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Research Article

Photometry and Low Dispersion Spectroscopy with ESA *Gaia*

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The ESA satellite to be launched in 2012 will focus on highly precise astrometry of stars and all objects down to limiting magnitude 20. Albeit focusing on astrometry related matters, the satellite will also provide photometric and spectral information and hence important inputs for various branches of astrophysics. Within the *Gaia* Variability Unit CU7 and related work package Specific Object Studies there are subwork packages accepted for optical counterparts of celestial high-energy sources and cataclysmic variables. Although the sampling of the photometric data will not be optimal for this type of work, the strength of *Gaia* in such analyses is the fine spectral resolution (spectrophotometry and ultra-low dispersion spectroscopy) which will allow the correct classication of related triggers. We will review the available low dispersion spectral surveys and discuss their use for a simulation and tests of the *Gaia* algorithms and *Gaia* data.

1. Introduction

For many years, the state of art in celestial cartography has been the Schmidt surveys of Palomar and ESO, and their digitized counterparts. *Gaia* will provide the detailed 3-d distributions and space motions of all these stars, complete to mag 20. The measurement precision, reaching a few millionths of second of arc, will be unprecedented [1]. This will allow our Galaxy to be mapped, for the rst time, in three dimensions. It is obvious that, with the above briefly described performance, *Gaia* will provide valuable inputs to various research fields of contemporaneous astronomy and astrophysics including the field of high-energy sources. Most of the variable object research will be performed within the *Gaia* Variability Coordination Unit CU7. To study the optical counterparts of celestial high-energy sources, there will be several advantages provided by *Gaia*. First, this will be a deep limiting magnitude of 20 [2], much deeper than most of previous studies and global surveys. For example, no detailed statistics of variable stars has been investigated for magnitudes fainter than 18. Secondly, the time period covered by *Gaia* observations, that is, 5 years, will also allow some studies requiring long-term monitoring, recently provided mostly by astronomical plate archives and small or magnitude-limited sky CCD surveys. But perhaps the most important benefit of *Gaia* for these studies will surely be the color (spectral) resolution thanks to the low resolution (prism) *Gaia* spectroscope. This will allow some detailed studies involving analysis of the color and spectral changes not possible before. The details of studies of the optical counterparts of high-energy sources have been recently evaluated and are described in more detail mostly by the dedicated sub-workpackages within the workpackage Specific objects studies within the *Gaia* CU7 [3, 4]. The main objective of the sub-workpackage mentioned above is the investigation and analysis of optical counterparts of high-energy astrophysical sources (including High-Mass X-Ray Binaries, Low-Mass X-Ray Binaries, X-Ray Transients, X-Ray Novae, Optical Transients and Optical Afterglows related to X-Ray Flashes and Gamma-Ray Bursts, Microquasars, etc.) based on the *Gaia* data as a complex analysis with additional data.

2. Spectral Coverage by *Gaia*

The G band (in yellow) with GBP, GRP and GRV S of *Gaia* are illustrated on Figure 1. The bands are constructed by multiplying the CCDs QE (red enhanced for RP and RVS, blue enhanced for BP), and the optical transmission curves taken from the *Gaia*ParamDB.

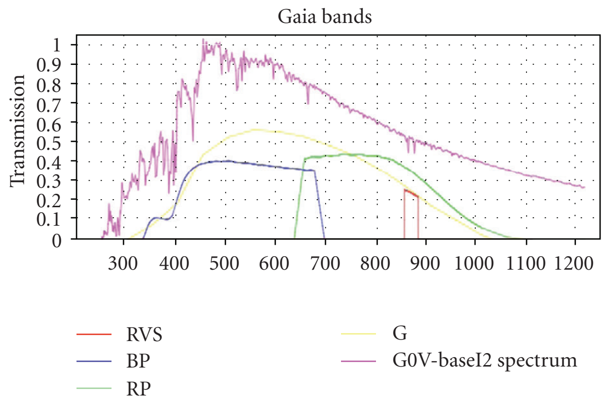


Figure 1: The spectral coverage by *Gaia* [5].

The use of dispersive element (prisma) generates ultra low-dispersion spectra. One disperser called BP for Blue Photometer operates in the wavelength range 330–660 nm; the other called RP for Red Photometer covers the wavelength range 650–1000 nm (Figure 1). The dispersion is higher at short wavelengths, and ranges from 4 to 32 nm/pixel for BP and from 7 to15 nm/pixel for RP [5].

3. Variable Objects by *Gaia*

As already mentioned in Section 1, perhaps the most important benet of *Gaia* for the variable star studies will surely be the ne color resolution. This will allow some detailed studies involving analyzes of color and spectral changes not possible before. The details of variable star studies with *Gaia* have been recently evaluated and are described in more detail mostly by the dedicated sub-workpackages within the workpackage Specic objects studies within the *Gaia* CU7. The participation of High Energy Astropysics (HEA) group at the Astronomical Institute of the Academy of Sciences of the Czech Republic in Ondrejov focuses on *Gaia* CU7 Variability Processing Unit with R. Hudec being a member of *Gaia* CU7 team. Two sub-work packages within the specic object studies on cataclysmic variables (CVs) and optical counterparts of high energy sources have been proposed, evaluated, accepted, and allocated to be managed by R. Hudec. Additional participation is expected in image processing—this includes the algorithms designed for scanned Schmidt spectral plates (simulation of *Gaia* data and variability studies based on Spectrophotometry). The further participation represents direct participation in *Gaia* CU7 Data Processing Center (DPC) as a natural continuation of the participation in *INTEGRAL* ISDC. This includes participation in the software development in a team, and Java and object oriented programming as a natural extension of the participation in *INTEGRAL* ISDC (since 1997). Another participation is represented by the robotic telescopes run with the same RTS2 operating software: BART, BOOTES1, BOOTES2, BOOTES-IR, FRAM, WATCHER, D50 cm CCD telescope (since 2007). Also small and private observatories are expected to participate.

4. Optical Counterparts of High-Energy Sources by *Gaia*

Most high energy sources have also an optical emission, mostly variable and accessible by *Gaia*. The monitoring of this variable optical emission provides important input to understanding of the physics of the source [6, 7]. The idea is to focus on the sources not included in other categories of variable sources (e.g., not on AGNs, CVs, etc.) covered by other sub-workpackages [3, 4]. The investigations and analyzes of optical counterparts of high energy sources based on the *Gaia* data also require complex analyzes with additional data. Specically, for selected targets, multispectral analyzes using *Gaia* and other databases (such as the satellite X-ray and gamma-ray data, optical ground-based data etc.) may be feasible. They will deal with the long-term light changes and their evolution, especially active states, outbursts, and ares. For the selected sources, dedicated complex analyzes will be undertaken, including spectrophotometry and investigation of the relation between the brightness and spectrum/color index. This will enable a study and understanding of related physical processes [8]. Also a statistics of the whole sample of objects will be made (Figure 2).

5. Three Observing Modes of *Gaia*

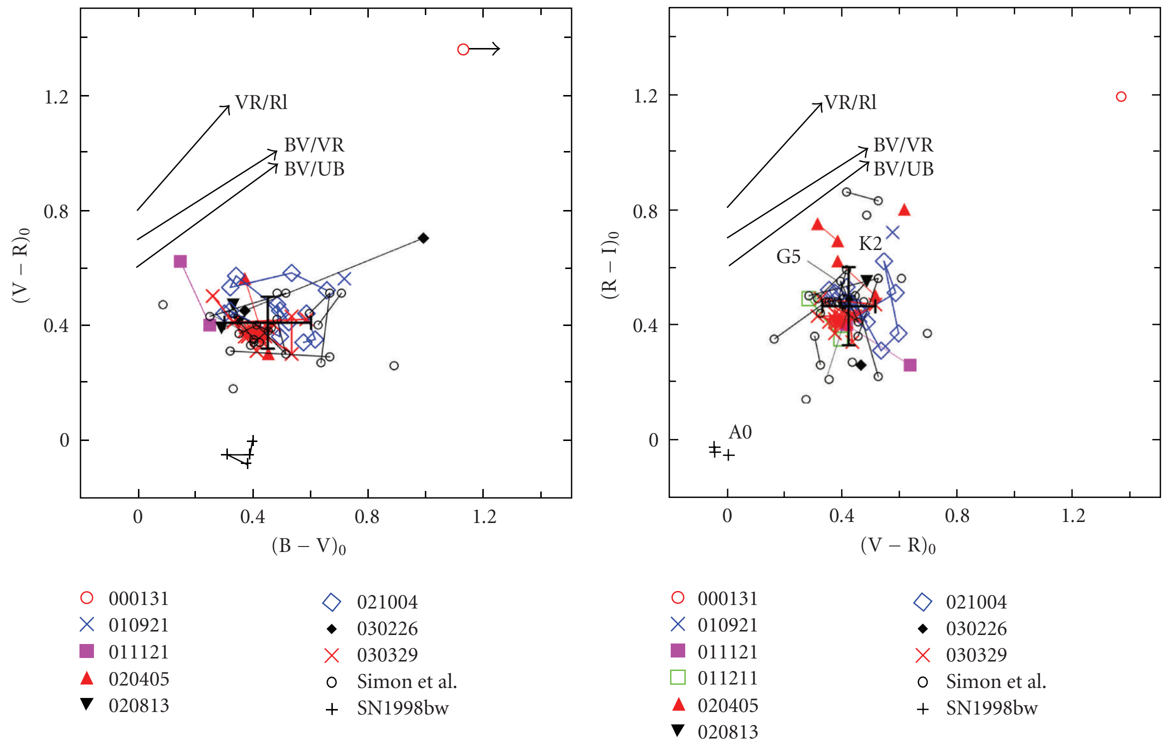
In this paper we focus of the "photometric mode" RP/BP. In reality, this mode generates ultra low-dispersion prism spectra. The use of the dispersive element (prisma) generates ultra low-dispersion spectra. One disperser called BP for Blue Photometer operates in the wavelength range 330–660 nm; the other called RP for Red Photometer covers the wavelength range 650–1000 nm (Figure 3). The dispersion is higher at short wavelengths, and ranges from 4 to 32 nm/pixel for BP and from 7 to 15 nm/pixel for RP.

6. Simulated *Gaia* Low Dispersion Spectra

Gaia's photometric instrument is based on a dispersive-prism approach such that starlight is not focused in a PSF-like spot but dispersed along the scan direction in a low-resolution spectrum. The instrument consists of two low-resolution fused-silica prisms dispersing all the light entering the field of view (FOV). Two CCD strips are dedicated to photometry, one for BP and one for RP. Both strips cover the full astrometric FOV in the across-scan direction.

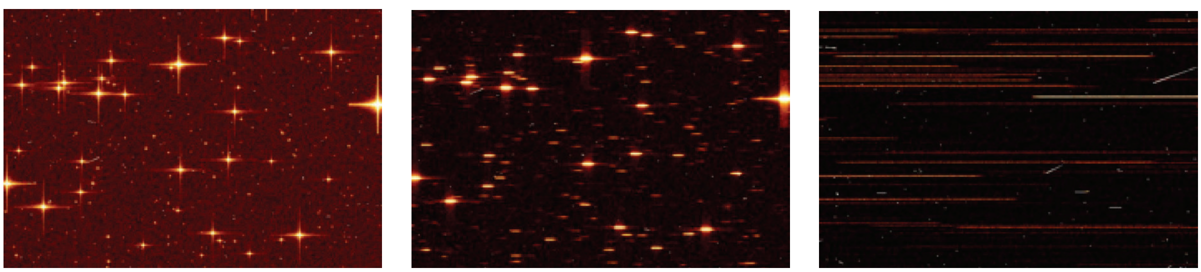
All BP and RP CCDs are operated in TDI (time-delayed integration) mode. The CCDs have 4500 (for BP) or 2900 (for RP) TDI lines and 1966 pixel columns (10×30 micron pixels). The spectral resolution is a function of wavelength as a result of the natural dispersion curve of fused silica. The BP and RP dispersers have been designed in such a way that BP and RP spectra have similar sizes (on the order of 30 pixels along scan) [5].

BP and RP spectra will be binned on-chip in the across-scan direction; no along-scan binning is foreseen. RP and BP will be able to reach the object densities on the sky of at least



(a) (b)

FIGURE 2: Examples of the color diagrams of opticl afterglows (OAs) of GRBs. The data for $t - T0 < 10.2$ d in the observer frame and corrected for the Galactic reddening are displayed. Multiple indices of the same OA are connected by lines for convenience. The mean colors (centroid) of the whole ensemble of OAs (except for GRB000131 and SN 1998bw) are marked by the large cross. The representative reddening paths for $E_{B-V} = 0.5$ and positions of the main-sequence stars are also shown. Adapted from [9–11].



AF RP RVS

(a) (b) (c)

FIGURE 3: Three observation modes of *Gaia*: AF = astrometric, RP = photometric, RVS = spectrophotometric [5].

750,000 objects deg^{-2}. The obtained images can be simulated by the GIBIS simulator (see Figure 4).

7. The Spectral Type Variability with *Gaia*

It is known that certain types of variable stars (VS) such as Miras, Cepheids, and peculiar VS exhibit large variations in their spectral types. This fields is, however, little exploited, as these studies were very laborious before (plates were mostly visually inspected) and limited. No review on the spectral variability among VS exists (Samus, personal comm. 2008).

The evaluation by computers and dedicated s/w will allow to search and investigate the spectral variability in the *Gaia* data and in digitized spectral plates. For example, the Mira variable X Cam [12] is known to exhibit spectral variations M0 to M6.5, accompanied by the photometric variations with the amplitude 1.4 mag in the R band (Figure 5).

The Cepheid Variables represent another example. Spectral type of all classical Cepheids definitely vary (Figure 6). At maximum, they all have the types around F5-F8. At minimum, the longer the period, the later is the spectral type (to K2) (Samus, 2008). Examples of the related spectral

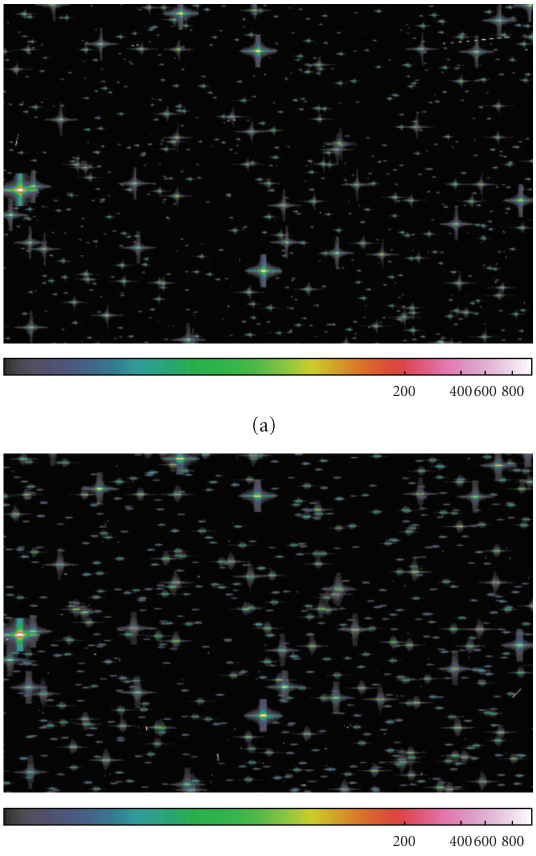


FIGURE 4: BP (a) and RP (b) images simulated by GIBIS simulator, the same sky field.

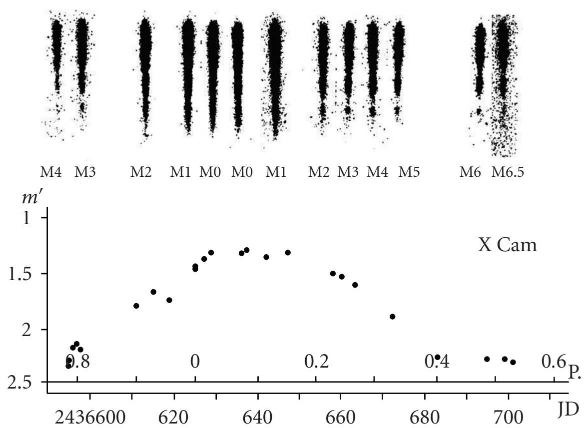


FIGURE 5: Spectral and photometric variability of X Cam [12].

and photometric variations of Cepheids were shown, for example, by Becker 1938 and Shapley 1916 [13, 14]. The spectral type changes of peculiar stars are also known: for example, the variable FG Sagittae changed its spectral type from B to M [15].

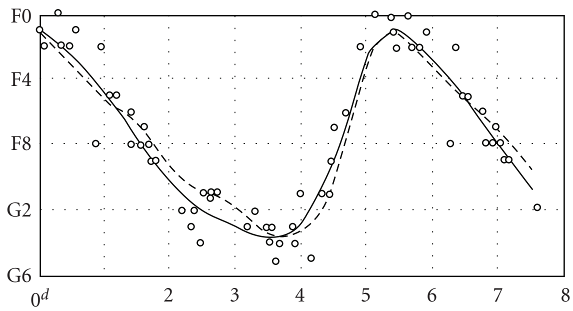


FIGURE 6: Relation of the light curve and spectral type for delta Cephei [13].

8. Suitable Low Dispersion Spectral Databases for *Gaia*

Before *Gaia*, low dispersion spectra were frequently taken in the last century by various photographic telescopes with the objective prisma. Some of them are listed here:

Schmidt Camera Sonneberg. The dispersion ~23 nm/mm at Hgamma for the 3 deg prisma. The scan resolution is 0.05 mm/px, thus about 0.5 nm/px. The dispersion ~10 nm/mm at Hgamma for the 7 deg prisma. The scan resolution is 0.02 mm/px, thus about 0.2 nm/px.

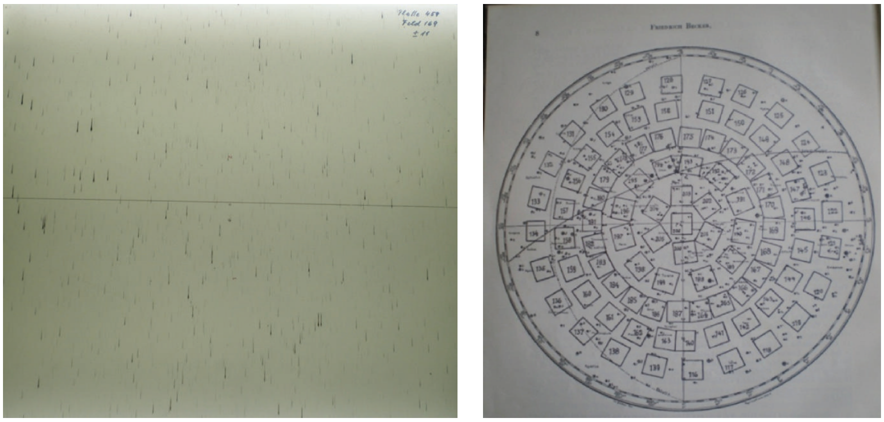
Bolivia Expedition Spectral Plates. The coverage of the southern sky with spectral and direct plates, Potsdam Observatory, plates stored at the Sonneberg Observatory. Hidden for ~75 years. Plates taken ~1924–1928, about 70 000 prism spectra estimated and published in Potsdam Publ. 26–19 in 1930 (Figure 7).

Hamburg Quasar Survey. A wide-angle objective prism survey searching for quasars with B < 17.5 on the northern sky. The survey plates have been taken with the former Hamburg Schmidt telescope, located at Calar Alto/Spain since 1980. For the surfy, the 1.7° prism was used providing unwidened objective prism spectra with a dispersion of 139 nm/mm at Hgamma. Under the conditions of good seeing, the FWHM of the images is 30 μm (plate resolution) giving a spectral resolution of 4.5 nm at Hgamma on the objective-prism plates. Online access (Figure 8).

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 = 17,056 deg^2. Online access (Figure 9). Sky coverage: DEC > −15°, all RA (except the Milky Way). Prisma spectral plates by the 1 m Schmidt telescope. Limiting magnitude: 17.5 in V, spectral range: 340–690 nm, spectral resolution 5 nm. Dispersion: 180 nm/mm near Hgamma.

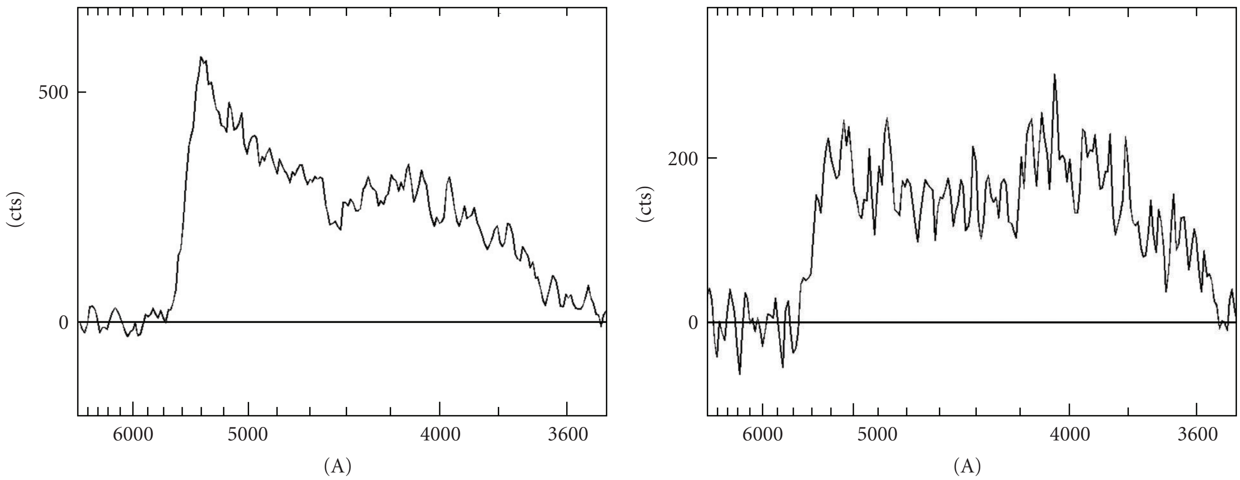
9. Algorithms for Automated Analyses of Digitized Spectral Plates

These algorithms are developed by informatics students [16]. The main goals are as follows: the automated classification of spectral classes, searches for spectral variability (both



(a) (b)

Figure 7: Bolivia Expedition spectral plates (a) and the southern sky coverage of the Bolivia Expedition spectral plates (b).



(a) (b)

Figure 8: Example spectra of cataclysmic variable (a) and blazar (b) (digitized Hamburg Survey).

continuum and lines), searches for objects with specific spectra, correlation of spectral and light ganges, searches for transients, and application for *Gaia*. The archival spectral plates taken with the objective prisma offer the possibility to simulate the *Gaia* low dispersion spectra and related procedures such as searches for the spectral variability and variability analyses based on the Spectrophotometry. We focus on the sets of spectral plates of the same sky region covering long time intervals with good sampling; this enables the simulating of the *Gaia* BP/RP outputs. The main task is the automatic classification of stellar objective prism spectra on digitised plates, a simulation and a feasibilty study for the low-dispersion *Gaia* spectra.

The important part here is the algorithm for an automated recognition of a low dispersion spectral image and its comparison with atlas images (specimen of stellar spectra of sample stars with defined spectral type). In addition spectral changes can be exploited and followed as well as searches for objects with strange spectra.

The algorithms should be able to take into account the background in the photographic emulsion which is not trivial as the background is variable. One method how to solve this is the histogram implementation resulting from digitised plate and reflecting the parameters of a real sky plates, yielding the optimized threshold filter. Then segmentation algorithm follows which recognizes the spectral elongated image. A recursive function is used there, as well as various convolution filters. The function to control the edge-surroundings gradient was also tested and added. The recognized spectral images are then normalized, and conequently the layered neuron network are used to analyze the vectors. The neuron network is then responsible for selection and allocation of model spectra. For more details see [16].

Table 1: Comparison of the parameters of *Gaia* BR and RP and of selected plate low dispersion spectra.

	Wavelength range, nm	Limiting magnitude	Dispersion at Hgamma, nm/mm	Spectral resolution, nm
Gaia	330–660, 650–1000	∼19	900	∼18?
Sonneberg Schmidt	340–650	18	10 and 23	∼3
Bolivia Expedition	340–650	14	9	∼3
Hamburg	340–540	19	139	4.5
Byurakan	340–690	17.5	180	5

10. The Ultra Low Dispersion Spectral Images by *Gaia*: Comparison of the *Gaia* Low Dispersion Spectra versus Spectral Plates

The dispersion represents an important parameter: (1) *Gaia* BP: 4–32 nm/pixel, that is, 400–3200 nm/mm, 9 nm/pixel, that is, 900 nm/mm at Hgamma, RP: 7–15 nm/pixel, that is, 700–1500 nm/mm. PSF FWHM ∼2 px, that is, spectral resolution is ∼18 nm (see Figure 10), (2) Plates Schmidt Sonneberg (typical mean value): the dispersion for the 7 deg prisma 10 nm/mm at Hgamma, and 23 nm/mm at Hgamma for the 3 deg prisma.The scan resolution is 0.02 mm/px, thus about 0.2 and 0.5 nm/px, respectively, (3) Bolivia Expedition plates: 9 nm/mm, with calibration spectrum, (4) Hamburg QSO Survey: 1.7 deg prisma, 139 nm/mm at Hgamma, spectral resolution of 4.5 nm at Hg, (5) Byurakan Survey: 1.5 deg prisma, 180 nm/mm at Hgamma, resolution 5 nm at Hgamma (Figure 1). Hence *Gaia* BP/RP dispersion ∼5 to 10 times less than typical digitised spectral prism plate, and spectral resolution ∼3 to 4 times less. Note that for plates the spectral resolution is seeing-limited hence the values represent the best values (see Table 1). *Gaia* BP/RP dispersion ∼5 to 10 times less than typical digitized spectral prism plate, and the spectral resolution ∼3 to 4 times less, but on the plates affected by bad seeing only ∼2 times less.

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 8 selected test fields, and (2) Feasibility study for application for the algorithms developed for the plates for *Gaia*.

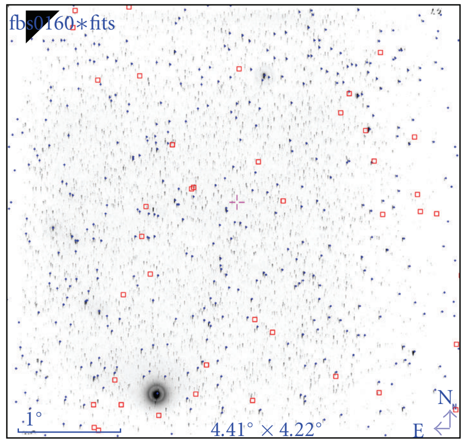


Figure 9: An example of the Byurakan Spectral Plate (FOV = 4°× 4°).

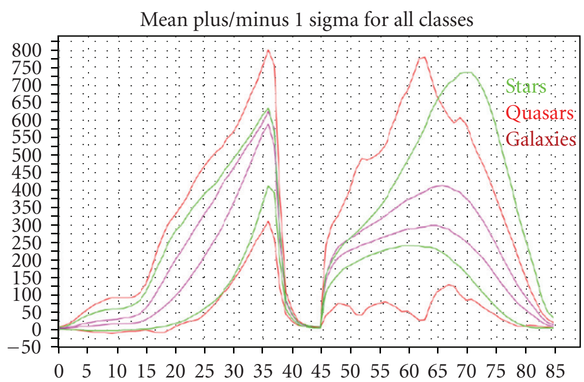


Figure 10: The simulated 1D low dispersion spectra by *Gaia* according to Bailer-Jones et al., 2008 [17]. The x-axis in pixels covers the BP and RP range, on y-axis is the intensity (arbitrary units). This picture shows that even for very low dispersion spectra without visible spectral lines valuable information can be obtained and scientifically used from the spectral continuum profile.

11. The Power of *Gaia* Spectrophotometry for Science

Despite of the low dispersion discussed above, the major strength of *Gaia* for many scientific fields will be the fine spectrophotometry, as the low dispersion spectra may be transferred to numerous well-defined color filters. As an example, the OAs of GRBs are known to exhibit quite specific color indices, distiguishing them from other types of the astrophysical objects [9, 10], hence a realiable classification of optical transients will be possible using this method (see also Figure 2). Colors of Microquasars may serve as another example. The color-color diagram in Figure 11 contains the microquasars of various types: (1) system with the optical emission dominated by the high-mass donor-Cyg X-1, (2) persistent systems with the optical emission dominated by the steady-state accretion disk-SS433, Sco X-1, (3) transient low-mass systems in outburst with the optical emission dominated by the accretion disk-GRO J1655-40, XTE J1118+480 (the disk is close to steady-state in outburst), and (3) the high-mass system CI Cam on the decline from its 1999 outburst to quiescence.

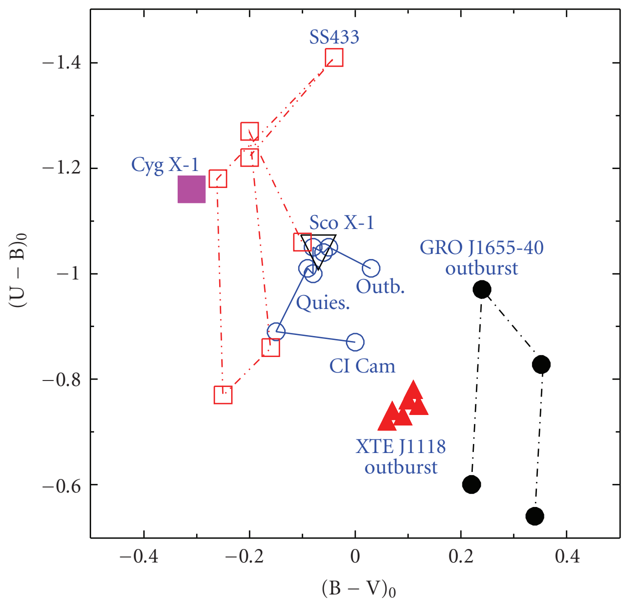


Figure 11: The color-color diagram for microquasars.

The systems plotted, irrespective of their types, display blue colors, with a trend of a diagonal formed by the individual objects. This method can be used even for the optically faint, and hence distant objects.

12. Conclusions

The *Gaia* mission of European Space Agency (ESA) will contribute essentially to scientic studies and physical understanding of variable stars in general and of optical counterparts of high energy sources, CVs and related objects in particular. The variability studies based on low-dispersion spectra are expected to provide unique novel data and can use the algorithms recently developed for the automatic analyzes of digitized spectral Schmidt plates. *Gaia* will provide ultra-low dispersion spectra by BP and RP representing a new challenge for astrophysicists and informatics. The nearest analogy is represented by the digitized prisma spectral plates: Sonneberg, Hamburg and Byurakan surveys. These digitised surveys can be used for a simulation and tests of the *Gaia* algorithms and *Gaia* data. Some algorithms have been already tested. Some types of variable stars are known to exhibit large spectral type changes; however, this field is little exploited and more discoveries can be expected with the *Gaia* data as *Gaia* will allows us to investigate the spectral behavior of huge amounts of objects over 5 years with good sampling for spectroscopy.

Acknowledgments

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