258. The Raritan and Passaic streams

THIS IS THE SECOND of my current series of three essays on stellar streams in our Galaxy's halo, and one of several on the topic extending back over the past four years. As I said in the introduction to my previous essay, the subject of stellar streams is at the forefront of Gaia's scientific impacts – and it continues to develop rapidly.

In essay 199, I summarised the search algorithms that are being used to identify these stellar streams. I gave an overview of their development over the past decade, and emphasised how these searches are being adapted to the specifics of the Gaia catalogue.

Essentially, they aim to identify a small number of member stars, of order 100–200, which may be spread out over the celestial sphere, with an uncertain stream morphology, and amongst a large number (of order 10^6) of background stars. Searches therefore benefit from accounting for any common kinematic and spectroscopic properties that the stream members might share.

ONE OF THESE ALGORITHMS is `Via Machinae`. It uses an 'unsupervised machine-learning algorithm for anomaly detection', `ANODE` (Shih et al., 2022; Shih et al., 2024), hereafter VM3–A. Its most recent version, using a modified anomaly detection method `CATHODE`, and referred to as `Via Machinae 3` (or VM3–C), yields a further improvement in detections (Hallin et al., 2025).

It is worth emphasising the interdisciplinary nature of these specific contributions: first author David Shih is a member of the New High Energy Theory Center, NHETC, at Rutgers (New Jersey), and both ANODE and CATHODE ('classifying anomalies through outer density estimation') were developed for finding new particles at the Large Hadron Collider (Hallin et al., 2022).

Amongst recent discoveries by Hallin et al. (2025), using VM3–A and VM3–C, are *Raritan* and *Passaic*.[1] The authors infer that these complex streams may indicate the presence of larger progenitors, such as dwarf galaxy streams, or non-trivial orbit dynamics resulting in bifurcation or fanning. Some background is appropriate.

THE USE of `ANODE` and `CATHODE` within `Via Machinae` transfers a classic problem in particle physics (the 'bump hunt')[2] into the field of astrophysics: while the underlying background is considered to be smooth and continuous in both cases, a physical anomaly (a new particle in high-energy physics or, in this case, a stellar stream) is seen as a localised overdensity in the relevant phase space.

Such a 'model agnostic' approach aims to identify particles which may exist outside of the Standard Model or, in this case, stellar streams independently of the progenitor orbit, i.e. without the need to invoke the mass, shape, or dark matter distribution of the Galaxy.

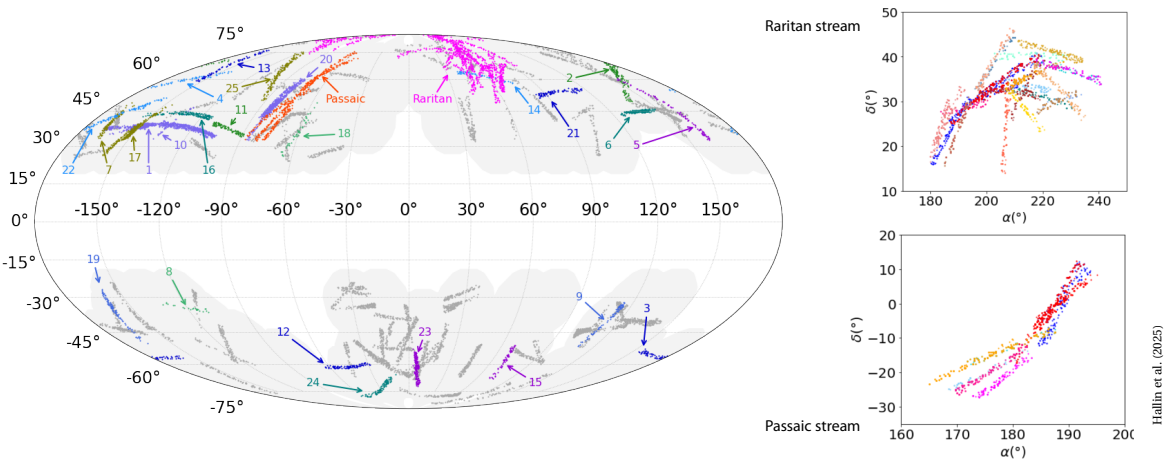
The algorithms employ 'sideband interpolation', splitting a sky patch into a signal region, where a stream might cross, and surrounding sidebands, containing only the general Galactic background. `ANODE` measures the probability density of the velocities and colours of background stars in the sidebands, then interpolates the background expected inside the signal region.

`CATHODE` goes further by employing neural networks to generate completely synthetic background stars inside the signal region (Hallin et al., 2022; Golling et al., 2024). Hallin et al. (2025) demonstrate that searches with VM3–A and VM3–C are somewhat complementary, albeit correlated, and that candidate streams found by both methods are more likely to be real.

Their searches were actually based on Gaia DR2, using one component of the proper motions as the 'primary resonant feature' where the signal is assumed to be localised, and with additional anomaly features taken to be the angular positions, colour, magnitude, and the orthogonal proper motion component. They detail their precise methodology in their Section 4.1, and their training sets and estimates of false positives in Section 5.1.

[1] Named after two rivers in New Jersey, the names adapted from the indigenous Algonquian languages.

[2] Reviews charting the development of the 'bump hunt' in particle physics, to the recent foundations of 'resonant anomaly detection', are given by Karagiorgi et al. (2022) and Belis et al. (2024). A more popular introduction, including the role of the bump hunt in the discovery of the Higgs boson, and subsequent developments in machine-learning, can be found here.



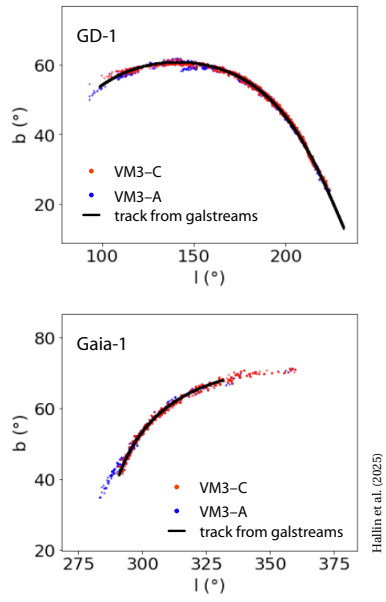
Applied to Gaia DR2, VM3–A and VM3–C both confirm more than ten previously-discovered streams. VM3–A and VM3–C overlap on the rediscovery of GD–1, Gaia–1, Jhelum, Fjorm, Gaia–8, Leiptr, Ylgr, ACS, Lethe and a number of Sagittarius fragments. VM3–C additionally finds Cetus–Palca; possibly a tidal stream associated to M68, the progenitor of Fjorm; and possibly part of the Triangulum–Pisces stream. Meanwhile, VM3–A finds Gaia–6 and Gaia–9, including a possible extension to Gaia–6 beyond that reported by Ibata et al. (2019).

In addition, Hallin et al. (2025) report 93 new candidates (65 in VM3–A, and 74 in VM3–C), including 17 that they refer to as 'gold plated', and discovered by both methods. Their sky location is shown in the main figure above. The part of the sky covered by the patches used in their work, at high Galactic latitudes, is shaded in grey.

Amongst these, visual inspection led to the identification of two complex 'stream clusters', in the northern Galactic hemisphere. They refer to these as the Raritan and Passaic streams, each covering some $30-40^\circ$. They are shown in greater detail to the right.

The morphology of these complexes are clearly inconsistent with simple, dynamically cold, globular cluster streams. They suggest that they could instead be signs of multiple tidal tails and other deviations from a single thin filament (bifurcation or fanning), which may develop as a result of more complex phenomena that have been previously observed or predicted.

These include the effects of multiple passages of highly eccentric progenitor orbits (Montuori et al., 2007; Johnston et al., 2008; Hozumi & Burkert, 2015; Pearson et al., 2015; Grillmair, 2025); chaotic orbits as a result of the Milky Way's dark matter halo not being fully integrable (Price-Whelan et al., 2016; Mestre et al., 2020); or streams overlapping multiple orbital resonances (Fardal et al., 2015; Yavetz et al., 2021; Yavetz et al., 2023).

Alternatively, these apparently distinct streams identified by `Via Machinae` could be remnants associated with the same progenitor, such as a much larger dwarf galaxy. They compare this with their own detection of fragments of the Sagittarius dwarf galaxy, rather than the entire stream (their Figure A2), Sagittarius being too wide to be picked up as one entity by a search algorithm optimised for the detection of narrow streams.

Finally, as an illustration of their algorithm's performance, I show below two examples of their stream detections for the previously known GD–1 (Grillmair & Dionatos, 2006) and Gaia–1 (Malhan et al., 2018), with the members detected by VM3–C (red) and VM3–A (blue), with the stream track from the `galstreams` library (Mateu, 2023) superposed as a black line.