212. Runaways stars in R136

I INTRODUCED THE SUBJECT of 'runaway stars' in essay 165, and made brief reference to the two known runaways in the young cluster R136 in the Large Magellanic Cloud. Recent results on runaways in this cluster merit a detailed discussion, but let me first summarise a few key points that I covered in that earlier essay.

Runaways are stars with such high space velocities, above an adopted 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 (essay 105). [The even more extreme 'hypervelocity stars', hurled out from close encounters with the supermassive black hole in the centre of our Galaxy (essay 166), do not concern us here.]

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 motions 'pointing back' to their likely origin.

There are two main theories for the origin of runaway stars, and both appear to operate. In the *binary-supernova scenario*, BSS (detailed in essay 165), the disruption of massive binary systems due to one or other of the two successive supernova explosions can result in large recoil velocities of the companion. In the *dynamical ejection scenario*, DES, a star is ejected as a result of dynamical interactions in a young, compact cluster.

In essay 165, I summarised the pre-Hipparcos history of runaways (based largely on radial velocities), the modest advances made with the Hipparcos observations of ~1000 O–B5 stars (still limited by the 1 milli-arcsec level accuracies of distances and proper motions), and the identification and characterisation of many new candidates with Gaia. These include 25 new candidates 'escaping' from the Orion Nebula Cluster, others from the Small Magellanic Cloud, and some 200 new candidates from the Gaia DR3 astrometry of existing catalogues of Galactic O and Be stars. A very broad conclusion is that dynamical ejection appears to dominate.

OBJECTIVES in studying runaway stars include gaining insights into massive star formation; better understanding the two-step ejection processes involved in the binary supernova scenario; and modelling the end products of the BSS scenario (which include pairs of high-velocity single pulsars, as well as binary pulsars).

A better characterisation of the dynamical ejection scenario is also leading to an improved understanding of stellar kinematics in clusters and associations. Associated 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).

As a result of one or other mechanism, it appears that at least 10 percent of OB stars are hurled out of their birth clusters before ending their lives as supernovae somewhere along their escape trajectory. Runaway stars often create spectacular 'bow shocks' as they plough through (and inform us about) the interstellar medium. Examples from HST–ACS imaging can be found here. A Spitzer image of the runaway ζ Oph can be found here.

AS HAS BECOME evident in the past few years, runaway stars also have an important role in the context of ΛCDM cosmology, where certain inconsistencies found in large-scale numerical simulations have been attributed to challenges in modelling the 'baryon cycle', i.e., how galaxies accrete and expel their gas (Naab & Ostriker, 2017). Stellar feedback (in which stars influence the surrounding environment through the injection of energy, momentum, and mass), is an important factor, involving contributions from protostellar jets, stellar winds, supernovae, and ionising radiation.

Runaway stars can travel hundreds of parsecs into the low-density interstellar medium, depositing momentum and energy, and affecting supernova rates and gas densities (e.g. Ceverino & Klypin, 2009; Andersson et al., 2020; Steinwandel et al., 2023; Andersson et al., 2023; 2024). For example, Andersson et al. (2020) found that including runaways leads to twice as many supernovae over a wide range of ISM densities.

GAIA IS PROVIDING some particularly interesting insights into runaway stars associated with the massive young cluster R136 in the Large Magellanic Cloud.

Named after the Radcliffe Observatory Magellanic Clouds Catalogue (Feast et al., 1960), R136 is the central concentration of stars in the NGC 2070 cluster, lies at the centre of (and illuminates) the Tarantula Nebula (aka 30 Doradus), and marks the nebula's most recent burst of star formation. Originally catalogued as the unresolved star HD 38268 ($V = 7.25$ mag), it comprises some 100 O and Wolf–Rayet stars within 5 pc/20 arcsec (Massey & Hunter, 1998; Doran et al., 2013).

With a cluster mass of $\sim 5 \times 10^5 M_\odot$, and a density far higher than typical OB associations, R136 hosts several extremely massive stars, including R136a1 ($200 M_\odot$, Crowther et al., 2010; Shenar et al., 2023). While these challenge the canonical stellar mass limit of around $150 M_\odot$ (e.g. Weidner & Kroupa, 2004), mergers of massive binaries may have produced a few single stars with such high masses (Banerjee et al., 2012). With an age of < 2 Myr, none of its members are significantly evolved, and none are thought to have exploded as supernovae.

THE FIRST runaways associated with R136 were provisionally identified using radial velocities from the VLT–FLAMES Tarantula Survey (Evans et al., 2011): VFTS 16 (Evans et al., 2010), and VFTS 682 (Banerjee et al., 2012) both of which were subsequently confirmed from their high proper motions in Gaia DR2 (Lennon et al., 2018, and Renzo et al., 2019, respectively).

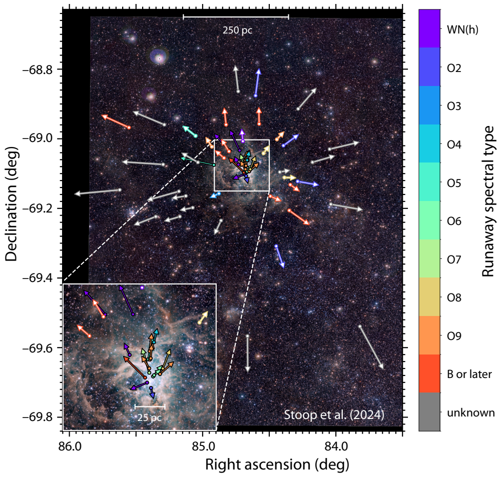
N-body simulations of dynamical ejections met with some success in explaining their existence (Banerjee et al., 2012; Perets & Šubr, 2012; Oh & Kroupa, 2016). Another model invoked a single very massive wide binary (their 'bully binary') to scatters massive stars out of their host cluster (Fujii & Portegies Zwart, 2011).

Another 10 candidates, reaching out to around 35–400 arcsec (10–100 pc), were identified from two-epoch (2011–14) HST observations (Platais et al., 2018).

Proper motions from Gaia DR2/DR3 ($\lesssim 0.4$ mas yr^{-1}, corresponding to velocities 100 km s^{-1}) were later used to confirm some of these candidates through a comparison of their inferred flight times (dynamical ages) with their evolutionary ages (Gebrehiwot & Teklehaimanot, 2021; Teklehaimanot & Gebrehiwot, 2024).

NEW INSIGHTS came from the rotational velocities derived from the VLT–FLAMES Tarantula Survey. Sana et al. (2022) identified an overabundance of rapid rotators ($v \sin i > 200$ km s^{-1}) among the runaway stars, and suggestive of two distinct populations: one slower moving but rapidly rotating, and one faster moving but more slowly rotating.

They argued that the former result from binary ejections (and dominate the massive runaway population), while the latter result from dynamical ejections.



A MAJOR ADVANCE in characterising the runaway population from R136 came with Gaia DR3. Stoop et al. (2024), starting with 80 000 sources with $G < 18$ mag and within 1 degree of R136, identified 55 massive runaway stars, increasing the number of known runaways escaping from the cluster core by an order of magnitude.

They have reached (projected) distances of 3–460 pc from R136. This implies that half have already left the 30 Dor region, such that their ionising radiation and stellar winds (and eventually their powerful supernovae) affect relatively tenuous areas beyond the nebula itself.

They classified the runaways as dynamical ejections falling into two distinct groups (image above). The first comprises massive stars ejected isotropically (with kinematic ages peaking around 1.8 Myr) which, they show, are consistent with dynamical interactions during and after the birth of R136. They also provide an independent age estimate of the cluster. The second group comprises 16 stars with kinematic ages around 0.2 Myr, ejected preferentially in a northerly direction, which they attribute to the effects of a later cluster interaction.

They found that 23–33% of the most luminous stars in R136 are runaways, a dynamical escape fraction significantly higher than the model predictions noted previously. And this confirms the growing picture that their role in shaping and heating the interstellar and Galactic medium, along with their role in driving Galactic outflows, is more important than previously thought.

THEORISTS HAVE been quick to examine the implications. Polak et al. (2024) have recently proposed a third mechanism for the formation of runaway stars, in addition to binary supernova and dynamical ejection.

In their 'sub-cluster ejection scenario', a subset of stars from an infalling sub-cluster is ejected out of the cluster via tidal interactions with the contracting gravitational potential of the assembling cluster. And they propose that the group of runaways ejected to the north of R136 is a promising example of such a scenario.