ASTRONOMY FROM WIDE-FIELD IMAGING

Part Nine:

GALACTIC STRUCTURE

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STAR COUNTS AND THE MILKY WAY STRUCTURE

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ABSTRACT. While the accuracy of photometric star counts rises, constraints on the stellar population characteristics improve and allow synthetic models to be conceived to explain the galactic structure. We show here how star counts have significantly contributed to build a comprehensive picture of galactic evolution and dynamics.

1. Introduction

Two approaches are commonly used to study galactic structure. The first consists of selecting samples of stars in a way to be able to deduce the physical relations between intrinsic parameters, and many of our ideas on galactic structure are due to it. However, this method is not free from biases because of the stellar selections. The second approach consists of observing complete sample of stars, and doing statistics of different observable parameters in order to quantify the stellar population distribution functions.

Fast measuring machines together with good quality photographic plates, as well as the emergence of large CCDs, have considerably improved our capability to produce reliable star counts in wide fields, enhancing the necessity to acquire efficient methods of data analysis (Section 2). The search for new methods led to building a synthetic model of the Milky Way, in order to check the overall picture of the Galaxy by comparison between model predictions and observations (see Section 3), allowing us to put new constraints on our knowledge of the Galaxy (Section 4).

2. Wide-field Photometric Surveys

General probes of galactic structure using photometric surveys have been entertained since the availability of the first large Schmidt telescopes. Most impressive for its time was the Basle Halo Program, started by Becker (1965). He designed a specific photometric system (the RGU system) whose passbands were selected to optimize Halo-Disc discrimination.

Table 1 is a tentative attempt to identify available star counts in at least 2 optical photometric bands. The most observed regions of the sky are certainly the galactic poles, appealing regions for the facility to interpret the vertical structure, with almost no problems of extinction. Many

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have been made only in one photometric band, but were discarded when multi-band surveys became available. These are not included in our list.

Table 1. Star count investigations involving several optical bands

Authors	Location	Bands	Limits	sq. deg.
Bok & Basinski (1964)	SGP	BV	13	
Basle Halo survey	15 fields	RGU	19	0.5-3.5
Richter et al. (1967)	NGP	UBV	20	1.30
Weistrop (1972)	NGP	UBV	18	13.5
Hawkins & Bessel (1988)	SGP, (335,-47),(1,-39)	RI	20	84.7
Shanks et al. (1980)	SGP	B_J, R	21.5	14.25
Hawkins (1980)	SGP	B_J, R	23	14.7
Chiu (1980)	NGP, SA68, SA51	BV p.m.	21	0.1
Kron (1980)	NGP, SA68	JF	22.5	0.3
Reid & Gilmore (1982)	SGP	VRI	18	18.4
Ratnatunga (1984)	SGP, (277,-50), (272,-39)	BV	16.5	≈ 20
Tritton & Morton (1984)	(37,-51)	BV	18	0.3
Gilmore et al. (1985)	SGP, (37,-51)	BV	18	11.5, 17
Friel & Cudworth (1986)	(37,+51) and (175,-49)	BV	15	4
Koo et al. (1986)	NGP	UJFN	22.5	0.097
Borra & Lepage (1986)	(197,38)	UJF	23	0.246
Rodgers & Harding (1986)	3 fields (bulge)	BV	20-21	0.2
Stobie & Ishida (1987)	NGP	UBV	19	21.46
Schilbach (1988)	17 fields	BV p.m.	18	16.3
Terndrup (1988)	4 fields (bulge)	BVI	20-22	4.2e-3
Hawkins & Bessel (1988)	SGP, (335,-47), (1,-39)	RI	20	84.7
Mohan et al. (1988)	SpA23 (179, 2.5)	UBV	17	2
Bienaymé et al. (1992)	(2,+47)	UBVp.m.	17.5	1.78
Yamagata & Yoshii (1991)	(200,+59)	UBV	18	16
Soubiran (1992)	NGP	BV p.m.	18	21
Ng et al. (1992)	Bulge	B_J, R	18	12.25
Majewski (1992)	SA57	UJF p.m.	22.5	0.3
Robin et al. (1992)	SpA23	UBV	25	8. e-3
Ng et al. (1993)	(1,-11)	BR	19	12.25
Ojha et al. (1993)	(167,47)	UBVp.m.	18	8.6

3. Models of the Galaxy for Interpreting Star Counts

The first generation of galaxy models dedicated to predict and interpret star counts were based on the equation of stellar statistics (van Rhijn 1965). From assumptions about the density laws and luminosity functions of stellar populations, they estimated the number of stars integrated

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along a line of sight. This was the approach used by Kate Brooks (King 1977), Van den Bergh (1980), Bahcall & Soneira (1980, BS), Gilmore (1981), Yoshii (1982, 1984), Pritchet (1983), Buser & Kaeser (1985) and many modified BS models. These models are generally able to fit star counts in magnitude and B-V colour, but the solution seems not to be unique regarding the results obtained for the galactic structure parameters (see for example the controversy about the existence of the thick disk population). In a recent model the empirical colour magnitude diagrams have been replaced by theoretical ones coming from stellar evolutionary tracks (Ng et al. 1993).

To go further in understanding the history of our Galaxy, it is necessary to account for the physical links between the density, velocity and metallicity distributions in the Galaxy. Theory of galactic dynamics and evolution, as well as the observations, show that the kinematics, the scale heights and the metallicities are related to the age of the population. Thus a reasonable way to model the Galaxy is to use the age as the basic parameter. The age distribution of a population can be predicted by a scenario of galactic and stellar evolution. This approach has the great advantage of being able to check the consistency between our knowledge of stellar evolution, galactic, chemical and dynamical evolution. Such a model can start from an evolution scenario (IMF, SFR), a set of evolutionary tracks, a galactic potential, a chemical evolution scenario and allow one to compute the present day stellar distribution all over the Galaxy, from the point of view of the photometry, astrometry, radial velocities and metallicities. By far this kind of model has less free parameters than any empirical models because parameters are self-consistently forced to follow physical laws. The limitation of this approach is the difficulty to handle the multivariate distributions of observational parameters which are needed to constrain the hypotheses.

Such a policy has been used by the Besançon group to build a self-consistent galaxy model. Robin & Crézé (1986a, 1986b) started using an evolutionary model from Rocca-Volmerange (1981). Then they introduced the dynamical constraints (Boltzmann and Poisson equations) allowing the determination of the scale heights of the disc, according to the potential (Bienaymé et al. 1987). The kinematical parameters were described in Robin & Oblak (1989). Then, in order to check the Initial Mass Function and the Star Formation history in the Galaxy, Haywood (1993) redesigned the evolution scheme from Rocca-Volmerange to a more detailed one using the most recent evolutionary tracks. The usefulness of this approach has been proved by the numerous results obtained in the last few years.

4. Star Count Constraints on Galactic Structure

While this is not by far the only way to study galactic structure, photometric stars counts have contributed substantially to the subject, and the use of galactic models sometimes eases the analysis. We describe here recent results obtained in the field of interpreting star counts in terms of galactic structure.

4.1 PRESENT STELLAR DISTRIBUTIONS

4.1.1 *The Disc Population.* The luminosity function of the disc population was first determined by star counts in the solar neighbourhood by Luyten (1968) and more recently by Wielen et al. (1982). To compute the faint end of the luminosity function, Reid & Gilmore (1982), Hawkins

& Bessel (1988), Leggett & Hawkins (1988) used automated star counts in the red and infrared bands. The luminosity function of the disc population in the solar neighbourhood is nowadays well known up to magnitude $M_V \approx 15$, with the so-called Wielen Dip at magnitudes 6 to 9, a maximum at 12 - 13 and a drop down to magnitude 15 at least. A controversy has arisen about the existence of brown dwarfs in the Galaxy, but Tinney et al. (1993) show that the mass function has a local minimum at 0.15 solar masses, may rise again below 0.1 but at a level where the contribution of these stars to the total mass remains small.

The disc scale length has long been assumed to be of the order of 3.5 to 5.5 kpc but this value was not constrained by available star counts. Most recently, UBV star counts in the anticentre direction allowed fixing the value at 2.5 ±0.3 kpc (Robin et al. 1992). This value is well in agreement with determination from infrared star counts (Kent et al. 1991, for a summary), and from asymmetric drift measurements. This result has been confirmed by other UBV star counts at medium latitudes in two opposite directions on the galactic meridian (Ojha et al., this conference). On the other hand, Yamagata & Yoshii (1992) found a value of 3.8 ±0.3 from star counts in similar directions, but their star counts seem to be discrepant compared with others (Soubiran 1992).

Star counts in the anticentre have also allowed the detection of a sharp cutoff in the radial density law of the stellar disc. Robin et al. (1992) using CCD counts in the UBV found the edge at a distance of 5.5 - 6 kpc from the sun, giving a galactic radius of about 14 kpc. The dominant population in these counts is the old disc. It may be related to the existence of a threshold for the star formation as observed in some external disc galaxies (Kennicut 1989). Moreover, the position of the cutoff coincides with the beginning of the HI flare. In the interpretation of this fact one should keep in mind that there are actually few star forming regions further than 15 kpc from the galactic centre, such that the edge of the stellar disc has possibly moved from the inside to the outside of the Galaxy during the evolution of the disc.

4.1.2 *The Halo Population*. The halo LF is still difficult to measure directly because it requires accurate deep counts. Moreover, the existence of the thick disc population, with characteristic relatively close to the halo but with a higher density, hardens the problem. It seems that the halo LF does not differ significantly from the globular cluster ones (Reid & Majewski, 1993, hereafter RM). The local density of the halo is found to be 0.1 to 0.2 percent of the disc locally.

The flattening of the halo has been proved to be of the order of 0.6 to 0.85 (see RM for a summary). It may be different in the internal part than in the remote part and interesting to measure for its possible link with the dark matter halo.

4.1.3 *The Intermediate Population*. A controversial population in the past, its existence is now well admitted, but the parameters characterizing this 'thick disc' are not well known. Concerning star counts, the thick disc is better identified by its U-B colour (because of its metallicity) or by its kinematics. While we know that stars exist with intermediate properties (metallicities, circular velocity, velocity dispersions) between the disc and the halo, the controversy remains to identify it as a tail of the disc, or as a flattened part of the halo, or even as a population of extragalactic origin (merger).

Star counts still lead to contradictory measures for its scale height. Gilmore & Reid (1983) found a value of 1200 pc, while RM propose a value larger than 1500 pc. Yoshii & Ishida (1987) found 1000 pc from star counts towards the pole, Yamagata & Yoshii (1992) 900 pc and Robin et al. (1993) 800 pc from a general fit of B-V star counts in 17 fields. The determined value of the thick disc scale height certainly depends on the model used for the disc since in the B-V counts the two populations are not well distinguished. Multivariate data (including U-B, V-I or proper motions) are necessary to definitely check this parameter.

The local density deduced from star counts generally depends on the assumed scale height, a higher scale height giving a smaller local density. The values range between 1% of the disc to more than 10% (Sandage & Fouts 1987). Yoshii et al. (1987) advocate a value of 2% but RM support 2.5% and Robin et al. (1993) found a value of 4 to 5% of the local mass density of the disc.

4.1.4 *The Bulge.* The visible bands are not most appropriate for studying the bulge populations firstly because of the large amount of extinction, secondly because the stars which are easy to observe in the bulge are red giants. Most studies of the bulge population rely on infrared star counts. Several attempts have been made to look into the transition between the bulge and the other populations using BV counts. Nevertheless results are contradictory, since Yoshii & Rodgers (1989) conclude that no differentiation between a thick disc and a bulge population is possible (at least regarding their data). Rodgers & Harding (1989) estimate that a spheroid with a standard local density but a shorter effective radius than usually taken (1.2 kpc) fits the bulge population.

4.2 CONSTRAINTS ON THEORY OF EVOLUTION

4.2.1 *Star Counts and Stellar Dynamics.* Most attempts to determine the galactic force perpendicular to the plane have been carried out using estimations of the density laws of selected sub-samples of stars, such as the K giants or the F dwarfs (Oort 1960; Bahcall 1984; Flynn & Fuchs 1993; Bahcall, Flynn & Gould 1992). They have given contradictory results about the local mass density because the samples are generally small and the local density of the tracer stars is not well known. Moreover this approach is biased towards an overestimation of the dynamical mass density (Crézé et al. 1989). However, two accurate determinations have been performed using different approaches. The first one relies on a star counts analysis by a synthetic model of the Galaxy (Bienaymé et al. 1987) made self-consistent using the Boltzmann and Poisson equations. The density laws obtained are translated to star count predictions which are compared with observations in several directions. They conclude an adequacy of the dynamical mass and the visible mass, with no need for local dark matter. Kuijken & Gilmore (1989, 1991) confirmed this result from a determination of the density and velocity distribution of K dwarfs.

Proper motion surveys associated with good photometry should give, in the near future, confirmation of these results by their ability to bring crossed constraints on the density laws and the velocity distributions.

4.2.2 *Metallicity Distributions using U-B Colour.* Spectroscopic or intermediate band observations allow us to determine the metallicity distribution in the solar neighbourhood. They have led to the measure of the radial metallicity gradient of -0.05 or -0.07 dex kpc^{-1}, while the vertical gradient is more controversial. The 'natural' vertical gradient, resulting from the age-metallicity relation and the diffusion of orbits, should have a value of -0.15 dex kpc^{-1} in the disc, while observed values range from 0 to -0.8 dex kpc^{-1}. It should be noted that the thick disc could be the cause of an overestimate of the disc gradient.

The only way to measure the metallicity distribution using wide band photometric star counts is to use the U-B colour. However the U band suffers many problems of calibration, partly due to the differences in instrumental bandpasses, and to not understood problems. When one compares U-B star counts from several authors in a similar direction one notices systematic differences, probably due to systematic errors in one or both data sets. Some attempts to use the U-G distribution to determine the metallicity gradient had been performed by the Basle group. Trefzger (1981) found a vertical gradient close to -0.3 dex kpc^{-1} in fair agreement with the 'natural' gradient and identified a significant radial gradient. Yoshii et al. (1987) deduced from their star counts the vertical gradient to be of -0.5 dex kpc^{-1} for the disc and -0.1 for the intermediate component.

4.2.3 *Constraining Star Formation History*. It has been shown (Robin et al. 1989) that star counts in UBV are sensitive enough to the age distribution of stars that it should be possible nowadays to constrain the Initial Mass Function and the Star Formation Rate. Haywood (1993) has tested the evolutionary scenario using both solar neighbourhood data and remote star counts. The solar neighbourhood luminosity function helps to restrict the range of possible parameters, while remote star counts allow one to test the age distribution, which is related to the scale heights and to the proper motion distribution. This is also to some extent sensitive to the emphasized age-velocity dispersion relation. Haywood et al. (this conference) show that available star counts between magnitude 6 and 22 constrain the SFR to have been constant or decreasing by less than a factor of 7 in the past.

4.3 ANALYSIS METHODS

Most statistical analyses use standard methods as least square fitting, and maximum likelihood estimations well suited to one or two dimensional data sets. Multivariate data analysis provides more powerful methods to deal with large multidimensional surveys. They allow one to search for significant signatures of stellar population characteristics in multivariate data sets. Chen (1993) has shown that multivariate analysis techniques allow the detection of information about hidden structures in the 5 dimensional space (V, B-V, U-B, μ_l, μ_b), otherwise unrecognisable. The method is able to identify eventual discordances between model predictions and observations and to relate them to the intrinsic parameters assumed for each population. This method will be developed to be applied to the analysis of forthcoming large digitised surveys.

5. Conclusion

Star count accuracy has highly improved in the past ten years. Apart from U-B photometry, they are generally good enough to probe the galactic structure. The use of synthetic models for the Galaxy has helped a lot to analyze these counts. More efficient methods of multivariate analysis are being developed to exploit the surveys coming with 2 to 3 photometric bands, and often proper motions. Surveys using CCD mosaics will enhance considerably the amount of deep and accurate photometric counts in the near future.

The still unanswered questions about evolution of the Galaxy should benefit from these wide-field surveys, among them the timing of the collapse of the Galaxy, the origin of the thick disc population, the link between the bulge and the other populations, and the history of the star formation rate. Finally the question of homogeneity of the Galaxy will probably be raised, allowing to us estimate the possible variations of the properties of a population on relatively small scales. This would directly constrain the scenario of Galaxy formation.

References

Bahcall, J.N. and Soneira, R.M., 1980. *Astrophys. J. Suppl.*, **44**, 73.
Bahcall, J.N., 1984a. *Astrophys. J.*, **276**, 156.
Bahcall, J.N., 1984b. *Astrophys. J.*, **287**, 926.
Bahcall, J.N., Flynn, C. and Gould, A., 1992. *Astrophys. J.*, **389**, 234.
Becker, W., 1965. *Z. Af.*, **62**, 54.
Bienaymé, O., Robin, A.C., and Crézé, M., 1987. *Astron. Astrophys.*, **180**, 94.
Bienaymé, O., Mohan, V., Crézé, M., Considère, S. and Robin, A.C., 1992. *Astron. Astrophys.*, **253**, 389.
Bok, J.J. and Basinski, J., 1964. *Mem. Mt. Stromlo Obs.*, **16**, 1.
Borra, E.F. and Lepage,R., 1986. *Astron. J.*, **92**, 203.
Buser, R. and Kaeser, U., 1985. *Astron. Astrophys.*, **145**, 1.
Chen, B., 1993. PhD Thesis, Strasbourg University.
Chiu, L.-T.G., 1980. *Astrophys. J. Suppl.*, **44**, 31.
Crézé, M., Robin, A.C. and Bienaymé, O., 1989. *Astron. Astrophys.*, **211**, 1.
Flynn, C. and Fuchs, B., 1993. In 'Panchromatic View of Galaxies — Their Evolutionary Puzzle', Meeting of the Astronomische Gesellschaft held at Kiel, March 1993.
Friel, E.D. and Cudworth, K.M., 1986. *Astron. J.*, **91**, 293.
Gilmore, G., 1981. *Mon. Not. R. astron. Soc.*, **195**, 183.
Gilmore, G. and Reid, I.N., 1983. *Mon. Not. R. astron. Soc.*, **202**, 1025.
Gilmore, G., Reid, I.N. and Hewett, P., 1985. *Mon. Not. R. astron. Soc.*, **213**, 257.
Hawkins, M.R.S., 1980. *Astrophys. J.*, **237**, 371.
Hawkins, M.R.S. and Bessel, M.S., 1988. *Mon. Not. R. astron. Soc.*, **234**, 177.
Haywood, M., 1993. *Astron. Astrophys.*, in press.
Kennicut, R.C. Jr., 1989. *Astrophys. J.*, **344**, 685.
Kent, S.M., Dame, T.M. and Fazio, G., 1991. *Astrophys. J.*, **378**, 131.
King, I., 1977. *Highlights of Astronomy*, Vol. 4 part II, p. 41.
Koo, D.C., Kron, R.G. and Cudworth, K.M., 1986. *Publ. Astron. Soc. Pacific*, **98**, 285.
Kron, R.G., 1980. *Astrophys. J. Suppl.*, **43**, 305.
Kuijken, K. and Gilmore, G., 1989. *Mon. Not. R. astron. Soc.*, **239**, 571.
Kuijken, K. and Gilmore, G., 1991. *Astrophys. J.*, **367**, L9.
Leggett, S.K. and Hawkins, M.R.S., 1988. *Mon. Not. R. astron. Soc.*, **234**, 1065.
Luyten, W.J., 1968. *Mon. Not. R. astron. Soc.*, **139**, 221.
Majewski, S.R., 1992. *Astrophys. J. Suppl.*, **78**, 76.
Mohan, V., Bijaoui, A., Crézé, M. and Robin, A.C., 1988. *Astron. Astrophys. Suppl.*, **73**, 85.
Ng, Y.K., Bertelli, G. and Chiosi, C., 1993. 'Galactic Bulges', IAU Symp. 153, Kluwer.
Oort, J.H., 1960. *Bull. Astron. Inst. Neth.*, **15**, 45.
Pritchet, C., 1983. *Astron. J.*, **88**, 1476.
Ratnatunga, K.U., 1984. PhD Thesis, Australian National University.
Reid, I.N. and Gilmore, G., 1982. *Mon. Not. R. astron. Soc.*, **201**, 73.
Reid, I.N. and Majewski, S.R., 1993. *Astrophys. J.*, **409**, 635 (RM).

Richter, N., Richter, L. and Ziener, R., 1967. IAU Symp. 29, p. 355.
Robin, A.C. and Crézé, M., 1986a. *Astron. Astrophys.*, **157**, 71.
Robin, A.C. and Crézé, M., 1986b. *Astron. Astrophys. Suppl.*, **64**, 53.
Robin, A.C., Crézé, M. and Mohan, V., 1989. *Astrophys. Space Sci.*, **156**, 9.
Robin, A.C. and Oblak, E., 1987. In 'Evolution of Galaxies', 10th IAU European Regional Meeting, vol 4, p. 323.
Robin, A.C., Crézé, M. and Mohan, V., 1992a. *Astron. Astrophys.*, **253**, 389.
Robin, A.C., Crézé, M. and Mohan, V., 1992b. *Astrophys. J.*, **400**, L25.
Rocca-Volmerange, B., Lequeux, J. and Maucherat-Joubert, M., 1981. *Astron. Astrophys.*, **104**, 177.
Rodgers, A.W. and Harding, P., 1989. *Astron. J.*, **97**, 1036.
Sandage, A. and Fouts, M., 1987. *Astron. J.*, **93**, 74.
Shanks, T., Phillips, S. and Fong, R., 1980. *Mon. Not. R. astron. Soc.*, **191**, 47p.
Soubiran, C., 1992. *Astron. Astrophys.*, **274**, 181.
Stobie, R.S. and Ishida, K., 1987. *Astron. J.*, **93**, 624.
Terndrup, D.M., 1988. *Astron. J.*, **96**, 884.
Trefzger, C.F., 1981. *Astron. Astrophys.*, **95**, 184.
Tritton, K.P. and Morton, D.C., 1984. *Mon. Not. R. astron. Soc.*, **209**, 429.
Weistrop, D., 1972. *Astron. J.*, **77**, 366, 849.
Wielen, R., Jahreiss, H. and Kruger, R., 1983. In 'The Nearby Stars and the Stellar Luminosity Function', IAU Coll. 76, p. 163.
Yamagata, T. and Yoshii, Y., 1992. *Astron. J.*, **103**, 117.
Yoshii, Y., 1982. *P.A.S.J.*, **34**, 365.
Yoshii, Y., 1984. *Astron. J.*, **89**, 1190.
Yoshii, Y., Ishida, K. and Stobie, R.S., 1987. *Astron. J.*, **92**, 323.
Yoshii, Y. and Rodgers, A.W., 1989. *Astron. J.*, **98**, 853.