206. Alerts – and tidal disruption events

I WILL CONTINUE with the theme of my last four essays, Gaia's science alerts (Hodgkin et al., 2021), and look here at the remarkable class of 'tidal disruption events'.

In September 2024 the Gaia Science Alerts database listed 25 919 alerts. Of these, 7 141 were assigned to 23 classes, with 25 inferred to be tidal disruption events. Before saying more about two of these events, let me summarise the phenomenon, their discovery history, and the insights that are being gained from them.

TIDAL DISRUPTION EVENTS, or TDEs, result from a star passing sufficiently close to a supermassive black hole that tidal forces overcome its self-gravity. Drawn-out material results in a tidal stream that loops around the black hole, some fraction on unbound orbits, the remainder forming an accretion disk, with bursts of electromagnetic radiation (spanning radio to γ-ray), fading over several months as the material is accreted (e.g., Carter & Luminet, 1983; Evans & Kochanek, 1989).

Their existence was predicted, 50 years ago, when supermassive black holes were still only hypothesised (Hills, 1975; Lacy et al., 1982; Rees, 1988). Interest in them was as a possible fuel source for quasars, with extreme events perhaps explaining some γ-ray bursts.

THE FIRST candidates were found with ROSAT (1990–99). Soft X-ray outbursts from otherwise quiescent galaxies were interpreted as the formation of the implied accretion disk (e.g., Bade et al., 1996; Komossa & Bade, 1999). Transient emission was discovered in the ultraviolet with GALEX (Gezari et al., 2006; Gezari et al., 2008), and at γ-ray wavelengths by the Neil Gehrels Swift Observatory (e.g., Bloom et al., 2011; Komossa, 2015).

Optical emission was first reported from archival SDSS images (van Velzen et al., 2011), and later from the surveys Pan–STARRS (e.g., Gezari et al., 2012; Chornock et al., 2014; Holoien et al., 2019), and PTF (e.g., Bloom et al., 2012; Arcavi et al., 2014). The large transient surveys ASAS–SN (e.g., Holoien et al., 2014; Holoien et al., 2016) and ZTF (e.g., Nicholl et al., 2020; van Velzen et al., 2021) have since found many more.

DISCOVERIES HAVE now been made in the infrared (e.g. van Velzen et al., 2016), and most recently in larger numbers from NEOWISE (Masterson et al., 2024). New discoveries in X-rays have been possible with eROSITA (Sazonov et al., 2021; Khorunzhev et al., 2022).

The first detection at radio wavelengths was made within 24 hr of the (Neil Gehrels Swift Observatory) discovery of Sw J1644+57 (Zauderer et al., 2011). Several dozen have since been detected as follow-up to alerts at optical wavelengths (Alexander et al., 2020), with the first radio discovery by Anderson et al. (2020).

There is an extensive literature on event modelling based on multi-wavelength light curves (e.g., Piran et al., 2015; Shiokawa et al., 2015; Guillochon & Ramirez-Ruiz, 2015; Bonnerot et al., 2016; Hayasaki et al., 2016; Mockler et al., 2019). One conclusion is that spectral properties depend on the viewing angle (Dai et al., 2018).

Meanwhile simulations show, for example, that because the tidal and Schwarzschild radii have different dependences on black hole mass, solar-type stars are accreted whole for black hole masses $\gtrsim 10^8 M_\odot$ (other than by the most rapidly spinning), while white dwarfs can be tidally disrupted for black hole masses $\lesssim 10^5 M_\odot$.

THE GROWING number of discoveries is today allowing increasingly detailed population studies (e.g. Gezari, 2021; Sazonov et al., 2021; van Velzen et al., 2021; Hammerstein et al., 2021; Yao et al., 2023).

In turn, these studies are raising questions about the nature of their host galaxies, and (for example) their suggested prevalence in systems which have undergone recent mergers. And there are outstanding questions about the observed versus predicted occurrence rate, the latter being of order 10^{-4} per galaxy per year (van Velzen & Farrar, 2014; Stone & van Velzen, 2016; Graur et al., 2018; Hinkle et al., 2020).

Today, tidal disruption events are probing the properties of previously dormant supermassive black holes, including their mass and spin (Kesden, 2012; Mockler et al., 2019; Pasham et al., 2019; Wen et al., 2022), and their nuclear environments (Alexander et al., 2020).

As of mid-2024, more than 100 tidal disruption events are known. The 25 discoveries from the Gaia alerts pipeline were typically alerted at $G \sim 17-18$ mag, compared with their historical 18–19 mag. Some were reported independently by the other transient surveys.

Eleven are 'confirmed TDEs' (Gaia19bvo, Gaia19eks, Gaia20ead, Gaia20fqa, Gaia22bdt, Gaia22cgf, Gaia22clk, Gaia22cwy, Gaia23cbw, Gaia24awm, Gaia24beb), and others are simply noted as 'coincident with known galaxies' (Gaia18dpo, Gaia20cxg, Gaia21drx, Gaia22anq, Gaia22dgl). In the following I will look at the two brightest.

Since 2016, the IAU Transient Name Server assigns names to confirmed supernovae, and 'Astronomical Transient' (AT) designators to other transients, including TDEs. And a literature search for a Gaia discovery (GaiaYYnnn) may only find that event under the ASASSN, ATLAS, ZTF, or ATYYnnn identifier.

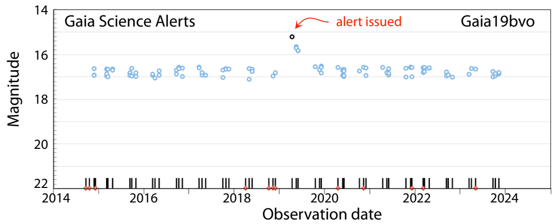
The brightest of Gaia's TDEs, `Gaia19bvo`, alerted at $G = 15.22$ mag on 2019 April 13 (historic $G = 16.81 \pm 0.14$ mag), was also discovered as ZTF17aaazdba/ASASSN–19dj, and is also referenced as AT2019azh.

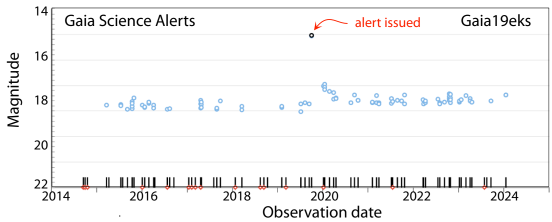
The 'Astronomer's Telegram' #nnnnn (ADS reference 2019ATelnnnnn) reported spectroscopy from the dedicated transit instruments NOT–NUTS (#12529) and ESO NTT–ePESSTO (#12530), both showing a featureless blue spectrum superimposed on a $z = 0.022$ (96 Mpc) galaxy.

Swift observations (#12568) found a 15-d optical/UV plateau, at a temperature of 30 000 K. The TDE classification is based on the event location in the galaxy centre, its blue colour, high blackbody temperature, and absence of supernova-like spectral features. The plateau suggests Eddington-limited accretion onto a $4 \times 10^6 M_\odot$ black hole. Radio emission was detected by MERLIN at 5 GHz on 2019 May 21 and June 11 (#12870), and by the (upgraded) GMRT at 1–1.45 GHz on November 8 (#13356). It was detected as a 'late-time brightening' X-ray source by ISS–NICER on October 19 (#13221).

High-cadence optical photometry and spectroscopy from –21 to 392 d relative to the peak emission was reported by Hinkle et al. (2021). For the first 16 d, the rise was consistent with a $L \propto t^2$ power law, peaking at a luminosity $L = 6.2 \times 10^{37}\,\mathrm{J\,s^{-1}}$. The X-ray flux increased by an order of magnitude 225 d after the peak, resulting from the expansion of the X-ray emitting region, with the late-time X-ray emission well matched by a blackbody with radius $r \simeq 10^{10}$ m, and temperature $T \simeq 6 \times 10^5$ K.

In the radio, more than two years of monitoring with VLA and MeerKAT, from –10 d to +810 d with respect to the optical peak, was reported by Goodwin et al. (2022). The source brightened slowly over 2 yr, showing fluctuations in the synchrotron emission from 450 d post-disruption. They deduced that the outflow is non-relativistic, and explicable as a spherical outflow from self-stream intersections, or by a mildly collimated outflow from accretion onto the supermassive black hole.





The second brightest of Gaia's TDEs, `Gaia19eks`, and the closest at the time, alerted at $G = 16.04$ mag on 2019 October 3 (historic $G = 18.79 \pm 0.12$), was a 3 mag brightening of a galaxy, and in the footprint of a gravitational wave event. Referenced as AT2019qiz, it was also discovered as ZTF19abzrhgq/ATLAS19vfr/PS19gdd.

The subsequent 'Astronomer's Telegrams' reported Keck–LRIS spectroscopy, classifying it as a rising TDE at $z = 0.015$ (#13131), along with optical/UV brightening and later decay by Swift (#13146, #13193), X-ray variability with Swift and ISS–NICER (#15217), and variable radio emission with ATCS (#13310, #13334).

Nicholl et al. (2020) found that the velocity dispersion of the host galaxy, combined with fits to the event light curve, indicate a star of mass $\simeq 1 M_\odot$ disrupted by a black hole of mass $\simeq 10^6 M_\odot$. The extensive ultraviolet, optical, and X-ray data indicate an early optical emission dominated by an outflow, with a luminosity evolution $\propto t^2$, consistent with a photosphere expanding at $v \geq 2000\,\mathrm{km\,s^{-1}}$. The light-curve rise begins 29 d before maximum light, peaking when the photosphere reaches the radius where optical photons can escape.

Short et al. (2023) found that between the optical flare and subsequent observations, the X-ray spectrum softened dramatically, with the 0.3–1 keV flux increasing by a factor 50, and the hard X-ray flux decreasing by a factor 6. WISE (infrared) fluxes rose over the same period, indicating the presence of an infrared echo. Detailed numerical modelling is described by Kovács-Stermeczky & Vinkó (2023).

With 25 detections to date, Gaia is discovering significant numbers of tidal disruption events, although most of them are also being reported by other transient surveys. Gaia's discoveries are contributing to the event statistics as well as to the light-curve characterisation, and Gaia is providing the accurate reference frame which is essential in associating these events with (the centres of) the previously quiescent galaxies.