# 77. The Galactic escape velocity

WHAT IS THE TOTAL MASS of our Galaxy? How far out does our Galaxy halo extend? The distribution of stellar velocities, and in particular the 'escape' velocity from the solar neighbourhood, holds a number of clues.

Indeed, the Galaxy's escape velocity has provided an important constraint on Galaxy models since the studies of J.C. Kapteyn and his doctoral student Jan Hendrik Oort nearly a century ago. But as perceptively pointed out by Oort (1928): *'It is very unlikely that the galactic system as a whole should contain a considerable number of stars whose velocities exceed the velocity of escape'*.[1]

MOST DYNAMICAL measurements are rather insensitive to the mass distribution in the halo's outer parts, since this exerts no net force as long as the halo is spherical or ellipsoidal. Nonetheless, local measurements can provide a constraint on the halo extent, since the escape speed from the Galaxy should exceed the largest speed of any star in the solar neighbourhood.

There are at least two caveats: (a) stars may be gravitationally bound to the Local Group of galaxies, and just passing through our Galaxy; (b) dynamical interactions involving binary stars in clusters can lead to ejected 'runaway stars' at above the escape velocity.

I WILL SKIP MOST of the mathematic details (see, e.g., Binney & Tremaine, 1987; Equation 2–192) and start by simply quoting some illustrative results for a simplified model in which the Galaxy is spherical, with a circular speed $\Theta_c$ constant out to a maximum radius $r_*$.

A number of nearby high-velocity stars have velocities, with respect to an inertial frame, of $\sim$500 km s$^{-1}$, and estimates between 1980–90 put the escape speed at around $v_{\rm esc} = 400 - 640$ km s$^{-1}$. Assuming, for example, $v_{\rm esc} = 500$ km s$^{-1}$(with $\Theta_c = 220$ km s$^{-1}$ and $R_0 = 8.5$ kpc), yields an outer halo limit of $r_* = 4.9R_0 \simeq 41$ kpc, and a total Galaxy mass of $4.6 \times 10^{11}\, M_\odot$.

[1] I can't resist noting that Jan Oort's `Wikipedia entry` includes a photograph of him, on horseback, reconnoitring the Chilean mountains for a location for the ESO observatory! And that, in my close involvement with Leiden University, I also had the pleasure of several conversations with him in his later years.

A STATISTICAL technique to infer the escape speed from the high-velocity tail of a uniform star sample was given by Leonard & Tremaine (1990). Their estimates were, however, strongly correlated with the *shape* of the high-velocity tail and, in turn, very sensitive to the errors on distances and proper motions.

Notwithstanding these limitations, their estimates from radial velocities were in the range 450–650 km s$^{-1}$. But they also argued that it is not possible to estimate the mass of the Galaxy using the local escape speed without detailed knowledge of how mass is distributed beyond to the solar circle. Even today, at least pre-Gaia, the mass of our Galaxy was still considered unknown to within a factor of four (Bland-Hawthorn & Gerhard, 2016).

USING SPACE MOTIONS from Hipparcos, and radial velocities from Coravel, the same technique was applied by Meillon et al. (1997) to a set of 5307 F–M stars, including all the subdwarfs and high-velocity stars known at the time. Estimates from the total space velocities were in the slightly smaller range $v_{\rm esc} = 440 - 490$ km s$^{-1}$, probably due to the absence from the Hipparcos catalogue of the (faintest) highest velocity stars in the reference compilation of Carney et al. (1994).

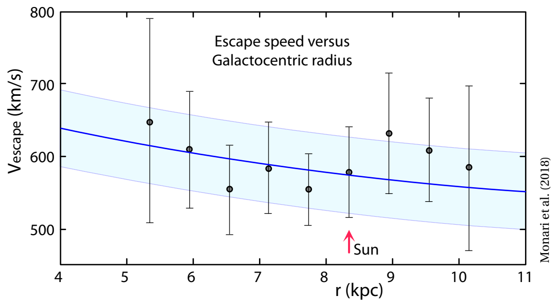
Meillon (1999) found only 10 Hipparcos stars with $V_{\rm tot} > 350$ km s$^{-1}$. They were, however, able to use the intersection of the two samples (770 stars) to re-calibrate the absolute magnitudes and hence derive improved distances of about 20 non-Hipparcos stars. Together they found 98 stars with $V_{\rm radial} \ge 250$ km s$^{-1}$, 33 with $V_{\rm tangential} \ge 300$ km s$^{-1}$, and 24 with $V_{\rm total} \ge 350$ km s$^{-1}$. Four had $V_{\rm total} \ge 400$ km s$^{-1}$, and the fastest had $V_{\rm total} = 458$ km s$^{-1}$. They concluded that the escape velocity is unlikely to exceed 530 km s$^{-1}$.

Along with estimates from the RAVE radial velocity survey of $v_{\rm esc} \simeq 544^{+64}_{-46}$ km s$^{-1}$ by Smith et al. (2007), and of $533^{+54}_{-41}$ km s$^{-1}$ by Piffle et al. (2014), this largely represented the state of knowledge pre-Gaia.

Importantly, working the other way around, detailed state-of-the-art models of our Galaxy's structure and mass distribution yielded consistent escape speeds, e.g. 550 km s$^{-1}$ according to Kafle et al. (2014).

WITH THE ONGOING availability of the Gaia results, we are therefore in a position to ask: Do the Gaia results provide an improved estimate of the escape speed from the Milky Way? Given the complex structure of our Galaxy, are there observable changes in the estimated escape speed as a function of Galactocentric radius? And do these estimates provide new constraints on our Galaxy's mass or mass distribution?

Of course, I would not be posing these questions if the answers were not respectively: yes, yes, and yes!




BEFORE LOOKING at the latest Gaia results, it is useful to clarify what is meant by 'the escape speed'. In principle, it could formally be defined as the velocity necessary to bring an ejected star to infinity. In practice, galaxy haloes (including our own) are not isolated systems, so that a limiting distance needs to be specified. A common definition adopts the virial radius, defined as 200 times the critical density, $r_{200}$, in turn containing the mass $M_{200}$ (see, e.g., Deason et al. 2019, Section 3.2).

Another point to emphasise is that the properties of galaxy haloes are today interpreted in the context of extensive numerical simulations. For example, Auriga is a suite of high-resolution Milky Way-mass haloes, spanning a mass range $M_{200} = 1-2\times10^{12}M_\odot$, and employing cosmological parameters consistent with the Planck Collaboration's (2014) data release (Grand et al., 2017). It has been successful in reproducing a number of observational properties of both central disks and stellar haloes, including the rotation curves, stellar masses and star formation rates of disks, and the kinematics and number density profiles of stellar haloes.

USING THE method of Leonard & Tremaine from 1990, Monari et al. (2018) used the Gaia DR2 data to estimate the escape speed over a range of Galactocentric radii from 5–10.5 kpc, based on an assumed distance of the Sun from the centre of the Galaxy of $R_0 = 8.34$ kpc, a circular velocity at the Sun of $\Theta_c = 240\,\mathrm{km\,s^{-1}}$, and specific values for our 'peculiar' solar motion with respect to the local standard of rest.

They used the velocity distribution of 2850 counter-rotating halo stars within 5 kpc, with distance errors below 10%, and with known line-of-sight velocities; the choice of counter-rotating stars is to ensure that the kinematic tail is representative of the stellar halo. They showed that the escape velocity decreases with Galactocentric radius, as expected in any reasonable Galactic potential, with a value at the Sun of $580\pm63\,\mathrm{km\,s^{-1}}$.

Current models of our Galaxy's structure typically comprise a bulge, a disk, and a dark matter halo. Interpreted in the context of the Navarro–Frenk–White dark matter halo profile, and using the mass–concentration relation of ΛCDM cosmology, gave the model parameters $M_{200} = 1.55^{+0.64}_{-0.51}\times10^{12}M_\odot$ and $c_{200} = 7.93^{+0.33}_{-0.27}$ (along with the uncertainty bands shown in the figure).

FURTHER ANALYSIS using DR2 was made by Deason et al. (2019). They used the inferred assembly history and phase-space distribution of halo stars to constrain the high-velocity tail of the stellar halo.

They found it to be strongly dependent on the velocity anisotropy and number density profile of the halo stars, with highly eccentric orbits having more extended high-velocity tails. Indeed, halo stars in the solar vicinity are known to have a strongly radial velocity anisotropy, considered attributable to the early accretion of a massive dwarf satellite galaxy of around $10^9M_\odot$.

Accordingly, and from their sample of 2300 (also counter-rotating) stars within 3 kpc, of which 240 have $v_{\rm tot} > 300\,\mathrm{km\,s^{-1}}$, they determined a local ($R_0 = 8.3$ kpc) escape speed of $528^{+24}_{-25}\,\mathrm{km\,s^{-1}}$, which they then also used to estimate the total Milky Way Galaxy mass, $M_{200} = 1.00^{+0.31}_{-0.24}\times10^{12}M_\odot$, and dark halo concentration parameter, $c_{200} = 10.9^{+4.4}_{-3.3}$.

A LARGER sample of $10^7$ halo stars, selected on the basis of their distances, photometry and proper motions, was similarly used by Koppelman et al. (2021). Their much larger sample provides a more *precise* estimate of the escape velocity, of $497\pm8\,\mathrm{km\,s^{-1}}$, which they estimate is biased low by 10%, yielding a true escape velocity most likely closer to $550\,\mathrm{km\,s^{-1}}$. Then assuming $\Theta_c = 232.8\,\mathrm{km\,s^{-1}}$, and correcting for their estimated bias, they derived $M_{200} = 1.11^{+0.08}_{-0.07}\times10^{12}M_\odot$, and $c_{200} = 11.8\pm0.3$. We can conclude, at least, that estimates of the Galaxy's escape velocity seems to be converging on a Milky Way mass of about $10^{12}M_\odot$.

DO THESE latest results have any implications for ongoing dark matter detection experiments, where the exclusion limits are affected by assumptions on the local dark matter escape velocity, the local dark matter density, and the circular velocity of the Sun?

Wu et al. (2019) found that the astrophysical uncertainties are, again, dominated by the uncertainty in the escape velocity at dark matter masses below 6 GeV, and can lead to a variation of 6 orders of magnitude in the exclusion limits at 4 GeV. They nonetheless found that the best-fit value for the escape velocity from Monari et al. (2018) leads to only minor changes on, e.g., the Gran Sasso XENON1T exclusion limits (Aprile et al., 2017).