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"Lyra" Space Stellar Survey and Establishing a Large Grid of Photometric Standards

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Abstract. The "Lyra" space experiment is currently being prepared in Russia. Its main goal is to perform high precision 10-color photometry for all $V < 16$ mag stars. Observations will be made using a 500-mm diameter 3-m focal length Ritchey-Chretien telescope with an afocal lens corrector mounted on the Russian segment of the International Space Station (ISS) and equipped with CCDs operated in the time delay and integration (drift, TDI) mode.

One of the most important tasks of the "Lyra" mission is to create a dense all-sky grid of high-precision photometric standards. The total number of standards should be on the order of several million, and to achieve this goal, more than 300 million stars will be measured in the course of the mission.

The photometric system must include standards in all ranges of magnitudes from the brightest stars down to 16th magnitude. Small random error will be achieved by providing sufficiently strong signal in all passbands and using highly accurate and stable detecting equipment. The random error of measured magnitudes is expected to be $0^m.001$–$0^m.003$ and about $0^m.01$ for stars brighter than 14th magnitude and fainter stars, respectively. The system must be free from systematic errors, which are to be minimized by careful ground-based calibration and by maintaining this calibration throughout the mission.

1. Introduction

The space experiment "Lyra" is currently in preparation in Russia (Mironov et al. 2010; Zakharov et al. 2012). Its primary aim will be to perform multicolor photometry for all $V < 16$ mag stars using a telescope mounted on the Russian segment of the International Space Station (ISS).

We plan:

- To produce multicolor photometric catalogs for 100-400 million objects down to $V < 16$ mag;
- To scan repeatedly the entire sky during 3-5 years (usually 20 times per year);
- To use 10 bands from 190 to 1000 nm;
- To achieve high photometric precision and accuracy for $3^m - 16^m$ stars;
- To create an extensive uniform system of photometric standards;

- To measure the coordinates of all objects with $V < 15$ mag with errors no greater than 1 mas and of those of all other objects with errors no greater than 10 mas.

The following events are planned in accordance with the "Lyra" schedule:

Design and manufacturing of equipment	2008 - 2015
Launch	2015
Performing of the experiment. Preprocessing. Preliminary catalog.	2015 - 2020
Finishing reduction. Production of the final catalog.	2020 - 2023

The main principles of the experiment are

- Scanning mode of observations.
- Time delay and integration (drift) mode.
- 10-band photometry.
- Full coverage of the sky.

2. The telescope

The telescope consists of four main units:

- the blind with a protective lid,
- the tube with optical system,
- the photometric unit and
- the fastening to attach the telescope to the ISS.

The lid has three holes with a lens through which scattered sunlight can illuminate the focal plane. The lid with holes is used for calibration.

The "Lyra" telescope parameters are

- Ritchey-Chretien telescope with an afocal lens corrector.
- Primary mirror diameter: 500 mm.
- Focal length: 3 m.
- Mirror material: SiC.
- Mass of the primary mirror: 2.5 kg.
- Mass of the secondary mirror: 0.5 kg.

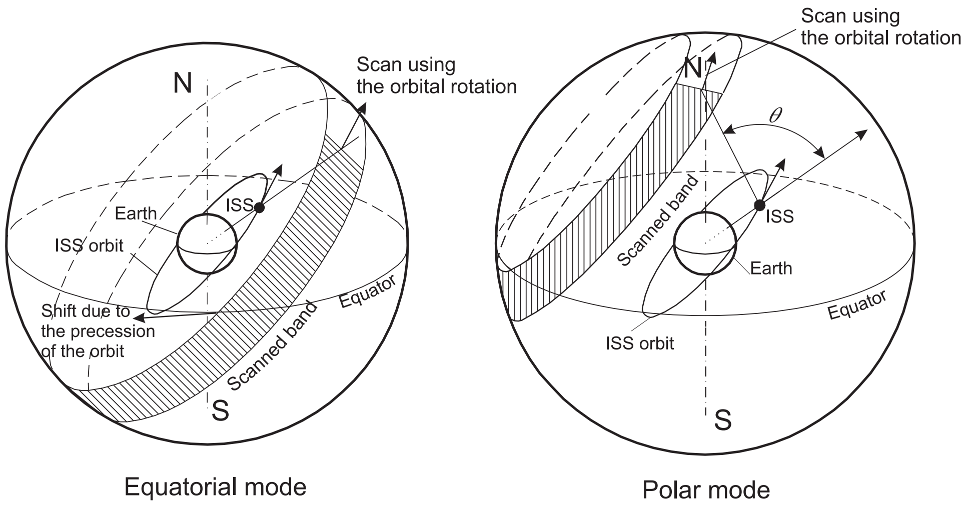

Figure 1. Principle of the sky scanning

3. Sky scanning

The ISS orbits the Earth with a period of 92 min. The inclination of the ISS orbit to the equator is 51.6 deg. One of the ISS axes always points toward the Earth. The telescope is fixed and fastened to the ISS. The sight axis is directed away from the Earth. During every revolution around the Earth, the field of view covers a ring strip on the sky. Precession shifts the strip by a quarter of a degree in every pass of the orbit. The precession period of the ISS is $P_{pr} = 70$ days and therefore each star will be observed on 4-5 successive revolutions.

If the sight line lies in the orbital plane then the covers over one precession period a large band in the sky along the equator between declinations $-52°$ and $+52°$ (the equator mode). To reach polar regions, we must incline the sight axes by the angle supplementary to the orbital inclination (the polar mode). A choice between the two modes will depend on the position of the Sun. (See Figure 1.)

4. Main photometer

The angular size of the corrected field of view will be about 2.0 degrees in the sky. Twenty-two 2250 x 300 CCDs connected in pairs will be installed in the focal plane. The pixel size is 12 x 12 μm (see Figure 2).

The first pair (CCDs 1 and 2) will be covered only by anti-reflective coating and provide a realization of the panchromatic passband. The remaining 10 pairs of CCDs will be covered by interference coating so as to create 10 different photometric bands in the 200-1000 nm spectral range. During scanning, star images will pass successively through all the CCDs and will be recorded in the TDI mode.

Vibrations of the station smear star images and distort their trajectories in the focal plane. To compensate for these motions, an image stabilization device will be used involving six auxiliary 512×512 pxl CCDs with a pixel size of $16 \times 16\,\mu$m installed around the field of the main photometer to measure the micro-tilts.

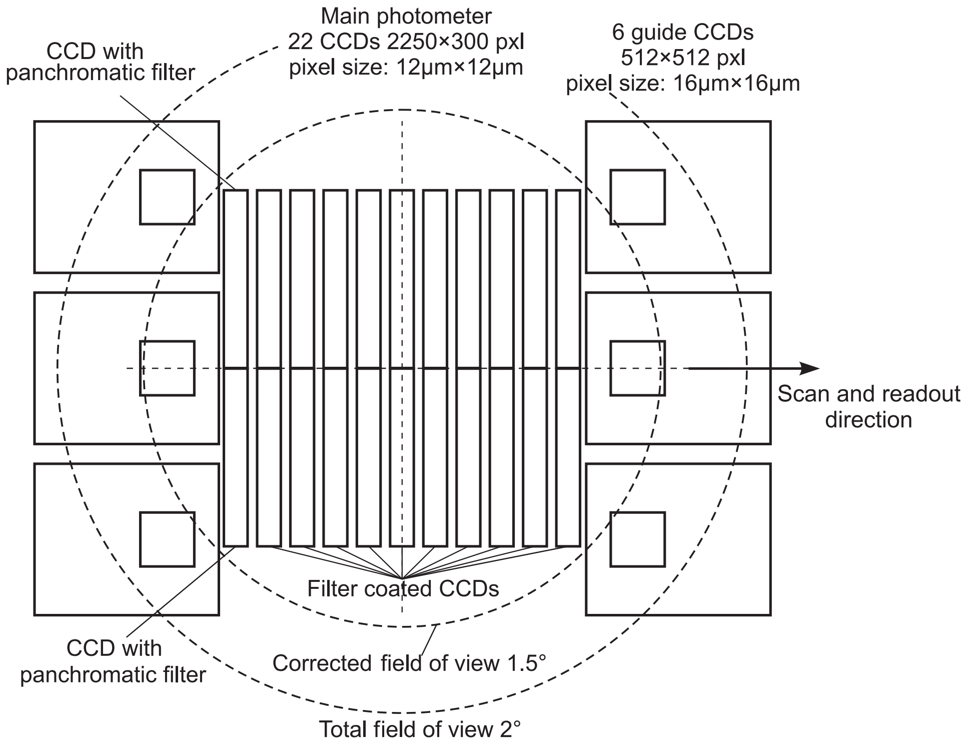

Figure 2. Focal plane assembly

Rocking and shaking of the station, will be tracked with those auxiliary CCDs. To compensate the tilts of the ISS, the entire focal plain assembly will be moved and rotated by a hexapod (a Gough-Stewart platform) (Stewart 1966) with an accuracy of about 1 micrometer.

5. Focal plane; filters

We plan to perform a multicolor all-sky survey in 10 passbands over the wavelength range from 190 to 1000 nm. The photometric system will be implemented by 10 pairs of back illumination CCDs (See Figure 3). In addition, another CCD will be set to implement a panchromatic band. The “Lyra” photometric system should make it possible to determine the basic physical parameters of stars and interstellar matter. The wavelength, position, and half-width of the proposed photometric bands are summarized in Table 1 and shown in Figure 3. The same table gives the magnitudes of the brightest and faintest objects that can be measured with a photometric uncertainty of $0^m.1$ or $0^m.01$.

Only one of the bands 4a, 7a and 10 will be retained based on the results of simulations which are currently carried out. A special mode will be used to observe for the brightest objects ($V < 7^m$).

Table 1. Filter summary: limiting V magnitudes for A0V stars

λ_0 (nm)	$\Delta\lambda$ (nm)	Brightest (saturated)	faintest for 5 years observations $\sigma = 0.001^m$	$\sigma = 0.01^m$
195	20	3.6	8.5	13.2
218	20	4.2	9.0	13.6
270	25	5.4	9.4	14.1
350(*W*)	80	6.4	10.6	15.3
374(*P*)	80	7.1	10.7	15.4
440(*B*)	100	8.5	12.6	17.3
550(*V*)	80	7.4	11.6	16.3
700(*R*)	80	6.0	11.1	15.8
785	80	7.4	11.0	15.7
825	80	7.2	10.8	15.5
930	80	6.8	10.3	14.9
1000	100	6.3	9.7	14.3
panchrom	600	10.3	15.0	18.5

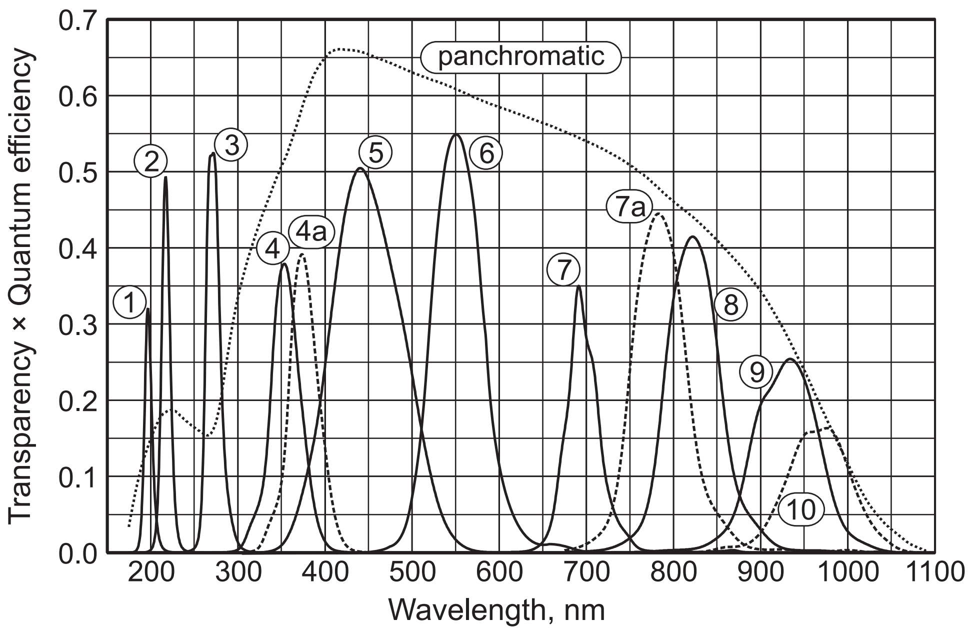

Figure 3. “Lyra” photometric bands

6. The requirements for the reference photometric standard system and for the stars included into the standard star catalog

One of the most important tasks of the “Lyra” experiment is to create a large grid of high-precision photometric standards.

An important question is: for what purpose do we need a reference system of standard stars?

The obvious one is: to set the zero point and the scale of the observed magnitudes. What do we want from a system of reference photometric standards?
With this system, we should be able:

- To calculate the atmospheric parameters in order to accurately take into account atmospheric extinction;
- To derive transformations between different photometric systems;
- To reduce the results of measurements obtained in the current instrumental system, whose spectral parameters are slowly drifting, into the common (standard!) photometric system.

Here are the requirements that standard star catalog must meet

- Stars should span a wide range of magnitudes;
- Stars should be selected from a representative sample of spectral types and luminosity classes;
- Catalog stars should densely and uniformly cover all the sky.

The stars included into catalog of photometric reference standards should have the following properties:

- Stars should exhibit no variations exceeding the instrumental error.
- Stars should have no close neighbors that would interfere with the measurements.
- Magnitudes of stars should be measured with error as small as possible depending on the magnitude, spectral type and photometric band.
- Stars should have spectral energy distributions allowing accurate reduction to the photometric bands different from those specified in the catalog.

In addition, the catalog of photometric reference standards must be supplemented by:

- A set of response curves of catalog's photometric bands.
- A set of typical spectral energy distributions for stars of different spectral types and luminosity classes in the spectral range corresponding to the reaction curves of catalog passbands; this set should include stars of different temperatures, photospheric pressures, elemental abundances, interstellar reddening, etc.
- A description of procedures and data for the calculation of the average atmospheric transmission curves under various ground conditions, and a description of procedures to derive observation-based corrections to the average atmospheric transmission.

The "Lyra" experiment should produce just such a catalog of standard stars supplemented by a set of necessary data and description of procedures.

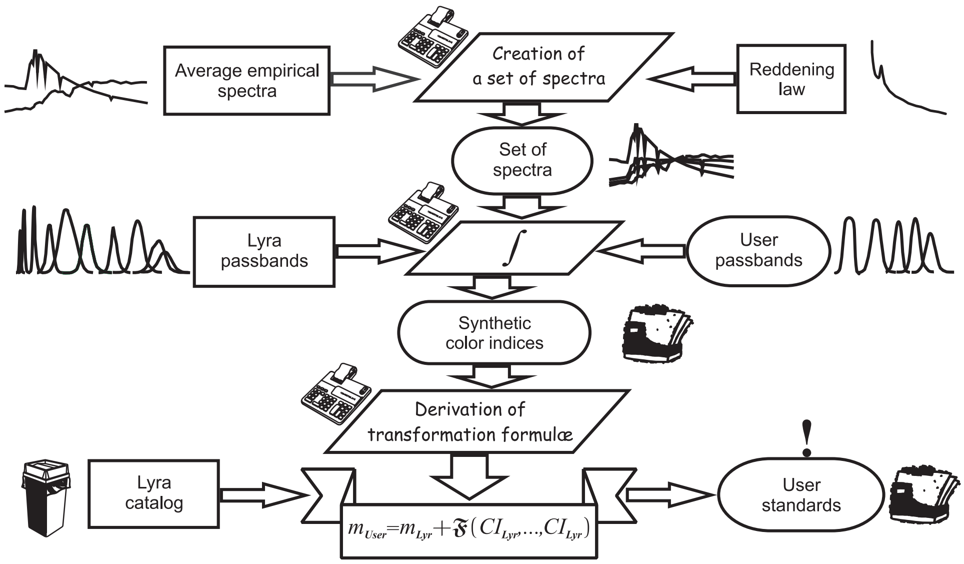

Figure 4. Creation of user's standard magnitudes

7. How can the catalog of magnitudes and color indices in the "Lyra" passbands be useful for the actual observer?

Precise and accurate catalog of standards enables the wide use of the synthetic photometry technique.

With a catalog having the above properties one can easily create a catalog of standards in their own photometric system (see Figure 4). No additional observations are required!

- A set of typical spectral energy distributions (SED) should be available for stars similar to those included in the catalog of standards.
- One has to adopt an interstellar reddening law.
- Reaction curves of the "Lyra" catalog and the response curves of the observer's instrument should be accurately known.

These data allow one to calculate a set of SEDs for stars with different reddening. It then remains to calculate synthetic color indices in the "Lyra" system and in the user's system, and, finally, you to derive the equation of transformation from the "Lyra" system to the user's system.

8. Can "Lyra" standard star catalog meet all the above requirements?

In order to understand how many stars usable as standards in various bands can be found for various spectral types, we performed a simulation based on an extrapolation of Hipparcos (ESA, SP-1200, 1997) and Catalog of Nearby Stars (Gliese & Jahreiss 1991) data. We estimate the expected average number of stars to be measured per one square degree with an random photometric error of less than $0^m.01$.

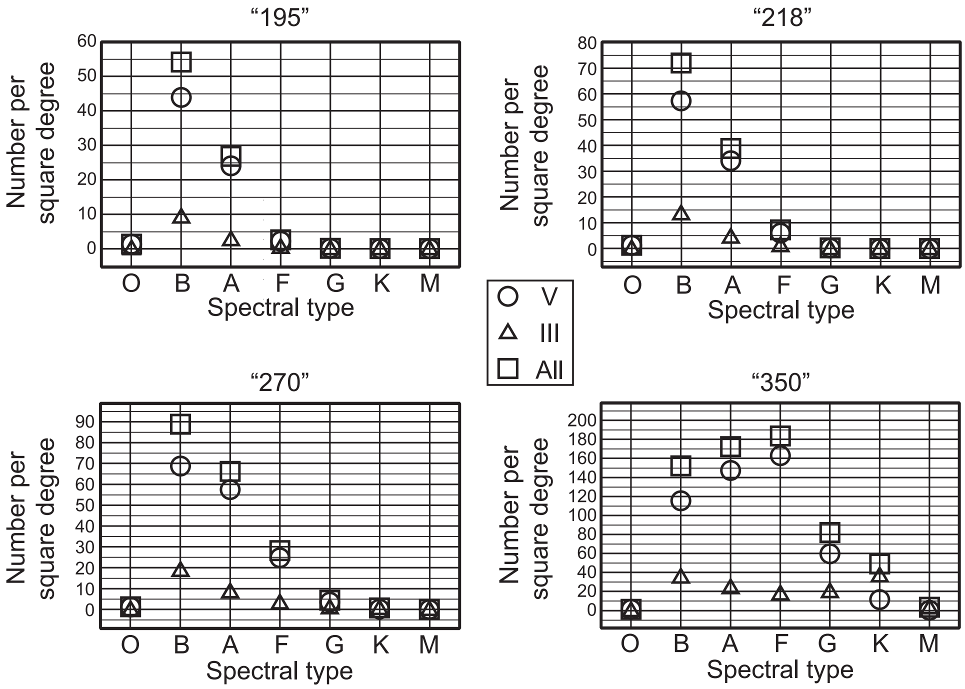

Figure 5. The expected average density of stars in ultraviolet passbands. Random error of less than $0^m.01$.

In the first three ultraviolet passbands (195, 218, 270) we will measure practically only stars of spectral types B and A (see Figure 5). In these bands we will have from about a dozen to one hundred stars (mostly the main sequence stars) per square degree will be observed. In the ”350” band there will be an appreciable number of F, G, and K stars: about several dozen per square degree.

The maximum number of stars will be observed in the ”440” band: more than 1,000 objects of various spectral types per square degree (see Figure 6).

In the ”550”, ”700” and ”785” bands K-type stars will be most numerous. The number of K-type giants exceeds that of red dwarfs. Note that K-type giants are dominant in the visible and infrared bands (see Figure 7).

The large number of stars to be measured in the “Lyra” experiment will certainly allow us to find a few million standards uniformly distributed over the sky. Even if only one percent of stars with good photometry will meet the requirement for standard stars there will be on the average about 40 standards per square degree.

Simultaneous measurements of magnitudes in 10 bands will make it possible to apply the correlation method for discovering of variable stars (Mironov et al. 2003). The method is based on searching for correlations between magnitude variations in different filters. It allows detection of variability with amplitudes as small as 0.3σ–1.0σ.

Magnitudes of the “Lyra” standard star catalog will be accurately transformable into other photometric (especially broadband) systems because

- “Lyra” bands cover the operating spectral range without gaps.

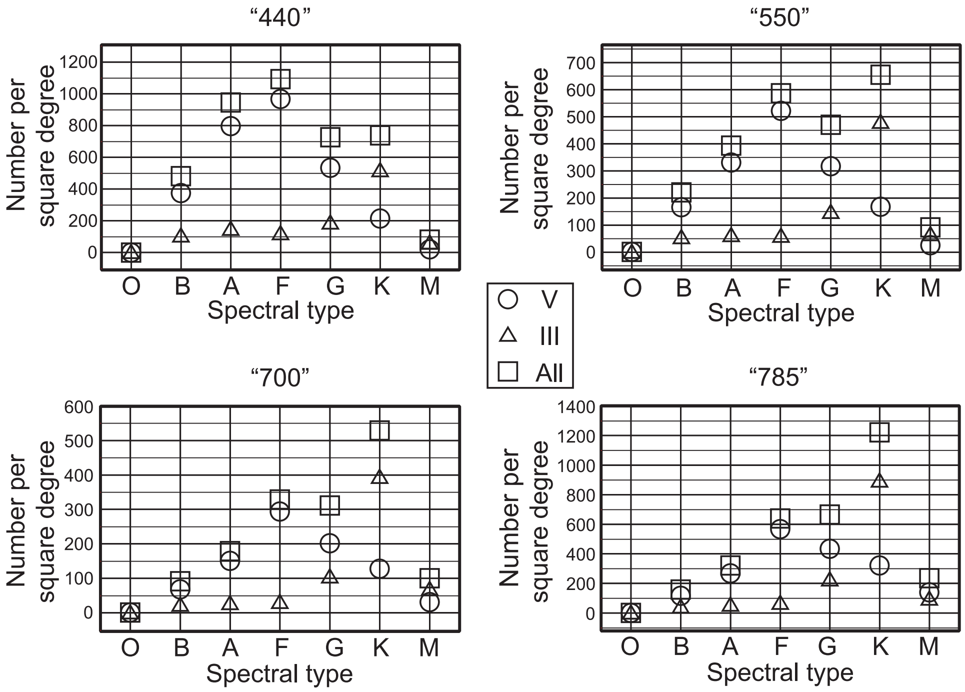

Figure 6. The expected average density of stars in visual passbands. Random error of less than $0^m.01$.

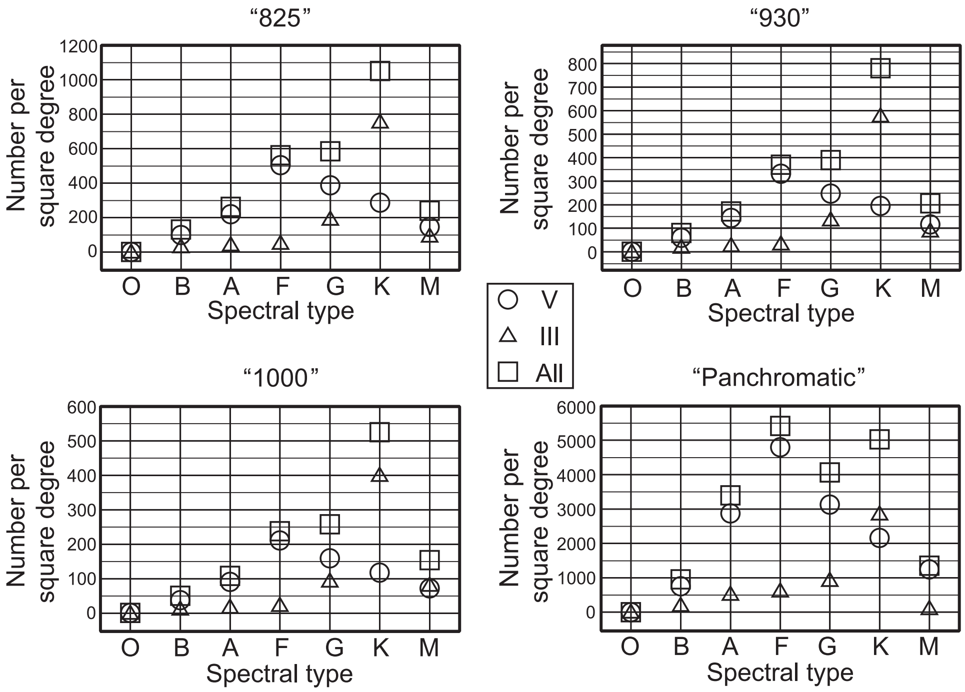

Figure 7. The expected average density of stars in infrared passbands. Random error of less than $0^m.01$.

- There are enough bands to take into account the great variety of stellar spectra and amounts of interstellar extinction.
- Stars can be tested for suitability as standards. The point is that "Lyra" magnitudes of standard stars in different passbands should be mutually transformable, i.e. there should exist a function (usually a third- or lower-order polynomial) to express any color index in terms of the other color indices with the required accuracy.

Magnitudes of the selected candidate standard stars will be put onto a single system by solving a large set of linear equations using the least-squares method, as described in Mironov et al. (2006).

9. "Lyra" calibration

We plan to perform the following steps for calibrations in preparation for and during the "Lyra" experiment.

The spectral quantum efficiency of all CCDs with the appropriate filters will be carefully measured. We emphasize that the interference filters will be applied directly to the silicon surface of the back illuminated CCD. These measurements will be made by comparing the response of the CCDs and that of a non-selective pyroelectric detector.

The absolute spectral sensitivity of the CCD will be determined by comparing the measurements with the radiation of a blackbody model at the Russian Research Institute of Optical and Physical Measurements, which is the keeper of the National standards of the spectral density of radiance and irradiance.

During the mission calibration frames will be taken regularly. The focal plane will be illuminated by a special illuminator whose spectral characteristics have been thoroughly studied on the Earth. The illuminator projects scattered sunlight onto the focal plane. The degradation of illuminators and detectors will be monitored by comparing the radiation of stars of different temperature known to exhibit no brightness variations.

Special efforts will be made to return the detector unit to the Earth after the mission and to do the post-mission determination of the spectral characteristics of all channels.

10. Conclusion

The above methods and procedures are currently developed at the Sternberg Astronomical Institute.

We are confident that the "Lyra" experiment will produce a universal catalog of standard stars to be used in a wide range of astronomical tasks.

References

ESA, SP-1200 1997, The Hipparcos and Tycho catalogues

Gliese, W., & Jahreiss, H. 1991, Astron. Rechen-Institut, Heidelberg

Mironov, A., Zakharov, A., & Ambartsumyan, A. 2006, in The Future of Photometric, Spectrophotometric and Polarimetric Standardization. Proceedengs of a meeting held in Blankenberge, Belgium 8-11 May 2006., edited by C. Sterken (San Francisco: Astronomical Society of the Pacific), vol. 364 of ASP Conference Series, 77

Mironov, A. V., Zakharov, A. I., & Nikolaev, F. N. 2003, Balt. Astr, 12, 589

Mironov, A. V., Zakharov, A. I., Prokhorov, M. E., Nikolaev, F. N., & Tuchin, M. N. 2010, in Variable Stars, the Galactic halo and Galaxy Formation. Proceedings of an international conference held in Zvenigorod, Russia, 12-16 October 2009., edited by C. Sterken, N. Samus, & L. Szabados (Moscow, Russia: Sternberg Astronomical Institute of Lomonosov Moscow University), vol. 1, 185

Stewart, D. 1965–1966, Proc. Institution of Mechanical Engineers 1965-1966 (UK), Vol.180, Pt.1, No 15, 180, 371

Zakharov, A. I., Mironov, A. V., Prokhorov, M. E., Biriukov, A. V., Stekol'shchikov, O. Y., & Tuchin, M. S. 2012, Astron. Rep. (in press)