# 202. Update on science alerts

As Gaia scans the sky, it detects and observes all objects brighter than $G \sim 20.7$ mag. Objects bright enough at that specific field-of-view crossing time, including regular or irregular variables, or moving objects within the solar system, are detected and observed.

Using Gaia's own data base of variable stars and solar system objects (such that pulsators, regular variables, and eclipsing binaries are largely excluded as alerts), sudden brightenings or dimmings, or entirely 'new objects', can be flagged. Alerts are then promptly issued to observers worldwide for follow-up photometric observations and spectroscopic classification.

Since the start of the mission, a group at the Institute of Astronomy, Cambridge, has been leading the processing of the satellite photometry, and a sub-group, led by Simon Hodgkin, handles these 'science alerts'.

I gave an introduction to this Gaia Science Alerts system in essay 36 (Sep 2021). Then, by the end of 2020, 15 000 alerts had been issued, 50 with $G < 12$, and 5000 had been classified: 500 cataclysmic variables, 100 AGN, 600 variable quasars, 2000 supernovae (1500 Type Ia, 500 Type II), and 50 microlensing events.

Subsequently, Hodgkin et al. (2021) have given a detailed description of the Gaia Science Alerts system for Gaia EDR3. This includes changes made as more data have become available, and more reliable and efficient detection algorithms have been developed.

The alerts pipeline has to handle many complications. There are modules optimised for detecting *new* sources, for bursts in previously known sources, and for light-curve skewness. 'Bad' transits, including prompt particle events and bright star artefacts, are largely suppressed by requiring detection in two successive fields of view. Solar system objects are identified by forward orbit prediction. A final assessment is done by eye.

Following the convention used for supernova discoveries (the prefix SN, followed by the discovery year, suffixed with a one or two-letter designation), successful 'transients' are designated GaiaYYaaa, GaiaYYaab...

Alerts are published via the `IAU Transient Name Server`, and as VOEvents using `4 Pi Sky` (Staley & Fender, 2016). They also populate their `Gaia Science Alert` www pages with new alerts, along with the data collected for each source, including detected and historic $G$-band magnitudes, the light curves, and the low-resolution Gaia ($B_P/R_P$) spectra (Delgado et al., 2019).

Their Figure 9 (alerts as a function of magnitude between 2014–19) shows that most alerts span the range $G = 13 - 21$, and peak at $G \simeq 18.5$ mag. Their Figure 10 shows the alert rate as a function of time, which has increased from ~1 per day in 2015, to ~12 per day in 2020.

There are, of course, several other transient surveys ongoing, including ASAS–SN (All-Sky Automated Survey for Supernovae; Kochanek et al., 2017), ATLAS (Asteroid Terrestrial-impact Last Alert System; Smith et al., 2020), Pan-STARRS (Chambers et al., 2016), and ZTF (Zwicky Transient Facility; Bellm et al., 2019). As one indicator of fidelity, these multiple surveys often results in the same event being identified by different surveys/names.

Of these, only Gaia and ASAS–SN cover the entire sky, including the Galactic plane. Gaia is also the only *catalogue-driven* transient survey – the others employ difference-imaging techniques. And Gaia is, today, the second-largest contributor to the IAU Transient Name Server (Hodgkin et al., 2021).

Various telescopes around the world are involved in follow-up photometric observations (e.g. Damljanović et al., 2018; Kvernadze et al., 2023), crucial for characterising the detailed light-curves, and for spectroscopy, crucial for object classification.

Various other studies have fed into the alerts system (e.g. Wevers et al., 2018; Zieliński et al., 2019), including those focussing on microlensing events (Gezer et al., 2022; Wyrzykowski et al., 2024), cataclysmic variables (Breedt, 2019; Mistry et al., 2022), transients in galactic nuclei, including 'tidal disruption events' (Kostrzewa-Rutkowska et al., 2018), gravitational wave event detection (Kostrzewa-Rutkowska et al., 2020), and the contribution of amateur astronomers (Romanov, 2022).

There were 3484 alerts in 14 classes in Hodgkin et al. (2021). On 2024 Aug 23 the database listed 25 919 alerts, with 7 141 assigned to 23 classes (assigning all SN to one class): AGN (187), BL Lac (154), CCSN (4), CV (779), dK (1) and dM (18), galaxy (4), ILRT (1), LBV (5), nova (46), QSO (1244), RCrB (16), SLSN (59), SN (4139), SN Impostor (1), SSO (2), star (32), symbiotic star (8), TDE (25), ULENS (42), VarStar (72), XRB (13), YSO (283).

[CCSN=core-collapse SN, ILRT=intermediate-luminosity red transients, LBV=luminous blue variable, SLSN=super-luminous SN, SSO=solar system object, TDE=tidal disruption event, ULENS=microlens, YSO=young stellar object]. The SN are further divided as SN (25), SN I (16), SN Ia (2617), SN Ia-CSM (9), SN Ia-pec (21), SN Iax (8), SN Ib (73), SN Ib/c (26), SN Ibm (18), SN Ic (81), SN Ic-BL (30), SN Ic-pec (1), SN II (875), SN IIb (54), SN IIl (3), SN IIn (166), SN IIp (116).

I list here a selection of these alerts, some presenting ongoing modelling challenges. Light curves can be accessed from the Gaia Science Alert pages.

**Supernovae**: among many discoveries are Gaia16apd, a UV-bright super-luminous SN (SLSN) (Kangas et al., 2016; Nicholl et al., 2017); Gaia16bvd, the first of a 'pair-instability' supernova (Gomez et al., 2019); Gaia16cfr, an interacting transient, with significant variability followed by two luminous events (Brennan et al., 2022); Gaia17biu, a nearby SLSN (Xiang et al., 2017; Bose et al., 2018); Gaia17dcj, a SN interacting with dense circumstellar material (Moran et al., 2023); Gaia22cbu, with periodic light-curve modulation (Moore et al., 2023).

**Supernova Impostor**: Gaia16ada is an example of powerful novae that resemble supernovae but which don't destroy their progenitor (Aghakhanloo et al., 2023).

**Changing-Look Quasars**: a class of AGN with strongly changing features, possibly attributable to tidal disruption events or episodic accretion (LaMassa et al., 2015; MacLeod et al., 2016, Yang et al., 2018). Gaia19bwn and Gaia19dsk are possible examples (Pursimo et al., 2019).

**Microlensing**: the 40 events to date include Gaia16aye: the first binary event in the Galactic disk, rather than bulge, and the first Earth–Gaia annual microlensing parallax (Wyrzykowski et al., 2020); Gaia18ajz, a $4.9M_\odot$ black hole candidate (Howil et al., 2024); Gaia18cbf, a very long duration event, with $t_\mathrm{E} = 491$ d (Kruszyńska et al., 2022); Gaia19bld, with gravitationally lensed arcs in rotation from VLTI–PIONIER (Cassan et al., 2022); Gaia20bof, a close binary lens, with dense photometry from the OMEGA Key Project (Bachelet et al., 2024).

Gaia22dkvL b is the first Gaia microlensing planet, also towards the disk, and only the third Gaia host listed in the NASA Exoplanet Archive (Wu et al., 2024).

**AM CVn**: Gaia14aae, the first fully-eclipsing AM CVn binary, and a modelling challenge (Campbell et al., 2015; Green et al., 2018: Green et al., 2019; Sarkar et al., 2023).

**Novae**: Gaia18blv, a luminous red nova with a supergiant progenitor (Blagorodnova et al., 2021); Gaia22alz, a very slow nova with a 180-d rise to peak (Aydi et al., 2023).

**Symbiotic stars**: Gaia22eor (V2756 Sgr), a symbiotic star detected in a deep eclipse (Merc et al., 2022); Gaia23clr (V2905 Sgr), a symbiotic star outburst (Merc et al., 2023; Merc et al., 2024); Gaia23ckh (V390 Sco), a symbiotic outburst of the Mira variable (Merc et al., 2024).

**Young Stellar Objects (YSO)**: I addressed these in my previous essay 201, along with the pre-main-sequence classes displaying abrupt changes in magnitude and spectral type (the FU Ori and EX Lup, aka EXors).

Pre-Gaia, around 10 FU Ori stars were known. Gaia discoveries include Gaia17bpi (Hillenbrand et al., 2018); Gaia18dvy (Szegedi-Elek et al., 2020); Gaia18dvz (Hodapp et al., 2019); Gaia19ajj (Hillenbrand et al., 2019).

The related class of EXors include Gaia17aeq (Sicilia-Aguilar et al., 2017; Cieza et al., 2018; Kashi et al., 2019); Gaia19fct (Park et al., 2022; Ghosh et al., 2022), Gaia20eae (Cruz-Sáenz de Miera et al., 2022); Gaia21elv (Nagy et al., 2023); Gaia21bty (Siwak et al., 2023); Gaia23bab (Giannini et al., 2024); and the possibles Gaia20bwa and Gaia20fgx (Nagy et al., 2022).

**Dippers**: the science alerts pipeline also flags sources that *fade* significantly. A number of new YSOs (Young Stellar Objects), and other 'dipping' sources, such as VY Scl stars, have been discovered by Gaia, including Gaia17afn (the young star V555 Ori), showing a dipper-like variability (Nagy et al., 2021).

**Centres of galaxies**: A growing number of transients are found in galaxy centres, where outbursts may be due to a change in the black hole accretion flow, or to a tidal disruption event. Gaia16aax is in a QSO-hosting galaxy, which brightened by about 1 mag over 1 year, before fading to its pre-outburst state (Cannizzaro et al., 2020).

**Tidal disruption events (TDE)**: These results from a star passing close to a supermassive black hole (Hills, 1975; Rees, 1988; Kochanek, 2016). Pulled apart by the black hole's tidal force, the star is disrupted, producing a tidal stream of material that loops around the black hole.

As of May 2024, roughly 100 TDEs are known, most discovered through the optical transient surveys ZTF, ASAS–SN, and Gaia (Nicholl et al., 2020; Zhang, 2024). Amongst the 25 Gaia alert discoveries are Gaia20fck/ATLAS20belb (Charalampopoulos et al., 2023); and Gaia20cjk/AT2020ksf at $z = 0.092$ (Wevers et al., 2024).

**Gravitational waves**: Discovery of the electro-magnetic counterpart to the gravitational wave event GW170817 (Abbott et al., 2017) has motivated studies to extend Gaia's alert limit to $G > 19$, while allowing a single transit to trigger an alert (Kostrzewa-Rutkowska et al., 2020). Tests and preparations for the 4th observing run of the LIGO–Virgo–KAGRA collaboration that started on 2023 May 24, GaiaX, are described by Biswas et al. (2023).