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Observations of Optical Counterparts of High-Energy Sources with ESA Gaia

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Abstract Albeit focussing on astrometry, the ESA Gaia mission will provide important scientific results for many other areas of contemporaneous astronomy and astrophysics. In this paper we discuss the application of Gaia results to analysis of the optical counterparts of celestial high-energy sources.

Key words: high-energy sources — optical counterparts — Gaia

1 INTRODUCTION

Gaia is a cornerstone astrophysical mission of the European Space Agency ESA (see *http://astro. estec. esa. nl*). It is a global space astrometry mission (Perryman 2005). Its goal is to make the largest, most precise map of our Galaxy by surveying an unprecedented number of stars. Gaia is a mission that will conduct a census of billions stars in our Galaxy. It will monitor each of its target sources about 100 times over a five-year period. It is expected to discover hundreds of thousands of new celestial objects, such as extra-solar planets and failed stars called brown dwarfs. Within our own Solar System, Gaia should also identify tens of thousands of asteroids. Gaia will measure the positions, distances, space motions, and many physical characteristics of some one billion stars in our Galaxy and beyond. 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 sources, complete to the 20th magnitude. The measurement precision, reaching a few microarcseconds, will be unprecedented. This will allow our Galaxy to be mapped, for the first time, in three dimensions. Some millions of sources will be measured with a distance accuracy of better than 1 per cent; some 100 million or more to better than 10 per cent. Gaia's resulting scientific harvest is of almost inconceivable extent and implication. It will provide detailed information on stellar evolution and star formation in our Galaxy. It will clarify the origin and formation history of our Galaxy. The Gaia results will precisely identify relics of tidally-disrupted accretion debris, probe the distribution of dark matter, establish the luminosity function for pre-main sequence stars, detect and categorize rapid evolutionary stellar phases, place unprecedented constraints on the age, internal structure and evolution of all stellar types, establish a rigorous distance scale framework throughout the Galaxy and beyond, and classify star formation and kinematic and dynamical behavior within the Local Group of galaxies. Gaia will pinpoint exotic objects in colossal and almost unimaginable numbers: many thousands of extra-solar planets will be discovered (from both their astrometric wobble and from photometric transits) and their detailed orbits and masses determined; tens of thousands of brown dwarfs and white dwarfs (WDs) will be identified; tens of thousands of extragalactic supernovae will be discovered; Solar System studies will receive a massive impetus through the detection of many tens of thousands of new minor planets; near-Earth objects, inner Trojans and even new trans-Neptunian objects, including Plutinos,

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may be discovered. Gaia will follow the bending of star light by the Sun and major planets over the entire celestial sphere, and therefore directly observe the structure of space-time (the accuracy of its measurement of General Relativistic light bending may reveal the long-sought scalar correction to its tensor form). All this, and more, through the accurate measurement of star positions.

2 OPTICAL COUNTERPARTS OF HIGH–ENERGY SOURCES

It is obvious that, with the above briefly described performance, the 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 (Jordi & Carrasco 2007), 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, 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 resolution (prism) Gaia spectroscope. This will allow some detailed studies involving analysis of color and spectral changes not possible before. Another valuable input will come from the parallax measurements – the knowledge of directly measured distances of the sources will be highly beneficial. 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 (Hudec et al. 2007a, b).

3 THE OBJECTIVE

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 complex analysis with additional data.

4 THE HIGH ENERGY SOURCES PERSPECTIVES

In this section we briefly list and discuss the main types of the cosmic high-energy sources whose optical counterparts are expected to be investigated by Gaia.

High-Mass X-Ray Binaries (HMXBs) – systems consisting of a compact, mass accreting object (neutron star (NS) or a black hole (BH), rarely also a WD) and an early-type star (O, B) donating mass (donor). Basic modes of mass transfer: (a) Roche lobe overflow. (b) Radial stellar wind in case of supergiant donors. (c) Circumstellar disk in case of a Be main sequence star. Periastron passage of the compact object leads to a periodic variability in some HMXBs, especially if they contain a Be component and have an eccentric orbit (see also below). The optical luminosity of HMXBs is usually dominated by the donor star, not by the matter flowing onto the compact object. The usual kinds of the optical activity are the orbital modulation and long-term fluctuations, only rarely outbursts. About a hundred HMXBs have been discovered in X-rays in our Galaxy and the Magellanic Clouds but it is very probable that more of them are hidden because they are in a low X-ray state or their X-ray emission is highly absorbed. CI Cam can serve as an example – it showed itself as an X-ray binary only thanks to its very powerful X-ray to radio outburst in 1998.

Low-Mass X-Ray Binaries (LMXBs) – systems consisting of a compact object (NS or BH) and a Roche lobe filling companion star donating mass. The spectral type of the donor and the orbital period are related. It is usually a late type main-sequence star, but also rare cases where it is a subgiant, giant or a WD are known (depending on the orbital period ranging from about 11 min to several days (rarely months), mostly several hours). The optical luminosity is often dominated or at least largely influenced by the matter flowing onto the compact object. LMXBs are often highly variable on various time scales, from seconds to decades (see Fig. 2). They display various kinds of activity, like high/low state transitions (e.g. HZ Her/Her X-1, see Fig. 1) or outbursts (see below). Some of them display also the orbital modulation caused by irradiation of the donor (e.g. HZ Her) or eclipses of the accretion disk by the donor.

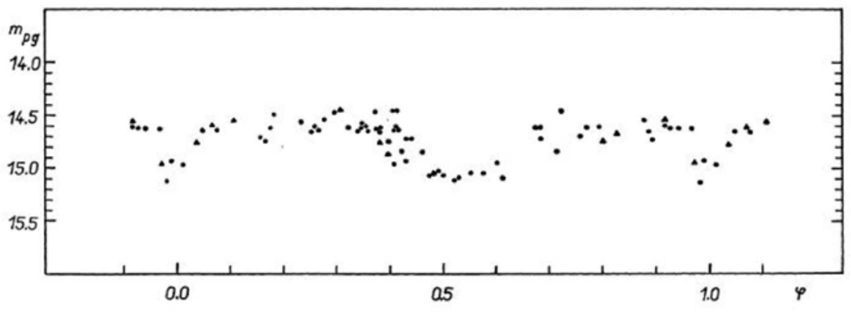


Fig. 1 The optical orbital modulation of HZ Her, the optical counterpart of Her X-1, during its rare inactive state. Circles denote the observations between JD 2428630–2429789. Triangles mark the data between JD 2427543–2427657 (Hudec & Wenzel 1976).

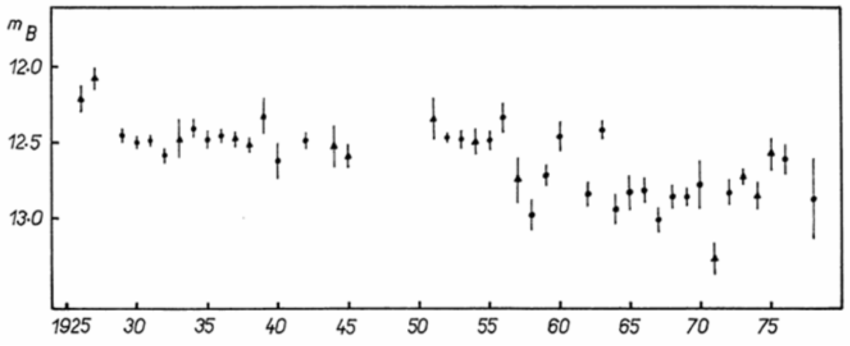


Fig. 2 Long-term optical light evolution of V818 Sco, the optical counterpart of Sco X-1. Annular mean values are given. Error bars show the standard deviation of the mean. Time axis is displayed in years (Hudec 1981).

X-ray transients (XTs) – a subtype of HMXBs and LMXBs. They are characteristic by their transient increase of X-ray flux, often by several orders of magnitude. Some XTs in quiescence may not be detectable in X-rays by the current instruments. In the optical, the quiescent luminosity may be dominated by the donor star even in the case of a LMXB.

XTs can be sorted according to the physical processes:

(a) Soft X-ray transients (SXTs), also called X-ray novae, are caused by the thermal instability of the accretion disk in a LMXB. The physical process is analogous to that in dwarf novae, but is more energetic and irradiation of the disk by X-rays from the close vicinity of the compact object plays a large role during outburst. Both X-ray and optical outburst is observed (e.g. Aql X-1/V1333 Aql, XTE J1118+480/KV UMa). The optical luminosity rises by several magnitudes. The duration of the outburst is weeks to months, while the recurrence time (i.e. interval between outbursts) is months to decades.

(b) Hard X-ray transients – (i) Type I outbursts are dependent on the orbital period. They occur during periastron passage of the compact object and are attributed to an increase of the mass accretion from the Be donor. This mechanism suggests periodicity but these outbursts do not need to occur during every passage. The reason is that the amount of the circumstellar matter originated from the Be donor undergoes long-term variations. Usually the increase of the optical flux in the continuum is quite small during the X-ray outburst, but there are some important exceptions: A0538–66 in LMC displays the optical outbursts with

an amplitude of about 2 mag with the period of 16.5 days. (ii) Type II outbursts are independent on the orbital phase, i.e. on the position of the compact object on its orbit. They are probably caused by a dramatic expansion of the circumstellar disk.

(c) Very fast X-ray transients – quite new kind of transient, only a few are known yet. Each outburst, yet observed only in X-rays, lasts for at most several hours, but they can be relatively frequent (the recurrence time is of days in some cases). They seem to occur in some HMXBs but the outburst mechanism is uncertain. The optical activity of the source is unknown, especially it is not known if the X-ray outburst is accompanied by any optical brightening. Also the general optical activity (brightness and color changes) including long-term variations is not known because these objects were only recently identified.

Microquasars – X-ray binaries which possess relativistic jets, i.e. collimated outflows of matter moving at relativistic velocities from the compact component (e.g. V4641 Sgr). Usually they share the properties of HMXBs. Some of them display large-amplitude outbursts in various spectral passbands, from far X-rays through optical to radio (e.g. V4641 Sgr, CI Cam). The 1998 outburst of CI Cam lasted about 2 days in X-rays, but was longer in the optical, with the amplitude about 2 mag.

Optical transients (OTs) and Optical afterglows (OAs) related to X-ray flashes (XRFs) and gamma-ray bursts (GRBs) – GRBs are the most energetic events in the Universe. They are caused either by a core-collapse of a very massive star or a collision of two compact objects. The GRB event lasts typically from seconds to minutes, but is often followed by an OA which lasts for days or even longer. These mechanisms suggest that GRB or XRF can occur only once in a given object. Typically, OAs reach the optical magnitude around 18 in the initial phase, but some are brighter. The maximum apparent optical magnitude of the brightest OA was around 9 for several minutes. The specific spectral profile of many OAs gives us a good hope to identify them among transients on the basis of even a single spectrophotometric observation with Gaia. Furthermore, it will be possible to investigate the field observed with Gaia where a GRB was recently observed by a gamma-ray satellite like e.g. Swift and search for a possible optical transient (even a search for delayed transients can be made). The long-lasting coverage of the sky with the Gaia instruments also gives us a hope to search for the so-called orphan afterglows. These objects are GRBs from which no gamma-ray emission was detected (despite it is emitted) because of a different beaming of the high-energy and optical emission – they are predicted by theory. In addition, the Gaia Science Alerts are expected to be generated at least for some of the strong cases of OAs observed by Gaia, mostly in the cases when the fading OA will be covered by several following transits of the object in the focal plane.

The relatively dense coverage of the light curves especially of X-ray binaries in the optical passband can be achieved with the ground-based monitoring telescopes, like those operated by the Ondřejov group (e.g. BART).

The great and unique power of the Gaia mission will be the study of the photometric properties of the optical counterparts of high–energy sources, in particular, in a large number of filters (spectrophotometry). In co-operation with the ground-based instruments, the state of the activity of a given object observed by Gaia can be identified in many cases. The Gaia data will enable us to create detailed color-color and color-magnitude diagrams and analyze the position of an optical counterpart of a given X-ray source in a given state of its activity. Also shifts of a given object in such diagrams during various states of its activity, as well as population studies will be of a great merit.

We also expect that the series of the Gaia data will enable us to analyze the rapid variations, like flickering and orbital modulation, at least in some cases.

Specifically we aim:

1. For selected targets, multispectral analysis using Gaia and other databases (such as the X-ray and gamma-ray satellite data, optical ground-based data etc.) may be feasible.
2. Analysis of long-term light changes and their evolution.
3. Analysis of active states, outbursts and flares.
4. The study and understanding of related physical processes.
5. Spectrophotometry, relation of brightness and spectrum/color.
6. For selected sources, dedicated complex analysis.
7. Statistics of the whole sample of objects.

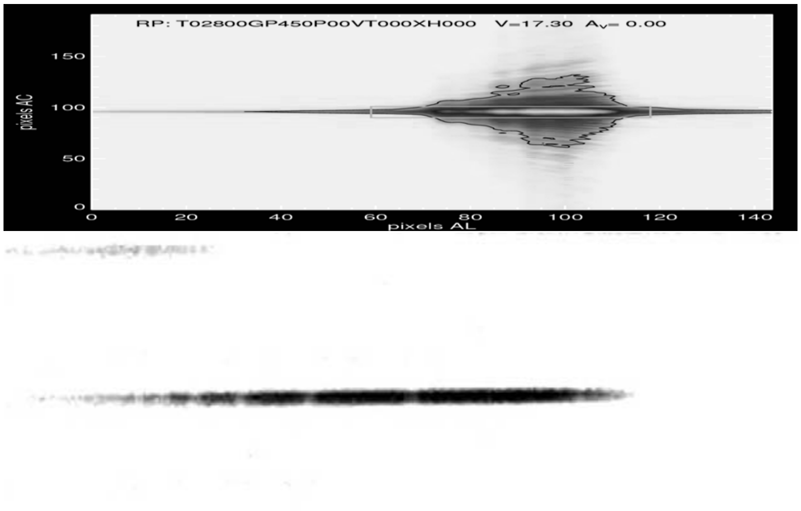


Fig. 3 The simulated Gaia low–dispersion spectrum (top) and a real low–dispersion spectrum from digitized Schmidt astronomical Sonneberg Observatory plate (bottom).

5 THE METHODS

Below we briefly list and discusss the suggested methods, and their results, proposed to achieve the objectives described above. More details are given in Hudec & Simon (2007a,b).

1. Use of the tools of standard time-series analysis (Fourier and wavelet analysis, methods of statistical time-series analysis (correlation, autocorrelation, noise and signal detection etc.), deterministic/chaotic behavior) to reveal the physical mechanisms of variations.
2. Study of the flaring behavior of objects including spectral changes (color-color diagrams, color evolution), study of the correlation between the brightness changes and spectral (color) variations, statistical analysis of the flaring behavior of the whole data sample.
3. Study of activity/inactivity modes incl. spectral changes, physical classification.
4. Complex analysis with Gaia and supplementary data including data from dedicated ground-based robotic telescopes as well as from other sources (inc. satellite data).

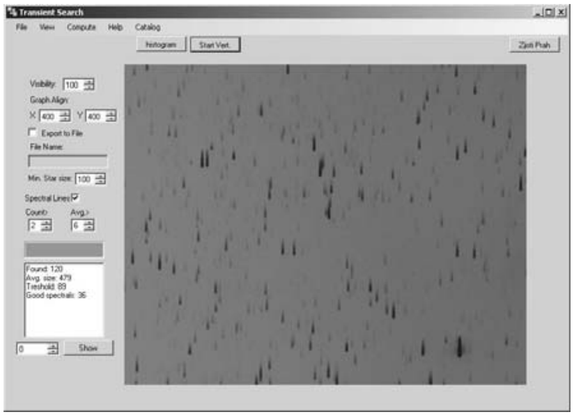
6 THE SCIENTIFIC IMPACT

The scientific impact on the subject, i.e. understanding and study of optical counterparts of high–energy sources, with the performance of Gaia can be briefly summarized as follows. Again, more details are given in Hudec & Simon (2007a,b).

1. The extension of analysis and understanding of the optical counterparts of high-energy sources toward fainter optical magnitudes. Detections and classification of new faint objects of this category.
2. Statistics and distribution of faint variable objects of this category. The exact number is difficult to estimate at this stage.
3. The correlation of spectral/color and light changes. Multispectral analysis based on the Gaia and supplementary data (optical ground-based, X-ray, gamma, radio etc.).
4. The determination of accurate distances (parallaxes) for many high–energy sources, based on their optical conterparts.

7 THE SPECTRAL POWER

The Gaia telescopes offer unique variability studies based on low-dispersion spectra, i.e. the energy resolution of recorded star images (as these are represented by prism low–dispersion spectra). In this context, the

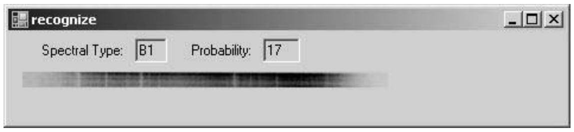


Visibility: 100
Graph Align:
X 400 Y 400
☐ Export to File
File Name:
Min. Star size: 100
Spectral Lines ☑
Count> 2 Avg.> 6

Found: 120
Avg. size: 479
Treshold: 89
Good spectrals: 36

0

Fig. 4 The automated analysis of part of digitized astronomical spectral Schmidt plate from the Sonneberg Observatory plate archive.



Spectral Type: B1 Probability: 17

Fig. 5 The computed classification details of particular star image on Schmidt spectral plate taken with objective prism.

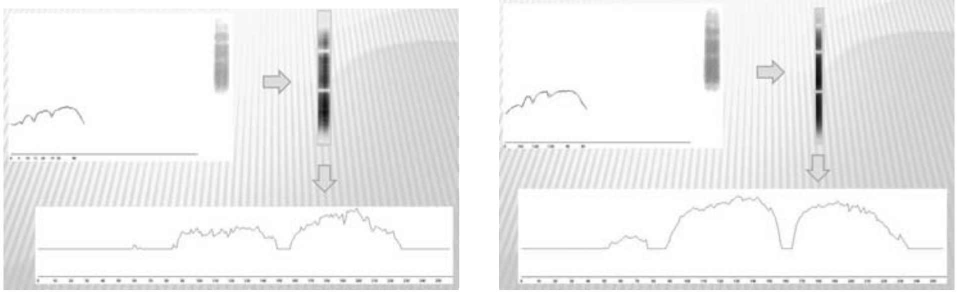


Fig. 6 Two examples of automated spectral classification of stars with low-dispersion spectra according to Hudec (2007). In each image, upper left is the star spectrum, and bottom right the automatically found model (atlas) spectrum.

application of algorithms developed for digitized astronomical archival plates (Hudec 2007) may be important for Gaia (see Fig. 3 showing example of simulated Gaia prism spectra and of digitized astronomical Schmidt plate prism spectra). The novel algorithms for automated analysis of digitized spectral plates have been recently developed by informatics students (Hudec 2007) and are suitable for

- Automated classification of spectral classes
- Searches for spectral variability (both continuum and lines)
- Searches for objects with specific spectra
- Correlation of spectral and light changes
- Searches for transients

The examples are shown in Figures 4 to 6. 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 spectral variability and variability analysis based on spectrophotometry (low dispersion prism spectra). In recent development, we focus on sets of spectral plates of the same sky region covering long time intervals with good sampling.

8 CONCLUSIONS

The Gaia mission of European Space Agency ESA will contribute essentially to scientific studies and physical understanding of the optical counterparts of high-energy sources. The variability studies of faint objects based on the optical low-resolution spectra are expected to provide unique novel data and may use the algorithms recently developed for automatic analysis of digitized spectral Schmidt plates.

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DISCUSSION

G. LAVAGETTO: Which is the chance to measure orbital periods of galactic binaries with Gaia?

R. HUDEC: Yes this is feasible for binaries within the magnitude limit of Gaia.

N. LUND: Will Gaia be able to study extended sources?

R. HUDEC: Yes, there are dedicated efforts to address this option.