CHAPTER 1

Introduction

The history of the development of the understanding of the Milky Way as a galaxy, is also the history of the mankind’s knowledge in astronomy. Many discoveries and advances that for many years seemed to concern topics not directly related to our galaxy, turned out to be important contributions to our knowledge of the Milky Way in the end. Nowadays, in spite of the enormous advances in theory and techniques, the Milky Way still maintains some of its secrets. In this chapter, we deliver a short review of the history of discoveries more directly related with the Milky Way, and the principal actors involved on it.

1.1 AN HISTORICAL OVERVIEW

From Galileo to Sapley’s model of the galaxy

The name “Milky Way” given to our galaxy, comes from the literal translation of the Latin “Via Lactea”, which is precisely in Greek the word for galaxy. The early conceptions of the Milky Way took a more solid consistency when Galileo, helped by his reinvention of the telescope during the XVIIth century, was able to resolve for the first time the Milky Way into separate stars. Until then, the Milky Way was thought to be nebulous structure. The fact that the Milky Way was an association of stars, did not have a strong bearing in the Aristotelian cosmology, which was the general conception of the epoch. Nevertheless, in spite of this change in the ideas driven by the new evidence, it was not until the next century that these new ideas about the Milky Way prompted another significant change.

Thomas Wright from Durham, in the mid eighteenth century, was a clockmaker who taught himself practical astronomy effectively enough to teach navigation and to work as a land surveyor. In 1742, Wright published ‘Key to Heavens’ a volume explaining his ideas of the Universe. Nevertheless, it was not until 1750 that he presented his most influential work, An Original Theory or New Hypothesis of the Universe. Wright always tried to maintain a strong religious dimension in his models. The heavens, according to him, were the proof of God’s magnificent work.

In his model of 1750, the observed Universe was thought to be a combination of two
thin concentric spherical shells (Fig. 1.1). Stars were distributed over these spherical shells, and thus, according to the viewing angle we could see some of observed characteristics of the Milky Way. The Sun in Wright’s model was located halfway in the shell and hence looking along a tangent to the shell we would see a high concentration of stars, the sky in that direction would be filled with faint distant stars until just a diffuse glow was visible. On the other hand, an observer looking inwards or outwards in the thin portion of such universe, would see a sky sparsely populated in that direction. Hence, this model explained, to some extent, some of the observed properties of the Milky Way. The spherical symmetry for Wright was a natural consequence of God’s handiwork. In addition, he postulated a divine center of the Universe, which was the point around which the stars, including the Sun, moved in orbits. It was this movement which prevented the collapse of the Universe under gravitation. Wright considered his model just one of the many possible. Other models he proposed pursued the idea of the spherical shells, but this time simplified to rings, which reproduced in a better way the observed properties of the Milky Way at the time. However, in all these models he maintained his religious conception of the divine center.

Wright later in his life changed many of his ideas about the Milky Way, this was illustrated in his manuscript “Second thoughts”. It seems that he received a profound impression of different physical processes after the earthquake of Lisbon in 1755. And thus he changed his explanation of the Universe to an analogy of the earth’s interior, with new stars as new volcanoes, and the Milky Way appearance as a result of a sidereal flow of lava.

In spite of the change in his ideas in “Second thoughts”, many of the Wright’s initial concepts in his models were followed. Immanuel Kant (1704-1804) learned through a review of Wright’s books. Kant, inspired by this review, which misunderstood some fundamental points of Wright’s models, formulated his own ideas in Universal Natural History and Theory of the Heavens. The universe envisioned by Kant consisted of a disk of stars similar to the ring model of Wright. Kant also incorporated additional small el-

**Figure 1.1:** Wright’s model of the Milky Way. *An original Theory of the Universe* (1750).
liptical luminous patches, which at the time where known as “nebulous stars”. Kant’s model however did not explain the observed apparent absence of movements of stars. On the other hand, Kant considered that the normal matter as the Sun and planets might be created by condensation from primordial matter; where gravitational force played a important role allowing the thin diffuse matter to condense. Matter could thus form disks, and subsequently, larger bodies as the Sun, which in turn would evolve until it explodes and returns to the initial state of diffuse matter, in a cyclical process. Therefore, in Kant’s universe matter had a non-stationary state, which was against the philosophical point of view at the time.

Similarly to Kant’s ring model, Johann Heinrich Lambert (1728-1777) in his work *Cosmologische Briefe*, considered the Milky Way to be a convex lenticular structure, where the Sun and its neighborhood stars were just one if the many subsystem of the complete structure. At the same time, the Milky Way was part of a higher hierarchical system where many milky ways were included. Wright’s and Kant’s are essentially philosophical models, which were the response to the scarce scientific evidence of the Milky Way’s nature at the time. Lambert, on the other hand, who was a good mathematician, tried to find empirical equations to support his view of the universe for many years.

The first scientific research on the shape and size of the Universe which produced empirical evidence of the Milky Way’s structure was carried out by William Herschell, at the end of the eighteenth century. Herschell, who had the mightiest telescope of his time, first turned to the study of nebulae, discovering to his delight, that many of them were resolvable into multiple stars. He later discovered that many of the stars non-resolved were actually luminous gas. These results, which evidenced associations of stars in many nebulae, agreed well with the idea of gravitation drawing matter together and forming irregular patterns of stars as the ones observed.

In order to extend his understanding of the structure of the Milky Way, Herschel, by means of systematic methods, carried out a survey which consisted of extensive counts in 683 regions of the sky, these star counts he called “star-gauges”. His aim was to obtain an estimation of the shape of the Milky Way. Herschel, in the absence of knowledge on stellar distances made two important assumptions: he assumed that he could see the borders of the system, and that the stars in the latter were uniformly distributed. Even though Herschel knew his assumptions were just approximations, he believed they were enough to produce an acceptable representation of the Milky Way (see Fig. 1.2).

Notwithstanding, as the techniques of Herschel improved, he realized that many more stars were visible in each star-gauge, and therefore a uniform distribution was not possible. He found that stars were preferentially distributed in two opposites regions of the sky. Similarly, he found nebulae having the brightest patch in the middle and stars in resolvable clusters getting closer in the middle. Thus, later in his life, Herschel re-examined many of his postulates based on his early work. He recognized a preferred plane in which clusters of stars seemed to group. The star gauges of Herschel were continued by Otto Struve and also his own son John Herschel, who catalogued multiple new stars, nebulae and clusters, including observations in the southern hemisphere.
Struve and John Herschel reached similar conclusions, particularly that the Sun was slightly to the north of the galactic plane.

William Parsons in 1845, armed with a superior telescope with a 72-inch mirror (more powerful than Herschel’s) was able to resolve many of Herschel’s nebulae a spiral structure. In addition, in some of these systems he was able to resolve individual stars. These observations supported the idea of “island universes” outside of our own galaxy and equivalent to it. The spiral shape, on the other hand, suggested rotation around a central axis, a hypothesis without proof until the beginning of the twentieth century.

At the end of the nineteenth and the beginning of the twentieth century the advent of photographic plates considerably improved the quality of observations. Photographs allowed the detection of thousands of individual objects in a single plate and the study of faint objects, never observed in detail before. Thus, taking advantage of the new technical development, Kapteyn, von Seeliger and van Rhijn started a plan to study 200 selected regions of the sky. Their study consisted of an international cooperation to collect plates in order to obtain stellar counts, brightness estimations and spectral classifications; this was the Durchmusterung catalogue. Kapteyn, von Seelinger, and van Rhijn used the information in the catalogue to produce a model of the Milky Way by assuming average distances for stars with the same apparent brightness levels. However, they were aware this last assumption probably was only statistically valid. Kapteyn’s model made two more assumptions, apparent brightness falls off as the inverse of the square of the distance and the interstellar medium is completely transparent. The latter was a serious mistake, which perturbed significantly the determined structure of the model. Thus, the Kapteyn Universe was a flattened stellar system 10 kpc in diameter, and 2 kpc in thickness, where the Sun was located near the center.

Kapteyn soon realized that his model was extremely dependent on the assumption of a transparent interstellar medium. Any kind of absorption of the stellar light by an unknown medium would yield a misinterpretation of the distances. Absorption would make stars look dimmer and therefore they would seem to be farther than they actually are. The combined effect on the model would make the complete galaxy extend beyond its real limits. Aware of this serious dependence in his model, Kapteyn initiated many
studies in order to detect any possible interstellar absorption. Nevertheless, his results were inconclusive, and thus Kapteyn convinced himself that absorption if present was at least negligible and that his model was right to a reasonable degree.

Harlow Shapley was a young astronomer at Mount Wilson Observatory when he started to study globular clusters in 1914. Globular clusters are easily observed at great distances from the Sun due to their great brightness and appearance. Also, many of them are located at large distances above or below the galactic plane which make them less affected by the high absorption on the plane. Soon after he started, in 1915, Shapley noticed that globular clusters were inhomogeneously distributed over the sky. This distribution was symmetrical in galactic latitude below and above the galactic equator and favoured a particular direction, where globular cluster were evidently concentrated. Shapley realized that this distribution was characteristic of globular clusters, and thus he reasoned that if globular cluster, due to their size, were a important structural elements in the galaxy, they should be representative markers of the structure of the Milky Way. Hence, the apparent distribution of globular clusters must be a clear indication of the location of the Sun, which could not then be close to the center of the galaxy, as the Kapteyn Universe claimed, but rather quite far from it. The distances used by Shapley were obtained from the apparent brightness of variable stars as Cepheids, for which intrinsic brightness was known. Initially, accordingly to the size of the Kapteyn model, the distances found for the clusters placed them well beyond the limits of the galaxy. Shapley at first resolved this paradox by the combination of two systems, where the globular cluster were members of a second larger distribution than the galaxy. He later changed this position and boldly claimed that these globular clusters must be coupled to the Milky Way’s structure and therefore the galaxy should be 10 times bigger than the size predicted by Kapteyn. This claim caused many controversies, since the Kapteyn Universe was already generally accepted. Thus, both models were disputed for several years by the astronomers. Shapley’s estimated size for the Milky Way was somewhat too large mainly because of his assumption of negligible interstellar absorption.

Most of the opposition to Shapley’s model was rooted in the belief that spiral nebulae were galaxies similar to the Milky Way. Heber D. Curtis from the Lick observatory was one of those antagonist to Shapley’s ideas, he argued that if the spiral nebulae were galaxies of the size proposed by Shapley, they would necessarily have been inconceivably distant. Since there was no evidence that they were so distant, Shapley’s conception had to be wrong. The discovery of novae in spiral nebulae by George Ritchey in 1917 gave for first time the possibility to obtain reliable estimations of the distances to the spirals. Where these distances clearly placed the spirals outside the limits of the Milky Way, Curtis calculated a typical distance of 1 Mpc for spiral nebulae. But while novae were used by Curtis to support the island universe concept and the Kapteyn model dimensions for the Milky Way, new proper motion results in novae were used against the latter. Because Adriaan van Maanen, in 1916, calculated the proper motions for several spiral nebula and found, that if the these spiral were as distant as proposed by Curtis, their velocities were extremely large. Thus, two clearly opposite positions in astronomy coexisted at the time. Those favouring Shapleys model of the Milky
Way, which held that the dimensions of the Milky Way were directly related to the
distribution of globular clusters, and those favouring Curtis’ view, which supported
the Kaperyn Universe dimensions and considered the spiral nebulae as extragalactic
structures.

In this scenario both antagonist positions crashed in the “great debate” in the Na-
tional Academy for Sciences in 1920. In it, Shapley and Curtis debated his respec-
tive positions about the size of the Milky Way and the nature of spiral nebulae. Even
though the debate did not settle any of the questions addressed, it helped to bring to
the attention of the scientific community the main problems of each theory. However,
in the absence of crucial evidence, the opposing sides were not reconciled.

A few years after the debate, finally the nature of spiral nebulae was settled. Be-
cause Edward Hubble in 1923 could resolve with the new 100-inch telescope at Mount
Wilson the outer regions of M31 and M33. And these regions proved to be very similar
to those of group of stars previously resolved. Then when Chepeids stars were iden-
tified in both M31 and M33, a reliable distance estimation was possible by means of
the Chepeid brightness-period relation. Thus, a value of 300 kpc was calculated for the
distance to M31 and M33.

After Shapley’s model: Oort and Lindblad

At the same time, Jan Oort who dedicated several years to the study of high velocity
stars, found several facts which were difficult to reconcile with Kaperyn’s Universe.
The distribution of high velocity stars seemed to have a clear asymmetry above 62
km/sec, where below that value random directions dominated. Under the Kaperyn
Universe these high velocity stars could just belong to a different structure, dynami-
cally decoupled from the galaxy. On the other hand, the limit of 62 km/sec implied
an average radial velocity of 15 km/sec and a average mass of 5 M☉. Another difficult
fact to reconcile with Kaperyn’s theory was that globular clusters, which typically have
high velocities, could not be gravitationally bound to a galaxy as small as the one pro-
posed by Kaperyn. Consequently, since globular clusters were very massive, it seemed
quite unlikely that they would be created at a rate enough to replenish those escaped
due to the high velocities, and the small escape velocity of the galaxy in Kaperyn’s
model. All this led to Oort to infer that the systematic high velocities in stars, an also
in clusters, were associated with an intrinsic rotation around the galactic center.

It was Bertil Lindblad, a Swedish theorist, who connected all the facts in a coher-
ent picture. Lindblad in 1926 proposed a model for the galaxy opposed to Kaperyn,
in which the galaxy could be divided in several subsystems, each one of them with
a particular rotation velocity, symmetric with respect the same galactic center. This
differential rotation was responsible for the velocities observed in high velocity stars,
globular cluster and RR Lyrae variables. Thus, the sun belonged to a subsystem which
rotated in almost circular orbits around the galactic center with velocities around 200-
300 km/sec. And therefore, all those so-called low-velocity stars, were actually stars in
the same subsystem and probably in the solar neighborhood.

Soon after Lindblad’s model was published, Oort found abundant observational
data which supported the predictions in it (Oort 1927; 1928). Similiarl to the explana-
tion of the low-velocity stars, he considered the high-velocity stars as members of a subsystem which essentially rotated at low velocity with respect to the galactic center, and at the same time have a large velocity difference with respect to the Sun. In addition, Oort calculated the consequences of galactic rotation in the solar neighborhood by means of some constants which reflected the observed radial velocities and proper motions in the galaxy. Other astronomers also found similar evidence in other samples. J.S. Plaskett and J.A. Pearce proved that movements in O and B type stars were consistent with the rotation of the Lindblond-Oort model. Subsequently Shapley’s model of the Galaxy, and therefore the model of Lindblad and Oort, was generally accepted. However, in spite of the evidence, two important discrepancies in Shapley’s model remained, the proper motions of spiral nebulae, and the scales and distances in Shapey’s model. The key to the latter was the long sought absorption.

Hubble solved the inconsistency of proper motions in spirals in 1935, by re-measuring the original van Maanen data and adding new plates to his analysis. The measurements, carried out by himself, Baade and Nicholson, were in direct disagreement with van Maanen results. The conclusion was that van Maanen results were an artifact of the proper motion measurement, which was extremely complicated with the technology of the epoch. Hence, one of the principal arguments against the extragalactic nature of the spiral nebulae was over.

There was the general suspicion that some mechanism of absorption might be present in observations, the apparent structure of the Milky Way showed voids or obscure regions in which almost no stars were detectable. These areas devoid of stars were dynamically difficult to explain, since they implied the existence of numerous tunnel-shaped openings in the Galaxy. E.E. Barnard accumulated numerous plates showing such dark patches and lanes in the Milky Way at the beginning of the twentieth century. A majority of astronomers by 1920 accepted the presence of large clouds of obscuring matter in the galaxy, the matter of discussion then was the distribution of such matter. Indirect evidence of absorption appeared when Johannes Hartmann in 1904 noted that in a rapidly revolving binary star, δ Orionis, the ionized calcium lines Ca II did not participate in the generalized Doppler shift of the rest of the spectrum. Vesto M. Slipher found similar “stationary lines” in several other stars and thus concluded that these lines, stationaries when measured with respect the local system of stars, must have an interstellar origin outside the Solar System.

However, direct evidence of general absorption was not published until 1930 by R.J Trumpler. Trumpler was an expert in globular clusters, and during his research had used two methods to determine distances to the clusters. The first method concerned the measurement of brightness and colour for the stars in the cluster by means of their spectral types. Then by plotting apparent brightness versus spectral type and comparing this plot with well known relations of intrinsic brightness versus spectral type (Hertzsprung-Russel diagram), for stars in the solar neighborhood, he was able to make estimations of the distance to the cluster. The second method, consisted of the inverse relation between distance and apparent size of the cluster, where he assumed that all the clusters analyzed had almost equal linear diameter, and therefore their angular size was simply a distance effect. The problem that faced Trumpler was that both
measures of distance were inconsistent. Clusters with large distances had angular diameters larger than expected. Tumpler discarded the possibility that clusters increased their size with the distance, and assumed that some kind of interstellar absorption of light had to exist. Finally he calculated that if the latter alternative was correct, an absorption of 0.67 mag/kpc was expected. In addition he proved the consistency of his argument with the observed increase in reddening of stars at any given color with the increase of distance.

Another important discovery in the picture of spirals (which were at this point accepted as peers of the Milky Way) was the separation in stellar populations. The notion of stellar populations was introduced by Walter Baade in 1944. Baade studied the nucleus of the spiral M31, its companions M32 and NGC 205 and two more ellipticals. He realized that the brightest stars in the spheroidal central region of M31 were red giants, in contrast to the dominating blue supergiants found in arms. Hence, Baade defined two distinct stellar populations: "population I", which consisted of young objects associated with spiral structures and therefore preferentially located in arms; and population II, which consisted of objects associated with the spheroidal component of the galaxies or globular clusters. Examples of population I are objects of a wide range of ages, such as young hot stars in OB associations, Cepheids, dust lanes and ionized Hydrogen regions. Population II, on the other hand, are mainly associated with the old stars found in globular clusters, haloes and bulges.

Finally, the discovery in 1940 of the 21-cm radio emission line of neutral Hydrogen, originating in the interstellar medium, has been used to map the rotation and structure of the Hydrogen in the galaxy. The structure of neutral atomic Hydrogen has been used as a tracer of galactic structure (e.g. Binney et al. 1991), and thus is of key importance to understanding the dynamics of the galactic center.

The picture of the Milky Way reached from the discoveries and technical advancements described in this section is one of a spiral galaxy as many others observed. This simple statement has less than 70 years of general consensus as we have seen, albeit, it does represent just the general characteristics of the Milky Way. This incomplete picture is still under development, and as we will see in the next section, many secondary features have been unveiled in the last years.

### 1.2 Modern Conception of the Milky Way

#### 1.2.1 The Milky Way as a barred galaxy

De Vaucouleurs (1964) was the first to suggest that the Milky Way is actually a barred galaxy. De Vaucouleurs was led to this conclusion after a detailed comparison with others spiral galaxies using 21-cm emission line data. The spiral multiplicity of the Milky Way resembled more closely that of barred galaxies. However, the highest deviation from an axisymmetric potential is observed in the center of the galaxy, and therefore it is in the galactic center where most of the bar features should be sought. Peters (1975), suggested a model for the inner regions of the galaxy which could reproduce the 3 kpc arm and the excess of velocity observed in emission of HI in the so-called
forbidden regions. This excess of velocity of \( \sim 135 \, \text{km sec}^{-1} \) could hardly be expected in an axisymmetric potential. Thus, the model suggested by Peters involved gas flowing along concentric elliptical streamlines such as might be caused by a bar structure. Nevertheless, in spite of the encouraging results just described, the use of the 21-cm emission line implies some disadvantages, such as low spatial resolution and diffuse 21-cm continuum emission. This can be partially solved by using emission lines from the less abundant abundant molecules, such as CO, CS, or OH. Binney et al. (1991) generated a model using the 21-cm, CO, and CS line information. In their model, the gas flow results showed a marked bar structure in the galactic center, with a corotation radius of \( r = 2.4 \pm 0.5 \, \text{kpc} \), a bar pattern speed of \( 63 \, \text{km sec}^{-1} \, \text{kpc}^{-1} \), and a bar inclination of \( \phi_{\text{bar}} = 16 \pm 0.2^\circ \), with the closer end in the first galactic quadrant. According to the model, the CO emission arises in the places where gas is obliged to migrate from the \( x1 \) family of orbits to \( x2 \), which produce shocks that can be recognized in the \((l, v)\) diagram. The \( x1 \) family of orbits are prograde along the bar, while \( x2 \) are perpendicular to the bar structure. Similarly, the ring of molecular gas detected was associated to the bar’s outer Lindblad resonance, and the regions of low gas density inside 3.5 kpc with corotation. In addition, the advancement in the picture of the galactic bulge extends to other features. The centre itself which is associated with SgrA*, a radio source known for a long time, has been in the last decade proven to harbour a supermassive black hole of \((3.6 \pm 0.3) \times 10^6 \, \text{M}_\odot\) (Eisenhauer et al. 2005). The suspicion about the presence of a black hole in the galactic center had remained for years, proper motion measurements in the galactic center (even to radius as small as 0.01 pc) showed a excess of mass density of \( \sim 10^{12} \, \text{M}_\odot \, \text{pc}^{-3} \) (Ghez et al. 1998). Since a stellar cluster could not be responsible for such high mass, therefore, a black hole arose as the logical alternative. Eisenhauer et al. (2005), through detailed near-IR imaging spectroscopy, were able to obtain very accurate radial velocities and proper motions for 6 stars in the central 0.5”, the orbits of these stars were consistent with the effect of a supermassive black hole.

Near infrared observations are generally the natural choice for studies of the galactic bulge, this is due to the diminished effect of extinction at those wavelengths compared with bluer filters. Several project have taken advantage of this characteristic to obtain reliable data of the galactic bulge. The Infrared Astronomical Satellite (IRAS), launched in 1983, yielded the first survey of the galactic bulge at these wavelengths. A few years later, the Infrared Telescope (IRT), flown aboard the Space Shuttle in 1985 as part of the Spacelab 2 mission, scanned a large fraction of the sky in several infrared wavelengths with a resolution of \( \sim 1^\circ \). Its results were used by Kent, Dame & Fazio (1991) to obtain the three dimensional luminosity distribution of the Milky Way from a 2.4\micron\ map of the northern Galactic plane. Their results, however, were just fitted with axisymmetric distributions. On the contrary, Blitz & Spergel (1991) found abundant evidence for a galactic bar in the Matsumoto et al. (1982) IR data. The bar modeled was in the first galactic quadrant (the tip of the long end) and was consistent with previous predictions by Sinha (1979) and Liszt & Burton (1980), who first postulated a tilted bar to explain the observed kinematics of HI and CO. Blitz & Spergel (1991), however, were not able to constrain the tilt of the bar with their data. The most spectacular results regarding the galactic bar so far come from the Cosmic Background Explorer (COBE)
satellite. The COBE satellite produced low angular resolution maps of the Galactic bulge at 1.25, 2.2, 3.5 and 4.9 μm obtained from the Diffuse Infrared Background Experiment (DIRBE) instrument (Weiland et al. 1994). In such maps, after correction for extinction and subtraction of an empirical model for the Galactic disk, clear asymmetries arose, which were consistent with a triaxial bulge. Similarly, Dwek et al. (1995), also using COBE-DIRBE images, characterized the morphology and determined the infrared luminosity and mass for the Galactic bulge. They adopted several triaxial analytical functions to represent the volume emissivity of the source, finding that a barlike structure provided the best fit to the data compared to axisymmetric bulge models. This Gaussian-type bar with a “boxy” geometry was aligned with the Galactic plane, but rotated with its near-end in the first Galactic quadrant at an angle of 20° ± 10° with respect to Galactic center - Sun line, and axis ratio of 1 : 0.33 ± 0.11 : 0.23 ± 0.08. In addition, combined with HST information, this bar model produced a photometric determination for the mass of the bulge of ∼ 1.3 × 10^{10} M_\odot. Subsequent research focused on the COBE-DIRBE images produced deprojections of the 3-dimensional distribution of the bulge using several different techniques. Binney, Gerhard & Spergel (1997), used a non-parametric deprojection algorithm (Lucy’s method) for this purpose. Assuming 8-fold symmetry their model produced a bar with axis ratio 5:3:2 and a length of ∼ 1.8 kpc, which in turn implies a corotation radius of ∼ 3 kpc. More recently, Bissantz & Gerhard (2002), generated a new 3-D luminosity distribution for the inner Milky Way using a non-parametric penalized maximum-likelihood algorithm of deprojection. The algorithm also used as constraints the apparent magnitude (line-of-sight) distributions of clump giants, and included arms. This model thus led to a longer bar than previous deprojections (∼ 3.5 kpc), with axis ratio of 1:(0.3-0.4):0.3, and a bar inclination of 20° ≤ φ_{bar} ≤ 25°.

Star counts have also been used in the last years to disentangle some important bar parameters. Benjamin et al. (2005), used a catalog of ∼ 30 million mid-infrared sources, taken by the space telescope Spitzer, to determine the distribution of stars in Galactic longitude, latitude, and apparent magnitude. It was found that the simplest structure which justified the data was a linear bar of half-length ∼ 4.4 kpc and bar inclination φ_{bar} = 44° ± 10°. The apparent contradiction between the Galactic bar at φ_{bar} ∼ 20° or φ_{bar} ∼ 40°, which results from the different techniques, seems to be settled by the works of Lopez- Corredoira et al. (2007) and Cabrera-Lavers (2008). They have also analyzed infrared stars counts in the galactic center, and established that two structures seem to coexist in the bulge, a triaxial bulge roughly extending until |l| ≤ 10, and a thin, elongated bar of dimensions 7.8 × 1.2 × 0.2 kpc. Hence, the galactic bulge still seems to keep many of its secrets.

Microlensing (Alcock et al. 1995) has also been a source of information of the mass and velocity distribution of the galactic bulge. Microlensing occurs when a mass (the lens), presumably a stellar mass, crosses the line of sight of another observed star (the source). On galactic scales, multiple lensed images are separated by a few milliarcseconds, and therefore are rarely resolvable. However, the flux amplification effect in the observed star is easily observable and allows the determination of the masses involved in some cases. Even though these events are rare, the regular observation of millions
of stars allows the detection of hundreds of them every year. The microlensing optical depth is the probability that a source star at a certain distance from us is lensed, depending only on the mass density along the line of sight to this star. Thus, optical depth can be used as a diagnostic of the bulge structure. Paczyński (1994) showed that the value found in the galactic bulge for the optical depth $\tau = (3.3 \pm 1.2) \times 10^{-6}$ is three times higher than the value expected for an axisymmetric bulge. Therefore, he explained the optical depth with a bar about $15^\circ$ from the line of sight. Discrepancies between newer measurements of the optical depth and the values predicted for Milky Way’s models are still found.

1.2.2 Bar evolution

A considerable fraction of the total of disk galaxies is barred ($\sim 50\%$). Bars are then an important feature, which often appear during the evolution of some galaxies. Normally, in external galaxies the bar component is easily identifiable when the galaxy is face-on, or close to it. Even in a edge-on or end-on line of sight (the end of the bar in the line of sight) a bar will produce features in the bulge which can be detected. Thus, the abundant information collected in these bar galaxies can gives us important clues about the evolution of our own galaxy.

Distinctive components can be separated from the light distribution of spiral galaxies, where customary tools in the classification of the bulges are the Sersic index, flattening and color. The components thus recognized are normally a disk, a bulge and/or a bar, depending on the classification. A interesting example of detection of bars by different observational techniques is the work of Kuijken & Merrifield (1995), where direct kinematical evidence of the bar is obtained from the line of sight velocity diagram (LOSVD). In those diagrams, bulges containing a bar show a distinctive “eight-shape”, which is derived from the transition between bar orbits. Gas orbits can not intersect themselves, and as a result, there will be gaps in the LOSVD when a bar is present. Nowadays three different kind of bulges can be distinguish in the literature, the distinction in these bulge types is not only related to their external shape, but also to the underlying formation history that has led to the present state. Hence, the three types of bulges are: classical, boxy/peanut, and disky (Athanassoula 2005). Classical bulges are believed to be formed from gravitational collapse or hierarchical mergers of lesser objects, which occurs generally early and before the formation of the disk. These bulges closely resemble elliptical galaxies in their kinematics, radial profiles and stellar populations. Thus, old stellar populations and elliptical shapes dominate in these bulges. Boxy/peanut bulges on the other hand, are the natural consequence of bar evolution. A bar is formed in the disk presumably from a initial perturbation in the disk. The evolution of the orbit families in the bar produces later the bar buckling in which some orbits reach sometimes high latitudes, the projection of these high-latitude stellar families give the characteristic boxy/peanut shape. According to N-body simulations (e.g. Combes et al. 1990, Athanassoula 2003, and references therein) the evolution of the bar and its exchange of matter with the inner disk causes the stellar populations to be mixed up in the bulge/bar structure and the inner disk when the radius is simi-
lar. Nevertheless, the majority of the bulge/bar population age should be higher than those in the disk even though the bar instability can trigger some local star formation. Finally, disk-like bulges (or pseudo-bulges) combine some features of bars and disks. They seem to be formed in a similar way as the boxy/peanut bulges, from an instability in the preexisting disk. However, in this case it is the bar torque which drives gas to the inner disk. Thus, an inner disk is formed which extends until the inner Lindblad resonance, where a ring can also be formed. The new disk will accumulate mass and will trigger some star formation in the central part of the disk. In the end, a sizeable disk is formed. The properties of these bulges can sometimes be the ones expected in disk systems. They can contain a significant population of young stars and considerable amounts of gas. These two characteristics are more pronounced than in the two other types of bulges.

All this leads to a complicated picture of bar evolution, which can not easily be simplified. Moreover, the scenario of bar destruction due to the exchange of angular momentum with the inner disk, which in N-body simulations makes the bar more massive and slow until it destroys itself, as been proposed as a cyclical process (e.g. Combes 2007). In this process of destruction and reformation of bars in the center of galaxies gas seems to play a crucial role.

1.2.3 Modeling the dynamics of the Milky Way

A self-consistent model which agrees with the dynamical and photometric data in the galactic bulge has been a difficult goal to achieve. The scarcity of suitable data, and the technical problems involved have seriously restricted the number of models applied to the galactic bulge.

One of the few is Kent’s model (Kent 1992), which assumes a constant mass-to-light ratio in order to turn the luminosity model described in Kent, Dame, & Fazio (1991) into a mass model and potential. The Milky Way is assumed to be an oblate isotropic structure with a black hole in its center. The results of this model successfully reproduced a variety of stellar velocity dispersions, however, it was unable to reproduce the observed HI and CO rotation curve at small radius.

Schwarzschild (1979; 1982) formulated a technique which has been specially useful in the modeling of the Milky Way. The Schwarzschild technique, consists of the calculation of a suitable orbit library derived from a potential, which in turn is consistent with the density distribution of the galaxy studied. Armed with the orbits integrated in the potential, the phase-space distribution function is fitted by a Non-Negative-Least-Square algorithm (NNLS) to a set of observables. One of the main difficulties (as we will see in Chapter 4) of the Schwarzschild technique in barred galaxies is to define a library representative of the phase-space. This is due to the inability to determine the three integrals of motion of the barred potential, these are quantities conserved during the orbit trajectory, which are extremely useful to constrain the library to realistic orbits.

Zhao (1996), successfully applied the Schwarzschild technique in a self-consistent model for the Milky Way’s bulge. Zhao’s input information for the model included
the COBE-DIRBE deprojection by Dwek et al. (1995) and a set of different observations which consisted of radial velocities and proper motions in Baade’s Window (Sadler et al. 1996, and Spahnhauer et al. 1992 respectively), radial velocity and dispersions at the \((8^\circ,7^\circ)\) field (Minniti et al. 1992) and \((-1^\circ,2^\circ)\) field (Blum et al. 1994, 1995), the overall solid-body rotation curve from bulge stellar traces as Miras, SiO masers, OH/IR stars, and planetary nebulae (Dejonghe & Habing 1992). Zhao’s model yielded a best fit with a 7% difference with the input density distribution, and reproduced reasonably well other observables, such as the velocity dispersion. A considerable fraction of the orbits found in the best fit of the model were found to be chaotic, however regular orbits contributed most of the mass to the bar/bulge.

By contrast to Zhao’s model, a completely different technique was applied in Englmaier & Gerhard (1999). The latter used a sophisticated hydrodynamical code to model the gas flow inside \(\sim 10\) kpc radius. The potential consisted of a multipolar expansion of the deprojection described in Binney, Gerhard & Spergel (1997), and therefore from the COBE-DIRBE image. The model was able to reproduce many gas dynamical features with its four-armed spiral structure. In addition, an interesting bar radius of \(R_{\text{bar}} \sim 3.5\) kpc and bar inclination of \(\phi_{\text{bar}} \sim 20^\circ - 25^\circ\) were found.

Häfner’s dynamical model (2000) came back to Schwarzschild’s galaxy building technique. A similar approach to Zhao’s model was applied to the construction, combining a distribution function depending on classical integrals (regular orbits) and non-classical integrals (irregular orbits). Thus, the Schwarzschild technique was used to distinguish between the real distribution function and one generated only by the classical component. Similarly to the two previous models, Häfner’s model fitted the 3-dimensional mass density of Binney, Gerhard & Spergel (1997), obtained from the deprojection of the COBE-DIRBE surface photometry. In addition, he included the kinematical data from the fields Baade’s Window, the \((8^\circ,7^\circ)\) field (Minniti et al. 1992), the last two used in Zhao’s model also, and also the \((12^\circ,3^\circ)\) field. This model used a library containing 22168 regular orbits and succeeded in fitting the available data inside 3 kpc with reasonable accuracy. Most of the deviation from the input density occurred outside corotation. At the same time, a map of microlensing optical depth of the galactic center was generated.

1.3 This Thesis

This thesis, as its title announces, is about the 3-dimensional movements of stars in the galactic bulge, and the physical and structural implications derived from the stellar kinematics observed. Our approach to solve the endless problem of the uncertainties in the actual structure of the galactic bulge is based on the constraints on the phase-space distribution function defining the inner kiloparsecs of the galaxy. Thus, in order to obtain suitable bulge constraints, we have used the two techniques that can deliver such information, radial velocities and proper motions.

Every chapter of this thesis correspond to different stages in a project which attempts to unveil the structural properties of the galactic bulge through the study of regions with low foreground extinction. These regions, commonly named “windows”,
have historically been the natural solution to the fierce extinction due to the disk dust layer, which obscures the central regions of the galaxy. The complete project includes the observation of 10 fields across the galactic bulge: 3 fields at the center, close to the galactic minor axis; three more at positive longitudes, on the near end of the bar; and 4 more in the far-end of the bar, at negative longitudes. The project was originally intended to be entirely in the realm of the kinematics and dynamics, and therefore has little constraints related with abundances. However, we have not left this entirely unattended, as we explain below. This project is still on-going. The results of this thesis will be complemented in the near future with new information derived from the fields on the far-end of the bar. The work presented here deals with the fields close to the galactic minor axis and at positive longitudes.

In Chapter 2 we report on ~ 3200 new radial velocities, which have been obtained in 6 low foreground extinction windows of the galactic bulge. Our radial velocities were obtained using the VIMOS-IFU camera which allowed us to construct radial velocity cubes in each case. The importance of those cubes is related with the preexisting HST images in those fields (e.g. Kuijken & Rick 2002; Kuijken 2004), obtained from the HST archives. The IFU cubes, combined with the refined spatial information from the HST WFPC2 images, were used to disentangle the spectral information of each star using a new deconvolution algorithm. The results of this process are the stellar spectra in the positions indicated by the HST images. The spectra thus obtained by the new technique reach accuracies typically of ~ 30 km/sec, which is several times smaller than the observed velocity dispersion of the galactic bulge ~ 110 km/sec (Rich 1988; Sadler 1996), and therefore suitable for the study of dynamics, as we will see in chapter 4. The bulge density rapidly drops once we move off-axis. Consequently, for the three minor axis fields we collected ~ 2000 radial velocity measurements, while ~ 1200 such measurements were obtained for the three off-axis fields. In the case of the three minor-axis fields Sagittarius I, Baade’s Window, and near NGC 6558 it has been possible to go one step further and combine the new radial velocities with the proper motions of Kuijken & Rich (2002). Hence, we have constructed a small subsample of stars per field with well determined 3-Dimensional kinematic information. The results of this subsample highlight very clearly a distinction between the different populations present in the color-magnitude diagram (CMD) of each field. Main sequence, turn-off and Red Giant Branch (RGB) stars show a clear vertex deviation which can be directly related with a signature of triaxiality of the galactic bulge. On the other hand, bright blue main sequence stars beyond the turn-off show velocity ellipsoids inconsistent with the determined bulge populations. Thus, the bright blue main sequence stars in these fields seem to be strongly dominated by a disk population. At the same time, it has been observed that the signature of triaxiality decreases when moving off the plane, being weaker for field near NGC 6558, which has the lowest latitude (b ~ −6°). The latter gives us an important clue about the extent of the galactic bar and the influence of its potential on the inner kpc of the galaxy.

Spaenhauer et al (1992) was one of the first to obtain a reliable proper motion catalog for stars of the galactic bulge. Their work made use of plates taken several decades apart to obtain 432 proper motions for a sample of stars in Baade’s Window.
This sample was the starting point for subsequent studies which determined low resolution abundances in many of the stars originally measured (Terndrup et al. 1995; Sadler et al. 1996). In Chapter 3 we have explored this sample, which in addition to 3-Dimensional kinematics, count with calibrated abundances. The original low resolution abundances were recalibrated using the high resolution abundance scale by Fulbright et al. (2006). Thus, armed with a sample with 3-dimensional kinematics and suitable abundances, we have studied the velocity ellipsoids derived from several selection criteria. We found a significant vertex deviation in the metal rich population ($[Fe/H] > -0.5$), which did not appear in the metal poor subset. When analyzing the sample more closely as a function of metallicity, a sudden transition in the kinematics is found around $[Fe/H] = -0.5 \, \text{dex}$, from an apparently isotropic oblate disk to a bar. Similarly, a shallower trend toward lower vertical velocity dispersion ($\sigma_b$) at higher abundances was found.

Chapter 4 presents the development of a new Schwarzschild model for the Milky Way’s bulge. The model has been constructed to reproduce the distribution of proper motions and photometric parallaxes for the three minor axis fields in the project. For each field we selected a subsample of turn-off and main sequence stars in order to build the target (set of constraints) which is going to be fitted. In addition to the proper motions and photometric parallax, a density profile has been crucial to obtain a reasonable set of constraints. This density profile has been provided by the COBE-DIRBE images (Arendt et al. 1994; Weiland et al. 1994) of the galactic bulge. Several deprojections of the COBE images by different techniques were performed. In chapter 4 from an initial analytical deprojection with several free parameters we chose one particular bar model which was added to our set of constraints. This simple bar model consisted of a bar, a disk and a cuspy component. The bar model was used in turn to build a consistent potential with a multipolar expansion, where each orbit forming part of each model was integrated for approximately $\sim 10000$ rotational periods. A grid of 25 self-consistent Schwarzschild models was run, each one corresponding to a different combination of two important bar parameters, the bar pattern speed $\Omega_b$, and the bar inclination $\phi_{bar}$. Results of this set of models show an apparent degeneracy in the best $\chi^2$, which appears for bars at $30 - 40 \, \text{km sec}^{-1} \text{kpc}^{-1}$ of bar pattern speed and bar inclinations of $0^\circ$ or $40^\circ$. To break this degeneracy we introduced in the results the information provided by the radial velocities in chapter 2. Including the radial velocity information we could establish a best bar model which has a reasonable agreement with recent determinations of the galactic bar using other techniques (e.g. Benjamin et al. 2005). Our best bar model, on the other hand, produces a significant number of stochastic (chaotic) orbits, which accounts for a high percentage of the overall mass. Whether the latter is an artifact of the model or is a real effect of the structure and mass concentration applied we can only discern by improving the constraints of the target.

Finally, in Chapter 5 we report $\sim 11000$ new proper motions for the fields at positive longitudes Field 4-7 ($l, b = 3.58^\circ, -7.17^\circ$), Field 3-8 ($l, b = 2.91^\circ, -7.96^\circ$), and Field 10-8 ($l, b = 9.86^\circ, -7.61^\circ$). These proper motions, with a time-baseline of 8-9 years, have been calculated using a modification of the Anderson & King (2000) approach, originally intended for observations in WFPC2 with a suitable dithering pattern in
each epoch. The dithering is used to solve the undersampling of the Point Spread Function (PSF) of the images. Thus, the modifications of the original method correct part of the problems derived from the absence of dithering in the first epoch. This is done by means of an algorithm which refines iteratively the PSF from the stars in each image starting from an analytical model. Another relevant difference between these proper motions and those of the minor-axis fields is related to the instruments used in each epoch. While minor-axis epochs were always observed with WFPC2, the proper motions in chapter 5 consist of a combination of WFPC2 and ACS WFC for first and second epoch respectively, which implied small modifications to the procedure. The results of these stellar proper motions show a remarkable similarity with those of the fields close to the galactic minor axis (Kuijken & Rich 2002), where mean \( \mu_i \) behaviour can be directly related with the intrinsic rotation of the bulge. The latter means that even at the longitudes of the new fields we are able to observe a considerable fraction of bulge stars. Consistently, a distance effect can be seen in the velocity dispersions, stars lying farther away tend to show a smaller dispersion. A more refined search of changes in the velocity ellipsoid as a function of the distance did not produce significant differences, which also agrees with a previous study in Sagittarius-I using ACS WFC proper motions (Clarkson et al. 2008). Thus, the information provided for these fields in the near-end of the bar will provide unique constraints on our model in the near future.

1.4  Future prospects

This thesis, as we have mentioned in the previous section, is embedded in a project which includes 4 more fields in addition to the ones discussed here. There are several aspects of this work which are susceptible to being improved; the galactic bulge being such a vast subject, in theory it is possible/desirable to include a huge number of additional information in order to obtain a group of constraints that would tell us more about the structure and the history of the galactic bulge. Nevertheless, we can point out what we think are the most urgent modifications or improvements which would optimize future efforts on this project.

Chapter 2 explains the techniques and the implications of our new radial velocities (RV) in 6 fields of the galactic bulge, which map the center and the near end of the bar. New observations for the fields at negative longitudes, at the far-end of the bar are expected to be completed. Observation time in those far-end bar fields has been granted for 2009 in HST, after ACS WFC is repaired. With the second epoch of the proper motions completed, it would be possible to plan the respective VIMOS-IFU observations.

In Chapter 4 we explain the scope of our current Schwarzschild model. The model, in its present stage of development, is able to predict the distribution of radial velocities (RV), but does not include any constraint from RV. All the constraints come from density, proper motions, and photometric parallax. Even though it is still possible to combine the information of the RV with the proper motion and parallax, this combination would not have a physical meaning unless the \( \chi^2 \) of the model has a physical
meaning. Thus, the optimal procedure is to include the RV data directly in the model as a new set of constraints. The latter procedure would require a smoothing of the RV data, which represents a much smaller population. Despite this, we believe it is a reasonable assumption to consider the RV population as representative as the proper motion population, as long as we maintain the same constraints by the CMD and keep a reasonable ratio between RV and proper motion stars. Similarly, a more evident modification of the model, implies the expansion of it to include the new fields at positive longitudes. This would increase the maximum number of constraints in a factor of $7/4 = 1.75$. At the same time, we would urge the testing of other techniques of de-projection. Our current density profile makes use of a deprojection from a simple bar model which assumes eight-fold symmetry and just three components; in the future we would like to include additional features in the density profile that would break in some cases such symmetry, like arms and a dark halo. Similarly, gravitational stability in the best fit model must be addressed. A consistent N-body model is under development.

In Chapter 5, we have presented new proper motions in three new fields in the near-end of the bar. The procedure, as we already explained, consisted of combined observations by HST WFPC2 and ACS WFC for first and second epoch respectively. New observations, on the other hand, for the four fields in the far-end of the bar will be done with ACS WFC for the first and second epoch. ACS WFC in both epochs will provide a much better positional accuracy, which in turn will require some changes in the procedure (Anderson & King 2006). PSF variation across each image and local flux variations must thus be included in the procedure.

The project, of which this thesis forms a part, will continue. Once it is completed, it will provide significant insights into the bulge structure from the perspective of kinematics and dynamics. Several other projects with the same goal are currently on-going. The Bulge Radial Velocity Assay (BRAVA), and the VVV VISTA survey (Variables in the Via Lactea), are current examples of a vigorous topic which awaits with high expectations the first results of Gaia during the next decade.

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