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Tracing the Milky Way spiral arms. Now and in the Gaia era

Maria Monguió[1], Preben Grosbøl[2], Francesca Figueras[1], Teresa Antoja[3], and Jordi Torra[1]

[1] Dept. d'Astronomia i Meteorologia, Institut de Ciències del Cosmos(ICC), Universitat de Barcelona (IEEC-UB), Martí i Franquès 1, E08028 Barcelona, Spain
[2] European Southern Observatory, Garching, Germany
[3] Kapteyn Astronomical Institute, Groningen, Germany

Abstract

Whereas it is well established that spiral arms are important agents driving the evolution of the galactic disks, the observational evidences of the outer spiral arms in our Milky Way are frustratingly inconclusive. In order to shed some light on the still remaining open questions, we are developing a photometric and spectroscopic survey in the anticenter direction with the aim to detect the overdensity and the kinematic perturbation due to the Perseus arm. We show how preliminary Strömgren photometric data from B5–A3 stars suggest an overdensity at 1.5–2 kpc from the Sun, probably related with the Perseus arm. The photometric data already obtained is being used to select the targets for the spectroscopic survey. Radial velocities will be used to evaluate the amplitude of the kinematic perturbation due to the arm. We also present our first simulations to evaluate the capabilities of Gaia data and the already developed tools to derive the parameters of the density wave in the solar neighborhood.

1 State of the art

Although the spiral arm structure in the solar neighborhood is well known, key questions about the nature and origin of the spiral arms in our Milky Way (MW) are still open, some of them being [13]: what is the mechanism of the spiral phenomena? Are they transients or long-lived structures? What is the nature of their building blocks: stellar or gaseous? What is the structure at the far-side of the Galaxy? Recent Spitzer/IRAC infrared data [4] provides new insights into the spiral arms pattern in the inner region of the galactic disk, but we have a vague and very confused picture of the outer MW spiral arm structure. Few projects are going on in the anticenter. The VLBA project [11] provides accurate parallaxes, but only for 2–3 masers in massive star forming regions in the anticenter direction. In [14] the authors looked at the third galactic quadrant, and despite the very uncertain kinematic distances of CO clouds, and some open clusters and associations, they proposed that Perseus grand-design spiral arm is only defined by gas over a large extend in this direction. [4] proposed that the Milky Way has two major spiral arms (Scutum-Centaurus and Perseus) with the greatest stellar densities and two minor arms (Sagittarius and Norma) filled with gas and pockets of young stars. Thus, present knowledge of the nature and structure of the outer Perseus arm is still controversial.

2 Aim of the project

We propose a two step approach to confirm or refuse the up-to-day cartographic model: a) to map the stellar space density looking for over-densities of early-type stars tracing the Perseus arm in the anticenter direction (photometric survey), and b) to detect the velocity signature due to a density wave perturbation through accurate radial velocities of the selected targets (spectroscopic survey). The center or anti-center directions are optimal to develop this project as in this direction the influence of galactic rotation is minimized. Accurate Strömgren photometry is being collected with the Wide Field Camera (WFC) on the Isaac Newton Telescope (INT) to evaluate the overdensity of young B5–A3 stars due to the underlying density wave. This method is the unique safe strategy to locate the outer arm, as tangent points cannot be observed in the anticenter. It is likely that our galaxy has a relative weak perturbation (i.e. $< 10\%$ variation of the disk density), so accurate distances are critical to detect overdensities by statistical means. It is well known that peaks in the space density of very young O–B5 stars would mark current star formation, while somewhat older populations, e.g. B5–B9 and early A-stars, are expected to show a density variation due to the presence of a density wave. Stars must be old enough to respond to a potential perturbation but young enough to still have small intrinsic velocity dispersion (< 15 km/s according to [3]). Thus, B5-A3 stars are optimal for our studies. Strömgren $uvby\mathrm{H}\beta$ photometry is the natural system to identify them, yielding accurate estimates of individual distances and ages. In order to find a 10% peak to peak variation of the space density, we estimate we need a 8 square degree survey up to Strömgren $u \sim 20$ (at least a 3σ detection). With this photometric survey we obtain both, the stellar density distribution, and the target selection of late B and early A-stars to undertake the spectroscopic survey. For the radial velocity survey we are using WYFFOS at the William Herschel Telescope.

3 Photometric survey

Observations: Our photometric survey ($uvby\mathrm{H}\beta$) started in February 2009 using the WFC at INT. Data have been fully reduced for the first 12 WFC fields, i.e. 3 square degrees around $(\alpha, \delta) = (86.6, +28.2)$ deg. The crossmatch between data from the 6 bands demonstrates that the u filter is the most restrictive one. From the actual obtained data, fully reduced, we get a sample of about ~ 7500 stars with acceptable photometric errors, spectral types, distances and other physical parameters (derived following [8]).

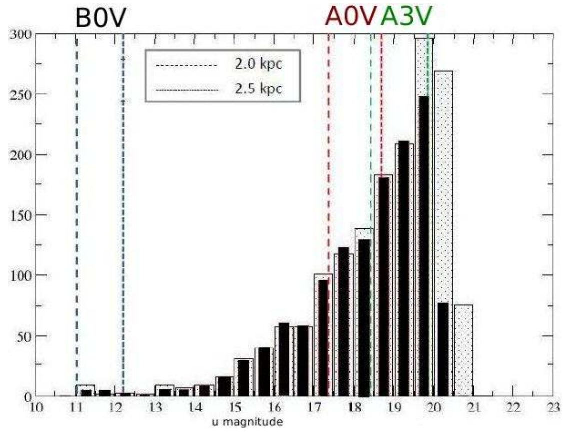

Figure 1: The ac308 central field in our INT survey has been used to evaluate the deepest u magnitude reached in the 2009A observing run. In black: histogram of the stars for which a mean u magnitude has been derived with the required SNR following our reduction strategy. In gray: histogram showing the limiting u magnitude reached when images from the seven pointings of ac308 have been stacked previous to magnitude derivation. This analysis shows that our standard reduction strategy –adopted to reach the required accuracy in photometric distances– and the used exposure time in the u filter ensure us to be complete up to $u = 19.5$ mag.

Completeness: As can be seen in Fig. 1, we checked that the obtained data allow us to ensure completeness only up to $\sim$ 2.2 kpc for A3 stars. In order to do that we used the central field ac308 that was observed several times as a standard field. Adding all the obtained exposures and comparing it with a single exposure, we can determine the limiting magnitude for which the sample is complete, that is $u \sim 19.5$.

Comparison with Besançon Galaxy Model (BGM): We compare our results of the radial distribution of A5–B3 stars with the expected star counts from the Besançon Galaxy model [12], which do not take into account the spiral arm overdensity. In Fig. 2 b we see significant differences between the observed and the expected distribution, the most important ones are the following: 1) smaller number of stars per volume density in the BGM data, possible explanations being the parameters adopted in the BGM for the luminosity function for B5–A3 stars, the extinction model or the density law of the disk (scale length, number of exponentials,...) among others, and 2) a possible overdensity in the observed sample around 1.5–2 kpc.

Preliminary overdensity: We can see in Fig. 2 a that the actual B5–A3 distance distribution shows a possible overdensity around 1.5–2 kpc from the Sun in the anticenter direction. We compare our distribution with an exponential disk with scale length of 2 kpc, and a star density at the Sun position of $(2.87 \pm 0.24) \times 10^{-4}$ stars pc^{-3} (from [10]). We point out that this overdensity can be associated to the presence of the Perseus arm, although we need better statistics and deeper data in order to confirm it.

Extinction: Figure 3 a shows the obtained extinction versus distance plot. We can see a change on the slope around 1.5–2 kpc which would be consistent with a dust layer at the

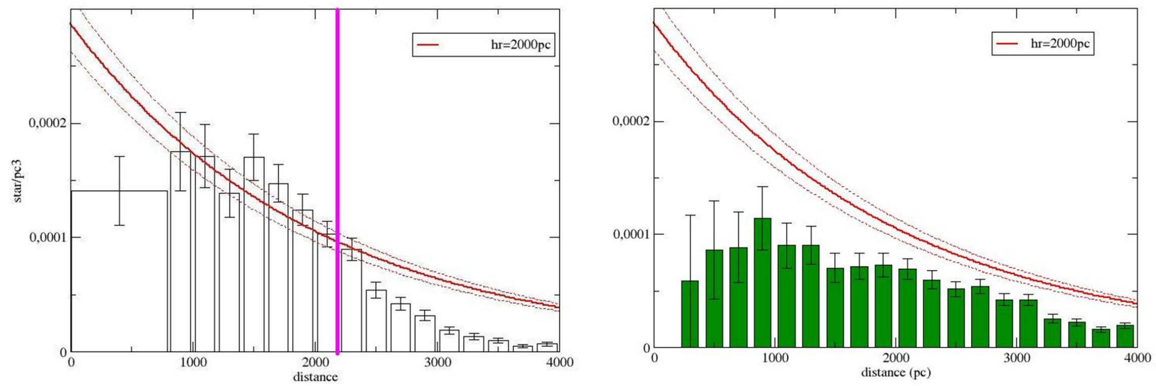

Figure 2: *a) (left)*: Stellar density distribution of B5–A3 stars in the anticenter direction (the histogram is volume corrected). From Fig. 1 we ensure our preliminary sample (3 deg^2) is complete up to 2.2 kpc (pink vertical line). At $r < 1$ kpc we have low statistics and some saturated stars. *b) (right)*: Stellar density distribution expected from Besançon Galaxy model. In both figures, a exponential disk density law with scale length of 2 kpc have been plotted for comparison. The zero point of the exponential law is $(2.87 \pm 0.24) \times 10^{-4}$ stars pc^{-3} obtained from [10].

inner side of Perseus arm. We also compare the obtained absorption with the absorption computed in the IPHAS (INT photometric Hα survey) catalog [5]. As we can see in Fig. 3 b a systematic difference is clearly seen between both derived absorptions.

4 Spectroscopic survey

We plan to obtain the radial velocities for our already selected stars using WYFFOS at William Herschel Telescope in order to study the kinematic perturbation due to the Perseus arm. We developed some simulations in order to establish the number of stars needed to achieve the detection of the perturbation. Assuming a value of the amplitude of the perturbation around $A = 2.5$ km/s –plausible according to the few available and uncertain estimates of this parameter [7, 9]– these simulations show that around 800 stars are needed. We should also take into account that some of the observed stars will be binary ($\sim 30\%$ according to [6]) so we have increased the number of stars till ~ 1000 stars. With the obtained spectra we also will be able to improve the estimates of the physical parameters ($T_{\rm eff}$, log g, absolute magnitudes and ages) of the B5–A3 selected targets and check the Strömgren calibrations.

5 Spiral arms as seen by Gaia

First simulations have been performed to analyze how the Gaia satellite (ESA, launch 2012) will see the spiral arms of the Milky Way and the precision we expect to find in the derivation of the parameters of this large scale structure. For that, three codes are being developed:

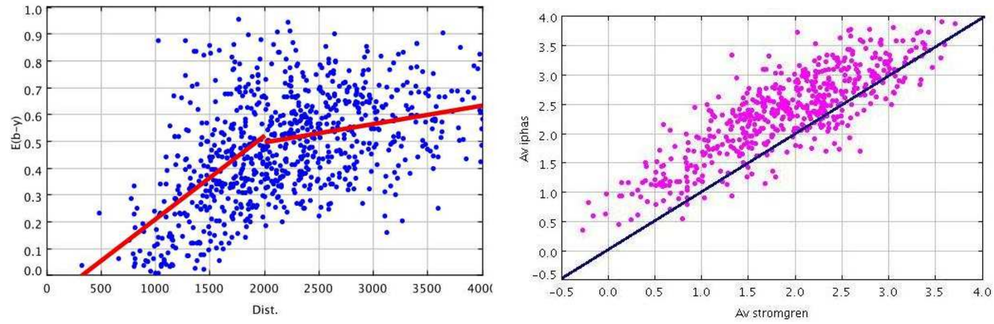

Figure 3: *a) (left)*: Extinction $E(b-y)$ against distance. Most of the reddening takes place in the first 1.5–2 kpc from the Sun, consistent with a dust layer at the inner side of Perseus arm. *b) (right)*: IPHAS against Strömgren visual absorption with a one to one line showing a possible over-estimation of the IPHAS absorption.

1) Star generator: Position of the stars in the galactic disk have been generated following an exponential disk plus a spiral arms overdensity with a logarithmic locus. Observed velocities are computed considering the intrinsic motion of the stars, the Sun velocity, the galactic rotation and the asymmetric drift [1]. Then, the spiral arm kinematic perturbation is added assuming Lin & Shu density waves theory.

2) Gaia errors: The expected Gaia errors for parallax, proper motion and radial velocities according to G magnitude and $V-I$ color have been computed for each star following the actual mission expectations (see Gaia web page[1]).

3) Simplified kinematic model at the solar neighborhood: As a first step, a simplified model [7] to recover the model parameters has been applied to the simulated sample. A least square fit (LSF) is made considering simultaneously radial velocities and proper motions. The parameters to be derived from the fit are: the Sun motion with respect to the LSR, first and second order terms of the rotation curve, the K Oort constant term for the expansion parameter, the radial and tangential amplitudes of the spiral perturbation, the phase of the spiral at the Sun position, and the ratio between the maximum value of the spiral radial force and the radial force due to the axisymmetric field.

Preliminary results show that for an accurate derivation of the galactic rotation parameters, even near the solar neighborhood, it is mandatory to take into account the spiral structure in the LSF. We stated that important correlations in our LSF do not allow us to take advantages of a future set of very accurate astrometric parameters expected from Gaia. Furthermore, a larger set of data may still show the systematic trends seen due to the high correlations present. In conclusion, a correct scientific exploitation of the Gaia data requires a more complex modeling and data treatment to take into account the variation of the radial and azimuthal kinematic spiral arm perturbation as a function of the galactocentric position (work in progress). Definitively, model needs to be improved at corrotation since resonant effects are not considered in the linear density wave theory approximation. Furthermore,

[1] http://www.rssd.esa.int/index.php?project=GAIA&page=Science_Performance

bar and spiral arms resonant effects like moving groups [2] shall also be considered at all galactocentric positions.

6 Preliminary conclusions

We obtained Strömgren photometry for 3 deg^2 in the anticenter direction. From this data, we obtain the physical parameters for $\sim$ 1000 B5–A3 stars. Their distance distribution shows a preliminary detection of an overdensity around 1.5–2 kpc, probably related with the Perseus arm. More and deeper data is needed in order to ensure the detection. We plan to obtain additional 5 deg^2 to complete de survey. From the already obtained data we select some stars useful for the radial velocity survey, that will be used to study the kinematic perturbation due to the Perseus arm. We also developed some simulations to evaluate the capabilities of Gaia to study the spiral arms, and also how the already available tools should be improved.

Acknowledgments

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