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Stories about the bar in the Milky Way

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Abstract

In this contribution, several aspects of the discovery of the Milky Way hosting a central bar are briefly reviewed, as well as some minimal introduction about the barred galaxies in the local Universe. The bulk of the contribution is however dedicated to the two main lines of thought about the true nature of the Galactic bar: that which argues for the Galactic bulge being elongated, i.e. a triaxial body, in the plane of the Galaxy, thus providing a bar-like structure in central regions. The angle of that structure with respect to the Sun-Galactic centre line is found to be $\sim 23^\circ$. And the second one which claims for the existence of a long thin bar, very much concentrated in the Galactic plane, and being a distinct structure of the central Bulge. The position angle in the latter case is calculated at $\sim 45^\circ$.

1 Introduction

Nowadays, there is an ample consensus about the Milky Way being a barred galaxy. However this consensus has only be reached not before the last decade, when the cluster of observational evidences has made very hard to accept any other explanation for the structure of the inner regions of the Galaxy. Even today the precise details about the geometry and position of the central Galactic bar and the nature of its stellar population are matters of controversy among the community, due partly to the practical difficulties in obtaining data with enough quality of that distant and obscured region of the Galaxy. On the other hand, the position of the Sun in the Galactic plane poses an additional complication in the data analysis and interpretation due to strong perspective effects. Nevertheless, examples of large central bars which dominate the surface brightness distribution in galaxies of morphological type like ours are readily observed in the local Universe.

That the central zone of the Galaxy could not participate in the ordered circular motion observed in the outer regions of the disc and must include more complicated structures as well as being the holding framework of high energy events was known since long ago. Oort and others, in the 1950's, did postulate the existence of an *explosive event* in the Galactic Centre to explain the several spiral features with unusually high radial velocities which were measured with the atomic hydrogen 21 cm line. De Vaucouleurs is widely recognized as the first astronomer who actually pointed out to the Milky Way hosting a central bar as a possible explanation to the observed motions of the gas in the Galactic interior [13]. In spite of this, the idea of a central bar, mostly constituted by stars, did not reach maturity until the advent of powerful stellar surveys in the NIR with high sensitivity and spatial resolution, coming from both ground and spatial telescopes, which happened at the end of the 1980's.

The rationale about the Milky Way being a barred galaxy has growing up following the many discoveries about the morphology of the central regions of the Galaxy, most coming from detailed NIR star counts. The first evidence for a bar-like distribution in the stars was derived from the asymmetries in the infrared surface brightness maps (e.g., [4, 14]) and in source counts [40, 22, 37], which both show systematically more stars at positive galactic longitudes within $\ell < 30°$ and close to the Galactic plane compared to the negative side. The exact morphology of the inner Galaxy, however, is still controversial. While some authors refer to the bar as a fatter structure, around 2.5 kpc in length with a position angle (PA) of $15° - 30°$ with respect to the Sun-Galactic Centre direction [14, 28, 38, 6, 16, 24, 7, 2], other researchers suggest that there is a long thin bar with a half length of 4 kpc and a position angle of around 45°. It is noteworthy that those authors supporting the 23° PA bar all examine the region at $|\ell| < 12°$, whereas those supporting the long bar with the larger PA are trying to explain counts for $10° < \ell < 30°$ and $-10° > \ell > -30°$.

2 A few words about bars in galaxies

Bars are common phenomena in galaxies. The most recent estimates point to at least 70% of the galaxies over $10^{10} M_\odot$ being disc galaxies (see [21]), out of which 2/3 are barred. This proportion is somewhat underestimated since the detection of bars is hampered by several observational effects, being internal extinction possibly the one which the largest effect. Because of this, automated classified catalogues steadily report lower fraction of barred galaxies than those which human intervention for the labeling. Bars are also more common in the local Universe than in distant galaxies (see [1]).

Connected with the barred type of a given galaxy it is becoming increasingly important the possibility of a secondary associated bar. Erwin [15] has nicely summarized the existing data for double barred galaxies on which a value as large as a 40% of barred galaxies being double barred, depending upon the Hubble type, is claimed. It is instructive to note, as quoted in [15], that some theoretical interest was first raised by [36], as they suggested that a system of nested bars could be an especially effective way to transfer gas from galactic scales down to near-nuclear scales and thereby feed active nuclei. In this model, the gas inflow driven by a large-scale bar produced a central concentration of mass which became dynamically decoupled and unstable, leading in turn to the formation of an independently rotating inner bar. That type of mechanisms in which large scale bars are the main responsible of feeding the high energy events that happen in the centre of galaxies have been argued repeatedly in the literature. But most recent investigations pointed at inner bars being not significant for the maintenance of the active nuclei (see [15, 35]).

3 How the Galactic bar becomes a reality

Since Oort pionnering work in the 1950's, the history of the Galactic bar really begins with the discovery of large non-circular velocities in the 3 kpc and 135 km/s spiral arms [34, 33]. See the introductory section in [27] for a rather detailed list of the early works in the subject.

As already mentioned in Section 1, most of the authors can be grouped into two distinct categories: those arguing for the Milky Way having a boxy bulge with its major axis on the Galactic plane and a PA of $\sim 20^\circ$ and which is assumed to produce the bar-like structure seeing in the observational data; and a second group which claims for two separate structures in the central Galaxy: the boxy bulge, as in the previous case, and a long thin Galactic bar, very much concentrated in the Plane, with a PA of $\sim 45^\circ$.

Among the authors in the first group it can be cited [4] who suggested a rotating triaxial spheroid to explain large-scale $l-v$ asymmetries in HI; [5] who modeled the Galaxy's HI, CO and CS emissions in the central region as driven by a bar with a PA of $\sim 16^\circ$; [14] analysing the COBE/DIRBE IR diffuse emission asymmetries in galactic longitudes; [39] using a private NIR point source catalogue; [16], modeling the COBE/DIRBE diffuse NIR maps; and [2], which again make use of dedicated surveys of the inner Galaxy in the NIR.

The same exercise in the second group will produce a shorter list: [30] modeled the HI distribution derived from $l-v$ diagrams in the inner 4 kpc of the Galaxy in terms of concentric elliptical orbits and found that a PA of 45° fitted the maximum number of radio features in the $l-v$ diagrams, including the 3 kpc and 135 km/s arms. [40] explored the structure of the stellar disk inside the solar circle using AGB star tracers and found a stellar bar with PA of -36°; [3] making use of data from the GLIMPSE project argued for a linear bar passing through the Galactic center tilted by 44°.

The group of Galactic structure of the IAC has made a substantial contribution to this topic since long ago. Our results clearly show the presence of a long thin bar, very much concentrated in the Galactic plane, and whose effects can be noticed over the whole disc. These results, together with some outline of the data and methods used in the analysis, will be summarized in the next section.

4 The Galactic bar as seen from Canarias

Our team has a long standing tradition in surveying the stellar population of the more distant and obscured regions of the Galaxy by means of NIR maps of increasing sensitivity and spatial resolution. Specially designed instrumentation, built at the IAC, has served to our purposes. [17] published the results of a small survey of selected areas in the Galactic plane using a

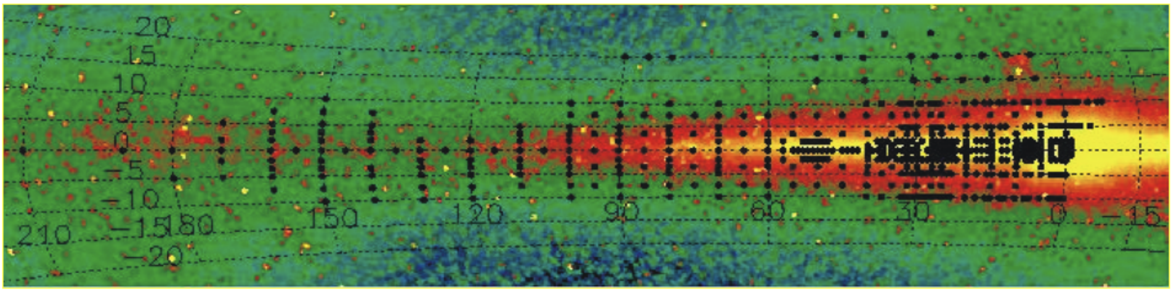

Figure 1: The pointings of the TCS–CAIN survey superimposed over a DIRBE 4,9 μm map of the Galactic plane.

single channel photometer driven at sidereal rate in the 1.5-m telescope at the Observatorio del Teide (not yet named as Carlos Sánchez Telescope, TCS). Even when the area covered was really small, this project served as a demonstrator of the power of the NIR counts to sound the inner Galaxy. The gain mostly comes from the much lower extinction compared to the optical bands so the measured stellar distribution very much follows the true one, contrary to the what it is observed in the optical bands where interstellar extinction tends not only to obscured but to blur the stellar counts, so creating *artificial* structures in the data.

The Two Micron Galactic Survey (TMGS) data [18] was the next observational project and the bar started to emerge in the data. Analyzing the TMGS K-band star counts [22] concluded the existence of a bar of radius 4 kpc, with the closest tip at $\ell = 27°$ and the farthest one at $\ell = -22°$, thus at PA of of 75°. [11] showed *tomographs* of the Galactic plane built from TMGS star counts on which the long bar appeared as a separate structure for the first time. [12] claimed the existence of a dust lane preceding the bar at negative longitudes as expected for a rotating bar, which would explain the higher extinction observed in this region.

The analysis of the TMGS data base resulted in spectroscopic follow-up of selected samples. Thus [19] and [24] reported a large excess of supergiants in the $\ell = 27°$ area, covered by the TMGS. That very high concentration of young sources points to the existence of a major star formation region in the Galactic plane, located just inside the assumed origin of the Scutum spiral arm. Such regions can form because of the concentrations of shocked gas where a galactic bar meets a spiral arm, as it is observed at the ends of the bars of face-on external galaxies. Thus, the presence of a massive star formation region is very strong supporting evidence for the presence of a bar in our Galaxy.

The TCS-CAIN survey project [8] constituted a major advance in the ability of sounding the most densely populated and obscured regions in the Galaxy by combining a sparse coverage of the most interesting areas over the whole Galactic plane (see Fig. 1) with a high sensitivity and spatial resolution. In Fig. 2 it is noticeable the gain of TCS-CAIN with respect to 2MASS in the internal zones of the Galaxy. A small subsets of the pointings were also covered with NOTCAM, which resulted in additional gains, as can also be seen in Fig. 2. It is of outmost importance to reach both sufficient sensitivity and spatial resolution to properly

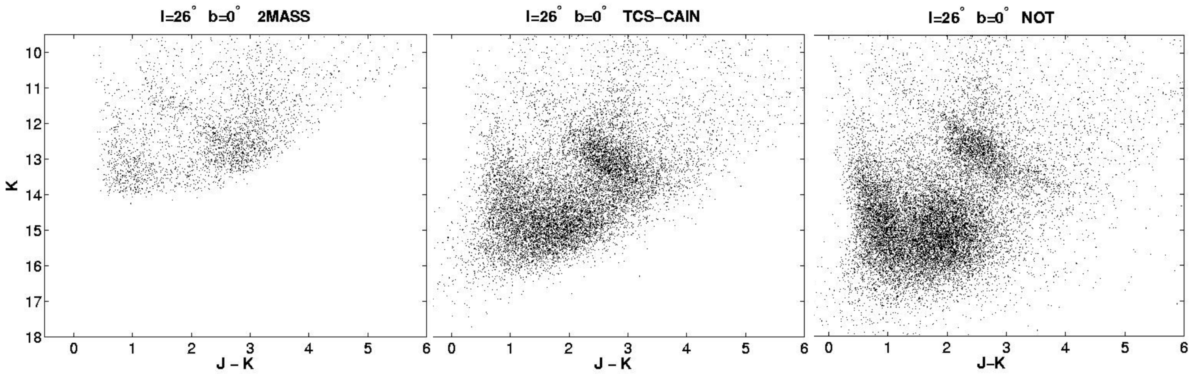

Figure 2: $J-K$ *vs.* K colour-magnitude diagrammes at $\ell=26°$ in the Plane, where the tip of the bar is expected. Left to right, the panels contain data from 2MASS, TCS-CAIN and NOTCAM. The advantage of gaining deeper sensitivity and higher spatial resolution, from left to right, is evident.

measure the true stellar population in these hidden and distant regions.

[23] made use of a preliminary data set of the TCS-CAIN survey [8] on which the red-clump stellar population could be identified and then used as a candle for distance calculation. By doing so, the geometry of the bar could be estimated, yielding a PA of 43°, after correcting the position of the farthest end of the bar, now at $\ell=-12°$. In this paper it was shown how the run of the excess in star counts over the standard exponential disc in the Galactic plane, see Fig. 3 left, showed clearly a morphological structure going further from the Sun as the line of sight penetrates into the Galaxy, i.e. decreasing the longitude. This excess, due to something else than the disc, is also visible when comparing the TCS-CAIN data with the predictions of the Besançon model, see Fig. 3 right, as demonstrated in [31].

The technique of detecting and using the red clump stars as distance estimators has been further refined by [25] and [9] and has yielded excellent results in the determination of the geometry and position of the Galactic bar. It relies, at first, on the fact that the red-clump population is conspicuous enough in the NIR colour-magnitude diagramme (CMD) so as it can be isolated and extracted. This is due to both its high density in the Galactic disc and the narrow locus that it occupies in the HR diagramme, which translates in a very well defined absolute magnitude with low dependence with metallicity and other parameters. As it can be seen in Fig. 2, this feature is clearly seen at $J-K\sim 2.5, K\sim 13$, so it is lost in the 2MASS catalogue due to its incompleteness in the inner Galaxy. Using this technique in the TCS-CAIN and UKIDSS data bases [9, 10] showed a markedly good coincidence in the two data sets to derive the long thin Galactic bar in the plane with very similar PAs, as it is shown in Fig. 4, with an extent of ~ 4 kpc in radius, also in good coincidence with previous determinations by the IAC team.

The data from the GLIMPSE project [3] very much confirmed the hypothesis of the existence of an in-plane long bar different from the bulge of the Milky Way with the same geometry and PA reported steadily by the IAC team. This result in conjunction with previous

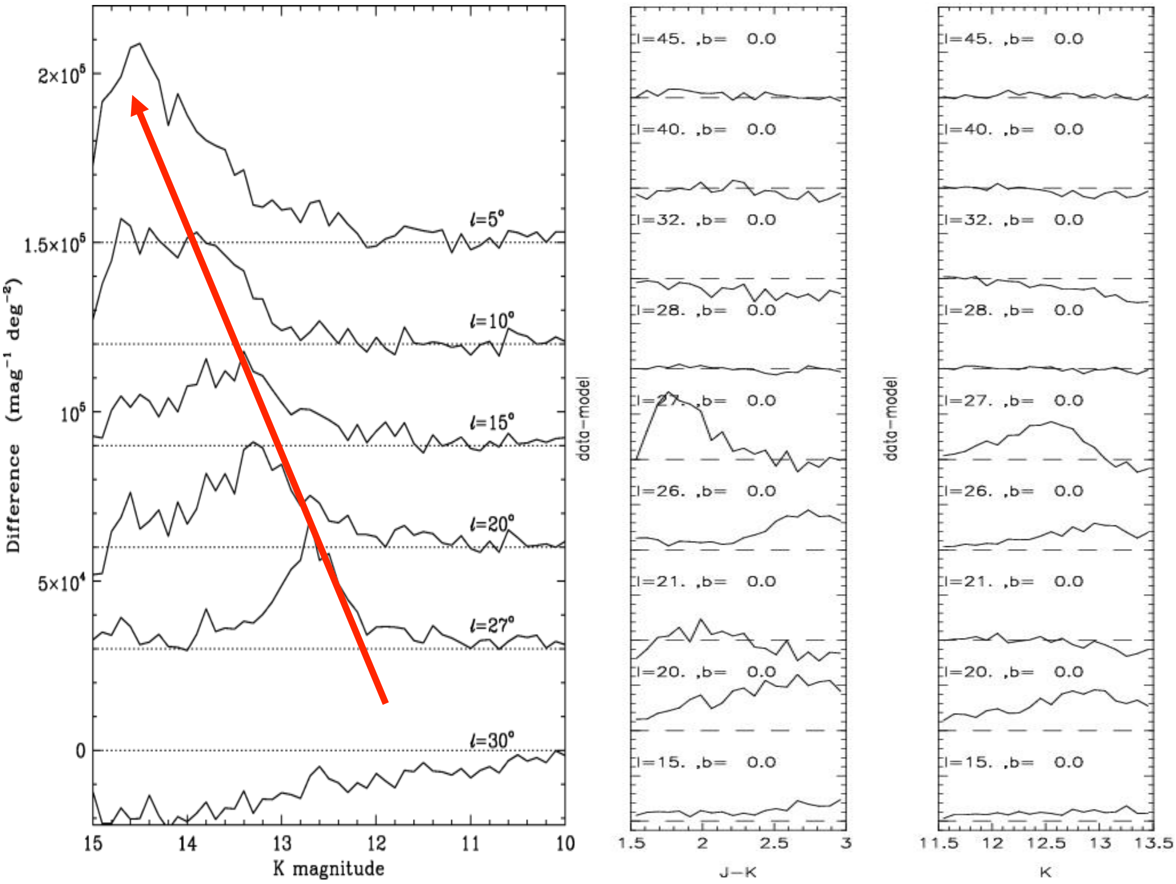

Figure 3: Left, TCS–CAIN K-band differential star counts (zero point of counts set at $\ell = 32°$) at $b = 0°$. The excess in counts is seen at progressively fainter magnitudes with decreasing longitude. Right panel, $J - K$, leftmost, and K, rightmost, differential counts of the TCS–CAIN survey versus the predictions of the Besançon model at several longitudes in the Galactic plane.

and new data analysis by our team has been discussed in [27] .

5 Results from other groups

Using more or less the same techniques that have been briefly described in the preceding section (NIR surveys, red-clump stars, . . .) other groups have produced results which do not aligned with the hypothesis of a long thin bar oriented at $\sim 45°$. It is interesting to note that many of these studies include, if not restricted to, the very central region of the Galaxy where the contribution of the Bulge population to the observed counts is expected to be the dominant one.

[2] presented a deep near-infrared wide-angle photometric analysis of the structure of

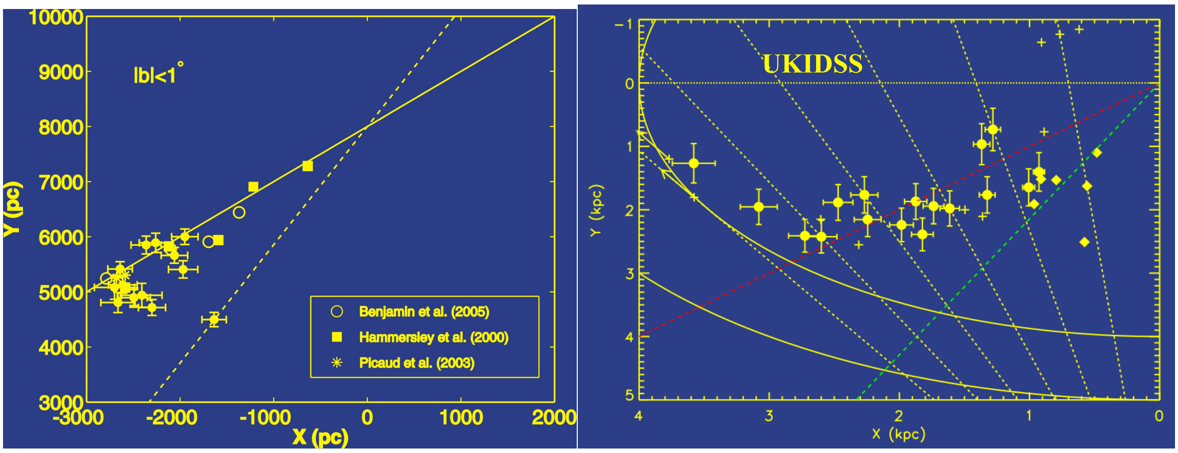

Figure 4: Positions of the maxima of the red clump population identified and extracted in the NIR CMDs of observed areas in the Galactic Plane. Left, using data from TCS-CAIN. Right, the same for the UKIDSS database.

the inner Galactic bar and central disc. The data were obtained with the CIRSI instrument on the du Pont 2.5-m telescope at Las Campanas Observatory. From this, they argued the presence of a triaxial structure at the centre of the Galaxy which is consistent with a bar at PA of $\sim 22°$, as shown in Fig. 5 left, extending to approximately 2.5 kpc from the Galactic Centre, i.e. around the measured radius of the Bulge along the Galactic plane. These authors only used 3 points to determine the bar geometry, which come from the measured position of the bulge red clump stars. A fourth data point at $\ell = -9.8°$ is discarded since did not aligned well with the rest and is attributed to a second structure in the inner Galaxy, a double triaxiality or an inner ring. In their plot, Fig. 5 left, it is included a data point from [23] at $\ell = 27°$. Interestingly, these two extreme points traces very nicely the long thin bar reported by the IAC team and other groups, as it is noted by an brown-orange thick line overplotted in Fig. 5 left, while the central 3 data points are aligned with the triaxial bulge reported by [7] and [26].

[29] did report the results of a NIR (JHK_s) survey along the Galactic plane, $-10.5° < \ell < 10.5°$ and $b = +1°$, with the IRSF 1.4 m telescope and the SIRIUS camera. By studying the locus of the red clump population in the NIR CMDs they infer the existence of an additional inner structure superimposed to the Galactic bar within $|\ell| < 4°$. While the paper is concentrated in this inner morphology, the data can also support the presence of the long bar, as can be sketched in Fig. 5 centre, where an brown-orange thick line has been overplotted roughly at the orientation of the bar found by the IAC team.

To end with this brief review of results which do not find evidences for the long Galactic bar at PA$\sim 45°$, at least as reported by the authors, [32] have recently presented a paper in which they analyse 44 bulge fields from the OGLE-II microlensing collaboration data base to constrain analytic triaxial models for the Galactic bar. They claim to have found a bar with PA $\sim 24° - 27°$, which is consistent with the findings of other groups in the central Galaxy. Interestingly, when some of the most exterior points are included in the model

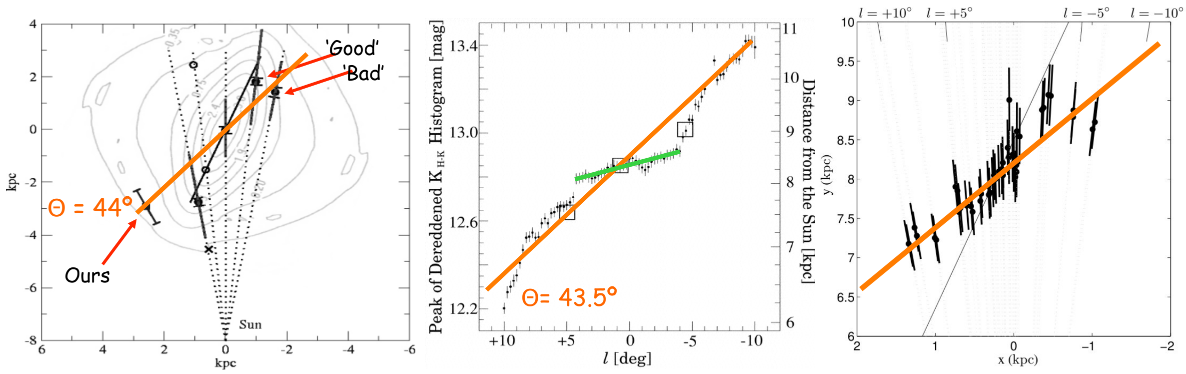

Figure 5: Positions of the maxima of the red clump stars measured by different groups, which are supposed to mark the position of the long axis of the bar. Left, results from [2], which included a data point from [23] at $\ell = 27°$, labeled as 'Ours'. Central panel taken from [29]; the green line belongs to the original figure. Left panel is taken from [32]. The panels have been annotated by us in brown-orange. See text for details.

fitting the result changes considerably. In the paper one can read "fields with $\ell < -4°$ and $\ell > 6°$ should be included in the modelling of the bar, as they are likely to provide further constraints on the final model. Initial attempts to model the bar using all fields failed because the fitting algorithm found a model with a bar angle of 45°, consistent with the observed data, but not consistent with the current understanding of the bar". This can be seen in Fig. 5 left, where an brown-orange thick line has been overplotted at that PA in contrast with the black line showing the orientation of the bar argued in that work.

6 Conclusions

While much work is still needed before the detailed morphological structure of the inner Galaxy will be revealed, it can be concluded in view of the many observational evidences that the existing data are consistent with a long thing bar with a PA of $\sim 45°$. This bar is strongly concentrated in the Galactic plane with a short scale height of the order of 100 pc. Coexisting with this bar, there is also another bar-like structure in the inner Galaxy as the Bulge is not a spherically symmetric body, but a triaxial body elongated in the Plane, with an orientation of $\sim 22°$. The global coupling between this two distinct structures has still to be described.

The stellar content of the bar is emerging (see [20]), but surely better spectroscopic surveys are needed to cover this topic. The project GALEP, to be developed with the EMIR instrument at the GTC, has as one of its main objectives to uncover the true nature of the stellar populations in the inner Galaxy.

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