SINGLE STARS

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Keywords: stars, stellar structure, stellar evolution, magnitudes, HR diagrams, asteroseismology, planetary nebulae, White Dwarfs, supernovae

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Summary

All what we know about celestial objects, and stars in particular, come from the detailed analysis of their light. Astronomers of the 20th century succeeded in determining most of the intrinsic properties of individual stars from clever studies of detailed observations, associated with computations and comparison with models. The first information needed to be able to reach the intrinsic properties of stars is their distances. After a general introduction, we discuss in Section 2 the most important methods used to determine the distances of individual stars. We then give information about stellar temperatures, chemical composition, masses and radii, rotation, etc. Section 3 is devoted to the computations of the stellar internal structure, and how this can be used to match the observations and derive stellar properties and evolution. An emphasis is given on time scales, and the very important HR diagram, key for our understanding of stars, is presented. In Section 4, we discuss variable stars and the new developments of asteroseismology, which represents the study of stellar oscillations: stars behave as resonant cavities, like musical instruments, and the observations of their oscillations give precise information on their internal structure. Finally, Section 5 is devoted to the late stages of stellar evolution, which are different according to their masses: low mass stars, with masses smaller than eight times the solar mass, end as White Dwarfs stars

whereas more massive stars explode and become neutron stars or black holes. The chapter ends with the conclusion in Section 6.

1. Introduction

Stars are giant gas balls in space, more precisely self gravitating spheres. Big gaseous spheres can form and remain stable without dissipating in the nearly empty surrounding space provided that they are huge enough to keep their outer layers under their own weight. Such spheres are allowed to bear the name of stars only if they are able to become stable in the long term due to energy production by nuclear reactions. During their early evolution, they must reach in their center a temperature of the order of 15 million degrees, necessary for the nuclear fusion of hydrogen. To achieve such a state, their mass must be at least 8% of that of the Sun ($M_{\odot}$), that is about 1.5×10^{29} kg. Below that mass, gaseous spheres can form but they do not become real stars. They are called "brown dwarfs". The upper mass limit of stars is less precise, as it depends on complex physical phenomena occurring in massive stars, like radiation pressure effects. It is generally assumed as about 150 $M_{\odot}$.

Stars form in galactic nebulae, when adequate gaseous condensations are created by chance. The reason for such condensations can be of various types: shock waves coming from other stellar explosions, collisions inside galactic arms, interactions between galaxies, etc. Generally stars do not form individually: more than half of them are double or triple, and even single stars form collectively, many of them in the same original cloud. Then they may live their own life, moving their own way, independently from the other ones.

The general knowledge of the structure and evolution of single stars was settled during the 20th century. The basic equations were written at the very beginning of the century, but they could not be solved with a pencil on a sheet of paper. Astronomers became able to compute the internal structure of stars only with the emergence of numerical computers, at the middle of the century. At the present time, the structure and the evolution of single stars on the main-sequence are often thought of as solved and fully understood questions. This is only true at first sight as there are still many unknown problems in the details of stellar physics. For later stages of stellar evolution the problems are far from being solved! The situation is much more complicated when adding rotation, magnetic field, mass loss, and all kinds of stellar interaction with the surroundings.

Under such assumptions, the stars represent beautiful examples of natural physical laboratories. Their structure and evolution can be determined in a straightforward and clear way, and compared with the observations. However, stars in their natural environment do not have a completely solitary behavior. At the end of the 20th century, the existence of disks and planets around stars has been discovered. This seriously modifies the ideas concerning stellar formation and evolution in their early lives, as they may accrete outer matter in the long term. Later on in their evolution, they lose mass through stellar winds, and this ejection of matter can be very important in some cases.

Also stars rotate, which creates internal motions of matter, and they often have magnetic fields.

Studies of single stars in the 21^{st} century are focused on all these processes which perturb the clean but partial interpretations of the preceding century. Also a very important discovery has brought a new light in the comprehension of stars: many of them oscillate due to acoustic or gravity waves which propagate inside the big spheres and are observable in their outer layers. The study of these oscillations, or *asteroseismology*, leads to precise determination of the stellar observed parameters, and also to precise sounding of their internal structure.

2. Stellar Observational Data

All what we know about stars comes from the analysis of their light, at all wavelengths. The aim is to obtain from the observations the maximum information on the intrinsic parameters of the stars (luminosity, temperature, mass, chemical composition, radius if possible, etc.), so that it can later be compared with the theoretical computations and give constraints on their internal structure. The first important measures which have to be done to reach the stellar intrinsic parameters are their distances, so that we may have access to the real energy they radiate and not only to that received on the Earth.

2.1. Distances

2.1.1. Direct Methods

The distances of *close-by stars* can be measured directly by simple triangulation techniques. The notion of *close-by* depends on the precision of the observations. Before sending instruments in space, only 6000 stars could have their distances directly measured. As will be seen below, this number has increased to 250 000 with the *Hipparcos satellite*, and it will soon go up with the *space mission GAIA*, which should be launched at the end of 2012.

Triangulation is the kind of method applied by our brain with our two eyes to estimate the relative distances of the objects that we observe. Both eyes look at the same object and see it in a slightly different direction, due to their own separation (called the triangulation basis). The angle between the two observing directions of the same object may give its distance, if we know the triangulation basis. This method is widely used on Earth, using two well separated telescopes, to determine the distances of far sites.

The largest possible triangulation basis on Earth would be the Earth diameter itself, but it is not large enough to allow measurements of stellar distances. Astronomers had to find larger observing separations. Fortunately, the Earth orbits around the Sun, and its annual motion can be used in this respect. If one observes a close-by star in January and the same star in June, the line-on-sight is modified with respect to far-away stars, due to the Earth displacement.

In real observations, the same star is followed all the year round. If the stars did not move at all with respect to the Sun, the Earth motion would be the only process to take into account, and the star would seem to describe an ellipse in the sky. This virtual ellipse, projection in the sky of the Earth orbit, is called the *parallactic ellipse* and the angle under which the star "sees" the radius of the Earth orbit is the *parallax*. An important astronomical distance unit is defined from these observations: the *parsec* (abbreviated as *pc*), which is the distance of a star corresponding to a parallax of one arcsec. One can easily compute that 1 pc = 3×10^{16} m , which is approximately equal to 3.26 light-years (the fact that the parsec and the light-year represent units with similar orders of magnitude is pure coincidence).

The situation is indeed more complicated due to the fact that all stars move in the Galaxy, so that the observed star has a *proper motion* with respect to the Sun. A typical representation of the motion of a close-by star in the sky is given in Figure 1. The oscillations are due to the superposition of the parallactic ellipse to the stellar proper motion. The basic principles for these distance determinations by triangulation are quite simple, but their real applications to stars are difficult and need precise techniques that astronomers have developed.

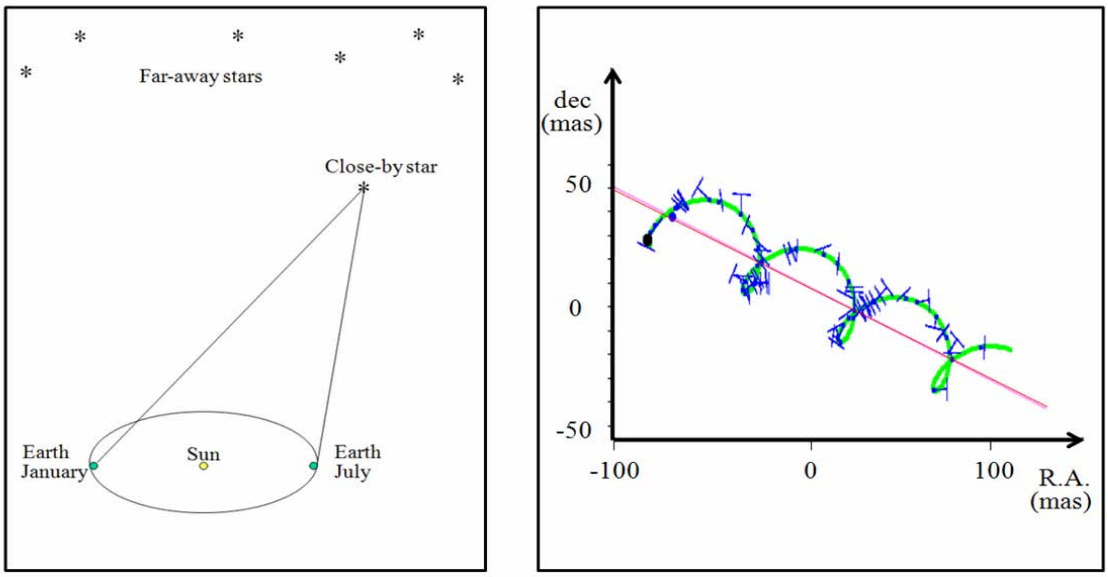

Figure 1.Apparent motions of close-by stars in the sky, due to the Earth rotation around the Sun. On the left: schematic drawing of the annual effect on the apparent stellar motion, due to the Earth. On the right: three-years motion on a celestial map of a typical star observed by Hipparcos. The axes represent the usual celestial coordinates: declination in ordinate and right ascension in abscissa. The values are given in units of milli arc seconds (mas). The red curve represents the motion the star would have without the Earth motion. The green curve represents the observed motion, which is a combination of the real motion with the "parallactic ellipse" , due to the Earth displacement. The short blue lines correspond to the uncertainties on the observations

Sending satellites in space allows much better precision on the measurement of very small angles than from the ground, because of the perturbations induced by the Earth atmosphere. The space mission GAÏA, of the European Space Agency, which should be launched in 2012, will be able to measure the distances of celestial objects up to 25000 pc with a precision of 10%. It will give a complete set of distance measurements with a precision better than 1% for all existing stars up to 100 pc. This amounts to ten to one hundred millions of stars.

2.1.2. Indirect Methods

Triangulation is a precise and powerful method, but at the present time, with the presently available instruments, it can be applied only to stars living in the solar neighborhood, inside our own Galaxy. The distances of far-away stars have to be determined with indirect methods. These methods mostly rely on the various statistical laws which can be derived from the sample of stars with well-known, directly measured, distances.

A special case concerns the stars which belong to a galactic stellar cluster, like that of the *Hyades*, also called the *Bull stream* (as the Hyades lie in the constellation of the Bull). These stars have all been formed at the same time, from the same interstellar cloud, and most of them have kept similar motions in the galactic frame, which are that of the original cloud. This can help in determining their distances, as discussed below.

Observed from the Earth, the velocity of a star can be developed in two components; the first one on the *line-of-sight*, namely the *radial velocity*, that can be directly determined using the *Doppler effect*, and the second one, the *tangential velocity*, that cannot be determined unless one knows the distance of the star. What astronomers can easily measure, by observing the same star during several decades, is its *proper motion* that is its angular displacement with time on the night sky, measured with respect to far-away stars. If the distance is unknown, it is impossible to derive whether it is a close-by star with a small tangential velocity, or a more distant star with a larger velocity. Inversely, if one knows the real tangential velocity from a different determination, like in the Bull stream, the measure of the proper motion leads to the stellar distance.

In most cases, stellar distances are obtained by finding a way to determine the energy that the considered star radiates per second, using statistical laws and established correlations. Knowing this energy, and the energy received on Earth from the same star per second and per surface unit, one can find the distance of the star. This is discussed in more details in Section 2.2. A very important case concerns the pulsating stars, like the *Cepheids* and *RR Lyrae* stars, which present periodic oscillations of their emitted light. As a general rule, the brighter the star, the longer the period of the oscillations. Precise correlations have been obtained, which are used to determine the intrinsic stellar radiated energy, and thereby its distance. This important subject is discussed in Section 4.

2.2. Stellar Luminosities

By definition, the *luminosity* of a star is the total energy radiated per second by the star in all directions and all wavelengths. This is an intrinsic quantity for the star, which does not depend on the observer. The solar luminosity is $L_\odot = 4\times10^{26}$ watts. On Earth, the observer cannot measure directly the stellar luminosity. He measures a radiation flux per surface unit, coming from the star, which is generally referred to as the *brightness*.

If the distance D of the star is known, the luminosity can in principle be determined from the observed light flux F by the simple equation:

$$L = F\left(4\pi D^2\right) \quad (1)$$

However the determination of the stellar brightness is complicated by two different problems. The first one is that the Earth's atmosphere absorbs part of the radiation, and it may vary with time. The light flux has to be corrected for this effect. The second problem is that it is nearly impossible to measure directly a light flux integrated on all wavelengths. The instruments which are used are more sensitive in some wavelengths than in the others, and the way it varies depends on the type of instrument. As will be seen below, this complication is in fact very useful for the determination of the surface temperatures of stars.

2.2.1. Apparent Magnitude

In old (Hellenistic) times, the stars were classified in terms of *magnitudes* as seen with the naked eye. The brightest observed stars were said to be of *first magnitude*, the less visible ones were defined as *sixth magnitude* stars. The next magnitude in the scale was defined such that the corresponding stars appeared half as bright as the previous ones to the naked eye. In mathematics, such a scale is called logarithmic.

In modern ages, astronomers decided to keep that scale and to formalize it in the form of an equation, called *Pogson law* (from Norman Robert Pogson, 1856). By definition, the apparent magnitude difference between two stars is written:

$$m_1 - m_2 = -2.5\log\left(F_1/F_2\right) \quad (2)$$

where F_1 and F_2 are the light fluxes received from the stars above the Earth's atmosphere per surface unit. The zero of the scale is obtained by arbitrarily attributing a value to a given star (e.g. magnitude zero to the bright star *Vega*). In this scale, the bright star Sirius has an apparent magnitude of -1.4 whereas the full Moon has a magnitude -12.74. The most powerful telescopes at the present time can observe stars up to about magnitude 30.

As the fluxes are measured with specific instruments at specific wavelengths, with specific instrumental responses, they have to be measured exactly in the same way for the two stars. The resulting apparent magnitudes differ according to the instrumental bias. The apparent magnitude integrated in all wavelengths could in principle be measured using an instrument like a bolometer. For this reason, the total apparent magnitude is called "apparent bolometric magnitude". However, it is generally obtained using theoretical computations, as discussed below.

2.2.2. Absolute Magnitude

The apparent magnitude of a star depends on its distance, as it is related to the flux received on Earth. An absolute scale was needed to represent the intrinsic energy radiated from the star. For practical reasons, the *absolute magnitude* of a star has been defined as the magnitude the star would have if it was situated at a distance of 10 pc. The relation between the absolute magnitude and the apparent magnitude of the same star is easy to obtain, assuming that there are two different stars, the real one and a virtual one with the same luminosity, but situated at 10 pc (cf. Eq. (2)):

$$M - m = 5 - 5\log D \qquad (3)$$

where M is the absolute magnitude, m the apparent magnitude and D the distance measured in parsecs.

When the absolute magnitude is determined from the measured apparent magnitude and the stellar distance using Eq. (3), the question of the instrumental response and wavelength bias has to be taken into account. Different absolute magnitudes, using different filters for the observations, may be defined for the same star. The absolute magnitude integrated on all wavelengths is the *bolometric absolute magnitude*.

The bolometric absolute magnitude difference between two different stars is then simply related to their luminosities:

$$M_1 - M_2 = -2.5\log\left(L_1/L_2\right) \qquad (4)$$

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Biographical Sketches

Sylvie D. Vauclair is Professor at the University of Toulouse, in Physics and Astrophysics. She is also a Senior Member of "Institut Universitaire de France" (IUF). For her research work, she belongs to the "Institut de Recherche en Astronomie et Planétologie" (IRAP), which is supported by both the French National Center of Scientific Research (Centre National de la Recherche Scientifique, CNRS) and the University of Toulouse (Université Paul Sabatier, UPS).
She obtained her degrees at Université Paris 7 Denis Diderot and defended her PhD in 1975 at the Paris-Meudon Observatory. Her first permanent position was an assistant professorship ("maître-assistante") at the Paris 7 University. At that time she did her research at "Institut d'Astrophysique de Paris" and "Observatoire de Meudon". She also spent some time in Cambridge (UK), Moscow (Russia), and in the United States (SUNY at Stony Brook, Columbia University, NY and California Institute of Technology, Pasadena), where she did research and was a lecturer. She moved to Toulouse in 1981 where she obtained a full professor position. Since the beginning of her career, her major field of research concerns the evolution of the chemical element abundances in stars. More recently she became interested in helio and asteroseismology, and she studies more precisely the asteroseismology of the central stars of exoplanetary systems. She has published more than 200 scientific papers and several reviews. She is also strongly involved in the diffusion of knowledge. She gives many popular talks, has written several books for a large public and many popular papers, mostly in French. Her last popular book is "La Terre, l'Espace et au-delà", éd. Albin Michel, France. She obtained several prizes for her popular books.
Prof. Sylvie Vauclair is a member of the International Astronomical Union, of the Academia Europaea, of the Académie de l'Air et de l'Espace, and has been a member of many international committees (e.g. scientific committee of the International Space Science Institute, Bern, Switzerland; committee of the European Space Agency, etc.). She is also a member of many French committees and has important French distinctions like "chevalier de la legion d'honneur" and "officier des palmes académiques".

Gérard P. Vauclair is an astrophysicist. His present position is Director of Research Emeritus in Toulouse, France. His career included a pure research position at the National Center for Scientific Research (Centre National de la Recherche Scientifique, CNRS), France.
He obtained is PhD in 1972 at the Paris VII University. He has been working successively at Institut d'Astrophysique de Paris", at the "Paris-Meudon Observatory" and also temporarily at the Institut for Theoretical Astrophysics in Cambridge (UK), at the Astronomical Institute of the Academy of Sciences in Moscow (Russia) and at the California Institute of Technology (Pasadena, California, USA). In 1981 he moved to the University of Toulouse to participate in the creation of the new Astrophysics Laboratory of that University. His main scientific interests concern stellar evolution and asteroseismology: diffusion processes in stars, evolution and asteroseismology of the late stages of stellar evolution (central star of planetary nebulae, white dwarf stars) and central stars of planetary systems. He is the author of 228 publications including 141 in refereed reviews.
Dr. Gérard Vauclair has been the director of the "Laboratoire d'Astrophysique de Toulouse" from 1992 to 1999. He is a member of the International Astronomical Union. He served on a number of committees: the Scientific committee of the IAU Commission 35; the National Committee of Scientific Research; the Astronomy Group of the Centre National d'Etudes Spatiales (French Space Agency, CNES). He was one of the founders of the "Whole Earth Telescope" and he is still a member of this Network Directory Committee. He is also a member of the CoRoT (Convection, Rotation and planetary Transits) Satellite Scientific Committee.