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Investigation of high-energy sources in optical light by ESA Gaia

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Abstract. We refer on the project related to the ESA satellite Gaia to be launched in 2012 with focus on the high precision astrometry of stars and all objects down to limiting magnitude 20. 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 sub-work 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 (spectro-photometry and ultra-low dispersion spectroscopy) which will allow the correct classication of related triggers.

Key words. High-energy sources – Stars: Cataclysmic Variables – Satellites: Gaia – Spectroscopy: low-dispersion spectra

1. Introduction

The ESA Gaia satellite will provide the detailed 3-d distributions and space motions of all stars and other objects, complete to mag 20. The measurement precision, reaching a few millionths of second of arc, will be unprecedented. This will allow our Galaxy to be mapped, for the first time, in three dimensions Perryman (2005). 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 mag Jordi & Carrasco (2007), much deeper than most of the 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, i.e. 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 resolu-

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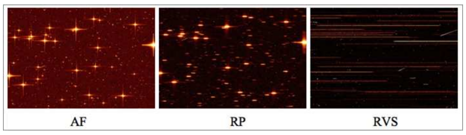

Fig. 1. Three observation modes of Gaia: AF = astrometric, RP = photometric, RVS = spectrophotometric Perryman et al. (2006).

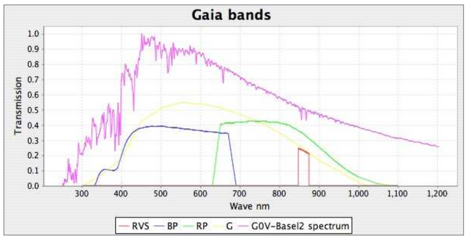

Fig. 2. The spectral coverage by Gaia Perryman et al. (2006)

tion (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 are described in detail in the dedicated sub-workpackages within the workpackage Specific objects studies within the Gaia CU7 Hudec & Simon (2007a,b). 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 and a complex analysis with additional data.

In this paper we focus of the photometric mode RP/BP. 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. 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 Perryman et al. (2006).

The spectral coverage of Gaia, i.e. the G band (in yellow) with GBP, GRP and GRV S, are illustrated in Fig. 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 GaiaParamDB.

2. High energy sources with ESA Gaia

In addition to the long-term photometry, the most important benefit of Gaia for the studies of high–energy (HE) sources will be the fine color resolution. 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 specific object studies on cataclysmic variables (CVs) and optical counterparts of high energy sources have been proposed, evaluated, accepted, and allocated to the first author of this paper. Additional participation is expected in image processing. This includes the algorithms designed for scanned Schmidt spectral plates (simulation of the Gaia data and variability studies based on spectro-photometry). The further participation represents an involvement in Gaia CU7 Data Processing Center (DPC) as a natural continuation of the participation in INTEGRAL ISDC. This includes the participation in the software development, 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), contributing to the sub-workpackage Supplementary Optical Observations.

3. 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. The investigations and analyzes of optical counterparts of high energy sources based on the Gaia data also require complex analyzes with additional data. Specifically, 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 flares. 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. Also a statistics of the whole sample of objects will be made. Examples of the color diagrams of optical afterglows (OAs) of GRBs are shown in Fig.3.

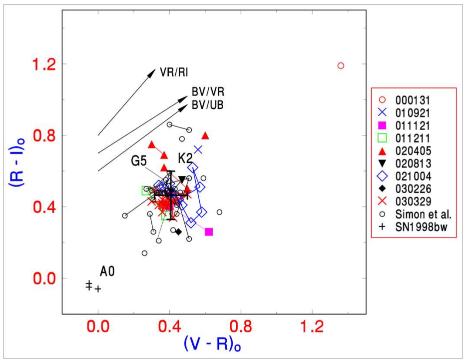

Fig. 3. Examples of the color diagrams of GRBs. The data for the time interval 0–10.2 d after the burst in the observer frame and corrected for the Galactic reddening are displayed. Multiple indices of the same OA are connected by lines for convenience. The mean colors (centroid) of the whole ensemble 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 Simon et al. (2001, 2004a)
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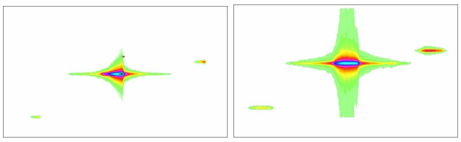

Fig. 4. BP (left) and BR (right) images simulated by GIBIS simulator, the same sky field.

4. Ultra–low dispersion spectroscopy with Gaia

The Gaia 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) Perryman et al. (2006).

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

5. The spectral type variability with Gaia

Certain types of variable stars (VS) such as Miras, Cepheids, and peculiar VS exhibit large variations in their spectral types e.g. Becker, 1938, Shapley 1916, Samus 2008 and Jarzebowski 1959. 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, 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.

6. 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: (1) Schmidt Camera Sonneberg. The dispersion $\sim$ 23 nm/mm at Hγ for the 3 deg prisma. The scan resolution is 0.05 mm/px, thus about 0.5 nm/px. The dispersion $\sim$ 10 nm/mm at Hγ for the 7 deg prisma. The scan resolution is 0.02 mm/px, thus about 0.2 nm/px. (2) Bolivia Expedition Spectral Plates. The coverage of the southern sky with spectral and direct plates, Potsdam Observatory, plates stored at the Sonneberg Observatory but hidden for $\sim$ 75 years. Plates taken $\sim$ 1924-1928, about 70 000 prism spectra estimated and published in Potsdam Publ. 26–19 in 1930. (3) 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 degree prism was used providing unwidened objective prism spectra with a dispersion of 139 nm/mm at Hγ. Under the conditions of good seeing, the FWHM of the images is 30 microns (plate resolution) giving a spectral resolution of 4.5 nm at Hγ on the objective-prism plates. Online access. (4) 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. Sky coverage: DEC>-15 deg, 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 Hγ.

7. The ultra low dispersion spectral images by Gaia

7.1. Algorithms

The algorithms for automated analyzes of digitized spectral plates are developed by informatics students Hudec (2007). The main goals are as follows: the automated classification of the spectral types, searches for the spectral variability (both the continuum and lines), searches for the objects with specific spectra, correlation of the 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 analyzes based on the spectro–photometry. We focus on the sets of spectral plates of the same sky region covering long time intervals with good sampling; this enables the simulation of the Gaia BP/RP outputs. The main task is the automatic classification of the stellar objective prism spectra on digitized plates, a simulation and a feasibilty study for the low-dispersion Gaia spectra.

7.2. Comparison of the Gaia low dispersion spectra versus spectral plates

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. The dispersion represents an important parameter: (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. PSF FWHM $\sim$ 2 px i.e. spectral resolution is $\sim$ 18 nm, (2) Schmidt Sonneberg plates (typical mean value): the dispersion for the 7 deg prisma 10 nm/mm at Hγ, and 23 nm/mm at Hγ 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 spektrum, (4) Hamburg QSO Survey: 1.7 deg prisma, 139 nm/mm at Hγ, spectral resolution of 4.5 nm at Hγ, (5) Byurakan Survey: 1.5 deg prisma, 180 nm/mm at Hγ, resolution 5 nm at Hγ. Hence Gaia BP/RP dispersion $\sim$ 5 to 10 times less than typical digitized spectral prism plate, and the spectral resolution $\sim$ 3 to 4 times less. Note that for the plates the spectral resolution is seeing -limited hence the values represent the best values. Gaia BP/RP dispersion is $\sim$ 5 to 10 times less than typical digitized spectral prism plate, and the spectral resolution $\sim$ 3 to 4 times less, but on the plates affected by bad seeing only $\sim$ 2 times less.

8. The power of spectro-photometry

Despite 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 Simon et al. (2001, 2004a,b), hence a realiable classification of optical transients will be possible using this method (see also Fig. 2). Colors of microquasars may serve as another example. The color-color diagram in Fig. 5 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. 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.

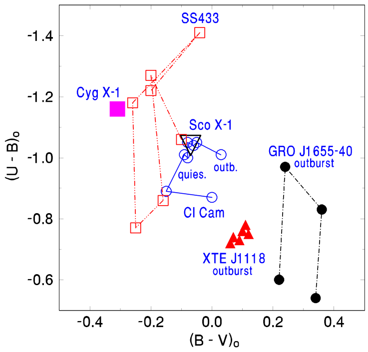

Fig. 5. The color-color diagram for microquasars.

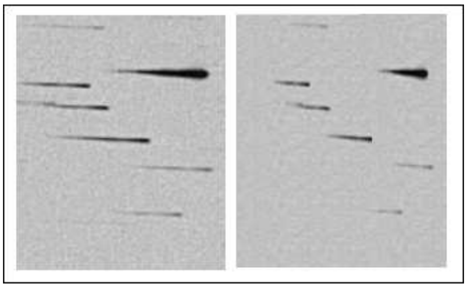

Fig. 6. Left: Part of digitised Byurakan Sky Survey plate (spectral resolution 10 nm/mm at Hγ), Right: Re-scaling to simulate the Gaia BR/RP resolution (18 nm/mm at Hγ) This is a part of the efforts to develop an alternative and real Gaia BP/RP simulator.

9. Conclusions

The Gaia mission of European Space Agency (ESA) will contribute essentially to scientific studies and physical understanding of VSs 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, Bolivia, 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 VSs 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.

10. DISCUSSION

MARIO MACRI: Can you comment on the contribution of Antimatter search in space experiments to the understanding of cosmological evolution?

FRANCO GIOVANNELLI: The detection of exotic cosmic rays due to pair annihilation of dark matter particles in the Milky Way halo is a viable techniques to search for supersymmetric dark matter candidates. The study of the spectrum of gamma-rays, antiprotons and positrons offers good possibilities to perform this search in a significant portion of the Minimal Supersymmetric Standard Model parameter space.

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