Tests of simulated Gaia BP/RP spectra with LDS (Low Dispersion Spectroscopy) photographic sky surveys

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Abstract. The LDS (Low Dispersion Spectroscopy) performed in various extended sky surveys with optical telescopes using objective prism and photographic plates offers an interesting opportunity to test simulated low-dispersion spectra for the Gaia BP/RP photometers and to compare them with real data, especially for objects with strong emission lines. We present a review of astrophysics with LDS performed in the past, as well as an overview of existing extended sky surveys (with photographic plates) providing LDS data. Some of them provide almost complete coverage of the northern or southern hemisphere (e.g. the Northern and Southern Mt Wilson - Michigan H\textsubscript{a} surveys or the German La Paz Bolivia Southern Spectral Sky Survey). We show examples of these data and discuss a comparison of existing LDS plate data with expected/simulated Gaia BP/RP data. We show examples of real data for objects with very strong and wide emission features confirming that such features will be detectable with Gaia BP/RP. We also discuss the importance of Gaia RP/BP low-dispersion spectroscopy for astrophysical studies.

1. Introduction
ESA-Gaia is an ambitious mission to chart a three-dimensional map of the Milky Way, in the process revealing the composition, formation, and evolution of the Galaxy. Gaia will provide unprecedented positional and radial velocity measurements with accuracies required to produce a stereoscopic and kinematic census of about one billion stars in our Galaxy and throughout the Local Group. It amounts to \(~1\) percent of the Galactic stellar population. Combined with astrophysical information for each star provided by onboard multi-color photometry, these data will have the necessary precision for quantifying the early formation, and subsequent dynamical, chemical, and star formation evolution of the Milky Way. The Gaia payload consists of a single integrated instrument, the design of which is characterized by a dual telescope concept, with a common structure and a common focal plane (\texttt{sci.esa.int/gaia/}). Both telescopes are based on a three-mirror anastigmatic (TMA) design. Beam combination is achieved in image space with a small beam combiner. Silicon-carbide (SiC) ultra-stable material is used for the mirrors and telescope structure. There will be a large common focal plane with an array of 106 CCDs. The large focal plane also includes areas dedicated to the spacecraft’s metrology.
and alignment measurements. Three instrument functions/modes are designed: (i) Astrometric mode for accurate measurements, even in densely populated sky regions of up to 3 million stars deg$^{-2}$, (ii) Photometric mode based on low-resolution, dispersive, spectro-photometry using the Blue and Red Photometers (BP and RP) for continuous spectra in the 320–1000 nm band for astrophysics and chromaticity calibration of the astrometry, and (iii) Spectroscopic (RVS) mode for high-resolution spectra, using a grating, and covering the narrow 847–874 nm band. The expected limiting magnitude is 20 in photometric mode (sci.esa.int/gaia).

In this paper we focus on the ‘photometric mode’ RP/BP of Gaia. In reality the use of dispersive elements (prism) produce ultra low-dispersion spectra. One disperser called BP (Blue Photometer) operates in the wavelength range of 330–660 nm; the other is called RP (Red Photometer) and covers the wavelength range 650–1000 nm. The dispersion increases at shorter wavelengths, and ranges from 4 to 32 nm/pixel for BP, and from 7 to 15 nm/pixel for RP (sci.esa.int/gaia). However, we note that the photometric CCDs are located at the edge of the focal plane where the quality of the images is more sensitive to aberrations than the astrometric images [1].

Evidently the Gaia BP/RP images (ultra low-dispersion spectra) can be simulated by LDS ground-based surveys with photographic plates. Hence, the survey data can be used to test the simulated LDS for Gaia. For Gaia, most important are the full northern or southern sky surveys, as they can provide for any object in the sky, above a certain magnitude threshold, the real spectrum, and in many cases, several or even many spectra at various times.

The BP and RP spectra will be binned on-chip in the across-scan direction, whereas along-scan binning is not foreseen. The RP and BP will be able to reach object densities on the sky of at least 750 000 objects deg$^{-2}$. The observed complex images can be simulated by the GIBIS simulator (Fig. 3). GIBIS is a pixel-level simulator of the Gaia mission intended to simulate how the Gaia instruments will observe the sky based on realistic simulations of the astronomical sources and instrumental properties. It is a research branch of the global Gaia Simulator (GaiaSimu) currently under development within Gaia Coordination Unit 2: Data Simulations.

2. Astrophysics with LDS in the past

The LDS (Low-Dispersion Spectroscopy) astrophysics was developed and performed at numerous observatories (many in the USA) between about 1909 and nearly 1980. Numerous LDS plates were observed with Schmidt telescopes (plates with objective prism, also called slitless spectra), but there were also other instruments using a prism. The LDS plates were used for various projects e.g., QSO, blue and emission-line galaxy searches, emission line and Ho surveys, stellar classification, determination of radial velocities in galactic fields, etc., but they were seldom used after about 1980. As a consequence current knowledge about LDS among astronomers (especially young astronomers) is very limited.

The LDS using astronomical photographic plates dates back more than 100 years, which allows us to investigate very long-term spectral changes. For example, LDS observed from 1909 at Carnegie Observatories, Pasadena, CA, USA, are shown in Fig. 2. It is important because certain types of variable stars (VS) such as Miras, Cepheids, and a few cases of other stars, mostly peculiar variables, exhibit large variations of their spectral types. The research field is, however, poorly exploited, as the studies were very laborious (plates mostly required visually inspection) and rather limited, and hence there is no review of the spectral variability of VS.

3. Low Dispersion Spectral survey plate databases

Before Gaia, low dispersion spectra were frequently observed in the last century with various photographic telescopes using the objective prism. Some of them are listed here (the dispersion data are given in the next section; we also note that many other similar surveys exist):
Schmidt Camera Sonneberg. Sky survey (selected fields) with the 50/70 cm Schmidt telescope. Online access not yet available but the scans can be provided upon request.

Bolivia Expedition Spectral Plates. These plates represent the coverage of the southern sky with spectral and direct plates, directed by the Potsdam Observatory. The plates are stored at Sonneberg Observatory and were observed during the years 1924–1928; in total ~70 000 prism spectra were estimated and published in Potsdam Publ. 26–19 in 1930.

Hamburg Quasar Survey. A wide-angle objective prism survey searching for quasars with $B<17^{m}.5$ in the northern sky. The survey plates have been observed with the former Hamburg Schmidt telescope located at Calar Alto/Spain since 1980. Online access is available.

Byurakan Survey. The Digitized First Byurakan Survey (DFBS) is the digitized version of the First Byurakan Survey (FBS). It is the largest spectroscopic database in the world, providing low-dispersion spectra for 20 000 000 objects on 1139 FBS fields which equals 17056 deg². Online access is available. Sky coverage: DEC $>15^\circ$, and all RA (except for the Milky Way). The prism spectral plates were observed by the 1 m Schmidt telescope. Limiting magnitude: $17^{m}.5$ in V. Spectral range: 340–690 nm, with a spectral resolution of 5 nm.

Spectral survey plates at PARI (Pisgah Astronomical Research Institute), NC, USA. The total list of LDS plates at PARI is as follows: HK Survey 4° prism, A-Stars Survey 1.8° prism, He Survey UV filters, High Luminosity Survey, IR Survey 4° prism, Red Survey 4° prism, OB Survey 4° prism, QSO Survey 1.8° prism, SGH Survey 1.8° prism, All-Sky Survey 4° prism, Blue Survey 10° prism, and anti center Survey 4° prism. Possibly the best suited for Gaia LDS simulations is the Case QSO-Survey. The telescope is the 61/91 cm Burrell Schmidt at Kitt Peak with 1.8° prism, plate FOV of 5 by 5, limiting $B$ magnitude of 18, the emulsion is IIIaJ Baked, and the spectral range from 330 nm to 530 nm. The Burrell Schmidt-type telescope of the Warner and Swasey Observatory at its new location on Kitt Peak in Arizona was used for a spectroscopic survey of the region with galactic latitude $>+30^\circ$, and declination $>+30^\circ$. The plates covering 5 by 5, were observed with the 1.8° prism, providing a dispersion of 135 nm/mm at H$_\gamma$. The categories of objects that were cataloged are blue and/or emission-line galaxies, probable H II regions, blue and/or emission-line stellar objects, known and probable blue stars, main-sequence late B- and A-type stars, suspected field horizontal-branch stars of types A and F including RR Lyrae variables, suspected F- and G-type subdwarfs showing UV excess, faint carbon and late M suspected halo giants, and peculiar objects [2].

The Henize Mt Wilson-Michigan Southern H$\alpha$ Sky Survey. 290 high-quality plates of 15 × 15 inches observed in 1950–1952 in South Africa using a dedicated telescope by Karl Henize (for his Dissertation). A few examples of prominent emission spectral features found by K. Henize are shown in Fig. 5. They were found in objective prism spectral sky surveys. The estimated rate of strong emission and normal stars is 1: 10 000 in the Michigan-Mt Wilson Southern H$\alpha$ Survey. There are hints that at least some of these strong emission features are variable. The used dedicated telescope was D25 cm, with a dispersion of 45 nm/mm at H$\alpha$. Note that filters were used in this program. A full-size plate is shown in Fig. 4.

MtWilson–Michigan Northern H$\alpha$ Sky Survey recently stored at Carnegie Observatories, Pasadena, CA, USA. This collection contains nearly 1000 LDS survey plates of various sizes and represents a northern analogy to the Henize MtWilson-Michigan Southern H$\alpha$ Sky Survey.

4. The Ultra-Low Dispersion Spectroscopy by Gaia

4.1. Ultra LDS provided by Gaia RP/BP

We have identified the following astrophysical aspects of the LDS provided by Gaia BP/RP.

- Strong emission lines (also variable)
- Prominent spectral variability
- Possibility of spectroscopic Gaia alerts
Follow-up by ground-based RTs with LDS
Plate Sky Surveys can serve as real LDS simulator
Confirm simulated spectra for any object brighter than ~18 mag., even at various epochs.

4.2. Algorithms
The algorithms for automated analyses of digitized spectral plates were developed by students of informatics [3]. The main goals are as follows: the automated classification of spectral classes, searches for spectral variability (both in the continuum and lines), searches for objects with specific spectra, correlation of spectral and brightness variability, searches for transients, and the application to Gaia. The archival spectral plates observed with the objective prism offer the possibility to simulate the Gaia low-dispersion spectra and related procedures such as searches for spectral variability and variability analyses based on spectrophotometry. We focus on the sets of spectral plates in the same region of the sky over long-term intervals with good sampling that allow us to simulate Gaia BP/RP output. The main task is the automated classification of the stellar objective prism spectra from digitized plates, and a simulation and feasibility study for low-dispersion Gaia spectra.

4.3. Comparison of the Gaia Low Dispersion Spectra versus spectral plates
The comparison of low-dispersion spectra expected from the Gaia RP/RP photometers with those recorded in various astronomical photographic spectral sky surveys is an important task. The motivation of these studies is as follows: (1) Comparison of the simulated Gaia BP/RP images with those obtained from digitized Schmidt spectral plates (both using dispersive elements) for selected test fields, and (2) Feasibility study for the application of algorithms developed for the plates to Gaia. The dispersion is an important parameter and is briefly further discussed: (1) Gaia BP: 4–32 nm/pixel i.e., 400–3200 nm/mm, 9 nm/pixel i.e., 900 nm/mm at Hγ, RP: 7–15 nm/pixel i.e., 700–1500 nm/mm. A PSF FWHM~2 px i.e., the spectral resolution is ~18 nm. (2) Plates Schmidt Sonneberg (typical mean value): the dispersion for the 7° prism 10 nm/mm at Hγ, and 23 nm/mm at Hγ for the 3° prism. (3) Bolivia Expedition plates: 9 nm/mm, with calibration spectrum. (4) Hamburg QSO Survey: 1.7° prism, 139 nm/mm at Hγ, spectral resolution of 4.5 nm at Hγ. (5) Byurakan Survey: 1.5° prism, 180 nm/mm at Hγ, resolution 5 nm at Hγ, and (6) PARI prism dispersion: 150 nm/mm at 450 nm. We find that the Gaia BP/RP dispersion is ~5 to 10 times smaller than the dispersion of typical digitized spectral prism plates, and the spectral resolution of Gaia is ~3 to 4 times less compared to plates. Note that for plates the spectral resolution is seeing-limited, hence, the values represent the best values. For plates affected by bad seeing the spectral resolution is only ~2 times better than compared to Gaia BP/RP.

It confirms that in the already available sky plate archives there are photographic spectral records with low-dispersion spectra very similar to what Gaia BP/RP will provide.
Figure 2. Probably the oldest astronomical objective prism plates of Mt Wilson Observatory at Carnegie Observatories in Pasadena, CA, USA, were observed in 1909. These data are not only of historical interest because they can be used to study long-term spectral evolution and/or changes of particular objects.

Figure 3. Comparison of the Case sky survey LDS plate (left-hand panel) and simulated (Gibis simulator) Gaia BP output (right-hand panel) for similar dispersions (but different sky regions).

4.4. Most important LDS plate surveys/databases for simulated Gaia LDS
We have identified the following plate surveys as the most promising for the application to Gaia (simulations, algorithm tests, tests of simulated LDS).

- German La Paz Bolivia Expedition: Southern Sky Coverage D
- Hamburg Quasar Spectral Survey D
- Digitized Byurakan Spectral Survey D
- Northern H alpha MtWilson-Michigan Sky Survey PD
- Southern H alpha MtWilson-Michigan Sky Survey PD
Figure 4. Example of Henize Mt Wilson-Michigan Southern Sky Hα Survey plate, manually evaluated and marked by K. Henize.

Figure 5. Examples of marked objects with very strong emission lines with spectral dispersion similar to the Gaia BP/RP. Southern Michigan-Mount Wilson Hα sky survey by K. Henize with plates located at PARI, NC, USA. Note that the marked objects show no continuum, only strong emission features.

Note: The listed surveys represent an almost full-sky hemisphere coverage. D = Digitized, PD = Partly Digitized.

5. The Spectrophotometry
Despite the very low dispersion discussed above, the major strength of Gaia data for many fields of science will be in spectrophotometry, because the low-dispersion spectra may be converted to numerous well-defined color filters. For example, Optical Afterglows (OAs) of Gamma-Ray Bursts (GRBs) are known to exhibit rather specific color indices that distinguish them from other types of the astrophysical objects [4,5]. A reliable classification of optical transients will
Figure 6. The flux profiles of LDS of selected objects (cataclysmic variables and blazars from the digitized Hamburg QSO survey.

Figure 7. The Hamburg QSO digitized plates were used for the identification of ROSAT X-ray sources. Here we show a few examples. For more details see [9].

Figure 8. The prominent spectral features marked on LDS plates at PARI, NC, USA.
hence, in principle, be possible with this method. Colors of microquasars may serve as another example; they display blue colors with a diagonal trend formed by individual objects. This method can be used for optically faint, hence distant, objects as well. Apart from these examples color studies may improve our current understanding of various types of astrophysical objects, including cataclysmic variables and various types of high-energy sources.

We note however that the color indices cannot be calculated without the decontamination of BP/RP spectra [6,1]. The energy redistribution effect in the Gaia BP and RP spectra arising from contamination by the wings of the image profiles has been mentioned and investigated by [6], [7], and [8]. According to them, Gaia spectra may be used for stellar classification either after applying contamination corrections, or by using standard calibration stars with known physical parameters and observed by the Gaia spectrophotometers. According to [6], in the latter case, there is no possibility to calculate real spectral energy distributions, magnitudes, color indices, color excesses, or other photometric quantities. The classification must be performed by matching the observed pseudo-energy distributions of target and standard stars, or by using pattern-recognition algorithms (or template matching) over the entire spectrum to estimate the astrophysical stellar parameters.

6. Conclusion
The ESA-Gaia satellite will provide ultra-low dispersion spectra with the BP and RP photometers and present new challenges for astrophysics and informatics. The nearest analogy is the digitized prism (slitless) spectral plates of LDS sky surveys. Digitized surveys can be used for simulations and tests of Gaia data and algorithms. Some Gaia algorithms have been already proposed and tested. Some types of variable stars are known to exhibit large changes of spectral type. The research field is however poorly exploited and perhaps more discoveries can be expected with Gaia data because the Gaia mission will allow us to investigate the spectral behavior of a huge amount of objects observed during 5 years with good spectroscopic sampling. However, the Gaia data must be first decontaminated for scientific applications, as we discuss in this paper. We note that for investigations of (possible) prominent spectral changes with Gaia BP/RP data we will mostly rely on the overall spectral continuum flux profile and on bright and wide emission spectral features (and/or color changes) instead of absorption lines. The latter spectral lines will be hardly visible with the Gaia photometers due to the very small spectral dispersion.

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8. References
[1] Straizys V 2010 personal comm.
[2] Pesch P and Sanduleak N 1984 in Astronomy with Schmidt-type Telescopes, Proceedings of the 78th IAU Coll. in Asiago Italy Aug 30 – Sep 2 1983, ed. M Capaccioli (Reidel Publ. Dordrecht) p 53
[3] Hudec L 2007 Algorithms for spectral classification of stars, BSc. Thesis Charles University Prague
[4] Simon V, Hudec R, Pizzichini G and Masetti N 2001 A&A 377 450
[5] Simon V, Hudec R, Pizzichini G and Masetti N 2004 in Gamma-Ray Bursts: 30 Years of Discovery Gamma-Ray Burst Symp. (AIP Conf. Proc.) 727 487
[6] Straizys V et al 2006 Baltic Astronomy 15 449
[7] Montegrippo P et al 2007 GAIA-C5-TN-OABO-PMN-001-1, Gaia Livelink
[8] Montegrippo P 2009 GAIA-C5-TN-OABO-PMN-002, Gaia Livelink
[9] Zickgraf F J et al 2003 A&A 406 535