59. Supernovae with Gaia

In preparing the scientific case for Gaia two decades ago, early estimates suggested that, with a faint limit of around 20 mag, the mission could detect supernovae to distances of around 500 Mpc, i.e. to redshifts $z \sim 0.1$. This would yield some 100 000 supernovae discoveries, of all types, over its 5-year nominal lifetime (Høg et al., 1999). Later pre-launch estimates pointed to numbers closer to 10 000 (Altavilla et al., 2012).

Actual Gaia discoveries are based on the photometric light-curves assembled from the satellite's repeated sky scanning. These are used to trigger ground-based observations to follow the light curves over the subsequent weeks, including some events 'caught' before maximum. Identifying possible supernovae forms part of the activities of the Alerts Working Group (essay #36).

Apart from simply adding to the number of known supernovae (and given that many other searches are ongoing), what sort of scientific results might be expected from the Gaia measurements?

Supernovae are dramatic and violent end-points of stellar evolution, and they lie at the heart of many important problems of modern astronomy. Their detailed taxonomy (they are classified according to their light curves, rather than their inferred physical origin), as well as their possible formation pathways, are both rather involved, and the underlying physics still somewhat uncertain. For this top-level perspective, I will distinguish here between just two physical classes:

(a) In *thermal runaway* events, low-mass (long-lived) stars accumulate material from a companion star (either a binary companion, or via a white dwarf–white dwarf collision). At some point, this leads to a rapid 'runaway' nuclear fusion reaction, releasing a burst of energy sufficient to disperse the star in a supernova explosion.

Type Ia supernovae fall into this class: they follow a characteristic light curve, and they present very uniform properties which make them important distance indicators ('standard candles') over intergalactic scales. Indeed, they provided the first evidence for an accelerating expansion of the Universe (Riess et al., 1998).

The wider importance of these type Ia events to cosmology is that the velocity field in the Universe is dominated by the Hubble expansion, while smaller-scale spatial structure is characterised by sheet-like regions with a high density of visible matter separated by large voids. Small-scale streaming motions of the luminous matter is not easily measured, requiring distance determinations independent of the Hubble law.

(b) In *core collapse* events, massive (short-lived) stars undergo collapse when nuclear fusion no longer sustains the stellar core against its own gravity. The prompt collapse may cause violent expulsion of its outer layers as a supernova or, if the release of gravitational potential energy is limited, the star may collapse into a black hole or neutron star with little radiated energy. According to the star's metallicity and mass (in the range $10-100 M_\odot$), different mechanisms, and different taxonomic classes (amongst them type I b/c and type II) may result.

As a result of these complex formation pathways, supernovae provide laboratories for studying extreme nuclear processes, being involved in the formation of neutron stars, black holes, millisecond pulsars and gamma-ray bursts. They are sources of gravitational waves, neutrinos, and high-energy cosmic rays.

And they, along with their precursors, are implicated in the evolutionary history and accretion rates of interacting binary systems, low mass X-ray binaries, and globular cluster X-ray sources.

Supernovae play a major role in the chemical, kinematic, and dynamical evolution of galaxies. They are the main producers of heavy elements, and are fundamental for understanding abundances and abundance patterns in galaxy clusters and in the intergalactic medium.

And supernovae rates provide a probe of the star-formation history in galaxies: due to the short lifetime of their progenitor stars, the type II (core-collapse) rate is proportional to the current star-formation rate, while type Ia rates reflect the convolution of the star-formation history with the distribution of the time difference between progenitor star formation and their explosion.

After this preamble, I will take a brief tour of some of the Gaia studies related to supernovae, their remnants, and their progenitors, published so far.

Star parallaxes are providing improved distances of past events and their remnant structures. For the Cygnus Loop, Fesen et al. (2021) used EDR3 parallaxes of stars in or behind the supernova shell (based on their absorption lines) to set a precise distance of 725 ± 15 pc, with an uncertainty comparable to its 18 pc radius.

For the Vela complex associated with the Vela pulsar, Hottier et al. (2021) used 18 million stars over 450 sq. deg. to reveal the detailed morphology of the cavity shell. The 'last word' on the distances and kinematics of the proposed companions of Tycho's supernova using DR2 data is given by Ruiz-Lapuente et al. (2019).

The Gaia data, supported by simulation models, are providing new insights into supernova progenitors. Kochanek (2022) analysed luminous stars in the vicinity of the Vela pulsar to estimate the mass of the exploding star, finding a low progenitor mass of $8-10\,M_\odot$.

Deep imaging of SN 1972E, the nearest type Ia supernova in more than a century, rules out models in which the companion is a He star, or a high-luminosity main-sequence star, as previously favoured in the literature.

Fast-moving stars have long-been prized as forensic tools in astronomy, their space motions pointing back to the violent events that launched them. With the release of Gaia DR2, Shen et al. (2021) reported three hypervelocity white dwarfs, with velocities between 1000–3000 km s^{-1}, consistent with having been companion white dwarfs in pre-SN Ia binary systems.

Van der Meij et al. (2021) used EDR3 data to show that the runaway X-ray binary HD 153919/4U 1700–37 originates in the association Sco OB1: a supernova in a compact binary can result in a high recoil velocity of the system, subsequently observable as a spectroscopic binary, a high-mass X-ray binary, and ultimately as a gravitational-wave event. Their models imply a progenitor mass $> 60 M_\odot$, most likely a neutron star, and a possible prototype for gravitational wave events such as GW 190412 (Abbott et al. 2020).

A statistical assessment of the intrinsic velocities of neutron star progenitors was made by Yang et al. (2021). They considered 24 young (< 3 Myr) pulsars with precise parallaxes (from radio observations), and compared their space velocities with the velocities and velocity dispersions of nearby stars from Gaia DR2.

By showing that their transverse velocities are generally comparable to the velocity dispersion of stars in the local group of low-velocity pulsars, they could demonstrated that the intrinsic velocities of neutron star progenitors should be taken into account when consider their natal 'kicks' and subsequent binary evolution.

The fraction of progenitors in binaries or triples, and the fraction that survive the supernova explosion, are important for evolution models, and for predictions of the gravitational wave source populations. And these fractions can be determined by observations.

Kochanek (2021) used the Gaia EDR3 data to search 10 supernova remnants containing compact objects with proper motions for unbound binaries or triples. The Gaia data confirm the one known example of an unbound binary, HD 37424 in G180.0–01.7 related to the pulsar PSR J0538+2817, but found no other examples. Combined with previous searches for bound and unbound binaries, they found that some 70% of supernova producing neutron stars are not binaries at the time of explosion, around 15% produce bound binaries, and some 10% produce unbound binaries.

The specific conclusions in the case of HD 37424 are illustrative: at birth, the progenitor of PSR J0538+2817 was probably a $13-19\,M_\odot$ star and, at the time of explosion, a Roche-limited star transferring mass to HD 37424, eventually producing a type II supernova.

The recent and ongoing discoveries of merging binary black holes by the LIGO–Virgo and KAGRA gravitational wave observatories have stimulated a renewed interest in understanding the origins of black hole binaries in short-period orbits, and indeed how massive stars evolve and eventually collapse to form these compact objects.

Current estimates are that there are some 10^7-10^9 stellar mass black holes in our own Galaxy (e.g. Brown & Bethe, 1994). But discovering them using traditional methods such as X-ray or radio observations is notoriously difficult. As a result, these methods have resulted in only about 60 detections to date.

Detached binaries, those comprising a luminous companion orbiting a stellar mass black hole but without mass transfer, are almost impossible to detect using these well-established methods. Instead, several groups have argued that such detached systems could be detected from the orbital motion of the luminous component around its dark companion using Gaia astrometry (e.g. Barstow et al. 2014; Wiktorowicz et al. 2020).

In some of the most recent simulations, Chawla et al. (2021) estimate that the extension of Gaia to 10 years of operation, should allow for the detection of 30–300 black holes with detached luminous companions, and with orbital periods of 10 years or less. Such detections should provide new and important constraints on the many complexities of binary star evolution.

The Gaia results to date have only touched on what will surely prove to be rich new seam of observations, facilitating the next steps in understanding the complexities of supernova progenitors, and these spectacularly cataclysmic events exploding around us.