The Milky Way

Structure, Dynamics, Formation and Evolution

Françoise Combes and James Lequeux

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CNRS EDITIONS

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Cover illustration: Messier 109 (also called NGC 3992), a nearby galaxy of similar morphology to the Milky Way, i.e. a clone of the Milky Way. This barred spiral galaxy gives the right impression of how might look our Galaxy, if seen face-on. © *NOAO/AURA/NSF*.

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Preface

What is this bright band across the sky? Although Democritus was already thinking, in the 5th century BC, that the Milky Way was "made of tiny heavenly bodies grouped so closely that they seem to us to be one" (Achilles Tatius, quoted by Jean Salem, "Democritus", our English translation), it was not until Galileo and his telescope that this bold idea was confirmed. Subsequently, the major obstacle to interpreting the observations, even of excellent quality, in order to establish the size of our Galaxy and the Sun's position within it, was the poor determination of distances. It was only in the 1930s that a correct representation of the Galaxy was obtained, showing that the Milky Way was a galaxy among others, with a radius of 15 kpc (45,000 light years) for its stellar component, of about 20 kpc for its gas component, and that the Sun was far from being at its center.

During the last two decades, new means of observation and new computing facilities have opened new horizons: the advent of space astrometry with the Hipparcos satellite of the European Space Agency (ESA) and its high precision astrometric measurements for more than 100,000 bright stars and very precise distances to 30,000 stars has led to a thorough knowledge of the solar neighborhood and to revised cosmic distance scales; systematic photometric observations over large areas of the sky such as the Sloan Digital Sky Survey (SDSS) have led to the discovery of new stellar streams in the halo; high-resolution spectroscopic observations with large telescopes have led to a much better understanding of the chemical evolution of the Galaxy; observation of millimeter and sub-millimeter waves has led to the discovery of many new molecules in the interstellar medium; and finally increasingly powerful computers have allowed increasingly detailed simulations of the formation and evolution of galaxies.

The coming decade is once again full of promise with the operation of satellites, telescopes and radio telescopes even more sensitive and / or more accurate than their predecessors.

In the optical domain, the ESA Gaia satellite, successor to Hipparcos and second astrometric satellite, was launched in December 2013. It will allow a fantastic step forward in the knowledge of all the stellar components of our Milky Way, with the identification and systematic measurement of one billion objects brighter than magnitude 20, with astrometric precision still 50 to 100 times higher than that of Hipparcos and parallel observation of their physical characteristics. Also in the optical domain, planned for the early 2020s, the E-ELT (European Extremely Large Telescope) will observe, in very great detail, very faint objects in our Galaxy and far beyond.

In the infrared, submillimeter and millimeter domains, essential information is obtained about the formation of stars. After the spectacular results of the Herschel European satellite, the mission of which completed in June 2013, ALMA (Atacama Large Millimeter / submillimeter Array), the global network observing in the millimeter wavelengths, has become fully operational. Later, the JWST (James Webb Space telescope), observing in the near-infrared, is due to be launched in 2018 with the largest telescope ever put into orbit, 6.5 m in diameter.

Finally, in the radio domain, extremely powerful for the study of the interstellar medium and in particular the gas, the first light from the SKA (Square Kilometer Array) project is expected in the 2020s.

A new golden age for astronomy, especially for the study of our Milky Way and Local Group galaxies, the next decade promises to be full of surprises and discoveries, and this book is precisely issued at the right time to focus on our present knowledge before these new steps.

With the precision achievable by space astrometry, this ancient specialty is now a vital tool for astrophysics (in the sense of the physical analysis of the sources observed). It brings cosmic distance scales both for the stellar and gaseous components, and the motions of stars in the solar neighborhood. Soon, thanks to Gaia, these data will be available all across the Milky Way and nearby galaxies. These observations provide clues to the structure of the Galaxy and of its various components, but also to the kinematics and dynamics of these, leading, for example, to a complete description of the orbits of the stars in the Galaxy. Various correlations may now be studied between the orbital characteristics (eccentricity, mean velocity, velocity dispersion) of carefully selected groups of stars and the abundances of chemical elements in their atmospheres. Only the combined study of these parameters allows interconnection of the various traces left by the successive steps of the formation and evolution of our Galaxy.

Astronomers are making progress in the understanding of our Milky Way by assembling the various parts of this puzzle, by comparing these to the characteristics of external galaxies, and by confronting all these observations to increasingly detailed numerical simulations. Conversely, the Milky Way is, of course, the galaxy studied in the highest detail (very accurate distances and motions for many different types of stars, detailed abundances of chemical elements in their atmosphere, detailed description of star forming regions, determination of star orbits very close to the central black hole, only to quote a few), and this provides an essential lighting in the interpretation of much more global observations available for other galaxies.

The book of Francoise Combes and James Lequeux takes us step by step through this rapidly evolving field, with a fascinating description of the present state of our knowledge. The two authors, internationally recognized specialists of the dynamics of galaxies and of the interstellar medium, both have a very broad culture in astronomy and perfect clarity of presentation. They are already the authors of many books on astronomy for the specialist as well as for the general public. This book will certainly become a reference in the field. It is a remarkable introduction to the description of this set of stars, gas and dust in which we live: Françoise Combes and James Lequeux introduce here these complex topics in a form that is concise but very educational, simple but thorough and rigorous. Student, specialist or simply curious, this book will encourage the reader to further deepen their knowledge and push some, I am sure, to embark on the adventure of research and of the interpretation of the mass of data expected from the future instruments of the 21st century.

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Contents

Physical and astronomical constants

Astronomical unit	$AU = 1.496 \times 10^{11}$ m
Light year	$ly = 9.46 \times 10^{15}$ m
Parsec	$pc = 3.086 \times 10^{16}$ m $= 3.262$ ly
Solar mass	$M_\odot = 1.989 \times 10^{30}$ kg
Solar luminosity	$L_\odot = 3.845 \times 10^{26}$ W
Tropical year	year = 365.242 days $= 3.156 \times 10^{7}$ s
Light velocity	$c = 2.997\,924\,58 \times 10^{8}$ m s^{-1}
Gravitation constant	$G = 6.673 \times 10^{-11}$ N m^{2} kg^{-2}
	$= 6.673 \times 10^{-8}$ dyne cm^{2} g^{-2}
Planck's constant	$h = 6.626 \times 10^{-34}$ W s^{-1}
Boltzmann's constant	$k = 1.381 \times 10^{-23}$ W K^{-1}
Stefan-Boltzmann's constant	$s = 5.671 \times 10^{-8}$ W m^{-2} K^{-4}
Mass of electron	$m_e = 9.109 \times 10^{-31}$ kg
Mass of proton	$m_p = 1.673 \times 10^{-27}$ kg
Rydberg energy	ryd $= 2.180 \times 10^{-18}$ J $= 13.606$ eV
Wavelength associated to 1 rydberg	91.176 nm
Mass energy of electron	0.511 MeV $= 8.187 \times 10^{-14}$ J
Mass energy of proton	938 MeV $= 1.503 \times 10^{-10}$ J

Units and conversion

Length	
meter (I.S. unit)	m = 100 cm
angström	A $= 10^{-8}$ cm $= 10^{-10}$ m
Mass	
kilogramme (I.S. unit)	kg $= 10^{3}$ g
Energy	
joule (I.S. unit)	J $= 10^{7}$ erg
Power	
watt (I.S. unit)	W $= 10^{7}$ erg s^{-1}
Flux density	
jansky (I.S. sub-unit)	Jy $= 10^{-26}$ W m^{-2} Hz^{-1} $= 10^{-23}$ erg s^{-1} cm^{-2} Hz^{-1}
Force	
newton (I.S. unit)	N $= 10^{5}$ dyne
Pressure	
pascal (I.S. unit)	Pa = N m^{-2} = 10 dyne cm^{-2} $= 10^{-5}$ bar
Magnetic field or induction	
tesla (I.S. unit)	T $= 10^{4}$ G (gauss)

Chapter 1
Introduction

The luminous band of the Milky Way (our galaxy, also named *the Galaxy*), which crosses the sky as a scarf, has been the object of many myths since prehistoric times. It was considered by the Greeks as due to milk escaped from Hera's breast as she refused to feed Heracles, discovering that he was not her son: hence the name of the Milky way, which is still in use. During the Middle ages, it was Saint-Jacques's path, supposed to orient the pilgrims on their way to Saint-Jacques of Compostelle. Claude Ptolémée (ca.90 – ca.168) produced a detailed description of the Milky Way, which remained unsurpassed for a long time. However, the true nature of the Milky Way was only revealed in 1610 by Galileo (1564-1642), whose astronomical telescope resolved for the first time its diffuse light into many individual stars: he wrote "The Milky Way is just a cluster of innumerous stars". Actually, all the stars and planets that we see in the sky belong to the Milky Way, and the only two objects which do not belong to it are the two Magellanic Clouds in the southern sky and the Andromeda galaxy in the northern sky.

1.1 Shape and dimensions of the Milky Way

One had to wait for a century and a half after Galileo to have the first ideas on the shape and the size of the Milky Way. Thomas Wright (1711-1786), in his 1750 book entitled *An original Theory or new Hypothesis of the Universe*, described the Milky Way as a flat stellar system inside which we are located, a system that would be a part of a gigantic spherical shell. However, this was more inspired by a medieval-type cosmogony than by a real scientific reflection. Others, like Emanuel Swedenborg (1688-1772), Immanuel Kant (1727-1804) and Johann Heinrich Lambert (1728-1777), limited themselves to similar considerations. However, they all considered that the stars of the Milky Way should rotate around some unknown center to ensure the stability of the system. But it was William Herschel (1738-1822) who performed the first serious scientific studies of our Galaxy.

Herschel knew that some stars are not really fixed in the sky, but possess a *proper motion* (lateral displacement). Already, Edmond Halley (1656-1742) had suspected that Aldébaran, Sirius and Arcturus could have a proper motion, and Jacques Cassini (1677-1756) had clearly seen in 1738 the proper motion of Arcturus. In 1783, Herschel, who himself had made new observations of stellar positions, noticed that the dozen proper motions, that were known, corresponded to displacements towards a privileged direction. He concluded that it was in fact the Sun that moved in the opposite direction, the *apex*, in the Hercules constellation. This was the beginning of the kinematical studies of stars. However, the velocity of the solar motion was then unknown, for the lack of distance estimates (it is of the order of 20 km s^{-1}, see section 2.3).

Herschel was also the first to attempt to obtain a better geometrical image of the Milky Way, from star counts in various directions. For this, he assumed that all stars have the same intrinsic flux, and thus that their apparent flux decreases as the inverse square of their distance. This allowed him to estimate roughly their distance, at least as a relative value. He also assumed that the number of stars per unit volume was the same everywhere. For him, the faintest observed stars were lying at the limit of the system. He obtained in this way in 1784-85 a 3-D geometrical description of the Milky Way, and represented a cut perpendicular to the Galactic plane of symmetry as shown in Figure 1.1. He claimed that the Milky Way had a size of 800 times the mean distance between the stars in the Galactic plane, and only 150 times in the perpendicular direction. The real dimensions were unknown because no distance of any star had been determined, apart from that of the Sun. What was the ratio of the apparent flux of the Sun and of a bright star like Sirius, and were these stars comparable? The beginnings of an answer to these questions came only during the first half of the 19th century.

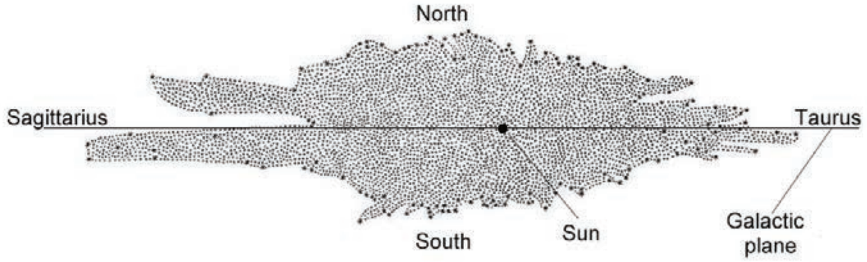

FIG. 1.1 – A cut of the Milky Way perpendicular to its plane of symmetry, as drawn by Herschel. To the left, the lack of stars corresponds to the dark band that splits the Milky Way in the direction of Sagittarius, due to extinction by interstellar dust, something that Herschel could not know. From Herschel, W. (1785) *Philosophical Transactions* 75, 213-266.

However, Herschel had legitimate doubts about the hypotheses he had to make in his work. He realized that stars should exist, fainter than those he could see in his telescopes, and that makes it impossible to determine the real limits of the Milky Way. In his late papers, following on from 1817-18, he admitted that "the Milky Way is unfathomable".

This record of failure slowed the further works, until the Russian astronomer Otto Struve (1819-1905) resumed them on new bases. He acknowledged in 1847 that the density of stars in the Milky Way was far from uniform, contrary to Herschel's hypothesis: it decreases progressively with increasing distance from the Galactic plane. Now, some stellar distances were available, allowing the dimensions of the Milky Way to be obtained: Struve claimed that they were at least 8.17×10^8 astronomical units, i.e. 1.2×10^{17} km, or 13 000 light years, or 4 000 parsecs[1]. Finally, Struve suspected the possibility of interstellar extinction which would reduce the light from a star faster than the inverse square of its distance.

The next important step in the description of the Galaxy came from the Dutch astronomer Jacobus Cornelius Kapteyn (1851-1922), who made his laboratory in Groningen the main center of galactic studies worldwide. He had, at his disposal, photographs of the sky, deep and relatively complete stellar catalogues, and a number of determinations of proper motions and of radial velocities (the velocities of stars along the line of sight, as measured from the displacement of spectral lines using the Doppler-Fizeau effect). In 1906, he launched a large international project for the study of the distribution of stars in the Galaxy, consisting in systematically measuring the magnitudes, the proper motions and the radial velocities of stars in 206 zones of the sky, the *selected areas*. In the meantime, before the completion of this project which implied the cooperation of more than 40 different observatories, Kapteyn started his own study of the distribution of stars in the Milky Way. Now, he could account for the different intrinsic luminosity of the stars, which he described by a *luminosity function*. But this yielded a new difficulty: the distribution of the apparent magnitudes of stars resulted from the combination of their different luminosities and of their different distances. Kapteyn succeeded in solving this problem in a very ingenious way. He illustrated his results in the schematic form of Figure 1.2, which corresponds to his final model of 1922. For him, the Galaxy was a flattened ellipsoidal system, in which the Sun occupied a slightly eccentric position. This model was more schematic than that of Herschel, but represented considerable progress by showing how the density of stars decreases to the exterior of the Galaxy, and by the introduction of a distance scale.

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1 The astronomical unit (a.u.) is the half-major axis of the Earth's orbit, 1.496×10^{11} m. The parsec is the distance from which this half-major axis is seen under an angle of 1 arc second: 1 pc = 206 285 a.u. = 3.086×10^{16} m = 3.26 light-years.

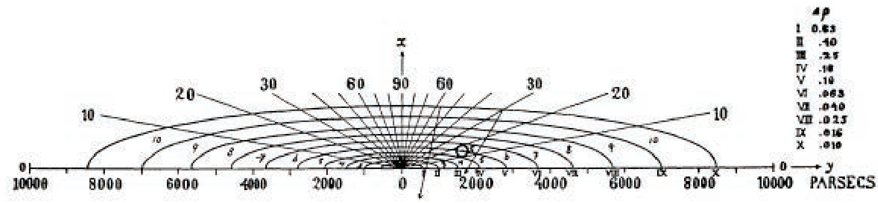

FIG. 1.2 – The Galaxy according to Kapteyn in 1922. It was schematized by a series of concentric ellipsoids, whose density decreased to the exterior according to the scale at the right of the figure. The circle represented the position of the Sun. From Kapteyn, J.C. (1922) *Astrophysical Journal* 55, 302-328, with the permission of the American Astronomical Society.

However, Kapteyn's model was wrong, because, similar to all his predecessors, he did not take into account interstellar extinction. Curiously, he had supposed the existence of extinction in his first works, but he rejected it later. In 1904, Johannes Franz Hartmann (1865-1936), at the Potsdam astrophysical observatory, had noticed in the spectrum of the star δ Orionis very narrow absorption lines that he attributed to calcium ions located in intervening gas clouds. In 1912, the American astronomer Vesto Slipher (1875-1969) discovered the interstellar dust grains illuminated by the light of the Pleiades stars, and suggested that this dust could well absorb the light of background stars. Finally, photographs by Edward E. Barnard (1857-1923) and Max Wolf (1863-1932) had shown the existence of regions of the Milky Way apparently devoid of stars, and this was attributed at the end of the 1910s to dark dust clouds. One then started to interpret the dark band that seems to split the Milky Way not by the absence of stars, but by extinction by dust.

This allowed the Swiss-American astronomer Robert J. Trumpler (1886-1956) to give, in 1930, a definitive description of the Galaxy. Trumpler noticed first that the angular diameter of the distant open clusters[2], which are close to the galactic plane, looked abnormally large if they were at the distance derived from their luminosity without any correction. But if an interstellar extinction exists, their distance is in fact smaller and everything returns to normal. Trumpler derived from this a numerical value for extinction by unit distance in the Galactic plane.

Next he examined the distribution of globular clusters of stars, the majority of which are far from the Galactic plane: their light is not affected much by interstellar extinction, which is clearly concentrated along the plane. Harlow Shapley (1885-1972) had shown previously that most of these clusters lie in one half of the sky and formed a spherical system whose center

[2] See the end of this chapter for illustrated definitions of the different objects encountered in the Milky Way.

was far from the Sun, in the direction of the Sagittarius constellation. He had estimated their distance thanks to the variable stars they contain (the RR Lyrae) and concluded that if they really belonged to the Milky Way, the center of their system should also be the center of the Galaxy, at a distance of about 20 000 parsecs. Trumpler, and then Joel Stebbins (1878-1966) and Albert Whitford (1905-2002) in 1936, revised this distance to 8 000 pc, a value confirmed by recent estimates. From all these studies resulted a model of the Galaxy represented in Figure 1.3, which is still completely valid today.

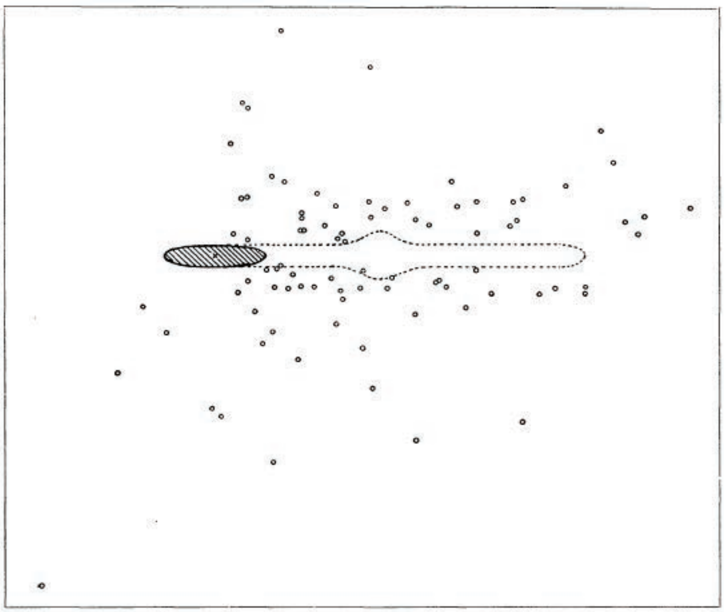

Fig. 1.3 – A cut of the Galaxy, according to Shapley, Trumpler, Stebbins and Whitford. The dotted contour encompasses most of the stars and interstellar matter. The hatched ellipse is Kapteyn's Galaxy, limited by interstellar extinction, with the Sun almost at its center. The small circles symbolize the globular clusters. From Trumpler, R.J. (1941) *Publications of the Astronomical Society of the Pacific* 53, 155-165, with permission of the Editor.

The astronomers at the time noticed that the Galaxy is rather similar to the Andromeda nebula and many similar objects. They became fully aware that the Milky Way is a galaxy similar to many others, and also that the Sun is far from its center, in a remote region.

1.2 Rotation and spiral structure

Let us say now a few words about the motions in the Galaxy. After enough radial velocities of globular clusters and external galaxies had been measured in the 1920s, it became clear that all the stars near the Sun move with an enormous velocity, about 300 km/s, with respect to the average of these objects: this was the discovery of the rotation of the Galaxy, which keeps its different parts, in particular the solar neighborhood, in equilibrium between the gravitational attraction of the central regions and the centrifugal force. The Swedish astronomer Bertil Lindblad (1895-1965) and his Dutch colleague Jan Oort (1900-1992) then showed that the Galactic disk does not rotate as a solid body, but that the regions closer to the center rotate faster than the external regions: this is the *differential rotation*. They could understand in this way a phenomenon discovered previously by Kapteyn. Kapteyn had observed that the stars near the Sun move along two opposed currents perpendicular to the direction of Sagittarius, which is that of the Galactic center. These two currents are a consequence of the differential rotation.

Thanks to the galactic rotation, it became possible to determine its mass. In this context, a major event for galactic astronomy, and for astronomy in general, occurred in 1951: the discovery of the radio emission of atomic interstellar hydrogen at the wavelength of 21 cm, the *21-cm line*. Predicted by the Dutch physicist Hendrick van de Hulst (1918-2000) and discovered in the USA by Harold I. Ewen (born 1922) and Edward M. Purcell (1912-1997), this line allowed, for the first time, observation of the whole Galaxy, because there is no interstellar extinction of radio waves. The radial velocity of the emitting regions can be obtained from the Doppler-Fizeau line shift. This makes it possible to determine the rotation velocity in the Milky Way as a function of the distance to the Galactic center (the rotation curve) and to draw the first complete map of the interstellar gas in the Galaxy (Fig. 1.4), which is dominated by hydrogen. Spiral arms can be seen over a large extent, while only the nearest ones could be suspected by optical observations: this confirmed the similarity of our Galaxy with external spiral galaxies.

In 1970, the discovery of radio lines of the interstellar CO (carbon monoxide) molecule opened new horizons for the knowledge of the Galaxy. This molecule is a good tracer of molecular gas, while it is difficult to observe the hydrogen molecule H_2. Much effort has been devoted to observe the CO lines at 2.6 and 1.3 millimeter wavelengths. Figure 1.5 is a comparison between an image of the inner half of the Milky Way and a map in the 2.6-mm CO line: there is a perfect correspondence between the absorption features due to interstellar dust and the molecular gas. Like for the 21-cm line, it is possible with the CO lines to obtain the distance of the emitting regions and thus to map the molecular gas. Its total mass is larger than that of the atomic gas.

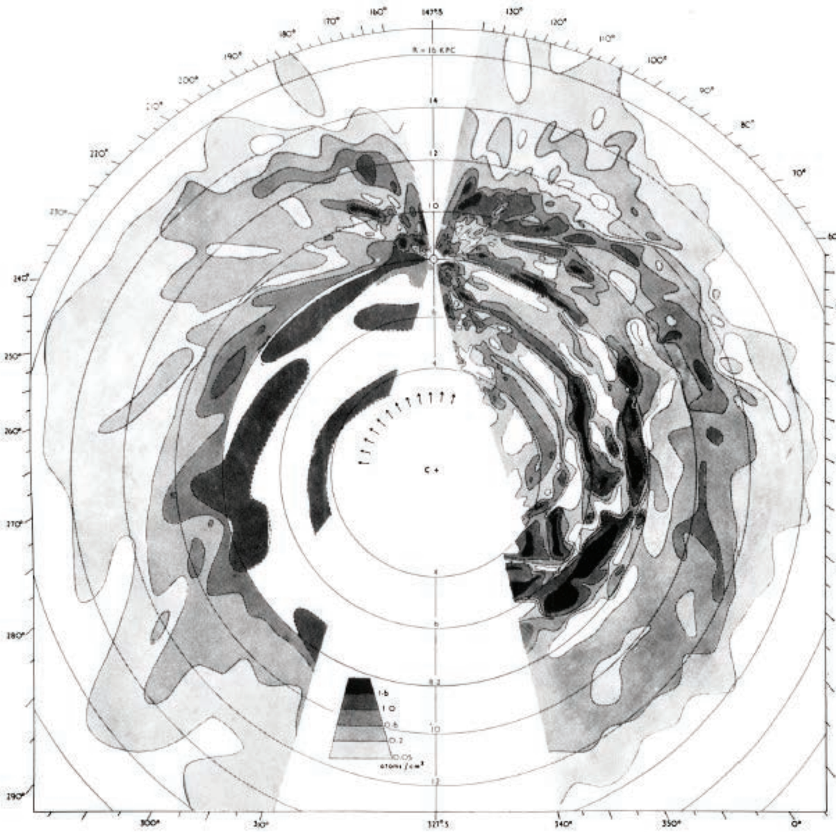

FIG. 1.4 – The first complete map of the Galaxy in the 21-cm line of atomic interstellar hydrogen. C is the Galactic center. The Sun is at 8 kpc above. The surface density of hydrogen is given by the gray levels. The spiral structure is visible, but the details are uncertain because the distances are obtained from the radial velocities assuming pure rotation, although there are important local velocity deviations. The system of galactic longitudes used in this map is obsolete. From Oort, J.H., Kerr F.T. & Westerhout, G. (1958), *Monthly Notices of the Royal Astronomical Society*, 118, 379-389, Wiley, with permission of the Editor.

Radioastronomy – the study of the Universe in radio waves – is also useful for observing gaseous nebulae[3]. They emit not only a continuum and emission lines in the visible, but also in radio. The wavelength shift of these lines gives the radial velocity. The radio observation allows information to

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[3] Also called HII regions, because they mainly contain ionized hydrogen. Astronomers use to designate the various degrees of ionization by the roman figures I for neutral, II for singly ionized, III for doubly ionized, etc.

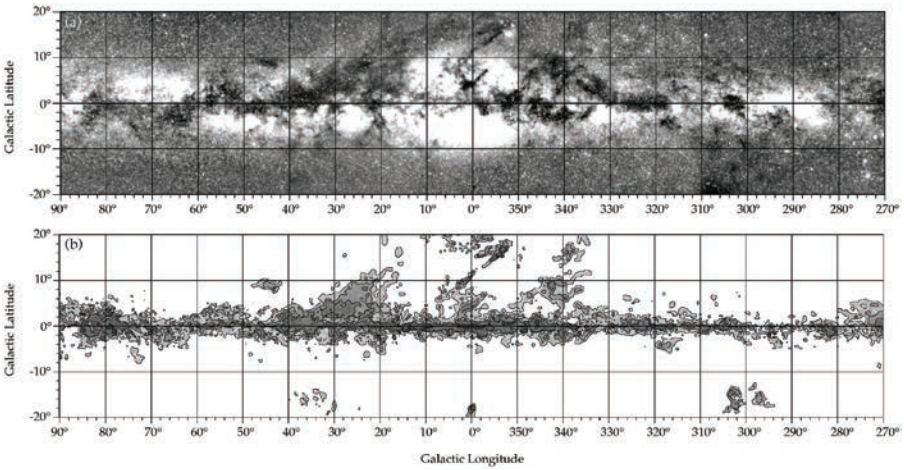

FIG. 1.5 – Comparison of extinction by interstellar dust and the distribution of the interstellar CO molecule. Top, a photographic mosaic of the half of the Milky Way centered on the direction of the Galactic center, which is at the origin of the coordinates. Bottom, a map in the 2.6-mm line of CO. The correspondence is generally excellent, showing that the molecular gas and the dust are well mixed. However, some dust does not correspond to molecular gas, and is associated with atomic or ionized gas. From Dame, T.M., Hartmann, D. & Thaddeus, P. (2001) *Astrophysical Journal* 547, 792-813, with permission of the American Astronomical Society.

be obtained on distant nebulae that are not visible optically, and derivation of their distance from their radial velocity. The observation of external spiral galaxies shows that gaseous nebulae are excellent tracers of spiral arms. In our Galaxy, Yvon and Yvonne Georgelin obtained in 1976, from visible and radio observations of gaseous nebulae, a map of the spiral arms of the Milky Way: an updated version is reproduced in Figure 1.6. Figure 1.7 is a photograph of an external galaxy that is generally considered as a twin of our own Galaxy.

What is the origin of the spiral structure? Since its discovery by Lord Rosse (1800-1867) in the middle of the 19th century, the question has been continuously raised. The discovery of the differential rotation has made any explanation even more problematic, because the deformation caused to the Galaxy destroys any feature in a time that is short with respect to the age of the Universe: as a consequence, only a small fraction of the galaxies should be spiral if the spiral arms are a material structures driven by the rotation. It became progressively clear that to survive, the arms cannot follow the rotation. A satisfactory solution to the problem of spiral arms was finally given in 1964 by the Sino-American astronomers Chia-Chiao Lin and Frank

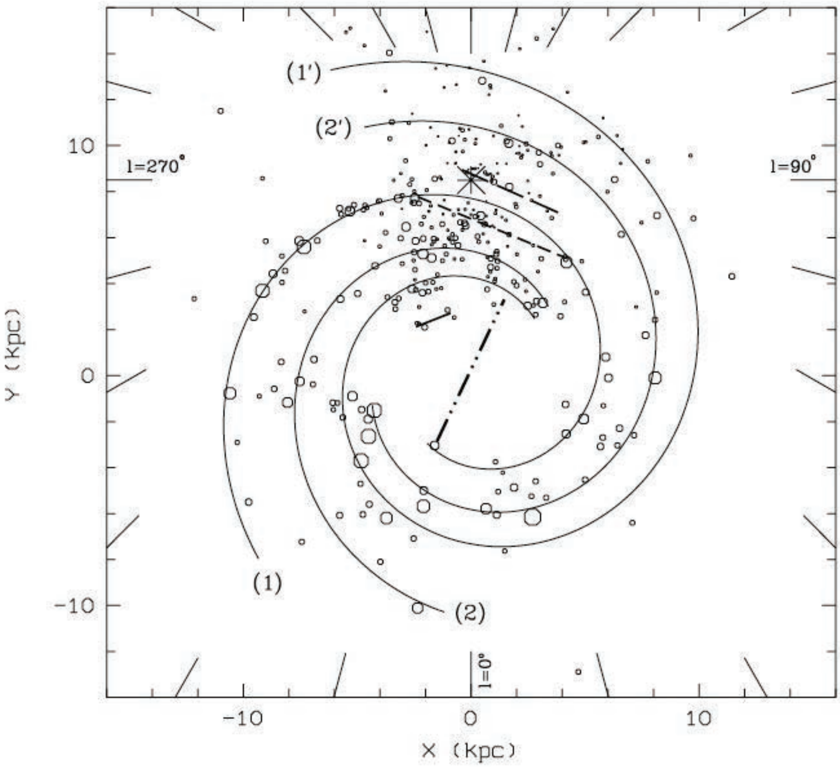

FIG. 1.6 – A map of the Galactic spiral arms obtained from observations of gaseous nebulae. The position of the Sun, here supposed to be at 8.5 kpc from the Galactic center, is represented by a star symbol. The circles represent nebulae with known distances; their size is linked to the far-ultraviolet flux of their ionizing stars. The best fit corresponds to a 4-arm logarithmic spiral. The central bar of the Galaxy is schematized by a dot-dot-dashed line. The local arm is drawn as the long-dashed line, and a foreseen deviation of the inner arm (Sagittarius-Carina) by a short-dashed line. Compare to Figure 1.4, for which the spiral arm pattern is less reliable. See also further Figure 3.4. From Russeil, D. (2003) *Astronomy & Astrophysics* 397, 133-146, with permission of ESO.

Shu : they showed that the arms are temporary compression regions of the material of the galactic disk, i.e. density waves rather similar to sound waves. When the interstellar gas enters such a density wave, its compression favors the formation of molecules and triggers the gravitational collapse of a fraction of the interstellar "clouds". As a consequence, the spiral arms are rich in compressed molecular gas that form stars by collapse. The most massive stars are very hot and produce a large amount of ultraviolet radiation, which ionize the surrounding gas, forming gaseous nebulae. All this is

- *planetary nebula:* a mass of gas ejected by a low-mass star at the end of its evolution and ionized by the radiation of the residual core of this star;

- *protosolar nebula:* a mass of gas and interstellar dust from which the Solar system formed.

- *protostellar nebula:* same, for a star.

Nova: a star increasing suddenly of brightness and decreasing gradually over a few weeks. Novae are very close double stars in which one component is a white dwarf: during its evolution, the other star ejects material that falls onto the white dwarf, warming considerably so that explosive thermonuclear reactions occur. Some novae are recurrent.

Nucleosynthesis: the formation of chemical elements by nuclear reactions in stars.

Parallax: an astronomical term often used to designate the distance of an object, usually expressed in parsecs;

- *geometric parallax:* obtained by triangulation using as a basis a large distance on the Earth or its orbit around the Sun;

- *photometric parallax:* obtained by comparing the apparent magnitude of a star with its absolute magnitude determined from its spectral characteristics;

- *statistical parallax:* obtained by using the global kinematic properties of a group of stars moving together.

Parsec: a unit of length widely used by astronomers, such that the semi-major axis of Earth's orbit is seen at the distance of 1 parsec over an angle of one arc second. 1 parsec = 3.26 light year = 3.08×10^{16} m.

Photodissociation region: a region below the surface of a neutral cloud subjected to ultraviolet radiation, such that only the elements of lower ionization potential than hydrogen are ionized, while most of the molecules are photodissociated.

Precession: the movement of the axis of a rotating body, which describes a cone under the influence of external forces; also, rotation of the orbit of a planet or a star.

Proper motion: the lateral movement of a star in the sky.

Pulsar: a stellar object emitting perfectly periodic radio pulses (and/or sometimes X-rays, optical or gamma-ray pulses). The period of pulsars is from a few milliseconds to a few seconds; they are neutron stars in very fast rotation.

Radial velocity: the velocity of approach or recession of a star, counted positively in the case of recession.

Radio astronomy: the branch of astronomy that studies the radio emissions in the Universe. The Sun, the planets, some stars, the atomic, ionized or molecular interstellar gas, the high-energy cosmic ray electrons, the pulsars, galaxies and quasars emit radio waves.

Radiogalaxy: a galaxy, generally elliptical, which emits an intense radio emission by the synchrotron radiation mechanism.

Radio source: a cosmic source of radio waves, more or less extended.

Rotation curve: for a flattened galaxy, the law describing the variation of the rotational speed with radius.

Spectral line: the reinforcement or decrease in intensity in the spectrum of an object occurring at a specific wavelength; the line is in emission if there is reinforcement, and in absorption if there is a decrease. The wavelength of a line is characteristic of the atom, ion or molecule that produces it.

Star:

- *Neutron star:* a very dense star (the Sun's mass within 10 km, or one billion tons per cm^3) whose material is degenerate, being composed mostly of neutrons. Pulsars and some X-ray sources are neutron stars, a residue from the explosion of supernovae.

- *Double* (*or binary*) *star:* about half of the stars are in pairs. Close double stars, which are more or less in contact, are the site of very interesting phenomena that change their evolution vis-à-vis that of isolated stars. Novae, X-ray sources, etc., are such binary stars.

- *Giant:* a star in an advanced stage of evolution, which begins to "burn" helium and carbon, and whose envelope is extended and relatively cold. This is the stage that follows the station on the main sequence. The giants called asymptotic branch giants are in the latest stage of their evolution.

- *Dwarf:* a star of the main sequence, of relatively small mass and dimensions (e.g. the Sun). White dwarfs, however, are stars at the end of their evolution.