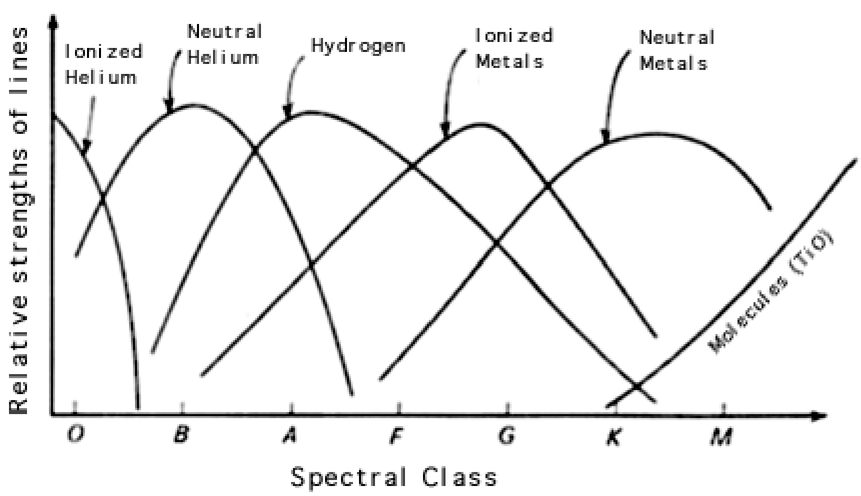
The Classification of Stellar Spectra

In 1802, William Wollaston noted that the spectrum of sunlight did not appear to be a continuous band of colours, but rather had a series of dark lines superimposed on it. Wollaston attributed the lines to natural boundaries between colours. Joseph Fraunhofer made a more careful set of observations of the solar spectrum in 1814 and found some 600 dark lines, and he specifically measured the wavelength of 324 of them. Many of the Fraunhofer lines in the solar spectrum retain the notations he created to designate them. In 1864, Sir William Huggins matched some of these dark lines in spectra from other stars with terrestrial substances, demonstrating that stars are made of the same materials of everyday material rather than exotic substances. This paved the way for modern spectroscopy.

Since even before the discovery of spectra, scientists had tried to find ways to categorize stars. By observing spectra, astronomers realized that large numbers of stars exhibit a small number of distinct patterns in their spectral lines. Classification by spectral features quickly proved to be a powerful tool for understanding stars.

The current spectral classification scheme was developed at Harvard Observatory in the early 20th century. Work was begun by Henry Draper who photographed the first spectrum of Vega in 1872. After his death, his wife donated the equipment and a sum of money to the Observatory to continue his work. The bulk of the classification work was done by Annie Jump Cannon from 1918 to 1924. The original scheme used capital letters running alphabetically, but subsequent revisions have reduced this as stellar evolution and typing has become better understood. The work was published in the Henry Draper Catalogue (HD) and Henry Draper Extension (HDE) which contained spectra of 225,000 stars down to ninth magnitude.

The scheme is based on lines which are mainly sensitive to stellar surface temperatures rather than actual compositional differences, gravity, or luminosity. Important lines are the hydrogen Balmer lines, lines of neutral and singly ionized helium, iron lines, the H and K doublet of ionized calcium at 396.8 and 393.3 nm, the G band due to the CH molecule, the 422.7 nm neutral calcium line, several metal lines around 431 nm, and the lines of titanium oxide.



Standard Stellar Types (O, B, A, F, G, K, and M)

While the differences in spectra might seem to indicate different chemical compositions, in almost all instances, it actually reflects different surface temperatures. With some exceptions (e.g. the R, N, and S stellar types discussed below), material on the surface of stars is "primitive": there is no significant chemical or nuclear processing of the gaseous outer envelope of a star once it has formed. Fusion at the core of the star results in fundamental compositional changes, but material does not generally mix between the visible surface of the star and its core.

Ordered from highest temperature to lowest, the seven main stellar types are O, B, A, F, G, K, and M. Astronomers use one of several mnemonics to remember the order of the classification scheme. O, B, and A type stars are often referred to as *early* spectral types, while cool stars (G, K, and M) are known as *late* type stars. The nomenclature is rooted in long-obsolete ideas about stellar evolution, but the terminology remains. The spectral characteristics of these types are summarized below:

Type	Color	Approximate Surface Temperature	Main Characteristics	Examples
O	Blue	> 25,000 K	Singly ionized helium lines either in emission or absorption. Strong ultraviolet continuum.	10 Lacertra
B	Blue	11,000 - 25,000	Neutral helium lines in absorption.	Rigel Spica
A	Blue	7,500 - 11,000	Hydrogen lines at maximum strength for A0 stars, decreasing thereafter.	Sirius Vega
F	Blue to White	6,000 - 7,500	Metallic lines become noticeable.	Canopus Procyon
G	White to Yellow	5,000 - 6,000	Solar-type spectra. Absorption lines of neutral metallic atoms and ions (e.g. once-ionized calcium) grow in strength.	Sun Capella
K	Orange to Red	3,500 - 5,000	Metallic lines dominate. Weak blue continuum.	Arcturus Aldebaran
M	Red	< 3,500	Molecular bands of titanium oxide noticeable.	Betelgeuse Antares

Subtypes

Within each of these seven broad categories, Canon assigned subclasses numbered 0 to 9. A star midway through the range between F0 and G0 would be an F5 type star. The Sun is a G2 type star.

Luminosity classes

The Harvard scheme specifies only the surface temperature and some spectral features of the star. A more precise classification would also include the luminosity of the star. The standard scheme used for this is called the Yerkes classification (or MMK, based on the initials of the authors William W. Morgan, Philip C. Keenan, and Edith Kellman). This scheme measures the shape and nature of certain spectral lines to measure surface gravities of stars. The gravitational acceleration on the surface of a giant star is much lower than for a dwarf star (since $g = G M / R^2$ and the radius of a giant star is much larger than a dwarf). Given the lower gravity, gas pressures and densities are much lower in giant stars than in dwarfs. These differences manifest themselves in different spectral line shapes which can be measured.

The Yerkes scheme uses six luminosity classes:

Ia	Most luminous supergiants

Ib	Less luminous supergiants
II	Luminous giants
III	Normal giants
IV	Subgiants
V	Main sequence stars (dwarfs)

Thus the Sun would be more fully specified as a G2V type star.

Additional categorization nomenclature

Spectra can reveal many other things about stars. Accordingly, lowercase letters are sometimes added to the end of a spectral type to indicate peculiarities.

Some Spectral Peculiarity Codes	
Code	*Meaning*
comp	Composite spectrum; two spectral types are blended, indicating that the star is an unresolved binary.
e	Emission lines are present (usually hydrogen).
m	Abnormally strong "metals" (elements other than hydrogen and helium) for a star of a given spectral type; usually applied to A stars.
n	Broad ("nebulous") absorption lines due to fast rotation.
nn	Very broad lines due to very fast rotation.
neb	A nebula's spectrum is mixed with the star's.
p	Unspecified peculiarity, except when used with type A, where it denotes abnormally strong lines of "metals" (related to Am stars).
s	Very narrow ("sharp") lines.
sh	Shell star (*B* to *F* main sequence star with emission lines from a shell of gas).
var	Varying spectral type.
wl	Weak lines (suggesting an ancient, "metal"-poor star)

Symbols can be added for elements showing abnormally strong lines. For example, Epsilon Ursae Majoris in the Big Dipper is type *A*0p IV:(CrEu), indicating strong chromium and europium lines. The colon means uncertainty in the IV luminosity class.

Asymptotic Giant Branch Stars (R, N, and S)

After exhausting the hydrogen supply in its core, nuclear fusion of hydrogen to helium will continue in a shell surrounding the core. The core will essentially be a hot degenerate helium star (or helium white dwarf) encased in a hydrogen burning shell. Grossly simplifying the process, helium produced in the shell around the inert core will add to the core's mass until degenerate pressure heats the core sufficiently to start helium fusion within the core. Helium fusion will then continue in the core until once again, the core fuel supply is exhausted and the star has an inert hot carbon-oxygen white dwarf core surrounded by an inner shell of helium fusion and an outer shell of hydrogen fusion. This double-shell burning phase is known as the **asymptotic giant branch** stage, a name based on how stellar evolution proceeds when charted on a Hertzprung-Russell diagram.

Stars in the asymptotic giant branch are short-lived. The degenerate core of the star is more massive that it was in the single-shell burning phase, and due to the peculiar nature of degenerate matter, the more massive core is physically smaller. The gravity experienced by overlying layers is hence stronger, requiring higher luminosities to maintain the balance between pressure and gravity. Thus the star expends energy at a very high rate and may well become a **red supergiant**. Stars in this phase of stellar evolution have proven to be challenging to model. One problem is that the helium shell burning is not stable. The layer of helium fusion is thin. Slight positive perturbations in the nuclear energy generate extra pressure and the region is enlarged slightly. But because the layer is thin, the change in height is slight and hence the change in pressure on the hotter region is changed very little. The higher temperature will likely increase the rate of nuclear reactions (many reactions processes are very temperature sensitive, such as the triple-alpha process which will most likely be dominate in the helium shell). Thus local reaction rates will pick up, generating more heat before it can diffuse. Thus large runaway reaction spots can start from small local condition changes. The runaway is only checked after considerable expansion and the creation of a convective cycle to carry away the excess energy. Yet even once the runaway is checked and the layer resettles, the same underlying physical problem remains. There is no real stable helium shell burning mode. Thus the star will experience spasms of energy generation with convective cells which may carry material all the way up to the hydrogen burning shell, followed by longer periods of relaxation back to the thin shell.

If the convective cells created during this helium fusion runaways reach all the way to the hydrogen fusion layer, this would potentially provide a mechanism for material deep within the star to be dredged up to its surface. This may nicely explain several stellar types which seem analogous with K and M stars temperature-wise, but show some other spectral features as if their outer atmospheres had been enriched with heavier element. These types are the R, N, and S types.

R and N type stars

A number of giant stars appear to be K or M type stars, but also show significant excess spectral features of carbon compounds. They are often referred to as "carbon stars" and many astronomers collectively refer to them as C type stars. The most common spectral features are from C_2, CN, and CH. The abundance of carbon to oxygen in these stars is four to five times higher than in normal stars. The presence of these carbon compounds will tend to absorb the blue portion of the spectrum, giving R and N type giants a distinctive red colour. R stars are those with hotter surfaces which otherwise more closely resemble K type stars. S type stars have cooler surfaces and more closely resemble M stars.

S type stars

S type stars have photospheres with enhanced abundances of *s*-process elements. These are isotopes of elements which have been formed from the capture of a free neutron (changing the isotope of the element) followed by a beta decay (a neutron decays into a proton and an electron, thus changing the element to one with a higher atomic number and an isotope with one less neutron). The *s*-process is one of the mechanisms by which elements with atomic numbers higher than 56 (Iron) can be made. The *s* stands for slow. By way of contrast, its partner *r*-process (for rapid) takes place when there are a sufficient supply of free neutrons for additional neutrons to be acquired in the atomic nucleus before the captured neutron has a chance to beta decay.

Instead of (or in addition to) the usual lines of titanium, scandium, and vanadium oxides characteristic of M type giants, S type stars show heavier elements such as zirconium, yttrium, and barium. A significant fraction of all S type stars are variable.

Peculiar Stars

Wolf-Rayet Stars (WR)

Wolf-Rayet stars are similar to O type stars, but have broad emission lines of hydrogen and ionized helium, carbon, nitrogen, and oxygen with very few absorption lines. Current theory holds that these stars exist in binary systems where the companion star has stripped away the Wolf-Rayet star's outer layers. Thus the spectra observed is from the exposed stellar interior rather than the normal surface material. The broadness of the lines also indicates that the material observed may be from high velocity gases streaming away from the star, with the range of velocities smearing out the observed lines.

T Tauri Stars (T)

T Tauri stars are very young stars, typically found in bright or dark interstellar clouds from which they have presumably just formed. Typically T Tauri stars are irregular variable stars, with unpredictable changes in their brightness. Their spectra contains bright emission lines and a number of "forbidden lines" (so-called because they are not observable in typical laboratory conditions) which indicate extremely low densities. Spectral lines also show Doppler shifts with respect to the rest velocity of the star, indicating that matter is streaming out from them.

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