove deviant points), is fit to the ratio, expressed in magnitudes, of the observed and standard continuum values. The function is then applied to each pixel value in the spectrum to produce the continuum calibrated versions of the data.

The Pickles continuum standard applied is identified in the header information for the spectrum, as well as in the accompanying database file, as is described in §5. For stars with spectral type earlier than F0, our strategy is to find the closest Pickles star in spectral class, since the Balmer discontinuity and spectral shape is more temperature sensitive than gravity sensitive at the higher temperatures. For stars of type F0 and later we place first emphasis on attaining the correct luminosity class. As noted above, there are 14 stars with a flat continuum applied. Users of our library also need to be aware that the assignment of a continuum standard for metal-poor stars is of limited validity.

To create a final spectrum from the separate exposures in different grating settings, a two step process is followed. First, the spectra are interpolated onto a linear wavelength sampling, with a common start wavelength and 0.4 Å/pixel wavelength step. Then the pieces are stitched together into a single final spectrum. In regions of wavelength overlap between exposures, the overlap pixel values are averaged. In cases where gaps appear between grating settings, the gap pixels are set to 0.0001, and the gap regions are recorded in the header and in the master database file (see §5). Since the individual pieces are fit to the same Pickles continuum SED, the overlap regions are automatically smoothly joined.

5. The Spectral Library

The completed spectral library consists of two principle components. The first is the collection of spectra with pertinent information provided in the headers. The second is a database table that contains the relevant information about each star. The table allows for easy perusal of the contents of the library. Here we present a brief description of the spectra and the database table. The complete description of the products may be found at *The Indo-U.S. Library of Coudé Feed Stellar Spectra* home page at `http://www.noao.edu/cflib/`.

5.1. Spectra

The library provides several versions of the spectra for each star to allow the user to interpret the effects of various stages in the pipeline reductions. First the individual extractions from each observation are available. The pixel values are in detector counts with a gain of 2.3 electrons per count. The extractions include two versions of the spectrum, the variance weighted and cosmic ray cleaned version and the simple sum. They also include the subtracted background and the estimated uncertainties based on the photon statistics of the detector pixels. No interpolation between pixels has been applied and the wavelengths

are defined by a dispersion function and a wavelength vector.

The variance weighted spectra and uncertainties, again in the original pixel wavelength bins, are provided with the telluric removal and continuum calibration.

The multiple observations of a star are merged together in another product. The continuum calibrated spectra for each star are interpolated to a uniform sampling of 3465 Å to 9469 Å in steps of 0.4 Å. As described earlier, a 0.0001 value is used when no observation covered a particular wavelength and the average is used when multiple exposures are available. This version does not include uncertainty information in the first release.

The available data formats are described in detail on the Library home page. The formats include FITS binary tables, FITS images, and simple text files. The FITS files consist of multiple extensions to collect all data from a single star in a single file. The image format uses an IRAF convention for spectral data.

The spectral files also contain header information from the original raw data and information derived from Simbad and the database of stellar parameters. Most of this header information is self-explanatory, hence we simply touch on a few key parameters here. For the individual pieces of the spectra, arising from specific grating settings, we include information on the grating and its tilt. For the stitched-together final spectrum, we include a parameter, COVERAGE, which gives the start and end wavelength of the spectrum. While all spectra have been rebinned to the same start and end wavelengths, if the coverage actually starts at a longer wavelength than the nominal start wavelength, the first pixels are filled with 0.0001. The same applies for any pixels at the red end which are beyond the extent of the actual data. The COVERAGE parameter gives the true start and end wavelengths of the data. There is also a GAPS parameter, which gives the wavelength intervals for which gaps exist, due to underlap between grating settings or to missing grating settings.

5.2. Database of Stellar Parameters

Information on each star in the database is included in the header of the spectral data files. For ease of use, we have also summarized much of the essential header information in both HTML and FITS Binary Table format at the Library home page at `http://www.noao.edu/cflib/`. For printing purposes, in this paper we have subdivided the master table into the three Tables 2, 3, and 4. We print only the first 10 lines of each table, while the full tables appear in the electronic version of the Journal and at the Library home page. Key elements of Table 2 are as follows. The first column contains the primary star ID, the second and third columns contain the FK5 RA and Dec (2000.0) coordinates

(as found in SIMBAD), and columns (4) and (5) contain the apparent V magnitude and B–V color (as found in SIMBAD). In column (6) is given the number of individual spectra obtained for the star, column (7) provides the wavelength region covered by the spectrum, and in column (8) we list any gaps present in the wavelength coverage. In Table 3 the first column is again the primary star designation. In columns (2) and (3) are listed the Spectral Type (from SIMBAD) and the spectral type that we selected from the Pickles (1998) spectrophotometric library used for the continuum calibration. If no spectral type match could be made, a "flat" designation is given, to indicate that the continuum has been normalized to unity. Next is the radial velocity, followed by the atmospheric parameters, T_{eff}, log g, and [Fe/H]. In column (8) is given the reference code for the atmospheric parameters. Finally, in Table 4 we give the primary star ID in column (1), and then follow with alternate name designations.

5.3. Preliminary Artificial Neural Network Analysis

As part of an effort to cross-check the reliability of both our reductions and the assembled information on the nature of the stars, we have conducted a preliminary automated analysis of the reduced spectra using an Artificial Neural Network (ANN) scheme. The ANN approach used here has been previously described in Gulati et al. (1994) and Singh, Gulati, & Gupta (1998). Our goal was to compare the spectral type for each star that we selected from the Pickles (1998) library, to use for continuum-calibration, against the actual listed MK spectral type in the SIMBAD database. Any major discrepancy between our selected spectral type and the derived ANN spectral type could indicate either a typographical error in our selection of the Pickles type, an error in the MK type given in SIMBAD (which we used as a basis for selecting the nearest available Pickles type), or some problem in our reduction procedure for that star.

Since we are making a cross-check with MK spectral types, we therefore restricted the ANN analysis to the blue spectral region of $\lambda\lambda 3510$ - 4700 Å. For the analysis we used the 158 spectra from the Jacoby, Hunter, & Christian (1984; hereafter JHC) continuum-calibrated spectral library as the training set. These spectra have a resolution of 4.5 Å FWHM, and we rebinned them to a sampling of 1.0 Å/pixel. We then broadened and rebinned our coudé feed spectra to the same resolution and sampling as the JHC spectra before applying the ANN analysis with the JHC spectra as the training set. We converted MK spectral types to a numerical code using the following scheme. The alphabetic MK class is coded into a numeric, with type O given a numeric code of 1000, B is 2000, F is 3000, etc. The decimal subclasses are multiplied by 100 and added in, thus a G2 star is coded as 5200. The

luminosity class is coded as follows: types I, II, II, IV, and V are coded as 1.5, 3.5, 5.5, 7.5, and 9.5, respectively. The luminosity class is also added in, hence a G2V is coded as 5209.5. Evidently, the luminosity class is given very low weight in the analysis. It was found that after application of the ANN scheme, we located approximately a dozen stars which had been inadvertently assigned the wrong Pickles spectral class. These stars were accordingly reassigned the correct nearest Pickles class and reanalyzed during the final reduction stage. Overall, we find a 2-σ scatter between the assigned Pickles type and the ANN-derived type of only 1.1 decimal subclasses. A few outliers, other than the ones with wrongly listed Pickles types, have been found, some of them being low metallicity stars, for which MK spectral types are rather meaningless. A few other cases involve late M stars, for which the blue spectral region is quite problematic for applying spectral classification. The remainder involve confusion between B stars with similar Balmer line strengths as A stars. We reserve a more complete analysis with ANN techniques to a future paper.

5.4. Availability of Spectral Database

As mentioned above, the entire spectral library is publicly available from the Library home page at `http://www.noao.edu/cflib/`. FTP access is also provided from `ftp://ftp.noao.edu/cflib/`. This currently provides version 1.0 of the library. We expect to release future versions, with improved calibrations and uncertainties and with updated stellar atmospheric parameters. The library will eventually be incorporated in the NOAO Science Archive and the Virtual Observatory to provide search and browse capabilities. We encourage interested users to advise us of any defects in the spectral library, and to alert us to improved atmospheric parameter information for stars, as well as to any new spectrophotometry that we may be able to use to improve continuum calibration on some or all of the stars.

6. Examples of Spectra

The primary purpose of this paper is to describe the spectral database in order to make it as generally useful as possible to a variety of investigators. However, in the following Section we show a few examples of the spectra, both to illustrate the quantity of information contained in the spectra, and also to illustrate some of the challenges involved in developing a reliable automated classification for stellar spectra.

In Fig. 2 we show the entire 3400 - 9500 Å spectral region covered by our observations

for the K0III star HD4128. The point of the plot is to show the large amount of information present in the spectrum, which is evident in the expanded wavelength regions. In Fig. 3 a series of 7 dwarf stars covering the range of spectral types from O through M are plotted, to illustrate the basic behavior of the spectra with changing temperature. We have restricted the plots to only the blue spectral region, in the wavelength interval where much of MK classification has been carried out.

In Fig 4 we compare the spectra of two stars which have similar spectral type, but very different T_{eff} and [Fe/H]. Specifically, the upper spectrum is of the star HD30562, which has T_{eff}=5860 and [Fe/H]=+0.13, while the lower spectrum is of HD157214, which has T_{eff}=5600 and [Fe/H]=-0.58. The factor of four difference in metallicity is so well balanced by the hotter temperature in the more metal-rich star that the two spectra are virtually indistinguishable. Essentially, Fig. 4 illustrates the long-known degeneracy between T_{eff} and [Fe/H], which for decades obscured the presence of a metallicity spread and chemical enrichment history in the Galaxy, and currently plagues the disentanglement of age from metallicity effects in the integrated spectra of galaxies (e.g., Worthey 1994).

There are several aspects to the Figure worth emphasizing. First is the remarkably strong degeneracy of temperature and metallicity effects. The second is the difficulty in measuring any one feature in the blue at intermediate spectral resolution, for anything but the hottest stars. To further illustrate the latter point, in Fig 5 we show the spectrum of HD30562 at its original spectral resolution (bottom), and smoothed with a σ of 1.5 pixels (top), bracketing the spectrum of the metal-poor ([Fe/H]=-1.2) dwarf HD105755 (middle). As can be seen in the Figure, a loss of spectral resolution gives the strong impression of a weaker lined spectrum, in that the smoothed spectrum of HD30562 on top comes considerably closer to duplicating that of HD105755 in the middle than the unsmoothed spectrum of HD30562. This effect illustrates the potential degeneracy between spectral resolution and line strength, a confusion which can also be challenging to disentangle.

A further point is that the great majority of information in the spectra is highly redundant, with only a handful of key features supplying unique information. For example, a close look at the strength of the SrIIλ4077 feature in Fig. 4 reveals that it is noticeably stronger in HD30562 than in HD157214. This is due to the lower surface gravity in HD30562 (log g=3.75) than in HD157214 (log g=4.27), which is reflected in the ionization balance that affects the strength of the singly ionized strontium feature relative to neighboring neutral iron lines. Thus the clean separation of atmospheric parameters requires a careful optimization of the spectral features to be employed, which poses a considerable challenge to automated spectral classification methods.

To further illustrate the subtlety of atmospheric effects, in Fig 6 we plot the spectra

of three late F/early G stars covering a range in surface gravity. The top star, HD187691 has log g=4.4, the middle star, HD111812 is a luminosity class III G0 star, and the bottom spectrum is of the star HD204867, a G0Ib star with log g=1.3. The most striking change along the sequence is in the strength of the SrIIλ4077 feature.

In short, the above illustrations indicate that optimization of the specific spectral features and criteria to be employed in extracting atmospheric parameters from stellar spectra, as well as the methods used to define the features, requires careful consideration. It is hoped that this library will serve as a useful tool in that regard for a variety of studies that will advance our understanding and utilization of stellar spectra.

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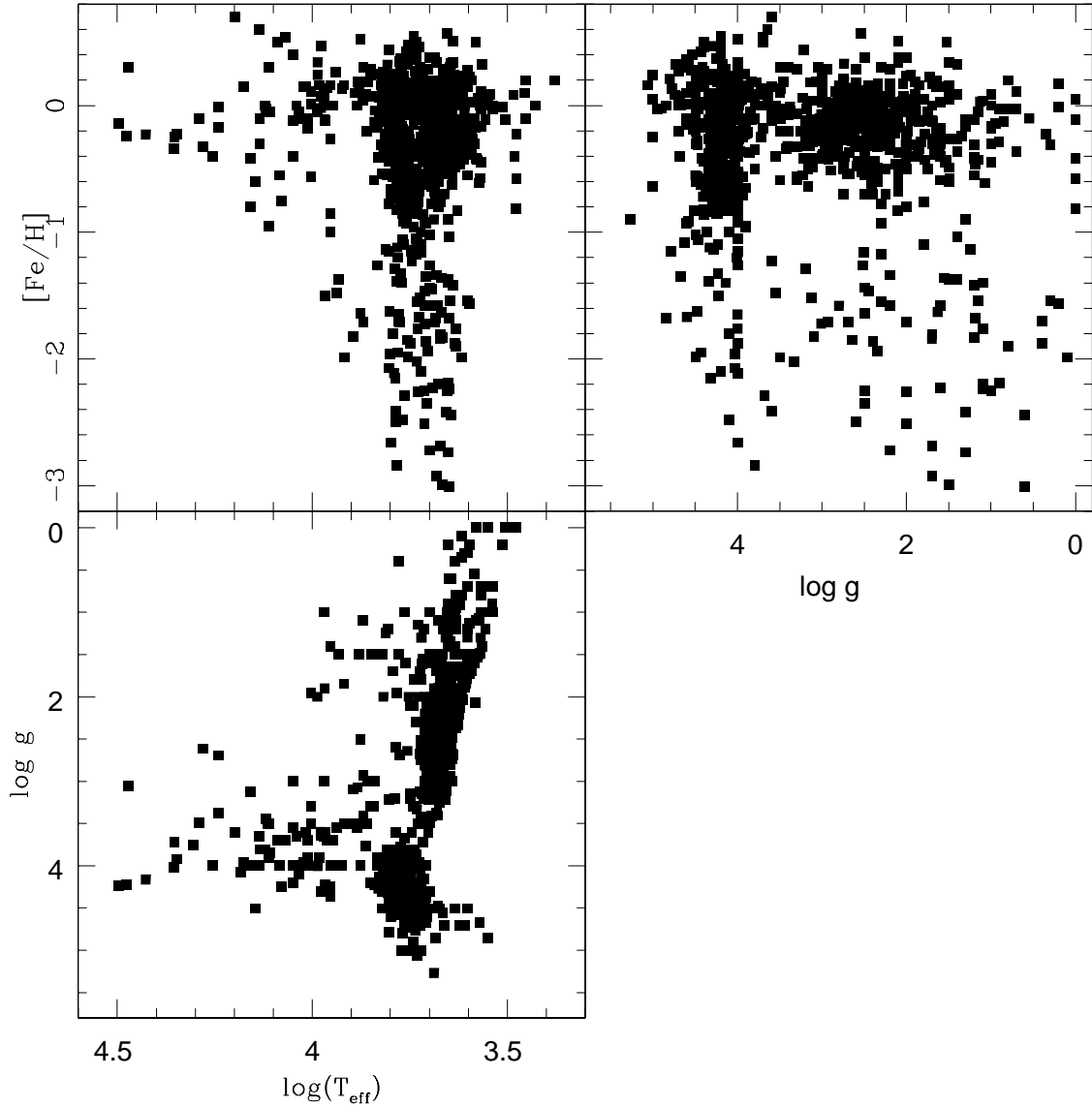Vazdekis, A., & Arimoto, N. 1999, ApJ, 525, 144

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Fig. 1.— The T$_{eff}$, [Fe/H], and log g coverage of the Coudé Feed spectral library. Coverage of the parameter space at temperatures hotter than 6000 K is limited. Note that a number of stars known to be dwarfs but with poorly determined log g have been assigned log g = 4.
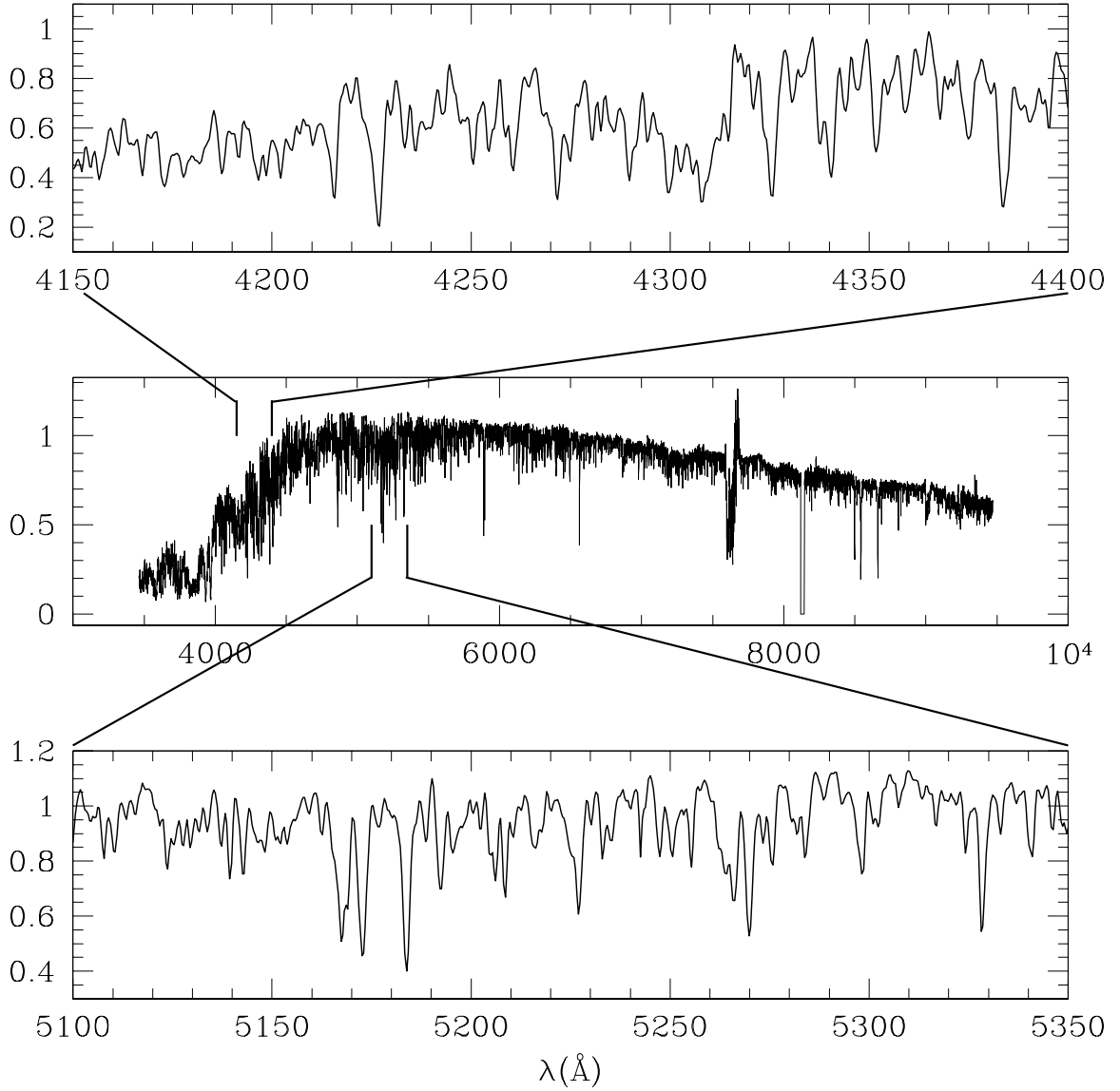
Fig. 2.— The spectrum of the K0III HD4128 is plotted, with expanded regions to show the large information content of the spectrum. Given that the S/N ratio exceeds 100:1 per pixel, essentially all features discernible in the spectrum are real.
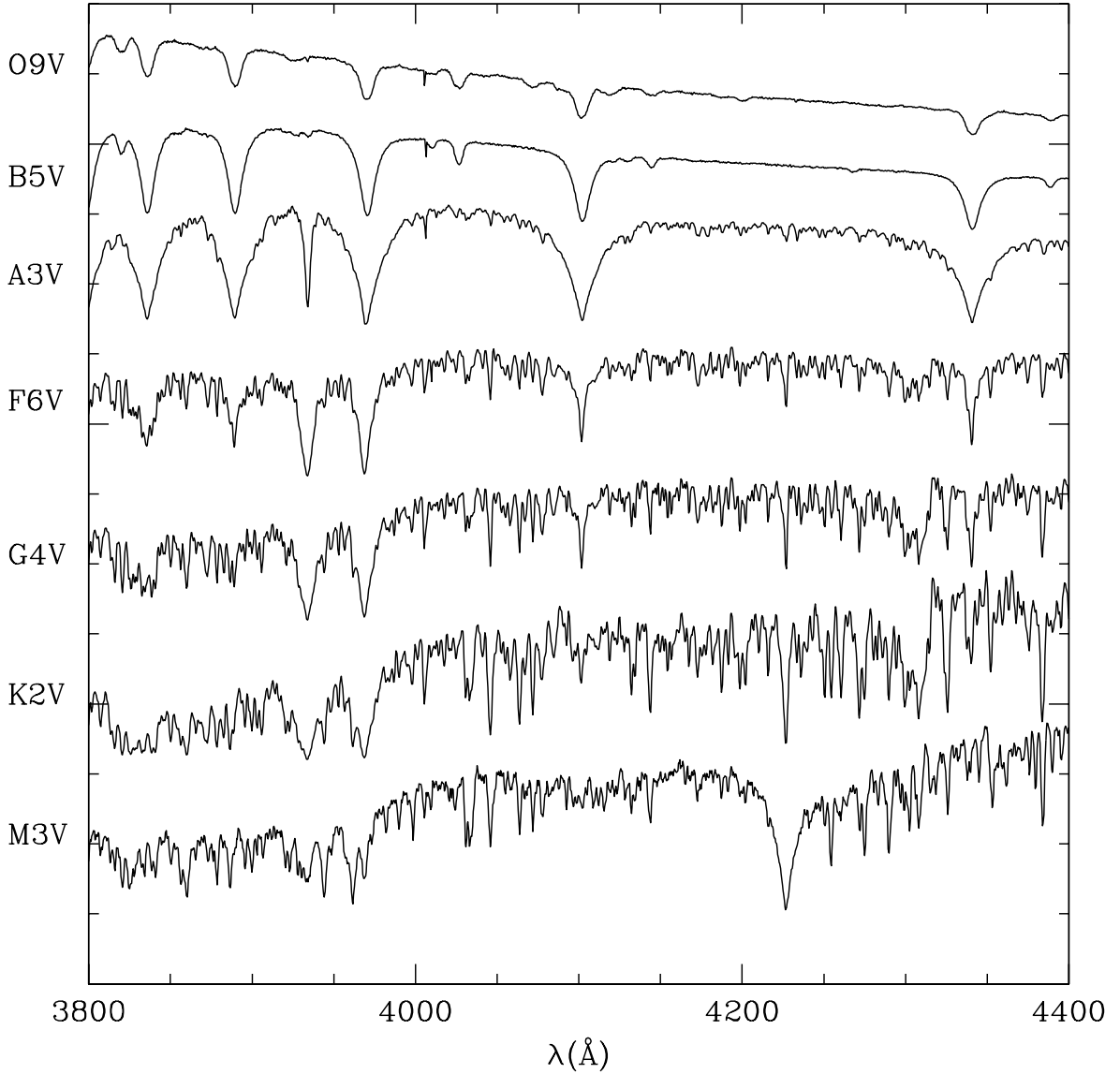
Fig. 3.— Spectra of 7 dwarf stars, covering a large range in MK spectral type, are plotted in the blue, to illustrate the basic dependence of spectral features with MK type. The stars plotted, top to bottom, are HD149757, HD158148, HD163624, HD173667, HD52711, HD166620, and HD173739. The spectral types are listed on the vertical axis.
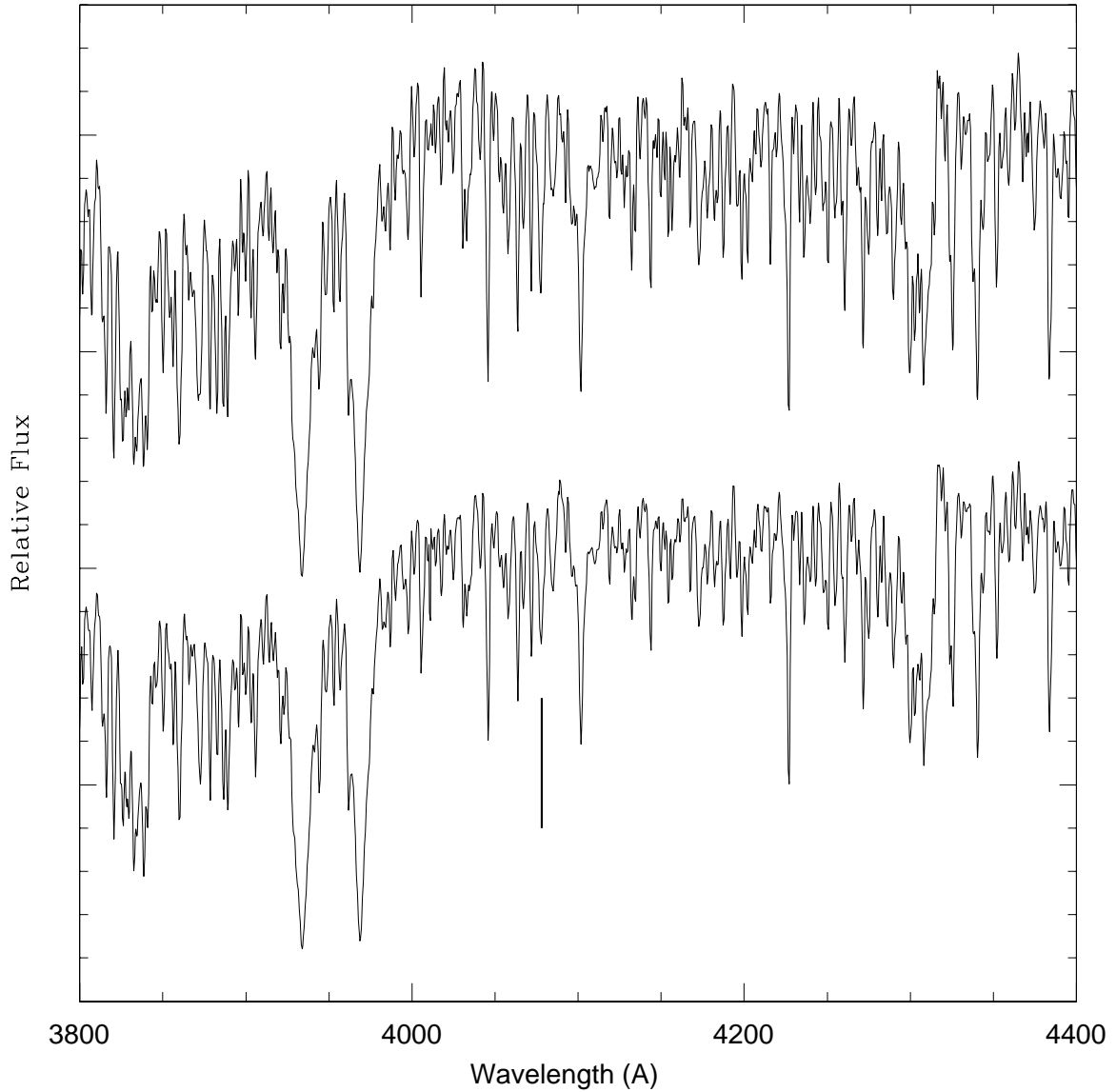
Fig. 4.— The spectrum of the metal-rich star HD30562 (top spectrum), with [Fe/H]=+0.14, is compared with that of the metal-poor star HD157214 (bottom spectrum), with [Fe/H]=-0.41. The remarkable similarity of the two spectra illustrates the degenerate effects of T_{eff} and [Fe/H] on the appearance of the spectra.
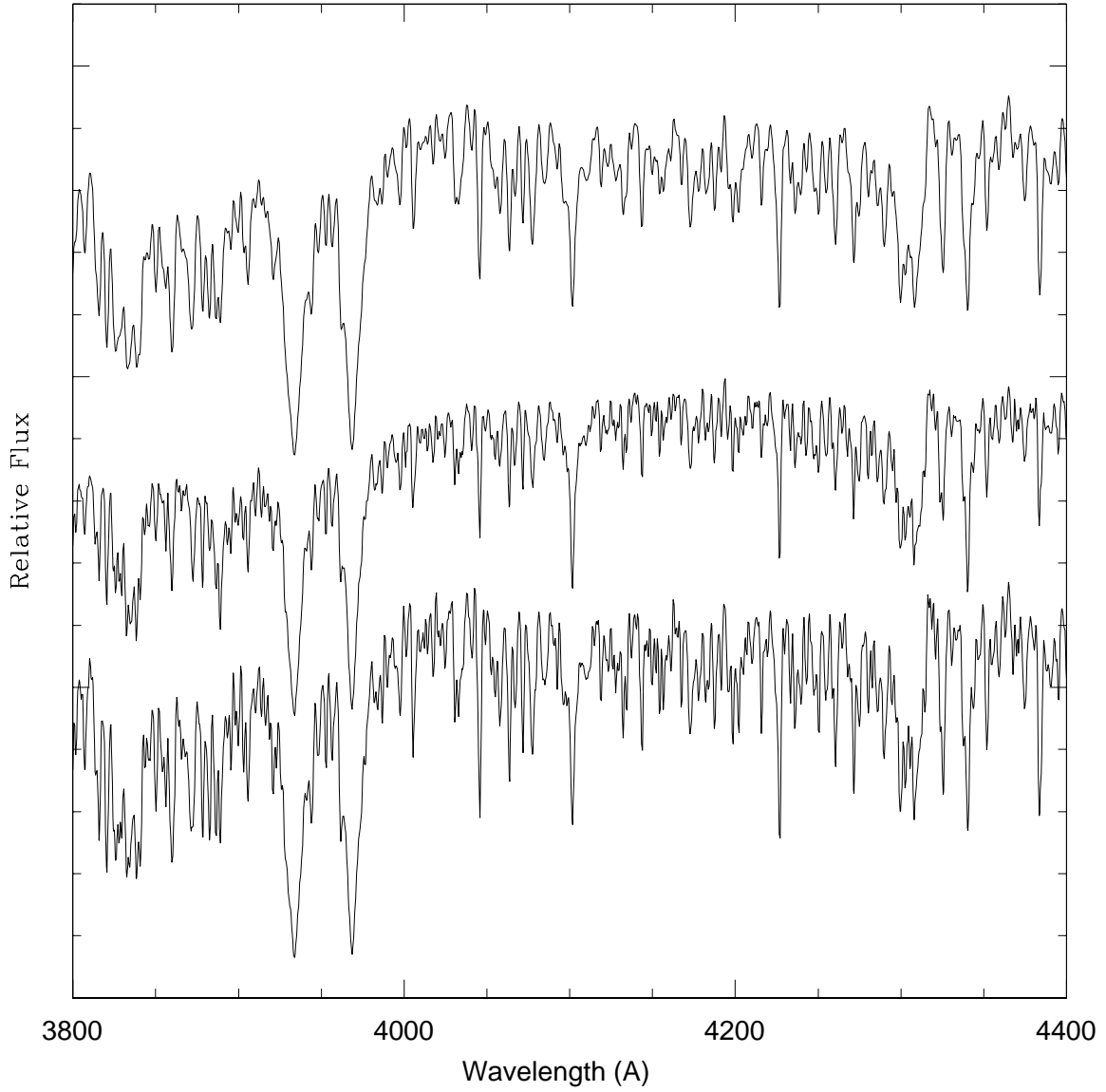
Fig. 5.— The unsmoothed (bottom) and smoothed (top) spectra of HD30562 are compared to the unsmoothed spectrum of the metal-poor star HD105755 (middle). In the top spectrum HD30562 has been smoothed with a gaussian σ of 1.5 pixels.
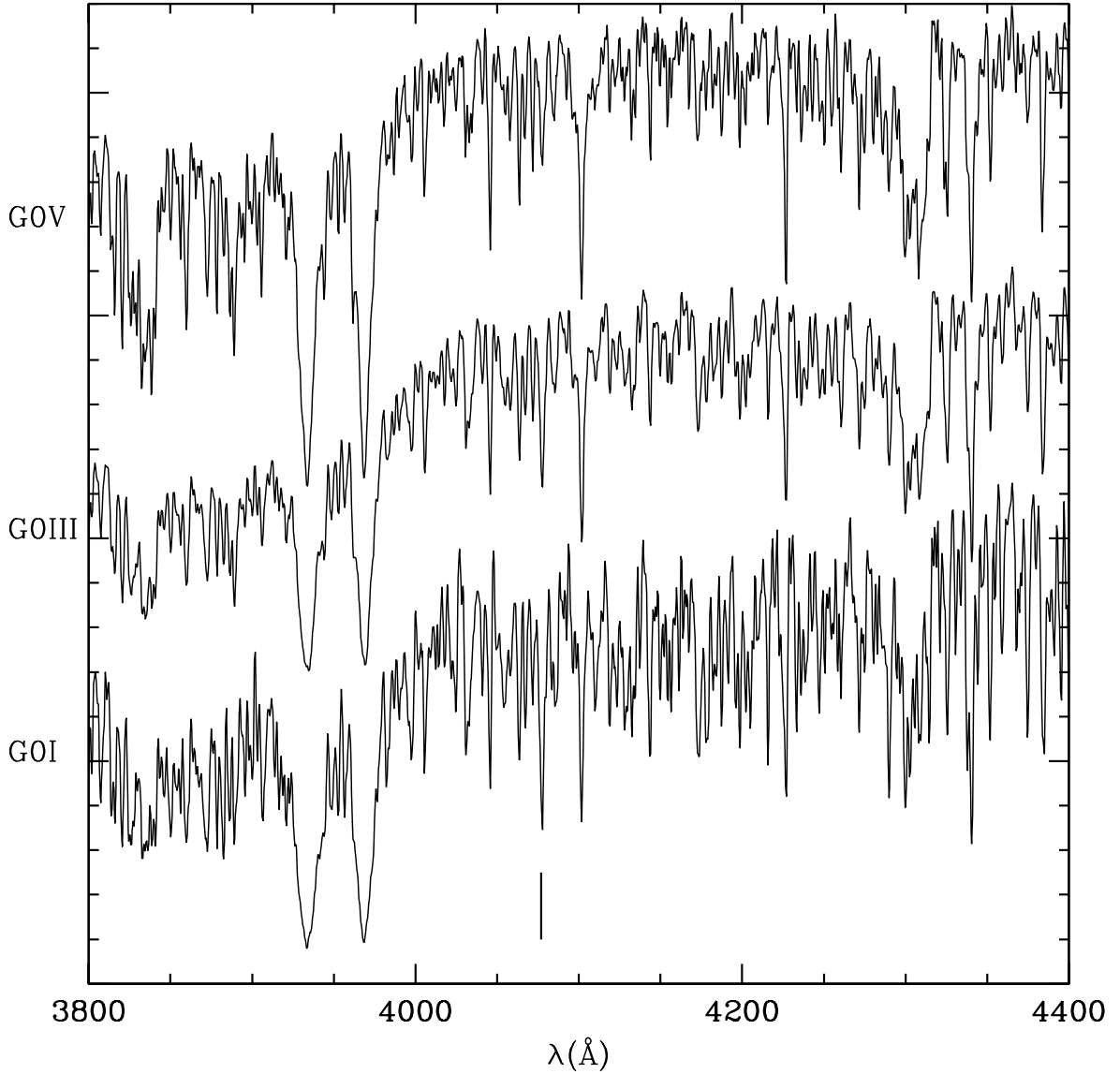
Fig. 6.— The spectra of three G0 stars with differing luminosity classes are compared, again in the restricted blue wavelength region. From top to bottom they are the G0V star HD184499, the G0III star HD111812, and the G0Ib star HD204867. The singly ionized SrIIλ4077 line, which shows strong sensitivity to luminosity class (i.e., surface gravity), is specifically marked in HD204867.

Table 1.   Wavelength Regions for Telluric Lines.

Start Wavelength	End Wavelength
6863	6964
6983	7058
7163	7400
8128	8393
8902	9600

Table 2.   Observational Parameters

Star ID	α (2000)	δ (2000)	V	B-V	N	Coverage (Å)	Gaps (Å)
G 4-44	02:51:58.36	+11:22:11.9	8.38	0.54	3	3465.0-7265.8	
G 5-40	03:27:39.70	+21:02:30.0	10.79	0.57	3	3465.0-7269.4	
G 7-6	03:50:22.97	+17:28:34.9	7.52	0.66	4	3465.0-8126.2	
G 11-45	12:12:28.84	-03:05:04.1	7.50	0.65	4	3465.0-8127.4	
G 12-21	12:12:01.37	+13:15:40.6	10.18	0.47	4	3465.0-8104.2	5413.0-5465.4
G 12-22	12:12:57.53	+10:02:15.8	7.92	0.79	3	3465.0-8106.2	4763.8-5467.4
G 12-24	12:13:13.12	+10:49:18.0	7.56	0.68	6	3465.0-9451.8	
G 15-20	15:22:42.55	+01:25:07.1	8.30	1.00	4	3465.0-8121.0	
G 16-13	15:50:58.93	+08:25:23.8	10.01	0.59	6	3465.0-9452.6	5415.8-5462.2
G 16-32	16:09:11.21	+06:22:43.3	5.94	1.03	6	3465.0-9469.0	5415.0-5461.8

Note. — Table 2 is published in its entirety in the electronic edition of the Astrophysical Journal Supplements. A portion is shown here for guidance regarding its form and content.

Table 3.   Physical Parameters

Star ID	Type	Pickles	V (km/s)	$T_{eff}(K)$	$\log_{10}(g)$	[Fe/H]	Reference
G 4-44	G5	G5V	6.2	5750	4.11	-0.69	2000A&A...353..722N (Nissen)
G 5-40	G0	G0V	-117.8	5863	4.24	-0.83	1997A&A...326..751N (Nissen)
G 7-6	G0	G0V	-9.3	5594	4.50	0.07	2001A&A...369.1048P (Prugniel)
G 11-45	G4V	G5V	14.1	5725	-	0.15	1997A&A...323..809F (Favata)
G 12-21	F2	F2V	95.0	5939	4.23	-1.33	2000A&A...353..722N (Nissen)
G 12-22	G8V	G8V	-8.8	5437	4.77	0.13	1998A&AS..129..237F (Feltzing)
G 12-24	G3V	G2V	-29.5	5337	4.00	-0.54	1994AJ....107.2240C (Carney)
G 15-20	K3V	K3V	-30.4	4765	4.47	0.19	1998A&AS..129..237F (Feltzing)
G 16-13	G0	G0V	-51.5	5593	4.00	-1.15	1994AJ....107.2240C (Carney)
G 16-32	K1.5IV	K1IV	-4.0	4768	3.40	-0.07	1999A&A...348..487R (Randich)

Note. — Table 3 is published in its entirety in the electronic edition of the Astrophysical Journal Supplements. A portion is shown here for guidance regarding its form and content.

Table 4.   Cross-references for Star Names

G	HD	BD	SAO	HR	HIP	Alternate
G 4-44	HD 17820	BD+10 380	SAO 93151		HIP 13366	G 76-35
G 5-40		BD+20 571				G 6-11
G 7-6	HD 24040	BD+17 638	SAO 93630		HIP 17960	
G 11-45	HD 106116	BD-02 3481	SAO 138647		HIP 59532	G 13-19
G 12-21	HD 106038	BD+14 2481	SAO 99984		HIP 59490	G 57-39
G 12-22	HD 106156	BD+10 2391	SAO 99991		HIP 59572	G 57-40
G 12-24	HD 106210	BD+11 2439	SAO 99995		HIP 59589	G 57-41
G 15-20	HD 136834	BD+01 3071	SAO 120966		HIP 75266	
G 16-13		BD+08 3095			HIP 77637	
G 16-32	HD 145148	BD+06 3169	SAO 121392	HR 6014	HIP 79137	

Note. — Table 4 is published in its entirety in the electronic edition of the Astrophysical Journal Supplements. A portion is shown here for guidance regarding its form and content.