165. Runaway stars

RUNAWAY STARS are stars with such high space velocities, generally considered to be above a threshold of 30 km s^{-1}, and sufficiently distinct from the overall stellar velocity distribution, that they must have been imparted by a particular formation process. Most are young massive O stars, or Wolf–Rayet stars (W–R stars being the final He-burning phase in the evolution of massive O stars of initial mass $\gtrsim 25 M_\odot$; essay 105).

The discovery of runaway stars followed from the realisation that many O stars (Blaauw, 1961; Gies & Bolton, 1986; Gies, 1987) and Wolf–Rayet stars (Moffat & Isserstedt, 1980; Moffat et al., 1998) lie well outside their likely birth places in open clusters and OB associations, with some clearly 'pointing back' to their likely origin.

They often create spectacular 'bow shocks' as they plough through the interstellar medium, most recently beautifully imaged by HST–ACS and JWST.

THERE ARE TWO main theories for the origin of runaway stars, and both appear to operate: the binary-supernova scenario, BSS, and the dynamical ejection scenario, DES, in which a star is ejected via dynamical interactions in a young, compact cluster.

Dynamical ejection models employ increasingly detailed N-body simulations to study the effects of mass segregation, binary fraction, period distribution, binary mass ratios, and eccentricities (e.g. Oh & Kroupa, 2016).

IN THE binary-supernova scenario, runaway stars result from the evolution of massive binary systems (van den Heuvel, 1973; Tutukov & Yungelson, 1973):

$$\mathrm{O+O} \;\rightarrow\; \mathrm{WR+O} \;\underset{\mathrm{SN}}{\rightarrow}\; \mathrm{c+O} \;\rightarrow\; \mathrm{c+WR} \;\underset{\mathrm{SN}}{\rightarrow}\; \mathrm{c\,(+)\,c}$$

Here, c denotes the compact companion (neutron star or black hole), left after the supernova explosion of its progenitor. Simply stated, the more massive star evolves fastest, while wind-driven mass-loss (assisted by Roche-lobe overflow in the closest massive binaries) makes O stars evolve into lower-mass (and themselves evolving) Wolf–Rayet stars. At the end of the Wolf–Rayet phase, in both cases, the star explodes as a supernova.

If the first supernova explosion is symmetric, the binary system remains bound, leading to the class of high-mass X-ray binaries. If the first supernova is asymmetric, the binary system may disrupt, depending on the magnitude and direction of the extra kick velocity (de Cuyper, 1982). In either case, with the supernova explosion duration being very short compared to the orbital period, the star receives a recoil velocity, and becomes a runaway, with velocities reaching 200 km s^{-1} for the 'tightest' and most massive pre-supernova binaries.

If the system has not already separated after the first supernova, the system will normally become unbound as a result of the second, producing two high-velocity, single pulsars. In rare cases, the binary can survive this second supernova, producing a binary pulsar (e.g. de Cuyper, 1985; Moffat et al., 1998).

PRE-HIPPARCOS STUDIES of runaway stars were based largely on radial velocities. The broad emission lines resulting from the high outflow velocities means, however, that the determination of radial velocities by classical Doppler techniques is itself greatly restricted.

More than 1000 O–B5 stars were included in the Hipparcos catalogue, including 153 of the 162 proposed runaway candidates known at the time. It also observed 67 Galactic Wolf–Rayet stars, including almost all down to $V = 12$ mag, and representing some one third of all Wolf–Rayet then known.

In the study by Moffat et al. (1998), only four of the O stars, and just one of the Wolf–Rayet stars, had reliable parallaxes, and only photometric distances were adopted for the remainder. At 1 mas yr^{-1} accuracy, runaways with transverse velocities of some 100 km s^{-1} could be detected out to distances of about 7 kpc.

Hoogerwerf et al. (2000, 2001) retraced the orbits of 56 runaway O and B stars within 700 pc, linking at least 21 of them to nearby associations and young open clusters, including the classical runaways 53 Ari (Ori OB1), ξ Per (Per OB2), and λ Cep (Cep OB3). Amongst them were a number of runaway 'pairs', including the 70° wide-separation AE Aur+μ Col, which they ascribed to a common origin, coinciding with the λ Ori cluster.

THE PRE-GAIA understanding of runaways was constrained by the limited availability of distances and proper motions (e.g. Moffat et al., 1998; Chevalier & Ilovaisky, 1998; van den Heuvel et al., 2000). Larger numbers, and accurate space motions, were considered essential to distinguish between the BSS/DES formation mechanisms, and their relation to known supernovae, supernova remnants, and high-mass X-ray binaries.

Also debated were suggestions that many massive runaways have high He abundance and rapid rotation, suggesting that at least these were formed through BSS. The 'blue straggler' nature of some was attributed to (hydrogen) mass transfer prior to the supernova explosion. Another discriminant amongst the possible mechanism should be the multiplicity of runaways, where a high multiplicity fraction would point to an efficient dynamical ejection rather than a predominantly binary-supernova origin (e.g. Kobulnicky & Chick, 2022).

These sorts of investigations would be expected to provide further insight into the formation of very massive stars, as well as an improved understanding of stellar kinematics in clusters and associations. They could also elucidate the existence of 'two-step ejections', in which dynamically ejected non-compact binaries can then experience re-acceleration of the surviving star following the subsequent supernova explosion of the primary (Pflamm-Altenburg & Kroupa, 2010).

I should note that the conventional definition of a 'runaway' adopts a 30 km s^{-1} 3-d space velocity threshold (e.g. Gies & Bolton, 1986), while unbound stars with a lower velocity are frequently referred to as 'walkaways'.

'Hypervelocity stars', moving with space velocities of 500–1000 km s^{-1} or more, cannot be explained by either the BSS supernova or DES ejection mechanism, and point to an even more extreme formation scenario. I will not detail these here, but refer to essay 22 (May 2021), and an update to appear as essay 166.

Neither will I say more on the related work on high-mass X-ray binaries, which is also benefitting from the Gaia data (e.g., Hambaryan et al., 2021; van der Meij et al., 2021), but also merits a separate treatment.

INVESTIGATIONS with Gaia DR2 include many individual runaways, together shedding light on the frequency and nature of ejection events in young clusters.

These include: identifying new candidates (Maíz Apellániz et al., 2018); confirming the ejection of VFTS 16 from R136 some 1.5 ± 0.2 Myr ago (Lennon et al., 2018); assigning the runaway J01020100–7122208 to the Milky Way halo rather than the SMC (Massey et al., 2018); confirmation of LP 40–365 as a white dwarf remnant of a peculiar Type Iax supernova (Raddi et al., 2018); association of the Sh 2–296 nebula with three successive ejected runaway stars (Fernandes et al., 2019); identification of 26 runaways originating in the dense Orion Trapezium nebula (McBride & Kounkel, 2019); confirmation that the 150$M_\odot$ VFTS 682 in 30 Dor is a runaway ejected from the R136 cluster (Renzo et al., 2019); other studies of the 30 Dor runaways (Gebrehiwot & Teklehaimanot, 2021); that the K giant HD 137071 was ejected in a massive BSS event 32 Myr ago (Comerón & Figueras, 2020); the nature of two runaways in Vela OB1 (Azatyan et al., 2020); and the confirmation of WR6 (Gvaramadze, 2020).

A SYSTEMATIC search around the Orion Nebula Cluster using Gaia DR2 was made by Farias et al. (2020). Their starting list of 17 000 sources out to 1 kpc resulted in 25 new candidates. A similar search by Schoettler et al. (2020) identified 9 runaways and 24 walkaways. The former is consistent with their N-body simulations over an age of 1.3–2.4 Myr, confirming the current cluster age estimate but based only on runaways. Detailed studies of the AE Aur+μ Col system using EDR3 were reported by Bobylev & Bajkova (2021).

Dorigo Jones et al. (2020) used DR2-based transverse velocities for 304 OB stars in the Small Magellanic Cloud to conclude that dynamical ejections dominate over supernova ejections by a factor 2–3, with two-step runaways likely dominating the BSS runaway population.

Focussing on the nature and origin of blue stars at high Galactic latitudes, Raddi et al. (2021) identified 12 B-type runaway candidates, of $2-6M_\odot$, out to 10 kpc, and with flight times compatible with their evolutionary ages. Three with high velocities >450 km s^{-1} challenge the BSS or DES ejection scenarios, suggesting mechanisms more aligned to those for hypervelocity stars.

Bhat et al. (2022) described a method to determine whether two or more objects come from the same location, tested against Orion runaways, and suggested that AE Aur+μ Col might not have originated together.

TWO LARGER-SCALE searches have been reported. Using EDR3, Kounkel et al. (2022) compiled a catalogue of 3354 young candidates within 500 pc that appear to have been ejected from their parent associations. Among the possible candidates they identified various pairs, with similar traceback times, that appear to have interacted in the ejection process.

Starting from the Galactic O-Star Catalog (GOSC) of Maíz Apellániz et al. (2013), and the Be Star Spectra (BeSS) Database of Neiner et al. (2011), Carretero-Castrillo et al. (2023) used Gaia DR3 astrometry to find 106 O-type runaways (42 new), and 69 Be-type runaways (47 new), with the percentage of runaways being 25% for O-type stars, and 5% for Be-type stars.

Their sample includes seven X-ray binaries and one gamma-ray binary. The higher percentages and higher velocities found for O-type compared to Be-type runaways again suggests that the dynamical ejection scenario is more favoured.