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A Science Alert System for Gaia and Similar All-Sky Space Missions

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Abstract. I use an example of the Gaia Astrometric Space Mission to discuss the implementation of a science alert system in a future all-sky observational program of large magnitude. The Gaia mission, scheduled for launch in 2011, will revolutionize Galactic astronomy by measuring stellar positions and motions at the precision level of microarcseconds. Gaia will scan the entire sky with a predefined spin and precession and observe approximately 1 billion stars down to a limiting magnitude of V = 20. In addition, the mission has the exciting potential to discover a huge number of transient events. However, due to its fixed observing pattern, the Gaia satellite will be unable to follow or unambiguously classify such events. An essential ingredient of the project will thus be how to deal with such discoveries and alert the international astrophysical community about their occurrence in an efficient manner. I discuss several ways to enhance the science alert system based on experience from microlensing surveys. I stress the role of pre-launch variability surveys and post-lunch follow-up facilities to boost the scientific return from the Gaia mission.

Gaia and its Science Alert System

The history of the Milky Way is imprinted in the distances and motions of stars that belong to different Galactic populations. Astrometry is therefore one of the principal ways to understand the origin and structure of our Galaxy. About two decades ago the ground based astrometric experiments reached a limit beyond which progress was technologically challenging. Hipparcos Space Mission (Perryman et al. 1997), that produced 1 milli-arc-second astrometry for about 120 000 stars, was a response to this challenge and enabled quantitative studies in many areas of astronomy. Next generation astrometric missions with super-Hipparcos characteristics will strongly constrain the Galactic potential and galaxy formation scenarios, set the local distance scale, make a census of small bodies in the solar system, detect thousands of unknown brown dwarfs and planets in the solar neighborhood and measure their characteristics. Binaries and microlensing will provide information about the masses of stars throughout the Galaxy. Many extra-galactic objects including hundreds of thousands of quasars are expected to be cataloged. Microarcsecond accuracy will be sufficient for stringent tests of fundamental physics. The two currently planned missions are the Gaia Astrometric Space Mission by ESA (`http://sci.esa.int`; Perryman et al. 2001) and Space Interferometry Mission (SIM) by NASA (`http://sim.jpl.nasa.gov`; Unwin et al. 1997) both scheduled for launch in 2011. Both experiments will yield microarcsecond precision, improving the Hipparcos performance by 2-3 orders of magnitude. SIM will be able to point at the objects of interest, but it will observe only about 10 thousand stars. The Gaia satellite will observe approximately 1 billion stars scanning the sky according to a predefined spin and precession. As a result, Gaia will find a huge number of fascinating transient events which it will not be able to follow or classify unambiguously. The Gaia team intends to alert the international astrophysical community about new discoveries through the so called science alert system (please see `http://www.ast.cam.ac.uk/~vasily/sawg` for related information).

It is easily understandable why a science alert system should become one of the main initiatives associated with the Gaia mission. The satellite launch is currently planned for 2011, and the observing period of 5 years will probably end some time in 2017. The release of the final catalog is scheduled for 2020. This is a very long time horizon, and this period will witness spectacular advances in astrophysical research. At the same time, the success of the Gaia mission requires that we maintain the scientific enthusiasm of professionals and general public throughout the duration of the experiment. Two undertakings seem essential in this respect. First, there should be early data releases, ideologically similar to the ones from 2MASS and SDSS. Second, everyday science alerts would be best indication that Gaia is collecting data and making an impact on astronomy.

Microlensing surveys as a model

The Gaia Alert System can enhance its performance by using the experience of microlensing surveys like MACHO. These surveys look for events that typically happen only once per 1-10 million observed stars (Paczyński 1996), and therefore by design they are massive photometric searches covering tens of square degrees on the sky. Surveys like MACHO, OGLE, EROS, MOA, SuperMACHO observe(d) 30-50 millions of stars in the Galactic bulge and/or Magellanic Clouds. As a result, from the very beginning they had to deal with large databases of variable stars (e.g., Cook et al. 1997; Żebruń et al. 2001; Woźniak et al. 2002) and developed algorithms to alert the community in real time about the unfolding microlensing events (e.g., Udalski et al. 1994; Pratt et al. 1996) Those have been extensively used by other researchers to schedule follow-up observations of particularly interesting events (e.g., PLANET: Albrow et al. 2000; An et al. 2002)(microFUN: Yoo et al. 2004) In addition, microlensing groups have committed a lot of effort to understand event detection efficiencies and develop robust selection criteria. For example, microlensing event selection by the MACHO Project (Alcock et al. 2000; Popowski et al. 2004) proved the feasibility of detection of very rare transient events. The database character and size of a typical microlensing survey is similar to what we expect from Gaia. Moreover, since at least 50% of microlensing science, including determination of lens masses, measurements of stellar limb darkening, or detection of planets, relies heavily on follow-up observations, alert systems of microlensing surveys function very efficiently to pick up promising candidates. Therefore, in the following sections, I will suggest solutions to various scientific and technical problems facing Gaia based on similarities between the Gaia and MACHO Projects. The comparative summary of the characteristics of the two projects is presented in Table 1.

Table 1. Comparison of the MACHO and Gaia Projects

	MACHO	Gaia
major goal	detection of microlensing	astrometry
status	completed: operations 1992-1999	planned: operations 2011-2017
number of stars	$\sim$ 75 million	$\sim$ 1 billion
field of view	$0.72^\circ \times 0.72^\circ \equiv 0.51\, deg^2$	$0.74^\circ \times 1.03^\circ \equiv 0.76\, deg^2$
total observed area	$90 - 95\, deg^2$	$41253\, deg^2$ (all sky)
daily coverage	$\sim 30\, deg^2$	$\sim 2000\, deg^2$
typical stellar densities	10^6 deg^{-2}	25000 deg^{-2}
facilities	ground-based, Australia	space-based, L2 point
telescope mirror	circular with 1.27m diameter	two: 1.4m × 0.5m each
observing mode	pointing	continuous scanning
pixels per field	$2 \times 4 \times 4194304 = 33.6 \cdot 10^6$	$170 \times 8847000 = 1.5 \cdot 10^9$
photometry	V, R	5 broad bands, 11 medium bands
limiting V-magnitude	21.5	20.0
data flow	$\sim$ 1 Terabyte/yr	$\sim$ 5 Terabyte/yr
alert reaction time	few hours	few days

Exclusion of variables as a foundation of every alert system

The most important and necessary criterion shared by all alert systems is the exclusion of known variables. Unrecognized variables will pollute an output of every alert system. Contamination constitutes almost 100% of alerts. The computation below documents this point for an all-sky survey like Gaia. Let me introduce the following notation:
η – frequency of variables in the observed population,
ϵ – efficiency of triggering alerts for variable stars of the observed population,
$N^*_{\rm obs}$ – number of stars observed per day,
$N^*_{\rm tot}$ – number of stars accessible to observations over the entire sky,
$S_{\rm obs}$ – area covered by scans per day,
$S_{\rm sky}$ – area of the entire sky.
Then the average number of alerts on the i-th day due to variable stars will be:

$$^{\rm var}N_i^{\rm alerts} = \epsilon\eta N^*_{{\rm obs},i} \overset{{\rm large}\, S_{\rm obs}}{\approx} \epsilon\eta \frac{S_{\rm obs}}{S_{\rm sky}} N^*_{\rm tot}. \tag{1}$$

When the area covered by scans each day is a non-negligible part of the sky, then local inhomogeneities in surface density of stars will roughly average out. In this case the number of observed stars is roughly the same each day and approximately scales with the observed area. This leads to the second equity in equation (1).
A conservative estimate for the Gaia mission would be:
$\eta \sim 10^{-2}$ (based on the frequency of variables from the MACHO Survey),
$\epsilon \sim 10^{-2}$,
$S_{\rm obs}/S_{\rm sky} = 0.5 \times 10^{-1}$,
$N^*_{\rm tot} = 10^9$.
Therefore, in the case of Gaia, a typical day could result in 5×10^3 fake alerts.

One could hope that the variable stars would occupy a very limited region of the parameter space and so could be easily rejected in the search of non-recurrent transient events. This does not seem to be the case. Figure 1 presents Wesenheit index (which is roughly reddening free magnitude) versus period relation for the MACHO variables in the Large Magellanic Cloud (LMC) taken from Cook et al. (1997). The diagram is populated by variables that differ by a factor of 1000-10000 in period and span at least 10 magnitudes in brightness. Since the Galactic targets will not be located at the same distance (as opposed to the ones in the LMC), the brightness distribution observed by Gaia will broaden substantially with respect to that in Figure 1. In conclusion, the variable star contamination of the alert system detections is persistent over many orders of magnitude in essential parameters.

The simulations of transient events by Belokurov & Evans (2002, 2003) suggest that microlensing and supernovae (see Table 2) will result in $\sim 5-10$ alerts per day each. Therefore, one expects that the number of *useful* alerts will be at the level of ~ 20 per day. With the *contaminating* alerts from variable stars at the level of $\sim 5 \times 10^3$ per day, the expected $S/N = 0.004$. Such a system would be entirely useless for the astronomical community. It is obvious that the alert system will function properly only if almost all of variable stars down to $V \sim 20$ are known. There are three main approaches to how this can be achieved:
(1) collect Gaia data for approximately 1 year after the launch: this should be sufficient for Gaia to construct a preliminary version of its own variable star database,

(2) organize a pre-launch experiment that will find most of the variable stars brighter than $V \sim 20$,
(3) pre-load the Gaia database with variables known from outside sources (e.g., already completed microlensing surveys like MACHO or future panoramic surveys like Pan-STARRS).

Solution (1) is extremely conservative. Solutions (2) and (3) increase the period of useful alerts by 25% (from 4 to 5 years)! Solution (3) is preferred to (2) since pre-loading with variables from outside sources is much less expensive and less challenging organizationally.

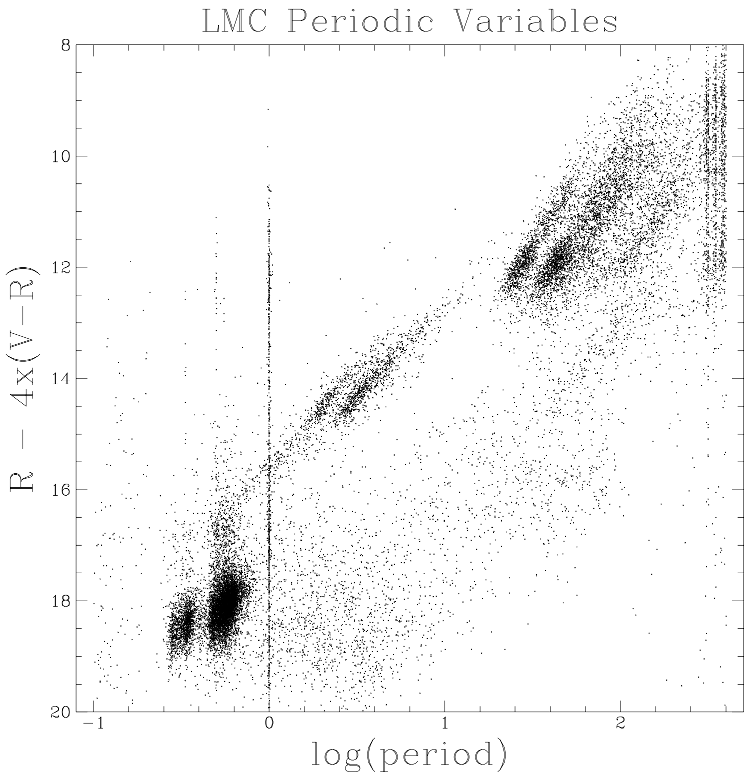

Figure 1. Wesenheit index – period diagram for variables in the Large Magellanic Cloud from Cook et al. (1997). Variables group into several families but cover a wide range in both period and magnitude.

Follow-up observations

Transient events observed by Gaia will have durations similar to microlensing events. Therefore, the examination of the importance of follow-up observations for the science based on microlensing events provides a good guidance for Gaia. Figure 1 shows that the CTIO and 74" MSO follow-up of two MACHO events was essential to constrain the parallax fit (for more details see Bennett et al. 2002) and to establish these events as candidates for black hole lenses. Similarly, follow-up was crucial in the study of finite source effect (Alcock et al. 1997)

Table 2. Two major known sources of transient events for Gaia

Source	Type/Signal	Number[a]
Microlensing[b]	Photometric	1300
	Astrometric	25000
Supernovae[c]	Type Ia	14300 (6300)
	Type Ib/c	1400 (500)
	Type II	5700 (1700)
		21400 (8500)

[a] Number of transients is reported over the duration of the Gaia mission. For supernovae, the numbers in parentheses represent cases when events were caught before the maximum light.

[b] From Belokurov & Evans (2002)

[c] From Belokurov & Evans (2003)

caustic crossing binary events (e.g., Albrow et al. 2000) and in several other cases. In addition, since the Gaia sampling is less frequent than the sampling of the MACHO survey (see Table 3), follow-up observations will be even more important for Gaia than they have been for microlensing surveys. We have to assess the need for follow-up facilities and develop the most efficient strategy for obtaining telescope time. For example we should: (1) determine whether it is desirable and feasible to follow all alerts, (2) consider if more network telescopes should be located in the Southern hemisphere because of the LMC, SMC and Galactic bulge, (3) understand whether guaranteed spectroscopic time on a 10m-class telescope with high resolution instrument would be a plus etc.

Table 3. Sampling frequency for the MACHO and Gaia surveys

Experiment	Number of observations per object per year
MACHO (bulge), high-priority fields	~ 130
MACHO (bulge), low/medium-priority fields	~ 35
Gaia	~ 16

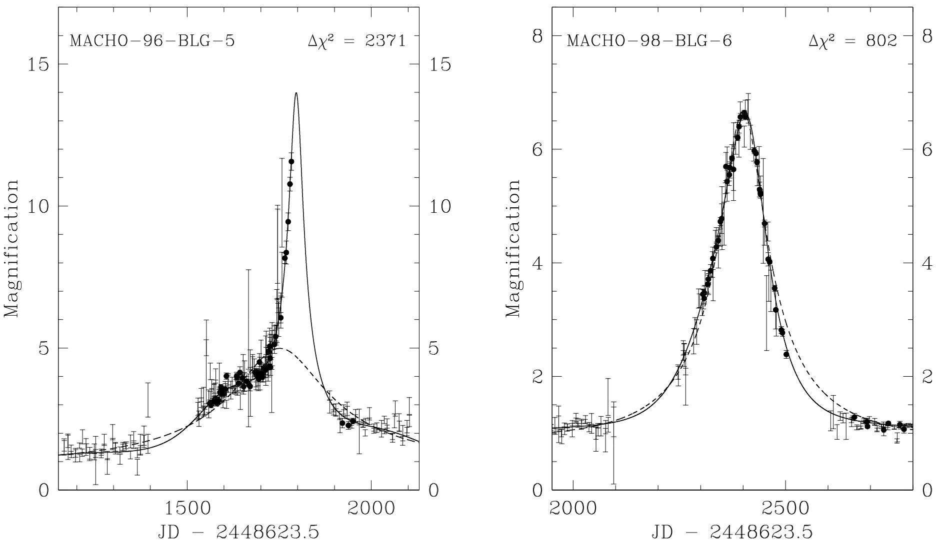

Figure 2. Light curves of two parallax events with possible black hole lenses out of six analyzed by Bennett et al. (2002). The dashed line is the standard microlensing fit and the solid line is the fit that accounts for the parallax effect. The data from the MACHO telescope are shown by error bars only. The follow-up observations from the CTIO 0.9 m telescope or from 74” Mount Stromlo Observatory telescope are marked with filled dots. It is clear that the follow-up measurements have been crucial in establishing the superior character of the parallax fit and constraining event parameters.

Conclusions

The Gaia astrometric mission has the exciting potential to discover a huge number of transient events, which will be reported to the astronomical community by the science alert system. This system will function efficiently from the very beginning if most of the variable stars down to $V \sim 20$ are identified before the Gaia launch in 2011. Follow-up observations will be essential to understand the nature and constrain the properties of the observed transient events.

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