Chapter One

The History and Philosophy of Stellar Spectral Classification

1.1 EARLY HISTORY

1.1.1 The Pioneers of Spectral Classification

> Thus, ladies and gentlemen, I have endeavored to set before you what the spectroscope has done for astronomy. . . . And much as it has done in the last 10 years we are yet upon the mere threshold of its discoveries.[1]

Prof. C. A. Young, speaking those concluding words before the American Institute at Cooper Union on "The Astronomical Conquests of the Spectroscope," was quite right. They were all witnessing exciting times for astronomy. Just ten years earlier, in 1863, each of Giovanni Battista Donati, George Airy, William Huggins, Lewis M. Rutherfurd, and Angelo Secchi had published pioneering papers on their stellar spectroscopic observations. Joseph Fraunhofer in Munich had first observed solar and stellar spectra in 1814, but after his death in 1826 the science of stellar spectroscopy languished. Brief revivals occurred from J. Lamont setting up Fraunhofer's equipment in Munich again, from William Swan, also a Scottish scientist, and from I. Porro in Paris, but the lasting revival had to wait Donati's modest descriptions of stellar spectra that began in 1860 in Florence.

With similar inspiration to Donati's, perhaps just "in the air" of the times, pioneering research fields in stellar spectroscopy were launched by the other four stellar spectroscopists who published in 1863. It was Airy who started the Royal Greenwich Observatory's extensive program to measure the Doppler motions of stars.

Huggins, from his observatory near London and with his assistant William Miller, pursued the coincidences between laboratory spark spectra and the lines found in stellar spectra. From these comparisons he concluded that "a common chemistry . . . exists throughout the universe" (Huggins 1909). He was also interested in the nature of nebulae, believing that the bright emission lines of some of these were due to nitrogen, not a mysterious 'nebulium.' He also investigated novae and cometary spectroscopy.

Rutherfurd was clearly a skilled instrumentalist who experimented with celestial photography and making diffraction gratings. From his private observatory in

[1] C. A. Young, as reported in the *New York Tribune*, Tuesday, January 28, 1873, p. 3.

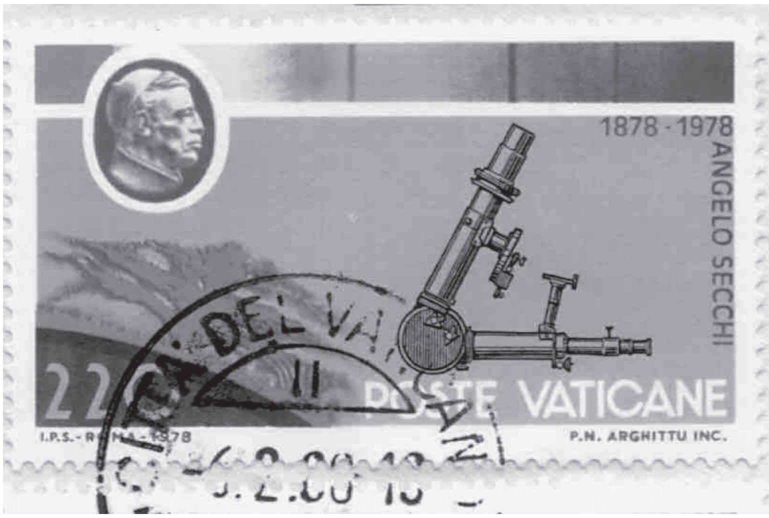

Figure 1.1 Vatican stamp commemorating the centenary of Father Angelo Secchi's death. Reproduced by permission of the Vatican City.

New York state he amassed sufficient spectra to attempt the classification of stars into three groups: those showing color like the Sun with many lines and bands; those like Sirius, which are white stars with lines unlike the Sun; and those like Rigel, which are also white but show no lines. Modern equivalent groups would be the late-type stars, the late-B to early-F stars, and the OB stars.

Secchi, after travels in the United States, returned to Italy and became director of the Roman College Observatory. His wide interests covered meteorology, terrestrial magnetism, sunspots and other solar chromospheric phenomena, double stars and comets, besides spectroscopy, as the stamp in Figure 1.1 commemorates. In 1863 he classified the spectra of stars into two classes, basically the early- ("I") and the late-types ("II").[2] In 1866 he added what are now the M-types ("III"), and two years later he identified some faint red stars as type "IV," the carbon stars. Later yet he felt compelled to separate some emission-line stars into a further class, "V." Discovering the carbon stars and correlating their bands with the "reversed spectrum of carbon," the laboratory emission spectrum, was a great achievement of Secchi. He also identified the strong lines in class I as due to hydrogen and surmised from their breadth in Sirius that "this could lead one to estimate the considerable pressure that the gas possesses in the atmosphere of this star" (Secchi 1870).

If we have written a little more on Secchi than on the other spectroscopic pioneers, one reason is because he was the most prolific in observations, with at least 4,000 classified stars to his name. He illustrates a first principle of classification—amass as many specimens as possible. These showed him that there were varieties

[2]The terms "early" and "late" refer to hotter and cooler stars respectively. They came from an understanding of stellar evolution that proved incorrect, but the terms stuck as convenient, a concession made in the 1922 IAU adoption of the Draper classification system.

of stellar spectra that could not be covered by his classes. His examination of the spectra also led him to consider the astrophysics behind the diversity that he found in them.

A competition among these four pioneers is invidious. In a solidly researched and well detailed history of astronomical spectroscopy, on which this shortened account depends, John Hearnshaw (1986, p. 52ff) reviews who might be considered the first stellar spectroscopist, but more telling are the similarities and differences he finds between each. Airy's recording of line positions eventually led to radial velocity work, though Secchi mentioned the possibility while Huggins actually attempted it. Rutherfurd, who prided himself on his efficient instrumentation, included what later became photometric color indices in his approach to classification, while Secchi relied purely on the spectral features. Huggins was interested in the composition of stars and in the physical conditions that led to the spectra seen, and Secchi's own observations brought these same questions to mind. They were all founders, all "caught up in the wave of enthusiasm for spectroscopy which followed Bunsen and Kirchhoff's announcement in 1859 and 1860 of the solution of the mystery of the Fraunhofer lines and their interpretation in terms of radiation theory spectrum analysis" (Brück 1979). Each of the founders had his own emphasis. So while Hearnshaw (1986, p. 77) makes a good case that Huggins be regarded as the founder of stellar spectroscopy, Secchi's pure and prolific approach makes him the father of stellar spectral classification along with the branches of astrophysics that his methodology encouraged.

1.1.2 More Foundational Classification Schemes

Hermann Carl Vogel's spectroscopic research first began at Bothkamp near Kiel, where he was appointed director in 1870, and continued at Potsdam some four years later (Figure 1.2). He combined Secchi's classes III and IV, since they were both based on broad bands, and went on to subdivide the resulting three classes. However, the discovery of helium both in stars and on earth was to revise his scheme in 1895, subdividing his class Ia.

One of the namers of "helium," Norman Lockyer in London, was also to offer his own spectral classification scheme that was developed around 1890. However, the differentiation of stars into ascending and descending temperature branches was based on his "meteoritic hypothesis" for the origin and subsequent evolution of stars (Figure 1.3). In this putting of theory before classification he joined Vogel in what gave rise to his particular scheme. Still, while Lockyer's undisciplined theories and so his classifications were never generally accepted, he did at least distinguish the spectra of giants and supergiants (heating on his ascending branch) from those of dwarfs (cooling, as the Sun was supposed to be doing).

An amateur astronomer, F. McLean, started an objective prism survey down to 3.5 magnitude from his backyard in Tunbridge Wells, Kent, and completed the survey two years later in 1897 when he visited the Cape Observatory, South Africa. His spectral classification system was able from the beginning to include the stars

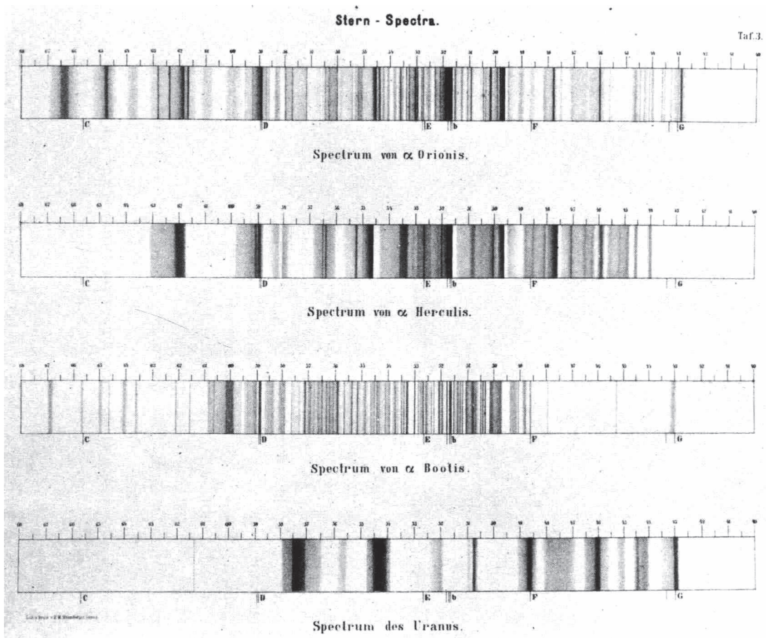

Figure 1.2 Stellar spectra drawn by Vogel at Bothkamp. Reproduced by permission of the Royal Society.

with neutral helium absorption. It was modeled on Secchi's, with Vogel-like revisions, and his groups corresponded to the MK series of B, A, F, G-K, M, and carbon stars. The spectra of stars seemed to be grouping themselves into consistent order, even under the eyes of different classifiers. These observers were also now using photography effectively to give themselves better quality spectra with which to work. One resulting remarkable discovery of McLean was to find that some lines in "helium stars" corresponded to the spark spectra for oxygen.

1.1.3 The Draper System

The developments in spectral classification that took place at the Harvard College Observatory, Cambridge, Massachusetts from 1885 for about four decades are most significant in our story (Figure 1.4). Here we have the energy of Edward C. Pickering who, as director, had the foresight to start an all-sky, spectroscopic survey. That foresight found an ally in Mrs. Anna Palmer Draper, who wanted to give a suitable memorial to the stellar spectroscopic activities of her late husband, Henry.

Accordingly, Mrs. Williamina Fleming was assigned to examine the first survey's spectra, from which came both a classification and an estimate of magnitude for the 10,351 stars in the Draper Memorial Catalogue of 1890. For its classification scheme Pickering and Fleming subdivided the four Secchi types so that thirteen "letter" types resulted, and to these were added O for Wolf–Rayet (WR)

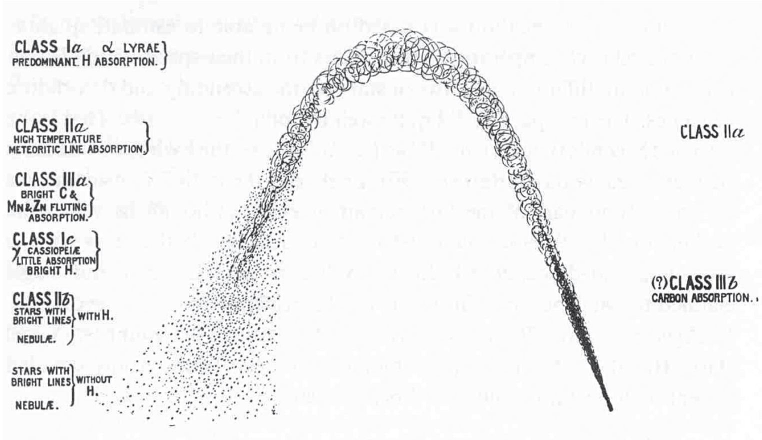

Figure 1.3 Lockyer's temperature curve for spectral evolution, showing his ascending branch of supergiants and giants and the descending branch of dwarfs. Reproduced by permission of the Royal Society.

Figure 1.4 A photograph taken in 1892 at the Harvard College Observatory showing Williamina Fleming (standing) and Annie Jump Cannon (far right, looking through eyepiece). Courtesy, Curator of astronomical photographs at Harvard College Observatory.

spectra with bright lines, P for planetary nebula spectra, and Q for spectra remaining unclassified. So these Draper Memorial types introduced the letters with which we are familiar today. Most of the letters persisted; the O and B types were later put at the head; some were dropped, others changed, such as the C stars with double lines probably due to an instrumental fault; and as always, there was plenty of scope to refine the types by further subdivision. However this was a most significant start, again helped by a much increased database of spectra.

The brighter stars were assigned to Miss Antonia Maury. To classify these more detailed spectra Maury reverted to Roman numerals for her 22 groups, I to XXII, the last being the WR stars. She was the first to place the Orion or B stars ahead of those with strongest hydrogen, the A stars. While she had in mind an evolutionary sequence in doing this, it was not explicitly a temperature sequence. Another innovation was that Maury's groups were further divided according to the appearance of the lines in their spectra. So the addition of lowercase letters would refer to whether the lines were average width (a), hazy (b), or sharp (c). The hazy no doubt included rapid rotators and unresolved double-lined binaries. The c stars were comparatively few in number but were the indication of a "collateral division" among stars, which we now know to be luminosity. Not everyone appreciated such details and divisions, which amounted to some 74 types; the supporters of Vogel's system back in Europe were particularly critical of all these complications in spectral classification.

Miss Annie Jump Cannon entered the Harvard scene to tackle the classification of the southern bright stars. Her 1901 classification scheme reverted to the letter types of Fleming, but updated for the Orion lines in the B stars and the Pickering series lines in the O stars. The letters were in the now familiar MK order—OBAFGKM (Table 1.1), so in this she followed Maury but put the WR stars firmly at the head. To cope with better precision available in the spectra, rather than adding letters along the lines of Maury adding Roman numerals, she was the first to subdivide the letters into decimal types. The notation for these decimal types settled into the now familiar A0, A2, etc. Among the stars not fitting into this scheme Cannon commented on those with peculiar silicon (also noted by Maury) or strontium, and particularly the metallic-line A stars, now called the Am stars.

With the publishing of the last of four catalogues in 1912 the Draper Catalogue was complete, as was its classification scheme. A Committee on the Classification of Stellar Spectra was formed to gather comments on whether this was the most useful scheme to date. The 28 replies from prominent spectroscopists in 7 countries were published by the committee's secretary, F. Schlesinger (1911). Most were favorable to the Draper system, with some understandable support for the Potsdam scheme of Vogel. Interestingly, Henry Norris Russell supported the non-alphabetical order of the letters since "This helps to keep the novice from thinking that it is based on some theory of evolution" (ibid.); and of significance was Karl Schwarzschild's recommendation to keep the number of variables limited since "ultimately the spectrum of a star might depend on nothing other than its mass, its age and its temperature" (ibid.). The tentative adoption of the Draper system became formal in Rome at the first General Assembly of the International Astronomical Union in 1922 (IAU 1922).

Work on peculiar stars continued at Harvard, particularly by Fleming up until her death in 1911. In October of that year Cannon started what Newall (1920) well described as "a piece of work of colossal magnitude," the Henry Draper (HD) Catalogue program (as distinct from the earlier Draper Catalogue of Stellar Spectra)

Table 1.1 The Principal Early Spectral Classifications

Secchi type	Vogel class	McLean division	Lockyer genus	Pickering class[a]	Maury group	Cannon class[b]
(V)	–	–	–	P	–	P
(V)	IIb	(Ia)	Argonian	O	XXII	Oa
(V)	IIb	(Ia)		O	XXII	Ob
(V)	IIb	(Ia)		O	XXII	Oc
(V)–I*O*	IIb	(Ia)		O	XXII	Od
(V)–I*O*	IIb	(Ia)		O	XXII	Oe
I*O*[c]	Ib	Ia		B	I	Oe5
I*O*	Ib	Ia	Alnitamian	B	II	B0
I*O*	Ib	Ia		B	III	B1
I*O*	Ib	Ia	Crucian	B	IV	B2
I*O*	Ib	Ia	Taurian	B	IV	B3
I*O*	Ib	Ib		BA	V	B5
I*O*–I	Ib	Ib	Algolian	BA	VI	B8
I*O*–I	Ib	Ib	Rigelian	BA	VI	B9
V	Ic1, Ic2	–	Crucian	D	L	OeSp-B9p
I	Ia2	II	Markabian	A	VII	A0
I	Ia2	II	Sirian	A	VIII	A0
I	Ia2	II	Cygnian	A	VIII	A2
I	Ia2	II		AF	IX	A2
I	Ia3	III		AF	IX–X	A3
I	Ia3	III		AF	X	A5
I	Ia3	III		F	XI	F0
I	Ia3	III		F	XI–XII	F2
I–II	Ia3–IIa	III	Procyonian	FG	XII	F5
II	IIa	IV	Polarian	G	XIII	F8
II	IIa	IV		G	XIV	G0
II	IIa	IV		GK	XIV–XV	G5
II	IIa	IV	Arcturian	K	XV	K0
II	IIa	IV		K	XV–XVI	K2
II–III	IIa–IIIa	IV–V	Aldebarian	KM	XVI	K5
III	IIIa	V	Antarian	Ma	XVII	M0 (Ma)
III	IIIa	V		Ma	XVIII	M0 (Ma)
III	IIIa	V		Mb	XIX	M3 (Mb)
III	IIIa	V		(Mc)	–	M6,5 (Mc)
III	IIIa	V		Md	XX	Md
–	–	–		–	–	S
IV	IIIb	VI			XXI (?)	R0
IV	IIIb	VI			XXI (?)	R3
IV	IIIb	VI			XXI (?)	R5
IV	IIIb	VI			XXI (?)	R8
IV	IIIb	VI	Piscian	Na	XXI	N0 (Na)
IV	IIIb	VI			XXI	N3 (Nb)
IV	IIIb	VI			XXI	Nc
–	–	–	–	–	–	Pec
–	–	–	–	–	–	Con

[a] In collaboration with Mrs. Fleming.
[b] The Draper Classification.
[c] Secchi's Orion subtype.
From Hearnshaw (1986), as adapted from Curtiss (1932).

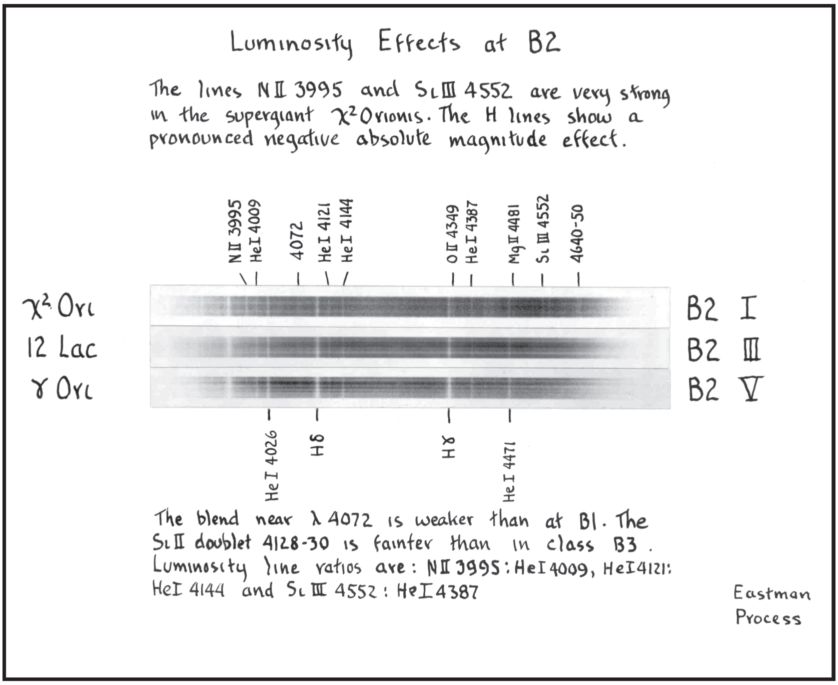

Figure 1.5 A plate from the spectral atlas of Morgan, Keenan, & Kellman (1943), showing a luminosity montage at B2. Reproduced courtesy University of Chicago Press.

to classify spectra of 225,300 stars. Four years later the classifying was essentially complete and the catalogue eventually all published by 1924 at the cost of $1 per star—real value for money! Its classification scheme was that of the Draper Catalogue, but with a little revision at the bottom end of the sequence. The earlier types were holding up well, even with such an enormous increase in data.

The HD catalogue was extended under Harlow Shapley, who was interested in questions of galactic structure. The additional 46,850 spectral types for fainter stars in the northern hemisphere, comprising the Henry Draper Extension (HDE), were again on the Draper system, even if G-star types were a bit earlier and M star types a bit later when compared with the main HD catalogue. By the time of her death in 1941 Cannon had classified over 395,000 stars (Hearnshaw 1986, p. 138). While this monument to her achievement will eventually be surpassed numerically by a machine, her profound impact on stellar and Galactic astronomy will certainly remain.

1.1.4 Preparing for the MK System

In the MKK Atlas of 1943 (Figure 1.5), which inaugurated the current MK system of stellar spectral classification, six investigators were acknowledged as having the most important influence on it: Antonia Maury, Annie Cannon, Norman Lockyer, Walter Adams, Bertil Lindblad, and E. Gwyn Williams. This was because the MK system, while inheriting the revised Draper system, brought the second dimension of luminosity firmly into the classification of stars.

We have indicated the development in temperature ordering, initiated by Lockyer, and the general acceptance of the letter and decimal type classes for spectral type, showing Maury's and Cannon's influence. In this story there have also been pointers to how the realization of a second dimension arose by the three astronomers just mentioned. Others involved in this development whom we have not yet mentioned must include Walter Adams and Arnold Kohlschütter working at the Mt. Wilson Observatory, with Adams later becoming its director. They repeated the discovery by Monck, Hertzsprung, and Russell of the relationship between the intrinsic luminosity of a star and its proper motion and parallax, but also noticed that there were spectral differences between the low and high luminosity stars. They identified some luminosity sensitive lines, and by using ratios of these lines with ones that were insensitive they calibrated a star's luminosity ratios against its absolute magnitude. The technique of spectroscopic parallaxes was born and with it a new way to probe Galactic structure. As an historical note, it was Adams who chaired the Spectral Classification Committee of the Rome IAU in 1922. An earlier historical curiosity was Russell at an RAS meeting in 1913 attributing the terms "giant" and "dwarf," perhaps erroneously (Hearnshaw 1986, p. 215), to Hertzsprung while discussing the diagram that later would carry both their names (thanks to Bengt Strömgren).

Lindblad is acknowledged in the MKK Atlas both for his connecting the width of the wings of Balmer Hζ with the luminosity of an early-type star and for discovering the luminosity sensitivity of the CN molecular bands in late-type stars. He started this work around 1921 at Mt. Wilson Observatory, thus inheriting the work of Adams and others, and continued it at Uppsala and Stockholm. From 1931 E. G. Williams also spent a couple of years at Mt. Wilson studying the lines in O and B stars. He showed that line ratios, rather than absolute line intensities, could improve the Draper subtypes for these stars. Among those line ratios were those for the neutral helium singlet-to-triplet series, as discovered earlier by Struve (1928). Struve (1929) also was critical in developing the explanation of the Stark effect for the luminosity sensitivity of hydrogen and helium lines. Another who could have been acknowledged by MKK includes Plaskett (1922), since he clearly separated WR from O stars, but no doubt a line has to be drawn somewhere of whom to mention, as here too.

1.1.5 The MK System

The most obvious new feature of the MK system is its fully-fledged luminosity classes, I to V, attached to the various temperature classes. These were introduced by W. W. Morgan after he had realized that in the $\log g - \log T$ diagram,[3] as in the observational H–R diagram, each grouping of stars from the main sequence

[3] g stands for the *surface gravity* of the star, which is correlated with luminosity class, in that class V stars (dwarfs) have high gravities and class I stars (supergiants) have low gravities. T stands for the *effective temperature* of the star, which is correlated with spectral class. Thus, the $\log g - \log T$ diagram is the theoretical

and upwards in luminosity formed a sequence of near constant log *g*. Stars readily wanted to be grouped according to gravity as well as according to temperature, and this grouping could be done by criteria in their spectra. This discovery was confirmed by Morgan finding that the color photometry of normal stars followed that of their spectral classification, so no third parameter was needed for such normal stars. This insight was taken to heart by Morgan's collaborator, Philip. C. Keenan, and celebrated in the 55 prints, produced by Miss Edith Kellman, of blue-violet slit spectra from the Yerkes 40″ refractor that comprised the 1943 MKK *Atlas of Stellar Spectra*. Just over half of these prints, 23, showed luminosity effects at different spectral types, so the emphasis of the Atlas was clear.

The MKK Atlas certainly also brought refinements to the criteria employed in classification. However, a large set of standard star spectra, "specimens," were included to demonstrate that the classifications were ultimately based on a morphological match with those standards rather than on the criteria, however much refined. So there were advances both in technique and in philosophy within the new system.

Thirteen of the MKK Atlas plates showed peculiarities in spectra. These plates indicated that the scheme was by no means the final word. A greater discrimination was possible and indeed there was "incompleteness in the system itself" (Morgan 1984). Other populations of stars were to be introduced (see §1.2), and new atlases were to be offered by both Morgan and Keenan, for instance, the Keenan–McNeil atlas—Figure 1.6 (Keenan & McNeil 1976)—and the Morgan, Abt, & Tapscott atlas (Figure 1.7, Morgan, Abt, & Tapscott 1978), but this MKK Atlas, with its grid of standard stars as a firm foundation, has remained definitive of the approach to classification by the MK System.

1.2 LATER DEVELOPMENTS

The publication of the MKK Atlas in 1943 introduced to astronomy a new and powerful tool, and Morgan and his colleagues were eager to use this tool to solve some of the "big questions" of the day. One such "big question" was the detection of spiral structure in the Milky Way Galaxy. Spiral structure in the Milky Way's neighbor, the Andromeda Galaxy, is correlated with the distribution of blue giant and supergiant stars, many of which are clustered in *OB associations*, and thus Morgan reasoned that if the distribution of this same class of stars could be plotted in the solar neighborhood, the local spiral structure could be discerned. Work therefore concentrated on deriving accurate absolute magnitudes for the B-type stars, so that their distances could be determined (e.g., Bidelman 1954). In 1951, at a meeting of the American Astronomical Society, Morgan, Sharpless, and Osterbrock announced the detection of spiral structure in the Milky Way (see Figure 1.8). A more detailed analysis was later published in Morgan, Whitford, & Code (1953).

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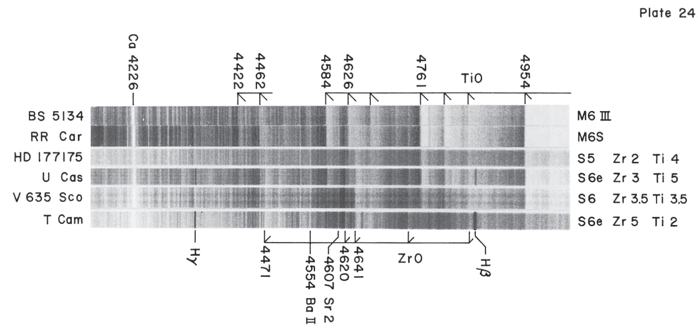
counterpart of the observational Hertzsprung–Russell (H–R) diagram, which plots luminosity versus spectral class. See Chapter 2 for more details on both parameters.



TRANSITION FROM M6 THROUGH M6S TO S6

For most temperature types beyond M1 there is a continuous sequence of stars extending to nearly pure type S (no noticeable TiO bands). Type S is defined by the presence of bands of ZrO, and the strongest and most easily detected of the blue bands are the λ4641 and λ4620 0,0 bands of the α-system ($C^3\Delta$-$X^3\Delta$). The λ4620 head lies just shortward of the λ4626 TiO band, and gives the spectrum a step-like appearance in weak S-stars.

For classification of S-stars the notation introduced by Keenan (1954) involved two numbers, the first giving the temperature type estimated from the total band strength, TiO plus ZrO, and the second being a relative abundance parameter derived from the ratio ZrO/TiO. This was not very satisfactory, and we now propose a revised notation in which the temperature type is followed by the absolute intensities of ZrO and TiO, as shown above for the lower four stars.

The two atomic lines due to heavy s-process elements that can be seen on this plate are Ba II 4554 and Sr I 4607, the latter a resonance line comprising multiplet (2). Both are strengthened in S-type spectra.

Figure 1.6 A plate from the spectral classification atlas of Keenan & McNeil (1976). Reproduced courtesy Raymond McNeil.

Morgan's inspiration that spectral classification could be used as a tool to probe the spiral structure of the Milky Way Galaxy marked the coming of age of the MK spectral classification system as a powerful technique for investigating problems in the fields of Galactic structure and stellar astrophysics. One of Morgan's graduate students, Nancy Grace Roman (Figure 1.9), made a critically important contribution to the study of Galactic structure and evolution. At that time (the early 1950s), astronomers were aware of the existence of two populations of stars in the Milky Way Galaxy, called Population I and Population II. The discovery of these two populations came about through the work of Walter Baade (Baade 1944) who, taking advantage of the blackout conditions in southern California during the war, was able to use the Mount Wilson 100-inch reflector to obtain high-resolution photographs that resolved the nucleus of the Andromeda Galaxy, its dwarf elliptical satellites M32 and NGC 205, as well as the ellipticals NGC 147 and NGC 185 into stars. Baade realized from these photographs that the stellar population in these spheroidal systems was dominated by K-type giants, very unlike the stellar population of the spiral arms of the Andromeda Galaxy and indeed the disk of our own Milky Way Galaxy, which are dominated by B supergiants. This led Baade to suggest that the stars in both Andromeda and the Milky Way could be divided into two populations. In Population I, Baade included the stellar types typical of the Galactic disk, i.e., stars in open clusters, OB stars, and most stars of the solar neighborhood, including the Sun. Population II, on the other hand, included

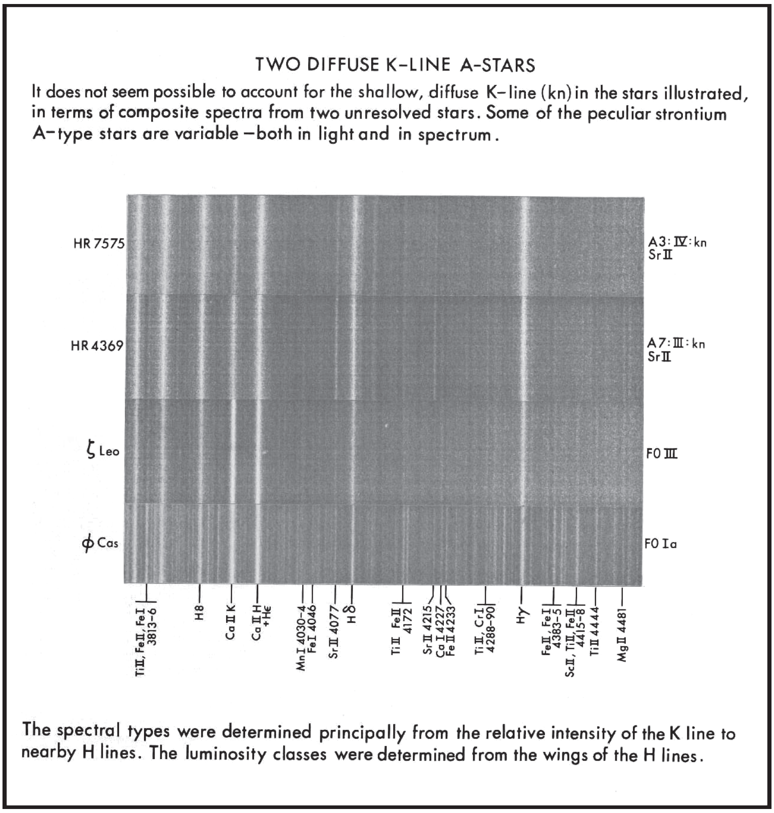


Figure 1.7 A plate from the spectral classification atlas of Morgan, Abt, & Tapscott (1978). Reproduced courtesy Helmut Abt.

some K-type giants, "cluster variables" (i.e., RR Lyrae variables), subdwarfs (i.e., stars that appear to lie below the main sequence on the Hertzsprung–Russell diagram), and stars in globular clusters. One distinguishing feature between the two populations in the Milky Way Galaxy was the velocity relative to that of the Sun. Population II objects are high-velocity objects, whereas Population I stars have low velocities.[4]

It was at this point that the work of Roman supplied a critical missing link. Roman (Roman 1950, 1952, 1954) studied samples of F, G, and K-type stars and discovered, though spectral classification, a set of weak-lined dwarf and giant stars that she found had, as a group, systematically higher velocities than the normal strong-lined stars. These weak-lined (low metal abundance), high-velocity stars were identified as Population II stars passing through the solar neighborhood. This discovery supplied the critical link between stellar kinematics and chemical

[4]The phrase "relative to the Sun" is important here, as the Sun executes a circular orbit around the center of the Galaxy with an orbital velocity of about 240 km/s. Stars executing similar orbits will have low velocities relative to the Sun, whereas stars with orbits out of the plane of the disk and/or elliptical orbits will have high relative velocities.

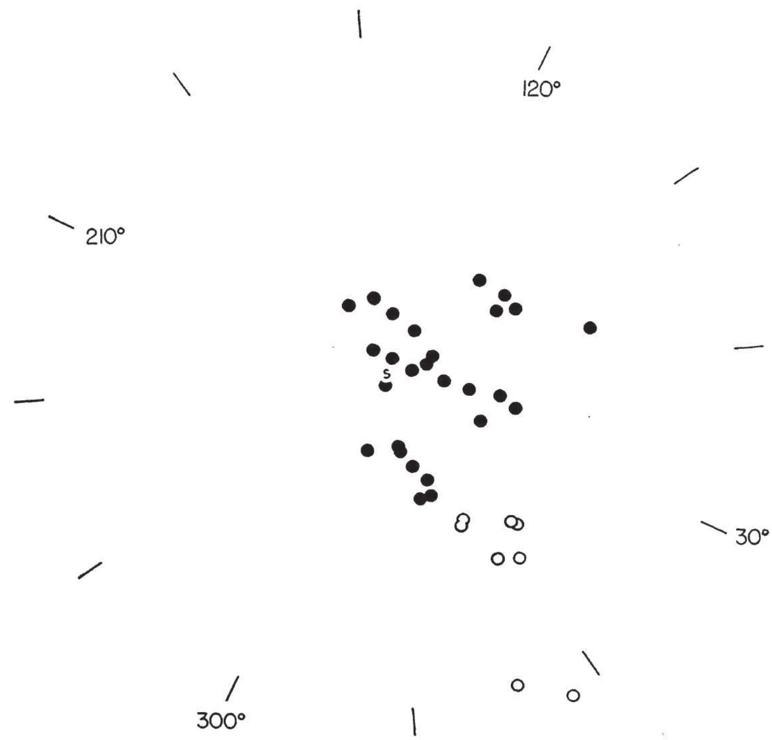


Figure 1.8 The delineation of spiral structure in the Milky Way Galaxy by Morgan, Whitford, & Code (1953) by plotting the space distribution of blue giants. The Sun is marked by an "S" at the center, and the Galactic center is at a longitude of 327° in this figure, toward the bottom of the page. The dark circles represent aggregates (OB associations) of blue giants, whereas the open circles represent single stars. The Sun appears to be on the inner edge of a linear feature, now known as the Orion–Cygnus arm. The linear feature lying between the Sun and the Galactic center is the Sagittarius arm. There is also an indication of yet another spiral arm, external to the Orion–Cygnus arm, now known as the Perseus arm. Reproduced by permission of the AAS.

composition that laid the groundwork for our current understanding of the formation and chemical evolution of the Galaxy. That is to say, the metal-rich nature of the Population I stars could now be understood as a consequence of the fact that they had been formed out of gas enriched with metals produced in the cores of earlier generations of stars. The resulting correlations between position in the Galaxy (bulge and halo for Population II stars, disk for Population I stars), kinematics (elliptical orbits not confined to the disk for Population II stars, versus circular orbits in the disk for Population I stars), and age (as now deduced through metal abundances and H–R diagrams of the two populations; old for Population II stars, relatively young for Population I stars) led to the modern picture of the formation and evolution of the Galaxy.

This ability of spectral classification to probe the structure and evolution of the Galaxy inspired many of the developments and applications of the MK Spectral

Figure 1.9 Nancy Grace Roman. Reproduced with the permission of the Swarthmore College Bulletin. Photographer Jean Gwaltney.

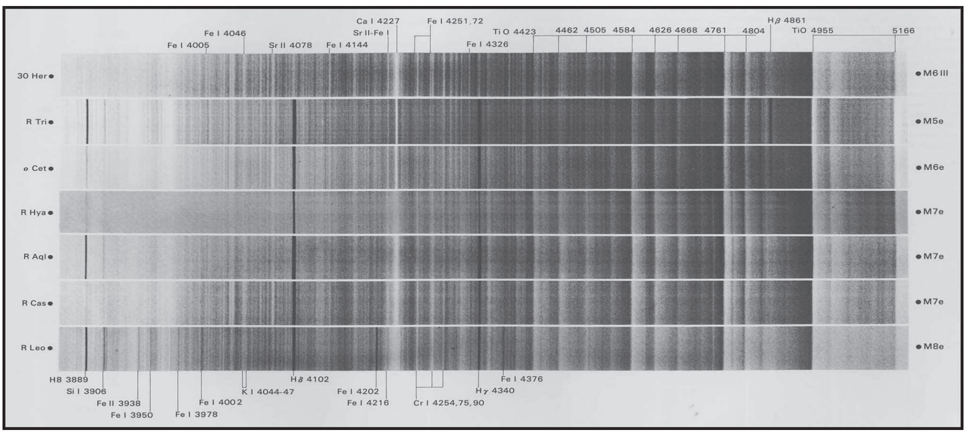


Figure 1.10 A page from the Yamashita spectral atlas illustrating the spectra of the Mira variables (Yamashita, Nariai, & Norimoto 1977). Reproduced courtesy University of Tokyo Press.

Classification system in the two decades that followed. An important development during this period was the invention, by W. W. Morgan and Harold Johnson, of the *UBV* photometric system (see §2.3 and Johnson & Morgan 1953), and its calibration in terms of MK spectral types. This seminal paper contained *UBV* observations of hundreds of field stars as well as many stars in the Pleiades and two other open clusters. These observations enabled the absolute-magnitude calibration of the B-type stars, the development of the "Q Method" for determining the reddening of B-type stars due to interstellar dust, and the definition of the "standard main sequence." The luminosity classification of the B-type stars was also refined in this paper, including the subdivision of the supergiant "I" class into luminosity types Ia and Ib (see §2.2.4). These developments made practical the determination of accurate distances to B-type stars, OB associations, and open clusters, and thus helped astronomers to refine and extend the spiral structure discovered by Morgan and associates in 1951. These studies reached their culmination with the discovery of the major Sagittarius–Carina spiral arm, and the presentation of the detailed local spiral structure based on optical tracers by Humphreys (1976).

In the decades of the 1960s through the 1980s, major efforts were made to study both spectroscopically and photometrically the bright O and B field stars (Lesh 1968; Hiltner, Garrison, & Schild 1969; Garrison, Hiltner, & Schild 1977) and many open clusters and OB associations (see Humphreys 1978) in the Milky Way Galaxy, and the most luminous OB supergiants in the Magellanic Clouds and the Andromeda Galaxy. These decades also saw the initiation of ambitious objective-prism surveys, such as those of Sanduleak, Stephenson, & Pesch (for instance, the Luminous Stars in the Northern and Southern Milky Way surveys, and the Case Low-Dispersion Northern Sky Survey) and MacConnell (for instance, his Hα and M-supergiant surveys) as well as the HD reclassification project, carried out by Nancy Houk (see, for instance, Houk 1994). These studies have had far-reaching consequences for the study of Galactic structure and stellar evolution. It is impossible in the space available to review the many results from these investigations, but a few of the more outstanding include the following: the establishment of the Humphreys–Davidson limit for the most luminous stars in a galaxy (see §11.2), the recording of the progenitor spectrum of SN1987A (Sanduleak –69° 202), the delineation of the detailed local spiral structure (see above), the discovery of the WO class of Wolf–Rayet stars (Sanduleak 1971), and the construction of a composite zero-age main sequence based on cluster H–R diagrams (Garrison 1978).

During these years, and continuing on to the present date, the MK system itself has undergone refinement and extension. These modifications to the MK system have included (1) an extension to both hotter and cooler stellar types, (2) the addition of dimensions other than those of temperature and luminosity, and (3) the extension to other wavelength regions, including the ultraviolet and the infrared. These extensions and refinements will be discussed in detail in later chapters, but it is worthwhile here to place them in the context of the historical development of the MK system.

On the original MKK (1943) system, the hottest O-type standard star, ζ Pup, was classified as O5, and the coolest main-sequence star was classified as M2 V. Later spectral atlases extended these limits to O4 (MAT atlas) and M5.5 (Keenan & McNeil atlas, based on the work of Boeshaar 1976). Walborn (see Chapter 3) first extended the hot limit to O3 in order to describe the spectra of certain stars in the η Carinae region (Walborn 1971), and then much more recently to O2 (Walborn et al. 2002), again based on the same hot O-type stars in the Carina Nebula, but this time using spectral features revealed in new, high signal-to-noise digital spectra. On the cool side, the main sequence was first extended in a systematic way to very late M-type dwarfs (M9) by Boeshaar & Tyson (1985) and then later by Kirkpatrick, Henry & McCarthy (1991) (see Chapter 9 for more details). The discovery of brown dwarfs necessitated the further extension of the MK spectral classification system first to the L-type dwarfs (see Chapter 9 and Kirkpatrick et al. 1999) and then to the ultra-cool T-type dwarfs (see Chapter 10 and Burgasser et al. 2002). It is possible that the MK system will need to be extended to even cooler objects, once those objects are discovered and observed spectroscopically.

The MK spectral classification system, at its outset, was designed to be a two-dimensional system with the dimensions corresponding to temperature and luminosity. But stars show a wild diversity that cannot be accommodated in a strictly two-dimensional classification system. As a consequence, additional dimensions, usually confined to limited regions of the H–R diagram, have been added. Keenan & McNeil (1976) and later Keenan (1985) first introduced the use of abundance indices to classify the metal-weak, metal-strong, and chemically peculiar G- and K-type giants. A perusal of the later chapters of this book will reveal a number of instances in which the MK system has been extended by the use of additional indices or dimensions, related not only to chemical abundances, but also to the presence and strength of emission lines and other spectral features.

The canonical MK system is based on spectra in the blue-violet spectral region. This choice was dictated by the spectral sensitivity of photographic emulsions of the first half of the twentieth century, but it has turned out to be a good choice for a number of reasons. One reason is that the blue-violet region has a much higher density of spectral lines than the red, and this is especially true for lines sensitive to the luminosity dimension. However, there are advantages to either setting up parallel classification systems in the ultraviolet and the infrared, or extending the applicability of the MK system to those spectral regions. For instance, the hottest stars are brightest in the ultraviolet, and thus the ultraviolet should be the natural realm for classification for those stars. Likewise, the coolest stars peak in the red and near-infrared, and so are best observed and classified there. Morgan himself advocated setting up completely autonomous classification systems in the ultraviolet and infrared (Morgan 1984), but as a matter of fact, the MK system and spectral types have, with a few exceptions, transferred quite successfully to those spectral regions. For some spectral classes this has been quite a surprise. For instance, the ultraviolet spectral region of the O-type stars is dominated by wind features, and it was thought that these features would be poorly correlated with the optical-region spectral types. But it turns out that these wind features correlate beautifully with spectral sequences established in the blue-violet (see Chapter 3).

Spectral classification systems for the O- and B-type stars have been set up in the ultraviolet (see Chapters 3 and 4 and Walborn et al. 1985; Walborn, Parker, & Nichols 1995; Rountree & Sonneborn 1993) and the infrared (see §3.4 and Hanson, Conti, & Rieke 1996). We will also present spectral sequences in the ultraviolet for the A-, F-, and G-type stars and in the infrared for A-type and cooler stars in later chapters of this book.

The large-scale photometric and spectroscopic surveys that are currently in progress, or in the planning stages, such as the Sloan Digital Sky Survey, *Gaia*, and RAVE (the RAdial Velocity Experiment) are one of the hallmarks of the current era of astronomical research. These surveys are returning and will return massive amounts of data, including stellar spectra. For instance, the sixth data release of the Sloan Digital Sky Survey brings the total number of stellar spectra observed in that project to nearly 300,000. While this is comparable to the number of stellar spectra Annie J. Cannon dealt with in her lifetime, *Gaia* will collect low-resolution spectra of hundreds of millions of stars. Such enormous quantities of spectral data cannot be classified using the traditional visual techniques employed by MK spectral classification; automatic methods of classification will have to be used. Such methods are currently under development, and are the subject of §13.5 of this book.

1.3 THE MK PROCESS

1.3.1 The Importance of Classification

Classification lies at the foundation of many of the natural and physical sciences because of the need to organize vast quantities of data into a manageable system. What, for instance, would the state of modern biology be without a comprehensive system for organizing the hundreds of thousands of species of plants, animals, and bacteria? But classification plays other roles besides mere organization. Classification is often the beginning of understanding and insight, achieved by perceiving relationships between disparate groups of objects. Classification can also identify the truly peculiar object, the object that does not fit comfortably into the general reference frame. Such objects are worthy of further study, as the peculiarity can often yield deep insights into the meaning and nature of normality.

The MK Spectral Classification System has served as the general reference frame for the classification of stellar spectra for over 60 years. In the previous two sections, we have reviewed the history of this system of classification; in this section, we delve more deeply into its philosophy and practice.

1.3.2 The Importance and Use of Standard Stars

The MK system is an example of a classification system set up using the principles of the *MK Process*. The MK Process is an Aristotelian, inductive approach to classification in general (Garrison 2001), which means that it is a methodology that formulates a classification system based on *specimens*, and that these specimens serve to define the system. In the case of the MK system, these specimens are the spectra of *standard stars*. Consistent with the MK Process, the MK system uses only the information present in the spectrum for classification purposes, and does not admit external information, such as information from photometry, theory, calibrations, or any other source into the determination of the classification of a particular star.

The autonomous nature of the MK system has been the key to its long-term stability and success, and means that the MK type is actually a fundamental datum of astronomy. The importance of keeping the classification system independent of theory and calibrations is clear. If the classification is based, even in part, on theory or a calibration, then when that theory or calibration changes (as it inevitably will), the classification will also then need to be changed. If, on the other hand, the classification is based only on comparison of the spectrum with the defining standards, the classification will be unchanged even when the theory or calibration changes. The resulting independence of the classification system means that when it is confronted with theory or another autonomous classification system (for instance, one based on photometry), that confrontation will be fruitful, and can yield new information and insights.

MK standard stars are those stars that have been selected to best exemplify the spectral class they represent. Spectral classification is carried out by comparing the unknown with the standard spectra; the classification is determined once the best match is found. Quite often, the unknown spectrum is found to fall between two or more standard spectra. In this case, interpolation is allowed. For instance, along the main sequence, there are standards for spectral types G0 V and G2 V. A star with a spectrum that appears intermediate to these two *spectral boxes* will be given a spectral type of G1 V.

For a system based on the MK Process to work in a practical way, the standards that define that system must be universally accepted. When the first MKK atlas was published (Morgan, Keenan, & Kellman 1943), it was accompanied by a list of standard stars. Later publications by Morgan & Keenan (Johnson & Morgan 1953; Morgan & Keenan 1973; Keenan & McNeil 1976; Morgan, Abt, & Tapscott 1978; Keenan & McNeil 1989) extended and refined the MK system. These publications added standards to the original corpus, and dropped some that had been found to be unsuitable. In addition, with the improvement in the quality of stellar spectra, the spectral types of some of the original spectral standards have been changed, but never enough to dislocate the system. The definition of standards has never been the exclusive preserve of Morgan and Keenan (Figure 1.11). Careful workers in the field, including R. F. Garrison (Figure 1.12), N. R. Walborn and R. O. Gray, have introduced new standards and have also refined the spectral types of existing standards. The introduction of new standards has, of course, played a vital role in the extension of the MK system, via the MK Process, to both hotter and cooler regimes. For instance, the extension of the MK system to the L and T dwarfs (see Chapters 9 and 10) has required the designation of standards for those types. If these new standards are carefully chosen, they will define an internally consistent system, and should survive. If not, they will ultimately be rejected by other classifiers. There is, therefore, in a sense, a "natural selection" process for standard stars!

Historically, the founders of the MK system, W. W. Morgan and P. C. Keenan, practiced somewhat incompatible policies for establishing standards. Morgan always insisted that a given spectral box be defined by a single standard star. Keenan,

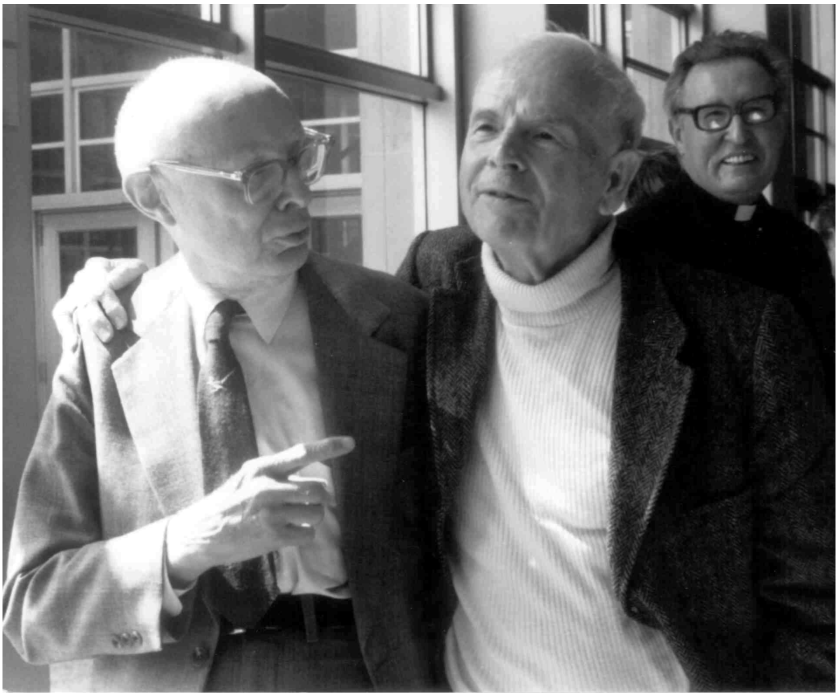


Figure 1.11 Keenan (left) and Morgan at the time of the MK Process conference, held in Toronto, June 1983. In the background is Father Martin McCarthy of the Vatican Observatory. Photo courtesy Nancy Houk.

Figure 1.12 Robert Garrison, Janet Rountree (Lesh), and W. W. Morgan, taken at the MK Process conference, June 1983. Photo courtesy Nancy Houk.

on the other hand, followed the practice of defining multiple standards for a single spectral box; in the Perkins Catalog (Keenan & McNeil 1989), for instance, Keenan & McNeil defined seven (!) standards for spectral class K0 III. Keenan (1994) justified this practice on the need for standards to be available all around the sky, including both the northern and southern hemispheres, but also due to the fact (Keenan 1984) that for the cool stars, and especially for the supergiants, spectral variability at some level is common, and that it is necessary to have as many spectral standards as possible in order to define an average type.

Partly in response to these differences in practice, R. F. Garrison has put considerable effort into systematizing a hierarchy of standards for the MK system (Garrison 1994). One of the purposes of this hierarchy is to ensure the stability of the MK system while at the same time support a flexible enough structure to allow extension and refinement of the MK system in the future. Garrison defines three levels of standards in this hierarchy: (1) the *Anchor Points*, (2) the *Primary Standards*, and (3) the *Secondary Standards*. The Anchor Points are standard stars whose classifications have not changed since the original publication of the MKK system in 1943. But to ensure that these Anchor Points are truly stable and consistent with the MK System of today, they must also have a reliable modern published type by either Morgan or Keenan, R. O. Gray for the A-type stars, Walborn for the O-type stars, or by Garrison himself. As Garrison states, these stars "represent the MK System as it was then and is now." These are the stars that provide the fundamental anchoring definitions for the system. The Anchor-Point standards do not populate a full grid of spectral boxes, however. For instance, there is no Anchor-Point standard for the F8 III box, and many other spectral boxes are unfilled. The Primary Standards help to fill in this grid, and consist of "the best known specimen of each spectral type and luminosity class." Finally, since the Anchor Points and Primary Standards are distributed randomly across the sky, with no attention paid to availability in either the northern or southern hemisphere, or to seasonal access, a set of Secondary Standards with reliable spectral types, checked largely by Garrison himself, but drawn from the lists of other experienced classifiers, is being compiled. These are, as far as possible, situated to be accessible to both hemispheres, and to be spaced in right ascension 6–8 hours apart. Garrison's hierarchical system thus upholds Morgan's stricture of having a single standard define a given spectral box (i.e., the Anchor Points), but at the same time recognizes the practicality of Keenan's approach by establishing standards all around the sky. Appendix A reproduces Garrison's hierarchy as it now stands.

The advent of large telescopes and sensitive detectors has resulted in a mini-crisis in the use of standard stars. Many of the MK standards, including the secondary standards in Garrison's hierarchy, are bright, and will saturate the detectors of even one-meter-class telescopes. Solutions to this problem include observing standards through neutral-density filters or with a stopped-down aperture. But neutral density filters may not be truly neutral, and can introduce artifacts into the spectrum. And stopping down a telescope to a smaller aperture changes the beam size, and thus the optical behavior of the spectrograph. A better solution would be to establish faint secondary standards that can be observed with a large telescope. This suggestion led to the establishment of the *Standard Star Working Group*[5] of the International Astronomical Union, one goal of which was the establishment of MK (and other) standards at the 10th and 15th magnitudes. This is a fairly easy task to accomplish for main-sequence stars, as it is only necessary to select

[5]http://stellar.phys.appstate.edu/ssn

suitable stars on open-cluster main sequences. But to find suitable unreddened giant and supergiant standards at 15th magnitude is very difficult indeed. Another problem is the reluctance of telescope time-allocation committees (TACs) to grant time for adequate observations of standard stars on large telescopes. This practice is understandable, but regrettable and ultimately short-sighted.

1.3.3 The Practice of Spectral Classification

The photographic emulsions available at the time of the original MKK system dictated many of the features of that system. For instance, those emulsions were sensitive only in the blue-violet part of the spectrum, and thus the canonical wavelength region for the MK system became (and continues to be) from about 3800 Å to the vicinity of Hβ (about 5000 Å). Because of the difficulties involved in producing calibrated tracings from these photographic spectra, classification was carried out using the original glass plates. This necessitated widening the spectra (perpendicular to the dispersion), as lines, line profiles, and molecular bands are difficult to see in narrow spectra. The spectrum was widened by trailing the star along the slit during the exposure. Dispersions of 60–150 Å/mm (corresponding, on Kodak IIa-O plates developed with a fine-grain developer, to spectral resolutions of about 1–3 Å) were most commonly used.

Because MK classification is carried out through comparison of the unknown spectrum with the MK standards, the most common way to proceed was to lay one plate (carrying the standard) on top of the plate carrying the unknown spectrum, emulsion to emulsion, and to view both through a dissecting microscope. This is the way that the two primary authors of this monograph learned spectral classification. It was a peaceful, relaxing process; both of us remember long, warm, summer days spent at the David Dunlap Observatory classifying our plates taken at Las Campanas in Chile. Another common technique to compare two or more photographic spectra was to use the spectra comparator (Abt 2003). Classification of photographic spectra could also be an aesthetic experience; while the spectra of rapidly rotating A-type stars are rather ugly, the stark simplicity of the spectra of A- and B-type supergiants is exquisite. Other types of spectra, such as those of the carbon stars, are similarly beautiful. Some of this is lost with modern digital spectra, but not all, fortunately. With photographic spectra, it was vitally important to ensure that the spectral material was as homogeneous as possible. What this meant is that it was necessary not only to obtain the spectra of standards and unknowns using the same telescope and spectrograph, but also to ensure uniformity of photographic development techniques. Standards and unknowns needed to be exposed to the same density so that they could be directly intercompared.

Today almost all spectral classification is carried out using digital spectra obtained with CCDs. The primary spectral region for ground-based spectral classification for O–M-type stars is still the blue-violet region, and the reason for this is no longer the sensitivity of the detector, but rather that this region has the highest concentration of temperature- and luminosity-sensitive criteria, plus, for the

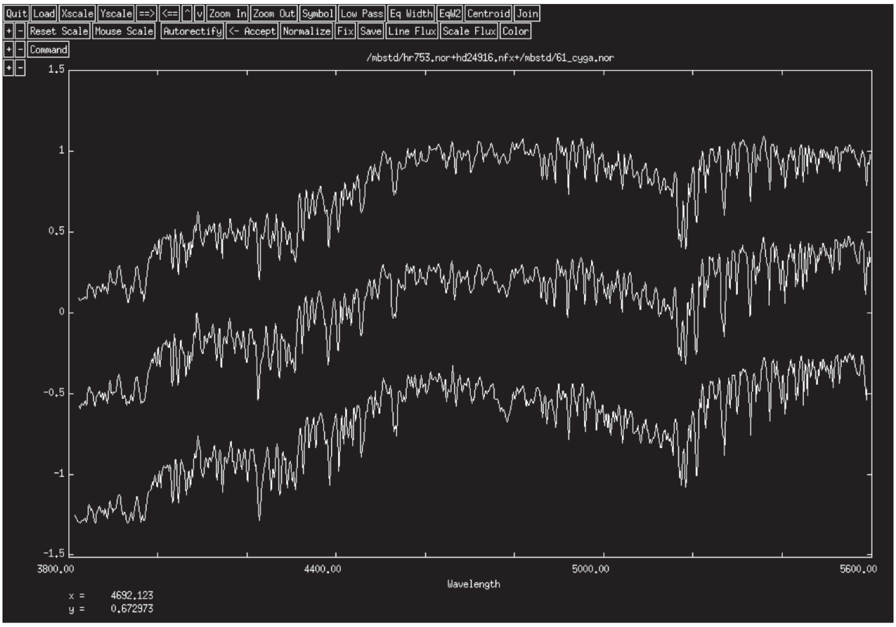


Figure 1.13 Using the authors' program xmk22 to classify spectra. The top and bottom spectra are MK standards for K3 V and K5 V, respectively; the middle spectrum is the unknown. The unknown has been successfully bracketed by the two standards; its spectral type is K4 V. This program is available on the book's website in both its Linux/UNIX version (xmk22) and a Windows version (Winmk)—see Appendix C.

cool stars, a splendid array of molecular bands, including bands of CH, CN, C_2, MgH, and TiO, amongst others. However, the sensitivity of new detectors from the X-ray to the far infrared has opened those regions of the electromagnetic spectrum to spectral classification, and we will describe later in this chapter, and throughout this book, extensions of the MK system to other wavelength regions. The spectral resolution in the blue-violet that seems to be ideal for use with digital spectra is about the same as was used with photographic spectra, i.e., about 1–4 Å (per 2 pixels). Attention to the signal-to-noise (S/N) of the digital spectra is also important; bearing in mind that the equivalent S/N of a well-widened, well-exposed photographic spectrum is on the order of 200–300 (Garrison 2001), precise spectral classification using digital spectra requires $S/N > 100$. Of course, for faint stars, compromise is necessary.

The spectral classification of digital spectra is still carried out by comparing the unknown to the MK standards. For most astronomers engaged in spectral classification, this comparison is still performed visually, but now on the computer screen (see Figure 1.13). However, efforts are now being made to develop techniques to classify spectra automatically, without human intervention; these techniques will be described in some detail in Chapter 13. The best of those techniques are faithful to the MK Process, and involve direct comparison of the unknown with the standards. With digital spectra, it is no longer necessary to widen the spectrum.

However, attention must still be paid to homogeneity of the spectral material; ideally the standards should be observed with the same equipment as the unknowns, and be processed identically. Fortunately, digital spectra allow this requirement to be somewhat relaxed; with modern software it is often possible to manipulate one set of spectra obtained with one instrument to match the resolution of another set of spectra, obtained with another instrument. But still, caution is necessary, as it can be difficult to entirely correct for factors such as scattered light and to exactly reproduce the line-spread function of a spectrograph by digital manipulation.

Spectral classification, whether carried out with photographic or digital spectra, requires the careful comparison of unknown and standard. This comparison is a *unitary* process, which means that all features of the spectrum are used in finding the match between unknown and standard, although this comparison is usually aided by certain *classification criteria*, i.e., lines, blends, line ratios, etc. Morgan (1984) described the process in the following way: "The classification act itself consists of comparisons with the series of standard spectra that define the boxes, with the question 'Is the unknown spectrum (x) "like" or "not like" this particular spectrum?' " Spectral classification is usually an iterative procedure; a rough temperature type is obtained, then a rough luminosity type, and then the unknown is compared in detail with surrounding standards. If the unknown is metal-weak or metal-strong, or chemically peculiar in some way, the comparison process can be even more involved. The complexity of this process is often underestimated by those who have never carried it out, and many think that this procedure is easily transferred to the computer. In reality, however, visual classification, which uses the powerful ability of the human brain to recognize and process complex patterns (such as, for instance, the human face) still has the advantage over the computer. Some continue to decry spectral classification as a subjective process. This is Keenan's (Keenan 1984) answer:

> First, I want to correct a misunderstanding which I hope is not shared by many. It has been said that when classification is carried out by visual inspection of spectrograms the process is purely subjective, and that the classifier is free to make arbitrary changes in the scheme of types assigned to the stars. This is *untrue!* It is subjective only in the sense that the ability of the human eye to match complex patterns is used, but the network of patterns defining the system is the same whether the comparison is made visually or by summing measured intensity ratios, or by deriving an electronic pattern recognition index. If I or anyone else made arbitrary changes in a system, that system would soon cease to be useful.

1.3.4 Extending the MK Classification System

The MK Classification system may be extended in two ways. The first is to extend the system to new classes of stars. Examples mentioned earlier in this chapter included the extensions of the MK system to both hotter and cooler stars, in particular hot O-type stars, and the cool L- and T-type dwarfs. Other examples include the extension to Population II stars, to certain types of peculiar stars, and even to populations of stars in external galaxies. The second way of extending the MK system is to different wavelength regions, for instance the ultraviolet, the infrared, and even the X-rays (see Chapter 3). How these extensions can and should be carried out is the subject of this section.

Excellent examples of how the MK system can be extended to new classes of stars are the subjects of Chapters 9 and 10: the extensions to the L- and T-type dwarfs. The authors of those chapters (Davy Kirkpatrick and Adam Burgasser) played crucial roles in those extensions. Both have a deep knowledge of and appreciation for the MK Process, and both used that philosophical system in their work. Both have described in their chapters how the classification systems were set up. In essence, they followed the advice of Morgan (1984) who stated "It could be said, with some truth, that the spectral forms have helped to classify themselves, by showing where they are most comfortable." What they did was to take a sample of spectra of the new class, and literally spread those spectra out on the floor or desk (see Figure 10.5), and then arrange them into a sequence. This was done without reference to theoretical expectations or preconceived notions; they simply allowed the spectra "to classify themselves." This process not only established the first rough outlines of the new classification systems, but also identified candidate standards and certain objects that did not fit, but were peculiar in some way. In the case of the L-type dwarfs, the sequence that emerged is a temperature sequence, and in both cases the peculiar objects are now being understood in terms of surface-gravity and/or metal-abundance differences. Of course the historical development of the OBAFGKM sequence of the MK system was much more complicated than this (see §1.1), but it is possible to establish that sequence without reference to theory. The authors tested this in 1999 at the Vatican Observatory Summer School, held at Castel Gandolfo, just outside of Rome. We had 25 highly intelligent beginning astronomy graduate students (from 24 countries!), most of whom had had little or no exposure to the MK system. We divided the class into 4 groups and gave each a set of stellar spectra observed in the red, centered on the Hα line, and asked them to arrange those spectra in the most logical order without giving any further guidance. All of the groups, quite independently, came up with the OBAFGKM sequence, simply because they allowed the spectra to show "where they are most comfortable." They also identified a number of peculiar objects. Many of those peculiar objects turned out to be giants and supergiants, and thus they had the beginnings of a luminosity dimension.

Extensions of the MK system have also been made to metal-weak stars, and to the chemically peculiar cool giant stars. How such extensions should be made was a subject of disagreement between Morgan and Keenan. Morgan (1984) insisted that parallel, but independent classification systems should be set up to classify stars of different degrees of metal richness or weakness. For instance, for weak-metal-line stars, Morgan advocated setting up three *systems*, denoted (m-1), (m-2),

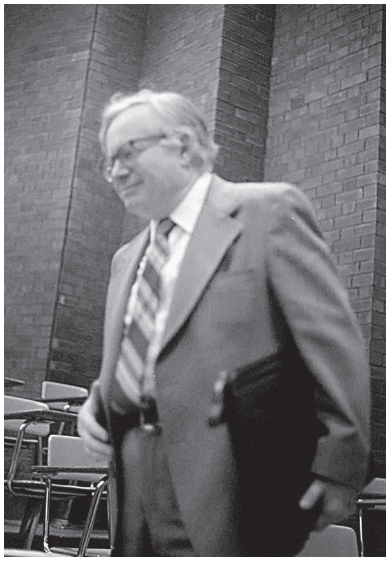


Figure 1.14 William Bidelman, taken at the MK Process conference, June 1983. Photo courtesy Nancy Houk.

and (m-3) for progressively greater line weakening. Morgan also stated: "For such systems to be completely autonomous, we cannot require them to be attachable to the MK System—or to each other. They complement each other; but they each must live separate, independent lives." Keenan (1987) has pointed out, however, that "the great majority of the so-called 'peculiar' stars fall into groups that are not sharply bounded but actually shade into the normal stars of the original MK system" and thus can be best classified by extending the MK system with the addition of further dimensions, rather than by setting up autonomous classification systems. It seems to the present authors that Morgan's approach is best applied to setting up classification systems in other wavelength regions, as these regions may sample different layers of the stellar atmosphere than the optical. There is thus ample reason to keep such classification systems independent of the original MK system. But setting up independent and autonomous systems in other contexts is not necessarily the best approach. Nature, at least on the macroscopic scale, is much more often characterized by continua than by jumps and discontinuities, and it is only right that our classification systems should reflect that reality, instead of imposing boundaries where they do not exist in the natural world.

The discussion in the previous paragraph suggests that classification systems set up in other wavelength regions should be kept independent of the original MK system in the blue-violet. What that means is that when one is seeking to set up such a classification system, it is really necessary to start from scratch. One should not assume, for instance, that a good standard in the blue-violet is also going to be a suitable standard for the ultraviolet or the infrared. Indeed, the procedure one follows should be similar to that followed by Kirkpatrick and Burgasser when they set up the classification systems for the L and T dwarfs (see above and Chapters 9 and 10). Obtain as large a sample as possible of spectra of stars in the wavelength region of choice, and then attempt to find sequences. Spectral classes should be defined, as much as possible, by the appearance or disappearance of some major spectral feature (for instance, the boundary between the O and B classes in the original MK system was fixed at the point where lines of He II disappear from spectra of classification resolution). These spectral classes need not correspond to the original MK classes. Chances are, there will be a fairly close correspondence unless one chooses a spectral region where the predominant features are not *photospheric*. But in any case, the notation used should be easily distinguishable from that used in the original MK system. Standards, likewise, should be chosen from the spectral material at hand to exemplify the newly formed spectral classes. Once the classification system is well-defined, detailed comparisons may then be made with the original MK system. If the correspondence between the two systems is close, then it may prove unnecessarily redundant to retain a distinct nomenclature. This is actually what happened when classification of the O-type stars was attempted in the ultraviolet. The O-star ultraviolet spectra are dominated by non-photospheric features, such as P Cygni profiles from the strong stellar winds. Nevertheless, sequences identified in the ultraviolet corresponded so closely with the original MK temperature and luminosity sequences, that a distinct nomenclature was found unnecessary (see Chapter 3), and classifications performed in the ultraviolet are essentially interchangeable with those carried out in the optical. On the other hand, Kirkpatrick (see §9.3.2) has found that spectral sequences in the near-infrared for the L dwarfs do not conform exactly with those in the optical, and thus an independent classification scheme needs to be established for the optical. Likewise, in the optical, Burgasser (see §10.5.2) has used a distinct notation for the T dwarfs, which are normally classified in the near-infrared.

Unfortunately, the practice outlined in the above paragraph has not been used in all cases. A prime example is the classification of the Wolf–Rayet stars (Chapter 11), in which spectral types in the optical have been used to "order" Wolf–Rayet spectra in the ultraviolet. In some cases (in particular the WN stars) this does not result in good sequences, implying the need for an independent classification system in the ultraviolet.

1.3.5 The Mandate of the MK System

In order to make proper use of any system of classification, it is necessary to understand the *mandate* of that system. The mandate of the original MK system is to describe the blue-violet spectrum of stars at classification resolution (1–4 Å) in terms of a set of standard stars. It is important for users to understand that this mandate does *not* include providing the basic physical parameters of stars such as the effective temperature, the radius, the mass, the luminosity, or the metallicity. Nor is determining the spectral type of a star equivalent to measuring its color on the Johnson *UBV* or any other photometric system (see §2.3). While the MK

Figure 1.15 Nancy Houk, at the microscope reclassifying spectra of HD stars for the Michigan Spectral Catalogue. Photo courtesy Nancy Houk.

system may be *calibrated* in terms of these quantities (see Appendix B), those calibrations are not part of the MK system, and *should not be used to judge the rightness or wrongness of a particular MK type or the suitability of a particular standard.* To do so would be to admit external information into the classification process, and destroy the independence of the MK system. An example will be useful in illustrating this point.

The Sun is the MK standard for the spectral type G2 V. The Sun, of course, is difficult to observe directly using spectrographs or photometers designed for stars, and so the normal practice is to observe the reflected spectrum from a solar-system body without an atmosphere. Bright asteroids such as Vesta or Ceres, or ice-covered moons such as Callisto, are commonly used for this purpose. However, because these bodies are not perfectly white or grey, their Johnson B–V colors do not give us the B–V index of the Sun (see §2.3 for more information on the Johnson *UBV* system). If we want to determine the B–V index for the Sun, or if we want to compare the Sun with its peers in terms of, for instance, sunspot activity, rotational velocity, etc., it is useful to find what are called "solar twins." The subject of solar twins is discussed in much more detail in §7.4.1. Hardorp (Hardorp 1978) was one of the first to try to find solar twins. He did this by observing a number of bright solar-type stars with a 20-Å resolution spectral scanner in the near ultraviolet (3640–4100 Å). Surprisingly, he found that no G2 V star in his sample matched the spectrum of the Sun, and those stars that did match had a $B-V$ averaging 0.66 instead of the 0.63 derived from the mean color of other G2 V stars. He suggested that this was due to an error in the spectral type of the Sun, and that the "MK system of spectral classification should be revised to take this into account" (Hardorp 1980). Almost all recent determinations of the $B{-}V$ index of the Sun have settled on a value near 0.63 (see, for instance, de Strobel 1996; Sekiguchi & Fukugita 2000), and it now appears that Hardorp's results were due to his use of a sample of solar-type stars that are metal-rich compared to the Sun (de Strobel 1996). If the MK system had been modified according to Hardorp's suggestion, we would have had to rescind that modification a few years later, and the stability, usefulness, and internal consistency of the MK system would have been compromised. But what if Hardorp had turned out to be right? This would have implied that the Sun is, indeed, different from its peers, and this would have been an important discovery made possible by the autonomy of the MK system. But this still would not have justified the removal of the Sun as the G2 V standard for the blue-violet MK system, *as the sun appears entirely normal with respect to its peers in the blue-violet*. It would, however, have implied that an independent classification system set up in Hardorp's spectral region would have the potential to yield interesting astrophysical information when confronted with the blue-violet MK system.

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