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A PROJECT FOR INVESTIGATION OF THE STELLAR POPULATION OF THE GALACTIC DISK

V. Straižys[1] and A.G. Davis Philip[2,3]

[1] *Institute of Theoretical Physics and Astronomy, Goštauto 12, Vilnius 2600, Lithuania*
[2] *Institute for Space Observations, 1125 Oxford Pl., Schenectady, NY 12308, U.S.A.*
[3] *Union College, Schenectady, NY 12308, U.S.A.*

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Abstract. The Vilnius seven-colour photometric system, when used with CCD detectors, makes it possible to obtain spectral types, luminosities, metallicities and the interstellar reddening to very faint stars at large distances from the Sun. A project for the investigation of stellar population in the galactic disk is proposed. It is based on CCD seven-colour photometry of stars down to 18th mag in 25 fields of $20' \times 20'$ size in the directions where the interstellar extinction is low. It is estimated that each area will contain about 2000 to 5000 stars. Spectral types, luminosity classes, absolute magnitudes, metallicities, interstellar reddenings and distances for all stars in the areas should be determined. These data can be used to obtain spatial densities of different types of stars, luminosity functions, vertical scale height, radial scale length and thick disk parameters in different directions of the galactic plane, including spiral arms, interarm regions and the central bulge. This information can be used to verify the existing models of the Galaxy (or to propose the new ones) near its plane. No other photometric system, currently in use, can do this type of work for all spectral types.

Key words: techniques: photometric – stars: fundamental parameters – stars: luminosity function – extinction – Galaxy: fundamental parameters – Galaxy: stellar content – Galaxy: structure

1. Models of the Galaxy

For determination of the space distribution of stars in the Galaxy most investigators have used the methods described in the classical book by Bok (1938). The methods use the inversion of the integral equation of stellar statistics, which gives the surface number density of stars for the unit interval of apparent magnitudes in the given direction as a function of space density, luminosity function and dust obscuration. The classical method usually used for interpretation of star counts, inverts the equation to solve it for density, the luminosity function and the obscuration.

A different approach to the problem was used by Bahcall and Soneira (1980, 1984) who assumed a model for the distribution of stars in the Galaxy, calculated the expected results in terms of the numbers of stars per unit magnitude per colour bin and iterated the model constants until the calculated results agreed with the observations. They used a relatively simple two-component Galaxy model, chosen by analogy with other spiral galaxies. It consists of a Population I disk and a Population II spheroid. Bahcall and Soneira have found that their simple model gives a sufficiently accurate picture of the observed distributions of stars in magnitudes and colours in a number of directions, all of which have galactic latitudes $> 20°$. This was done for magnitudes and colour indices in different broad-band photometric systems and in all cases the observed and predicted surface densities of stars coincided within the expected errors. It was concluded that this two-component model is a reasonable first approximation to the observed stellar content of the Galaxy. A little later, Gilmore and Reid (1983) and Gilmore (1984) proposed another model which contains a thick disk of lower density in addition to the thin disk and the spheroid. Robin and Crézé (1986a,b) have also introduced an intermediate population. Bahcall and Soneira (1984), Bahcall et al. (1985) and Bahcall (1986) have criticized the thick disk conception showing that their two-component model gives almost the same star number distribution in magnitudes and colours as the three-component model.

2. The Bahcall-Soneira model: a discussion

The assumed stellar density law for the disk in the Bahcall-Soneira model is the following:

$$n(D) = n(D, R_0) \exp[-z/H(M_V)] \exp[-(x - R_0)/h];$$

here $n(D)$ is the star density at a distance x from the galactic center and at a distance z from the plane of the disk, R_0 is the solar distance from the galactic center, $n(D, R_0)$ is the star density in the solar neighbourhood (luminosity function), $H(M_V)$ is the disk vertical scale height, and h is the disk radial scale length. Bahcall and Soneira used $R_0 = 8.0$ kpc and the local density of stars $n(D, R_0) = 0.13$ stars/pc^3. This value does not include stars fainter than $M_V = 16.5$ mag. The luminosity function, the scale height, and the scale length are considered to be the same everywhere in the disk.

The density of the spheroid stars as a function of the galactocentric distance was assumed to follow the exponential law. The density of the spheroid in the solar vicinity is only 1/500 of the disk density, so these stars will not be a major coponent of our study, but they are important to be studied individually.

The following values of the vertical scale height of the disk were taken: 90 pc for O–B–A stars with $M_V < 2.3$, 325 pc for G5–K–M main sequence stars with $M_V > 5.1$, and for F and early G main sequence stars the scale height was linearly interpolated between 90 and 325 pc; for disk giants and white dwarfs $H = 250$ pc was assumed. However, a glance at Fig. 2 of Bahcall and Soneira (1980) paper shows a great uncertainty of the scale height values for different types of stars. There are gaps, interpolations and extrapolations in it. Robin and Crézé (1986a) have used different scale height values, estimated from the spatial velocity dispersion related with the age. In addition, Kent et al. (1991) found evidence that the scale height for K and M giants is not constant but increases with radius at galactocentric distances > 5 kpc. It is not known, how the scale height behaves at the edge of the disk where the interstellar gas and possibly stars show a warp (Carney and Seitzer 1993).

The radial scale length of the disk, $h = 3.5$ kpc, was assumed. This value is estimated from the surface brightness of the Milky Way, from H I density observations in the Galaxy and from the mean density profile of external Sbc galaxies. However, later determinations of this quantity give very ambiguous results ranging between 1.8 kpc and 6 kpc (see reviews by Kent et al. 1991 and Robin et al. 1992a). The scale lengths of spiral galaxies may be uncertain by a factor of two (Knappen and Kruit 1991). Mohan et al. (1988) and Robin et al. (1992a,b) are in favor of a low value of $h = 2.5$ kpc which is based on star counts in the galactic plane in the anticenter direction. Kent et al. (1991) conclude that the measured scale lengths are so much different due to some assumptions used in different methods which may not be valid. Also, different components of the Galaxy must have different radial distributions. Consequently, the direct determination of scale lengths for different types of stars is very important.

In their second paper, Bahcall and Soneira (1984) decided to use the Wielen (1974) luminosity function for the solar neighbourhood. Is the luminosity function the same everywhere in the disk? In his classical papers on the luminosity function, McCuskey (1965, 1966) showed variations of the luminosity function with distance from the Sun and perpendicular to the galactic plane (see also Upgren 1963, Philip 1967 and Gilmore and Reid 1983). Theoretically, a unique luminosity function is not expected, since the disk contains regions differing in the age and metallicity. For example, spiral arms contain younger stars than the interarm regions. Also, there is a well-known metallicity gradient, i.e., decrease of metallicity with distance from the galactic center. A different luminosity function is expected in the thick disk (if it is real) and the central bulge, which have a different evolutionary history. Bahcall (1986) considers the possibility of luminosity function variations but he takes the function of the solar vicinity as an approximation, since there are not sufficient data in different directions and distances.

All tests of the model (Bahcall and Soneira 1981a,b, 1984; Bahcall and Ratnatunga 1985; Bahcall et al. 1983a,b, 1985; Ratnatunga et al. 1985; Gould et al. 1993) were made in fields with galactic latitude $|b| > 20°$, outside the zone of avoidance, where interstellar reddening is small. Bahcall et al. (1983a, 1985) emphasize the necessity of extending the verification of the model near the galactic plane and the central bulge. They suggest using deep star counts in the infrared photometric systems to reduce the effect of interstellar reddening. When approaching the galactic center region, the inclusion into the model of the third component, the bulge population, becomes necessary (Bahcall 1986, Kent et al. 1991).

Lately, predictions of the stellar distribution in the galactic plane have became available. Wainscoat et al. (1992) and Cohen (1993) have proposed a model, representing the galactic disk, bulge, ring, spiral arms and spheroid population. At high galactic latitudes the model does not differ significantly from the Bahcall-Soneira model. However, at low latitudes this model gives stellar distribution predictions, which must better represent the real situation. However, the predictions of this model have been verified only for the infrared objects.

It is important that Robin and Crézé (1986a) and Wainscoat et al. (1992) do not use the traditional luminosity function, which is a conglomerate of stars of different spectral and luminosity classes, but use a distribution of stars of different MK spectral types. This leads to a more exact prediction of stellar surface densities and makes for an easier comparison between predictions and observations, when MK spectral types are determined.

For the determination of luminosity functions or space density functions of stars of different MK types in different galactic longitudes and at different distances from the Sun, for the more precise determination of the scale height and the scale length of different types of stars, for the solution of the thick disk problem and for the verification of the galactic models at low galactic latitudes, a new observational survey near the galactic plane is necessary. To overcome the interference by interstellar dust, the survey must be based on the reddening-free two-dimensional classification of stars. The only method which can be used for this is medium-band CCD photometry of stars in a system which makes it possible to classify stars completely photometrically in the presence of interstellar reddening. Such is the seven-colour Vilnius photometric system. The combination of the Vilnius photometric system with CCD detectors of high sensitivity and a large field gives a unique possibility to investigate the galactic disk up to great distances from the Sun. No other photometric system, currently in use, can do this type of work for all spectral types.

3. The Vilnius photometric system

In 1962 the problem was raised at the Vilnius Observatory to select an optimum multicolour photometric system capable of classifying stars of any spectral type, luminosity class and reddening (Straižys 1963). The selection of passbands of an optimum system was based on photoelectrically determined energy distributions in spectra of stars of different types which appeared for the first time during the early 1960s. For the selection of the optimum positions of passbands, synthetic colour indices and reddening-free Q-parameters were calculated, by changing positions, widths and shapes of the response functions.

The characteristics of the final system passbands are given in Table 1. The passbands themselves, normalized to 100 at maximum transmission, are shown in Fig.1. The system has been described in detail by Straižys (1973, 1977, 1992).

Table 1. Mean wavelengths and half-widths of the passbands of the Vilnius photometric system

	U	P	X	Y	Z	V	S
λ (nm)	345	374	405	466	516	544	656
$\delta\lambda$ (nm)	40	26	22	26	21	26	20

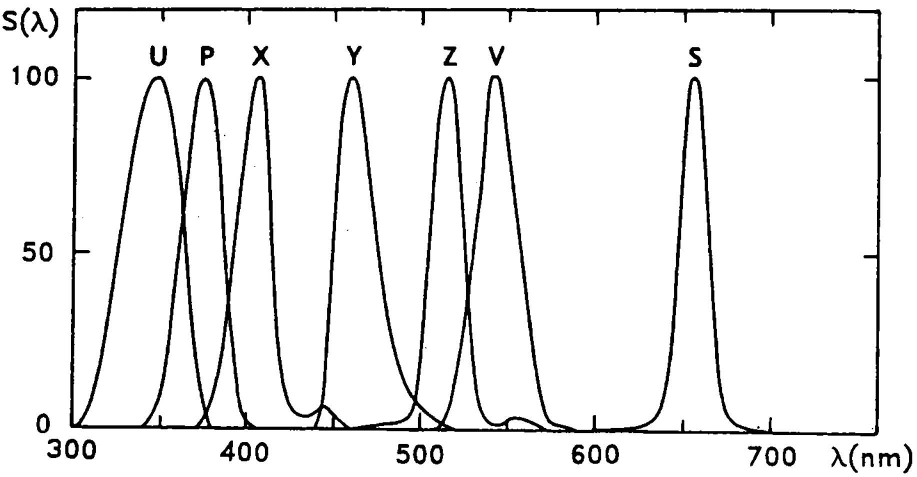

Fig. 1. Response functions of the Vilnius photometric system.

The positions of the passbands, plotted aside the flux distribution curves of the A0 V and K5 V stars, are shown in Figs. 2 and 3. The U passband measures intensity to the ultraviolet side from the Balmer jump. The P passband measures the absorption of the higher members of the Balmer series which is sensitive to surface gravity in B–A–F stars. The X passband measures the intensity to the red side from the Balmer jump for early-type stars as well as the amount of blocking by metal lines for late-type stars. The Y passband is placed near the break point of the interstellar extinction law and, in combination with other passbands, is important in distinguishing the temperature reddening and the interstellar reddening. The Z passband is placed on the wide absorption feature formed by the Mg I

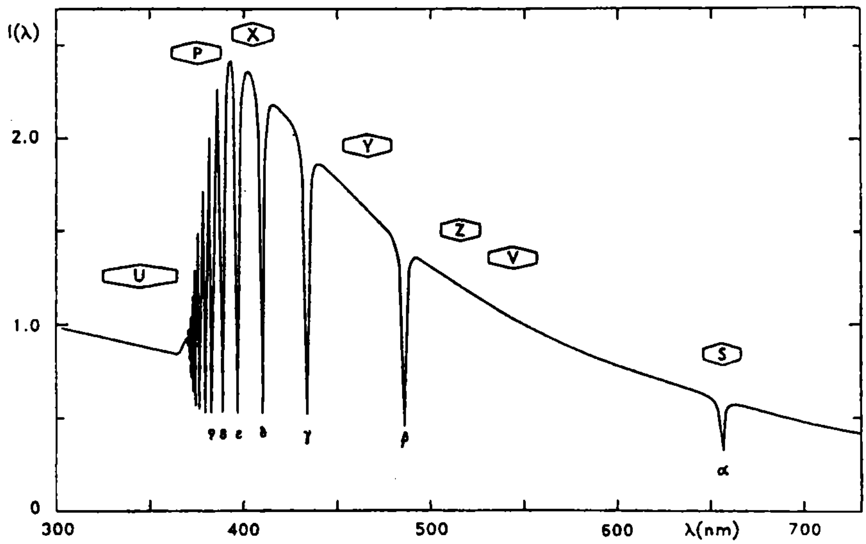

Fig. 2. Energy distribution in the spectrum of α Lyrae with positions and half-widths of the Vilnius system passbands.

triplet lines and a MgH molecular band. The depth of this feature is very sensitive to surface gravity or luminosity in K and M stars. The V passband is a medium-band analogue of V in the UBV system. The S passband is placed on the Hα line and plays a role of its emission discriminant among early-type stars. In late-type stars the S passband measures pseudocontinuum intensity. The Vilnius system allows one to classify stars of all temperatures in spectral classes (or temperatures) and absolute magnitudes (or surface gravities) when interstellar reddening is either absent or present. For classification of stars no information from stellar spectra is needed. The simplest method of classification is the use of interstellar reddening-free Q, Q diagrams calibrated in spectral types and absolute magnitudes or in temperatures and gravities.

The definition of a photometric Q-parameter is as follows:

$$Q_{1234} = (m_1 - m_2) - (E_{12}/E_{34})(m_3 - m_4),$$

where $m_1 - m_2$ and $m_3 - m_4$ are two colour indices and E_{12} and E_{34} are the corresponding colour excesses. These diagrams and other classification methods are described in the monograph "Multicolor Stellar Photometry" (Straižys 1992).

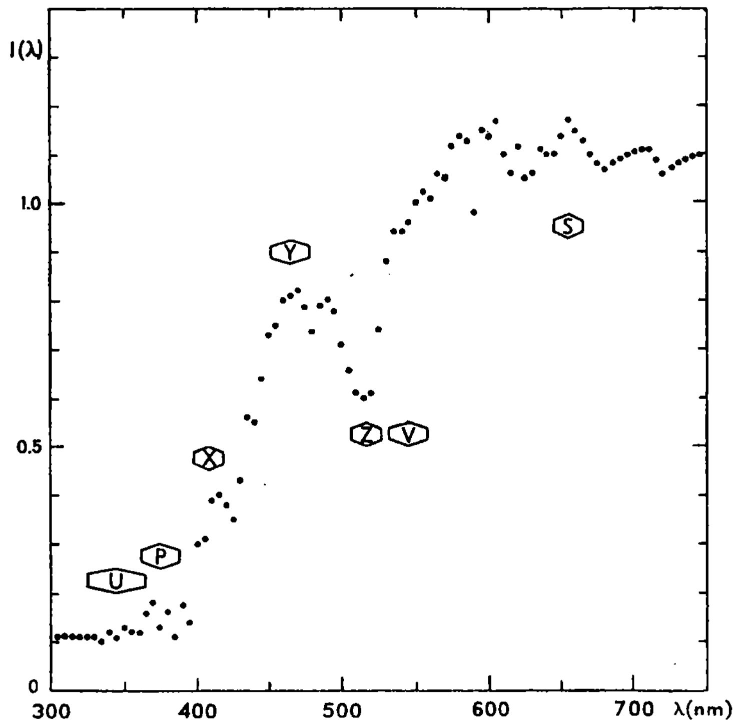

Fig. 3. Energy distribution in the spectrum of a K5 V star with positions and half-widths of the Vilnius system passbands.

The system also makes it possible to recognize photometrically the following peculiar types of stars: Be, extreme Am and Ap/Bp, F–G–K subdwarfs, metal-deficient giants and subgiants, carbon and barium stars, Herbig Ae/Be stars and T Tauri-type stars, white dwarfs and a number of types of unresolved binaries. No other system is capable of solving such a wide variety of classification problems when interstellar reddening is present.

The Vilnius photometric system enables one to classify about 90–95 % of stars in any galactic field where stars of different spectral classes, luminosities, metallicities, peculiarities and interstellar reddenings are mixed together. The remaining 5 to 10 % of stars, which cannot be recognized and classified photometrically, may be very interesting objects for spectroscopic investigation.

Especially great possibilities appear for investigation of star fields when the Vilnius system is used with CCD detectors. The first results of CCD photometry in the Vilnius system have been published by Boyle et al. (1990a,b, 1992) and Smriglio et al. (1991), giving classification of stars down to 15–17 mag. The CCD frames were obtained with an RCA 316×508 chip on the 0.9-m telescope at the Kitt Peak National Observatory, the field size being $5' \times 7'$. The exposure times were 20 min for two ultraviolet filters and 2–4 min for the other filters. This means that with exposures of the order of 1 hour for ultraviolet magnitudes it is possible to classify stars down to 18 mag with a 1-meter telescope or to 21 mag with a 4-meter telescope. A potential increase of limiting magnitude can be achieved by taking more ultraviolet sensitive CCD and more transparent ultraviolet filters.

4. The selected areas

For the investigation of space distribution of stars close to the galactic plane (for this project and for its future extensions), several tens of areas have been selected in the most transparent regions of the northern Milky Way with galactic latitudes $|b| < 10°$ and galactic longitudes l between 6° and 220°. The positions of the areas are based on visual examination of the stellar background within the zone of avoidance in the blue and red copies of the Mount Palomar Observatory Sky Survey atlas. The approximate location of the centers of 25 areas chosen for the present project are given in Table 2. Each of these areas is larger than 0.°5, so there is sufficient space to select smaller fields of about 20′ diameter for CCD photometry.

We estimate that the total interstellar extinction A_V in most of the areas with galactic latitude $|b| > 4°$ will be ≤ 1 mag. This estimation is based on colour excesses of globular clusters which are seen in some of these areas (Straižys 1982). The colour excesses, E_{B-V}, of most of these globular clusters are of the order of 0.3 and the extinction A_V must be close to 1.0. In the areas which are almost in the galactic plane the extinction will increase with distance. We expect, however, that in the areas of high background star density it is possible to reach a distance of a few kpc. In the transparent areas of the anticenter region the total extinction up to the edge of the galactic disk is of the order of 1.0 mag also (see Robin et al. 1992).

The maximum distances of different types of stars, accessible to photometry down to 18 mag, are given in Table 3, taking into account $A_V = 1.0$ mag (for M dwarfs $A_V = 0.5$ is used). In the same

Table 2. List of the transparent areas for the galactic structure study at low latitudes

Area	Nearby object	α(1950)	δ(1950)	*l*	*b*
1.	Small Sgr Cloud (OCl M24)	18^h15^m	−18.°0	13.°3	−1.°1
2.	North of GCl IC 1276 (Ser)	18 12	−5.6	23.6	+5.7
3.	GCl NGC 6712 (Sct)	18 50	−8.8	25.5	−4.5
4.	South of N Aql 1918	18 52	−1.0	32.5	−1.1
5.	At ζ Aql	19 01	+14.2	46.8	+3.9
6.	West of γ Aql	19 33	+11.3	48.0	−4.3
7.	At OCl NGC 6802 (Vul)	19 27	+19.7	54.8	+0.9
8.	GCl M71 (Vul)	19 52	+18.6	56.9	−3.8
9.	GCl M56 (Lyr)	19 15	+30.1	63.4	+7.6
10.	In SA 64 (Cyg)	19 58	+30.6	67.8	+0.4
11.	In the Veil Nebula (Cyg)	20 50	+31.2	73.6	−7.5
12.	At OCl IC 1311 (Cyg)	20 07	+40.8	77.9	+4.0
13.	Above North America Nebula	21 02	+46.2	87.8	−0.4
14.	Above OCl NGC 7245 (Lac)	22 10	+54.8	101.4	−1.0
15.	South of OCl M52 (Cas)	23 24	+60.9	112.9	0.0
16.	North of γ Cas	0 47	+64.0	122.9	+1.5
17.	At OCl NGC 1027 (Cas)	2 38	+61.3	135.9	+1.5
18.	At ψ Per	3 31	+48.0	149.6	−6.1
19.	At OCl NGC 1528 (Per)	4 12	+51.2	152.0	+0.3
20.	West of 5 Cam	4 42	+55.0	152.0	+6.0
21.	At ζ Aur	4 58	+41.3	164.7	−0.3
22.	Anticenter (Tau)	5 43	+30.0	179.2	+0.8
23.	West of γ Gem	6 22	+16.1	195.7	+1.7
24.	East of OCl NGC 2244 (Mon)	6 36	+4.7	207.4	−0.7
25.	South of 19 Mon	7 02	−6.2	220.0	0.0

table we give the volume of space in pc^3 embraced by the circular field of view of 20′ diameter. These volumes have been used to calculate maximum expected number of stars in the areas down to 18 mag, using the luminosity function for the solar vicinity. For the area in the galactic plane, the characteristic expected numbers of stars are the following: M-dwarfs < 115 (up to 525 pc), K-dwarfs < 230 (up to 1.6 kpc), G-dwarfs < 2000 (up to 3.3 kpc) and F-dwarfs < 15000 (up to 6.9 kpc). There is no sense to continue this method of calculation for more luminous stars since for such stars in many directions we leave the edge of the galactic disk. Probably it is more realis-

Table 3. Maximum distances of stars of some spectral types with $V = 18$ mag and $A_V = 1.0$ (for M0 V stars $A_V = 0.5$) and volumes of space up to these distances for a 20′ field

Sp. type	r_{max} pc	Volume in pc^3
M0 V	525	1240
K0 V	1600	35500
G0 V	3300	311800
F0 V	6900	2839400
A0 V	17400	–

tic to give the upper numbers of stars up to 5 kpc. In this case the following numbers of stars are obtained: F-dwarfs < 5500 and B–A main sequence stars and G–K–M giants < 2900. In any case, the total expected number of stars in a 20′ field down to 18 mag is several thousands of stars. For A–F–G–K–M main sequence stars and for G–K–M giants the number of stars is sufficient to obtain their space densities up to several kpc from the Sun. In some areas it would be very useful to obtain CCD photometry and classification of stars down to 21 mag, using a 4-meter telescope. In this case even M0-type dwarfs would be accessible up to 1.7 kpc distances in large numbers. However, on such large telescopes the angular size of CCD areas is usually much smaller.

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