Faint star counts and the Milky Way structure

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The Milky Way Galaxy offers a unique opportunity for testing theories of galaxy formation and evolution. I discuss how large surveys, both photometric and astrometric, of galactic stars are the keystones of investigations into such fundamental problems as the merging history - and future - of the Galaxy. This work features a sample survey plan to produce probes of stellar populations in the Milky Way. Objectives of this work are to trace the fine structure of our Galaxy through the statistical study of the stellar distributions according to their luminosity, colors and proper motions. The work has two steps : first acquiring a new photometric and astrometric sample survey in various galactic directions; secondly analysing the data using a model of population synthesis and determining the properties of populations in the Galaxy and constraints on the scenario of formation and evolution.

THE field of Galactic Structure is currently extremely active, due mostly to improvements in observational capabilities and the realization that our Galaxy is perhaps the one best-suited to testing theories of galaxy formation. The concept of stellar populations has proven to be one of the most useful ideas of modern astronomy. Most simply, it is the idea that we can define a *population* as a set of stars that possess shared characteristics such as composition, age, or kinematics, and that we can use the properties of the various stellar populations to determine the structure and evolutionary history of the Galaxy. The first modern definition of stellar populations was by Baade[1], who defined two stellar populations - the now famous populations I and II - based on color-magnitude diagrams and on the brightness of resolved stars in M31 and M32. Population I is composed of stars found in the disk of our Galaxy and in the Magellanic Clouds; a signature of this population is the presence of highly luminous O- and B- type stars and open clusters. Population II is made up of stars with color-magnitude diagrams like galactic globular clusters, which lack luminous blue stars; another signature of Population II is the presence of short-period Cepheid variables. Now it became clear that Population II was old and poor in metals, while Population I was metal rich and contains both young and old stars. The various doubts and worries about the Population I/II scheme came to a head in the famous Vatican Conference[2] of 1957, during which Baade's original two populations were replaced with five : extreme population I, older population I, disk population, intermediate population II, and halo population II. Since the Vatican Conference, the field of stellar populations has been very active, and we now have a wealth of detailed information on populations throughout the Galaxy. One of the main developments is that we now have a good picture of the intermediate population (thick disk) in our Galaxy, i.e. a component with characteristics intermediate to those of the thin disk and halo populations[3].

Studies of stellar populations often take as their starting point large scale surveys, with selection criteria involving one or more observable variables. The physical location of the stars is arguably the most important constraint. With these points in mind, we have carried out a sample survey in UBV photometry and proper motions in various directions in the Galaxy. Large Schmidt telescope plates are well suited for measuring photometric magnitudes and positions for large number of stars, because they have a large field (5×5 degree) and go sufficiently faint. By choosing a reasonable number of fields in various galactic directions, we expected to get a representative sample of the spatial distribution of the different stellar populations, which have led to understand the history of formation and evolution of the whole Galaxy. The kinematical studies of stellar populations are very important because it follow the galactic dynamics and keep memory of the evolution of the whole potential. Results discussed here concern the kinematics of thin disk and thick disk populations of our Galaxy and the scenario of formation for the thick disk population.

Observations and data reduction

The chosen directions constitute a complete set of fields at high and intermediate latitudes :

- Direction towards the galactic anticentre[4] ($l = 167°$, $b = 47°$).
- Direction towards the galactic centre[5] ($l = 3°$, $b = 47°$) near the globular cluster M5.
- Direction towards the galactic antirotation[6] ($l = 278°$, $b = 47°$).
- Direction towards the North Galactic Pole[7] ($l = 58°$, $b = 80°$).

The basic observational material for the survey is Schmidt plates. The plates used in our programme have been taken from Palomar, Tautenburg, ESO and OCA Schmidt telescopes. For each field the plates have been taken in UBV filters. In all we have a total of 58 plates for the various fields. Each plate has been scanned with the MAMA machine (Machine Automatique à Mesurer pour l'Astronomie) at Paris Observatory. A sampling step and pixel size of 10 microns has been used to scan the plates. The output of the MAMA machine is a catalogue of objects giving the positions X and Y, integrated density and the area of each object. The integrated densities are used to calibrate the plates photometrically while the combination of various Schmidt plates of a given field are used for proper motion determination involving a time base of $\sim$ 34 years. To photometrically calibrate the plates a number of photometric standards are required. The standards should cover the entire range of magnitudes to be studied. To obtain photometric standards we have observed a number of subfields in each field using the CCD system attached to the 1-metre telescope of the U.P. State Observatory at Nainital, India. A few standards have also been observed using the 1.2-metre telescope of Observatoire de Haute-Provence in France. Our final photometric and astrometric survey contains 55000 stars covering 50 square degree field.

Kinematical analysis

The distance of each star in the catalogue was determined by estimating absolute magnitude, which were obtained from a M_V *versus* B-V relation of main sequence stars of solar metallicity and taking into account the metallicity change as a function of the distance from the galactic plane. The cardinal components of the stellar space velocity (in km/s), U, V and W (where U is defined as positive in the direction of the galactic anticentre, V is positive in the direction of galactic rotation, and W is positive in the direction of NGP) were derived from proper motions, μ_l and μ_b (in arcsec per year) and line of sight distance d (in pc)[8].

The major factors contributing to distance errors are the photometric errors in the color σ_{B-V} and magnitude σ_V. From our surveys, we expect the mean errors in $\sigma_{B-V} = 0.1$ and $\sigma_V = 0.07$ for V = 11 to 18. From these values, our estimate of error of about 20% in distance seems to be realistic up to $z = 3$ kpc, where z is the distance above the galactic plane.

Kinematics of stellar populations

The kinematical properties of each stellar population are related to their spatial distributions. Scale height, velocity dispersions and asymmetric drift are linked by the Boltzmann equation. The proportion of each stellar population varies with the distance above the galactic plane and the selection of a stellar sample at a given distance allows to optimize the proportion of one population. Since kinematical data allow to improve this identification of populations, we have minimized bias from mutual contamination of each population at a given height by performing a kinematical separation of populations. To perform the kinematical separation, we have used a maximum likelihood method (SEM algorithm)[9] in order to deconvolve the multivariate Gaussian distributions and estimate the corresponding parameters. The aim of the SEM algorithm is to resolve the finite mixture density estimation problem under the maximum likelihood approach using a probabilistic teacher step. Through SEM one can obtain the number of components of the Gaussian mixture (without any assumption on this number), its mean values, dispersions and the percentage of each component with respect to the whole sample. We have used this method to separate the 2-D Gaussian velocity distributions (U,V) to identify the two components (thin disk and thick disk) of the Galaxy[10]. A multivariate discriminant analysis[11] is also used to distinguish the thick disk from other populations with the help of the model of population synthesis[12,13,14].

Thin disk population

For the thin disk population, we observe a continuous increase of the velocity dispersion with height[4,5]. It can be explained by the fact that the thin disk is a mixture of disks with various scale heights and velocity dispersions, since the disk is not formed in isothermal components. This results in a vertical gradient of velocity dispersions, since the disk is not resolved in isothermal components. For the thin disk population, we obtain a measure of the kinematic gradients, which appear to be : $\frac{\partial ln\sigma^2_{U+W}}{\partial R}$ = -0.18±0.03 kpc^{-1} and $\frac{\partial ln\sigma^2_{V}}{\partial R}$ = -0.05±0.02 kpc^{-1}. R is the galactocentric distance projected upon the galactic plane. Our results[10,11] confirm that the thin disk has a relatively short scale length of ~ 2.3±.5 kpc and scale height of ~ 258±50 pc.

Thick disk population and the merging history of the Milky Way

The thick disk population has been revisited under the light of these new data. We used also other photometric and astrometric sample survey in complementing direction, like the pole[7].

The sample of stars in 2 fields (galactic centre and anticentre) have been devided in 6 or 7 bins of distance, and in each bin of distance a fit has been performed with a SEM algorithm to identify Gaussian (U,V) components corresponding to the different populations[4,5]. The thick disk population has been identified as a discrete and distinct component. In our present study[11], the thick disk population appears to be isothermal, since the kinematical characteristics is nearly constant along the line of sight and so there is no vertical gradient.

For this reason, the velocity characteristics for this population are much better defined. For the thick disk population, the kinematic radial gradients appear to be almost zero : $\frac{\partial ln\sigma^2_{U+W}}{\partial R}$ = -0.008±0.01 kpc^{-1} and $\frac{\partial ln\sigma^2_V}{\partial R}$ = +0.02±0.02 kpc^{-1}. By combinning the kinematical results deduced from our 4 surveys (galactic centre, anticentre, antirotation and NGP), we have derived the velocity ellipsoid of the thick disk population[11]. The mean kinematic parameters are : (σ_U, σ_V, σ_W, V_{Lag}) = (72±4, 54±3, 40±3, 40±10) km/s. The most probable values of scale height and local normalization for the thick disk component are determined to be $h_z \simeq 759\pm50$ pc and $A_{thick} = 7.4^{+2.5}_{-1.5}$ % of the disk. The ratio of the number of thick disk stars in the galactic centre region to that in centre region yields h_R $\simeq$ 2.8–3.7 kpc for the scale length of thick disk[11].

These properties have been compared with several scenarios of formation. 'Top-Down' models, where the thick disk forms through a dissipational collapse, after the halo formation and before the thin disk has completely settled down, are in contradiction with the data, since they infer a continuity in the characteristics of the thick disk and thin disk and large kinematical vertical gradients. Alternatively, 'Bottom-Up' models suppose a formation of a thick disk after the complete collapse of the thin disk. We can eliminate those where the thick disk formed from a secular kinematic diffusion of thin disk stars (which would produce a continuity between thin and thick disks). It remains a scenario well in agreement with the present data : the thick disk could have been formed from the dynamical heating of the thin disk during the sink of a small galaxy into the Milky Way. This merging event has to happen at the beginning of the thin disk life time so that the gas can cool again and form stars in the long-lasting thin galactic disk that we see now. This violent bottom-up scenario leaves two important observational signatures. First the thick disk is a separate population distinct from the thin disk and the halo. Second, no gradient can be generated in the thick disk by the event, although a pre-existing gradient may survive the merger.

Conclusions

The thick disk population is found from all points of view (density laws, kinematics and metallicities) as a population well separated from the thin disk. It shows no gradient either on abundance[3] or on kinematics. The results emerging from the present study of the correlations between photometry and kinematics give a mounting evidence that the thick disk of the Galaxy is mostlikely a sequel of a dwarf satellite galaxy merging in the Milky Way disk during the early epoch of this disk. This interpretation emerged from an accurate characterization of the thick disk properties : the scale height and scale length of this component have been established, its rotation and velocity dispersion turned out to be quite distinct from both the disk itself and the halo. The local density of the thick disk component is twice what was previously assumed and the stellar colors do not reflect any significant chemical gradient.

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