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Gaia Alerts – An All-Sky Transient Survey

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Abstract. In addition to its main goal of measuring the parallaxes of 10^9 stars in the Galaxy, ESA's Gaia mission is also probing the time domain on a range of astrophysically interesting time-scales. The photometric measurements are processed for transient variability, and events that are discovered are published as a public alerts stream, known as *Gaia Science Alerts*. This talk gave an overview of the project to date, and highlighted its unique characteristics as a transient survey. It discussed briefly some of the recent scientific results which illustrate the broad range of science investigations enabled by the data. *Gaia Alerts* is particularly suited to the study of Galactic populations, as it covers the Galactic Plane with high astrometric precision and photometric accuracy.

Keywords. surveys, catalogues, stars: activity, stars: dwarf novæ, supernovæ: general

1. Gaia and the Time Domain

ESA's Gaia mission has been in nominal operation since July 2014. Its primary mission is to take a 3-D census of the Milky Way, with positional, photometric and spectroscopic observations of more than a billion stars in the Galaxy. The mission was originally planned to last 5 years, but a 2-year extension has recently been approved, and a further extension to 2024 is possible as well.

Gaia is conducting an all-sky survey down to a magnitude $G < 20.7$. Each observation includes an astrometric measurement, a flux measurement, and a low-resolution 'blue photometer/red photometer' slitless spectrum ($R \sim 100$). The spectra are commonly referred to as 'BP/RP spectra' and cover λ 3300–6800 and 6400–10500 Å, respectively. Targets brighter than $G = 12$ are additionally measured with the Radial Velocity Spectrograph (RVS), which spans λ 8450–8720 Å at a resolution of $R \sim 11\,500$.

Over its lifetime Gaia will scan the full sky an average of 200 times, delivering time-domain information for each object on time-scales ranging from seconds to weeks to years. The exact number and observing cadence of a given target depends on its location on sky, but a pair of observations, separated by 106.5 minutes, is typically followed by another pair of observations 2–4 weeks later.†

Gaia has numerous advantages compared to ground-based transient surveys. Its space-based location means that biases due to weather or variable seeing are dramatically reduced. The well-defined Scanning Law allows one to measure and account for the detection efficiencies of different types of transients. It covers the full sky at high spatial resolution (∼0.1 arcsec) and photometric precision (0.1% at $G = 15$, 3% at $G = 20.5$),

† In the future the nine photometric measurements recorded as the target crosses the focal plane will be made available as well (Gaia Data Release 4, scheduled for 2022). That will give light-curves with 4.5-second time resolution – ideal for identifying short time-scale variability. See e.g. Wevers *et al.* (2017).

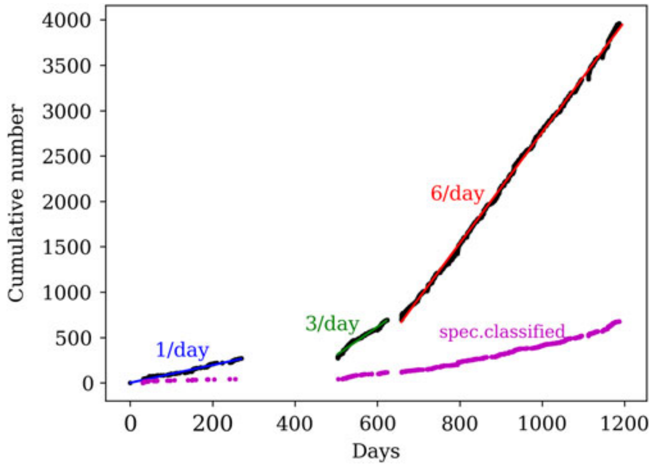

Figure 1. Cumulative number of alerts published since the start of *Gaia Science Alerts* in September 2014 (top line). After the initial validation phase and a short development phase, the alert rate has been stable at 6 alerts per day since July 2016. Approximately 17% of Gaia Alerts have been classified spectroscopically (bottom line), with a heavy bias towards supernovæ.

including the Galactic plane (which ground-based surveys usually have to avoid because of crowding). Gaia is an ideal survey for statistical studies of transient populations.

2. Gaia Science Alerts

The variability processing is based in Cambridge, UK, and is run as a separate step after the initial data processing and calibration have been performed at the Spanish operations station in Spain. We identify transient variables based on a set of well-defined criteria, and publish the transients as a sortable, searchable Alerts Stream at http://gsaweb.ast.cam.ac.uk/alerts/alertsindex, usually 2–3 days after the observation by the spacecraft. The Alerts Stream is public and the transients are also published simultaneously on the IAU Transient Name Server†, as VOEvents, an RSS feed, and on mobile-phone apps for iOS and Android. The Alerts index links to a dedicated page for each alert, which gives all of the Gaia data available for that transient, including data obtained both *before* and *after* the alert was issued.

To date (November 2017), more than 3800 alerts have been published, at a stable rate of 6 alerts per day (Fig. 1). Note that this is a 'cleaned' alerts stream, i.e., solar-system objects and periodic variable stars have already been removed, to provide a stream of true 'transient' sources. Given the depth and typical cadence of the Gaia Scanning Law, the transient stream is dominated by supernovæ. Follow-up observations are heavily biased towards supernovæ as well, owing to follow-ups by surveys such as ePESSTO (Smartt *et al.* 2015). Highlights include the superluminous supernovæ Gaia16apd (Nicholl *et al.* 2017) and Gaia17biu (Bose *et al.* 2017). Approximately 17% of alerts have already been identified spectroscopically.

Accretion variability accounts for a large fraction of the Galactic transients studied to date. Cataclysmic Variables (CV, a white dwarfs accreting from an M-dwarf companion) are the most common, being responsible for $\sim$20% of Gaia Alerts detected so far. CVs are detected as transients owing to a thermal instability in their accretion disks which

† TNS is the official IAU mechanism for reporting new astronomical transients; see the website https://wis-tns.weizmann.ac.il/

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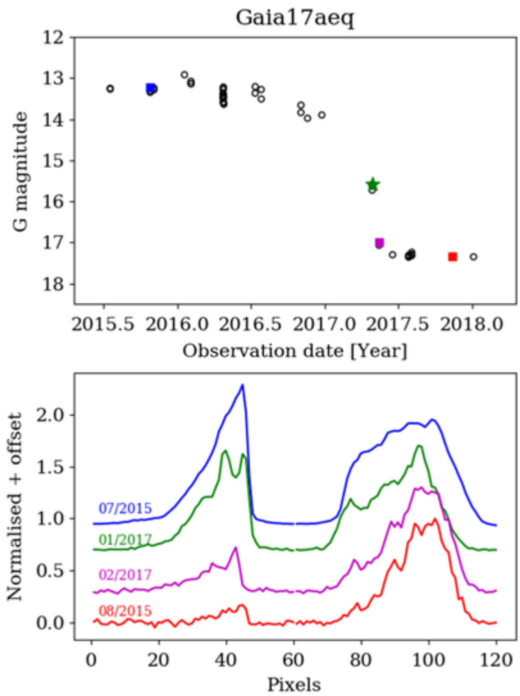

Figure 2. Light-curve and colour variation of the YSO ASASSN-13db/Gaia17aeq. The points in the light-curve for which the BP/RP spectra are shown are indicated with filled squares. The Gaia alert was issued when the target faded, at the point indicated by the star symbol.

causes quasi-periodic outbursts of several magnitudes. Follow-ups of these systems led to the discovery of the first fully eclipsing AM CVn star (an ultra-compact binary consisting of a white dwarf accreting helium from a semi-degenerate donor), which enabled the first direct measurement of the binary parameters in these rare systems to be made (Campbell *et al.* 2015, Green *et al.* 2018).

Gaia Alerts is also able to issue alerts uniquely on sources that fade significantly. In this way, many new Young Stellar Objects (YSOs) and other 'dipping' sources (such as VY Scl stars) have been discovered or recorded as alerts. Gaia17aeq is shown as an example in Fig. 2. This is an EXor variable – a YSO with a large proto-stellar accretion disk, characterised by large-amplitude eruptive variability. When Gaia's nominal observations started, the outburst was already in progress (see Sicilia-Aguilar *et al.* 2017. It was originally detected by the ASAS-SN survey, as ASASSN-13db); *Gaia Alerts* detected the accretion state change when it started to fade again towards quiescence (star symbol in Fig. 2). The time-series BP/RP spectra clearly illustrate the dramatic colour/spectral changes that accompany the flux variations in accretion events like these. ASASSN-13db/Gaia17aeq has the lowest mass of the stars that are known to show such outbursts (Holoien *et al.* 2014).

The high photometric and astrometric precision ($\sim$10 milliarcseconds per transit) also makes Gaia sensitive to microlensing events. Gravitational microlensing can cause a temporary magnification of a background star when a closer star passes in front of it. Gaia is expected to detect a few thousand such events over the lifetime of the mission; several candidate events have already been reported. Gaia recently detected the first binary microlensing event in the Galactic disk, in which a binary star is doubly lensing a distant K-star (Wyrzykowski *et al.* 2019).

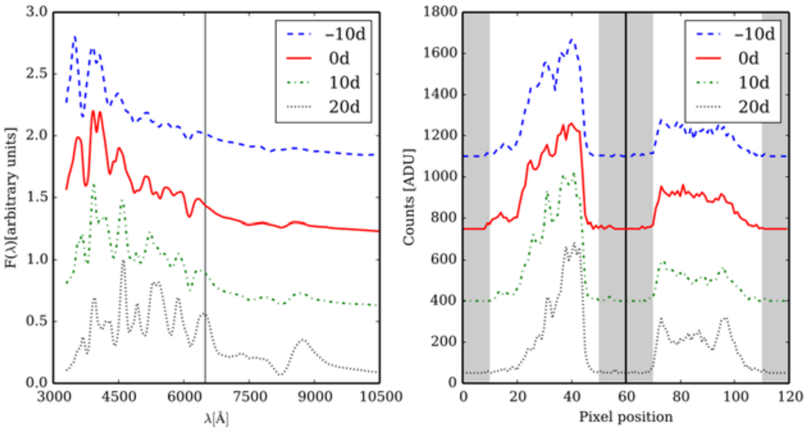

Figure 3. *Left:* Template spectra of a Type Ia supernova at various stages of brightness. *Right:* The same spectra re-sampled with the Gaia BP/RP response function, as used in the GS-TEC module. Spectra are in pixels and counts/ADU, but fully calibrated ones will be available from early 2018. (*Reproduced from Blagorodnova et al. 2014*.)

3. Next Step: Improved Alerts Classification

At present, classification of the alerts is based on the uncalibrated BP/RP spectra only (Blagorodnova *et al.* 2014). The spectra can enable one to distinguish between the major classes of variables, e.g., supernovæ, variable stars, AGN and CVs, and for bright transients ($G < 17$) it is even possible to distinguish between supernova types and to estimate the age from peak brightness (Fig. 3). However, there is still some ambiguity between certain classes of spectra, especially young, hostless supernovæ and CVs in outburst. Calibrations for the BP/RP spectra will be available early in 2018 and should already lead to significant improvements in the classification of alerts. We are also currently working on extending this classification module to include the light-curves and environmental information, using a supervised machine-learning approach.

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