The Development of Interstellar Meteoroid Streams

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Abstract

The origins of interstellar material and the details of its transport throughout the Galaxy are unknown but have wide-ranging implications. This material could seed the formation of planets in newly forming planetary systems while also dispersing chemical elements, organic molecules, or even life between star systems. This work models stellar systems ejecting macroscopic material within a simulated Milky Way. We analyze the motion of the ejecta as the material evolves into galactic "meteoroid streams" and then disperses, for hypothetical disk, bulge, and halo sources.

Goals

1. Provide a qualitative discussion of the behaviour of galactic meteoroid streams developing from a disk, bulge, and halo star
2. Establish the time it takes for the stream to extend over a scale comparable to the Galaxy (the "development time")
3. Compute the stream lifetime (the "dispersal time"), that is, how long a stream maintains its coherence before dispersing into the background "sporadic" population

Methods

The development and dispersal times may not have unambiguous definitions, we seek here primarily order of magnitude estimates:

$$t_{dev} = \frac{\pi\langle R_* \rangle}{v_{eject}} \qquad d_{r,v} \equiv \frac{\sigma_{r,v}}{\langle R_*, v_* \rangle}$$

$$t_{\text{Not Dispersed}} = t \text{ where } d_{r,v} < 0.5$$

$$t_{\text{Marginally Dispersed}} = t \text{ where } 0.5 \le d_{r,v} \le 1.0$$

$$t_{\text{Dispersed}} = t \text{ where } d_{r,v} > 1.0$$

Results

Table 1. The Origin Systems Used in The Simulations.

System	Galactocentric Position, $\vec{r}$ (AU)	Galactocentric Velocity, $\vec{v}$ (AU yr^{-1})	References
(1)	(2)	(3)	(4)
Sol	$-1.718185846475000 \times 10^9$	2.341583968361083	See Table 1[a]
	0.000000000000000	48.57003607609666	
	$5.569149802500000 \times 10^6$	1.52941295230791	
Bulge Star (*BS*)	$-1.037615760251184 2\times 10^7$	2.288884912688038	[1][b]
	$1.964744522935719 \times 10^6$	36.32352783244606	
	$8.734721908737150 \times 10^7$	30.55205404660455	
Halo Star (*HS*)	$-1.707790998206051 \times 10^9$	−50.95038424939479	[1][c]
	$-3.687409284554012 \times 10^5$	−9.575114433357243	
	$1.282093806311294 \times 10^7$	12.22017314800804	

Note—

a) Values from Table 1 are used to create a galactocentric coordinate system and *Sol*'s location within it.

b) The ICRS coordinates of *Gaia DR3 4060311556013654272* were taken from SIMBAD, chosen as it resides in the bulge (Lebzelter, T. et al. 2023). This was then converted to our galactocentric coordinates.

c) The ICRS coordinates of *HD 140283* were taken from SIMBAD, chosen as it resides in the halo (Bond et al. 2013). This was then converted to our galactocentric coordinates.

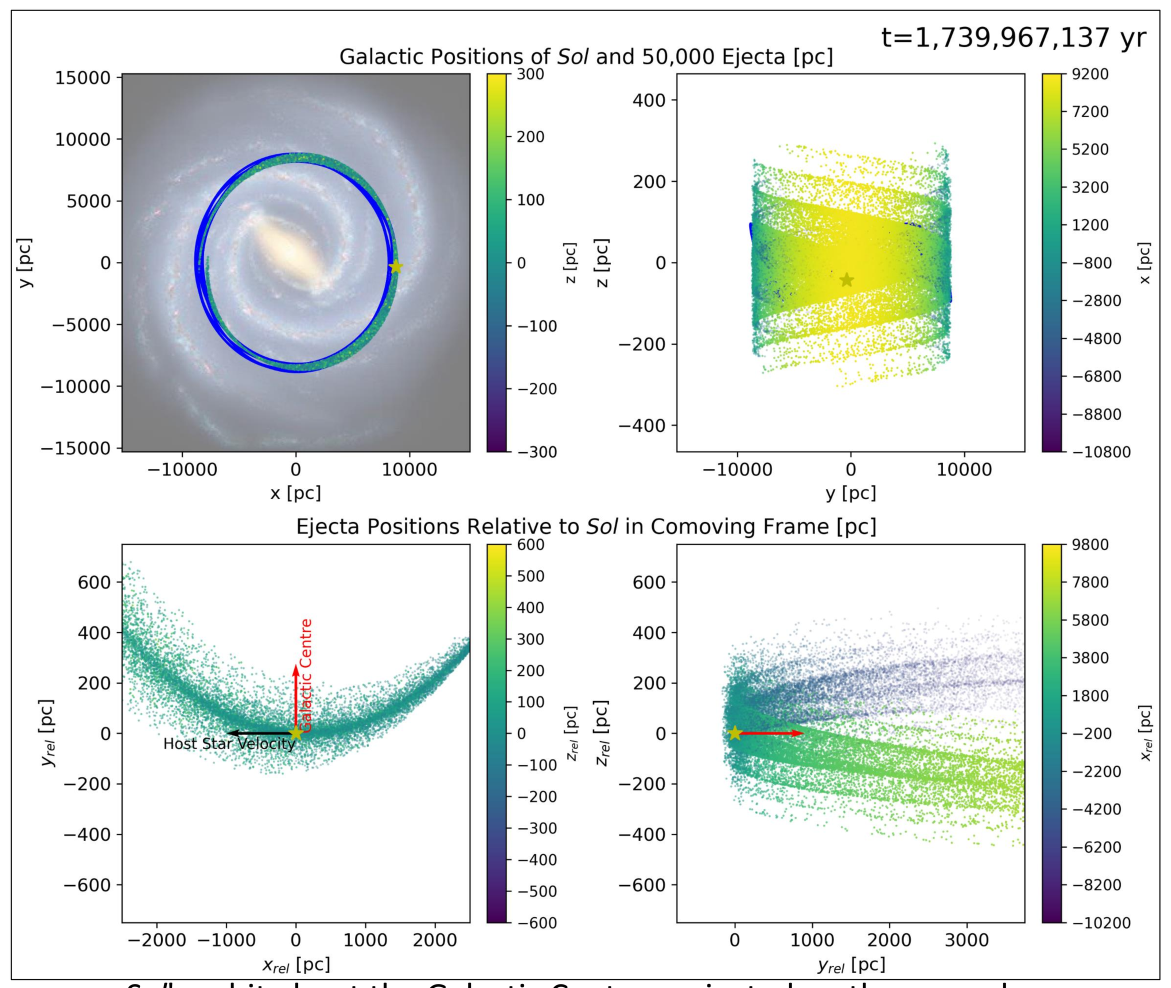
References— [1] Wenger et al. (2000)

Disk Star (*Sol*)

Sol ejects 50,000 particles and is advanced 4 Gyr with a time step of 2000 yr. The behaviour seen can be understood in terms of the epicycle approximation of galactic dynamics, useful in describing nearly-circular orbits in an axisymmetric potential. The motion in the *R* and *z* coordinates is approximately that of harmonic oscillators which oscillate at a radial (or epicycle) frequency (κ) and a vertical frequency (ν) respectively, where these may not be equal or even commensurate.

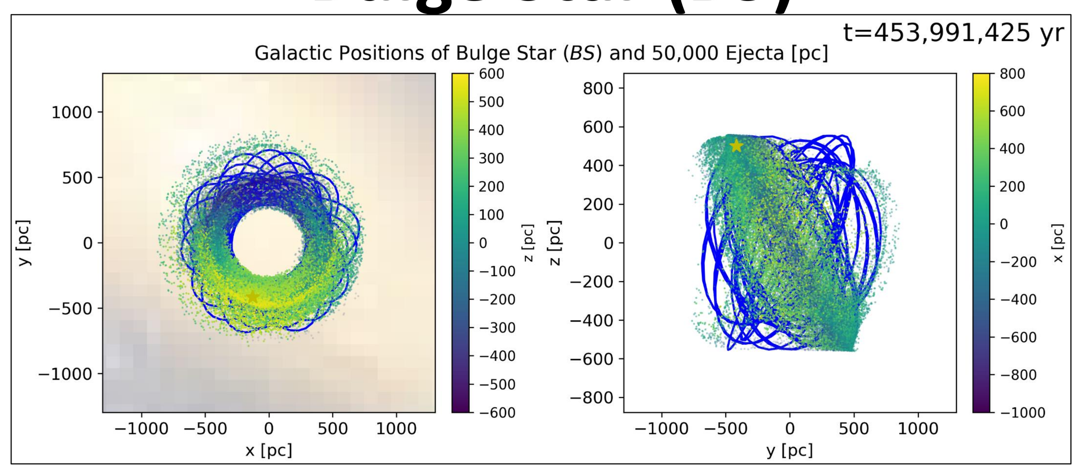
$$\kappa^2 \equiv \left(\frac{\partial^2 \phi_{\text{eff}}}{\partial R^2}\right)_{(R_g,0)} \qquad \nu^2 \equiv \left(\frac{\partial^2 \phi_{\text{eff}}}{\partial z^2}\right)_{(R_g,0)}$$

Variations in these introduce a banding structure in the evolution of this stream as we see material with different vertical and epicyclic frequencies slowly separating. The non-linearity of the oscillation plays a key role here.



Sol's orbit about the Galactic Centre projected on the *xy*, and *yz* planes (top row), as well as the orbits of the ejecta viewed in a comoving frame (bottom row).

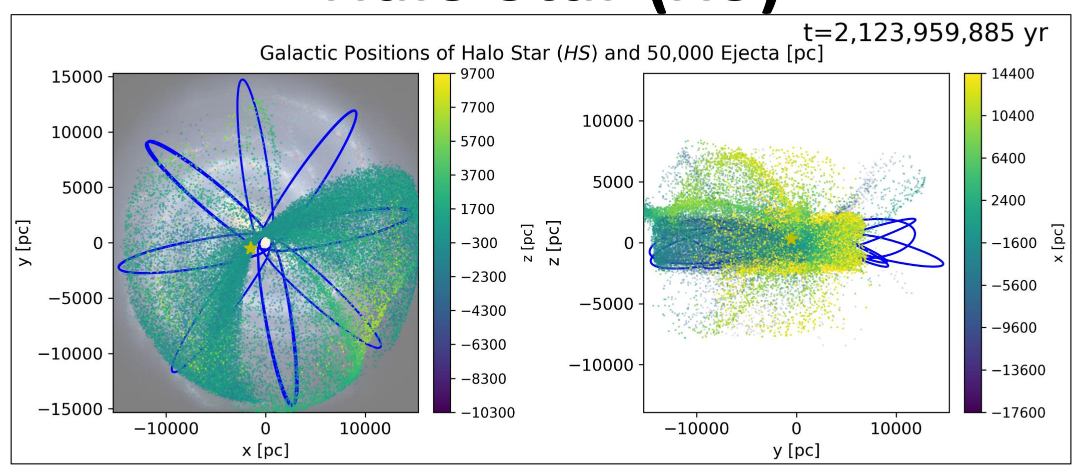
Bulge Star (*BS*)



BS's orbit about the Galactic Centre projected on the *xy*, and *yz* planes.

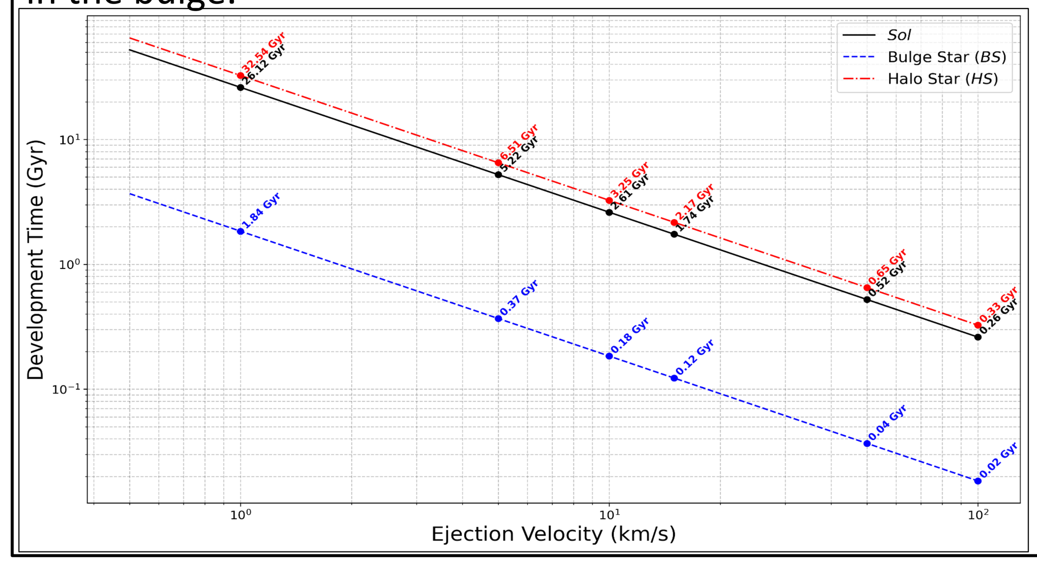
BS ejects 50,000 particles and is advanced 1 Gyr with a time step of 1000 yr. Quickly after the stream reaches development, it diverges and begins to envelop the majority of it's orbital space in an increasingly incoherent way. The ejected material quickly become a part of the background population of interstellar objects in the bulge.

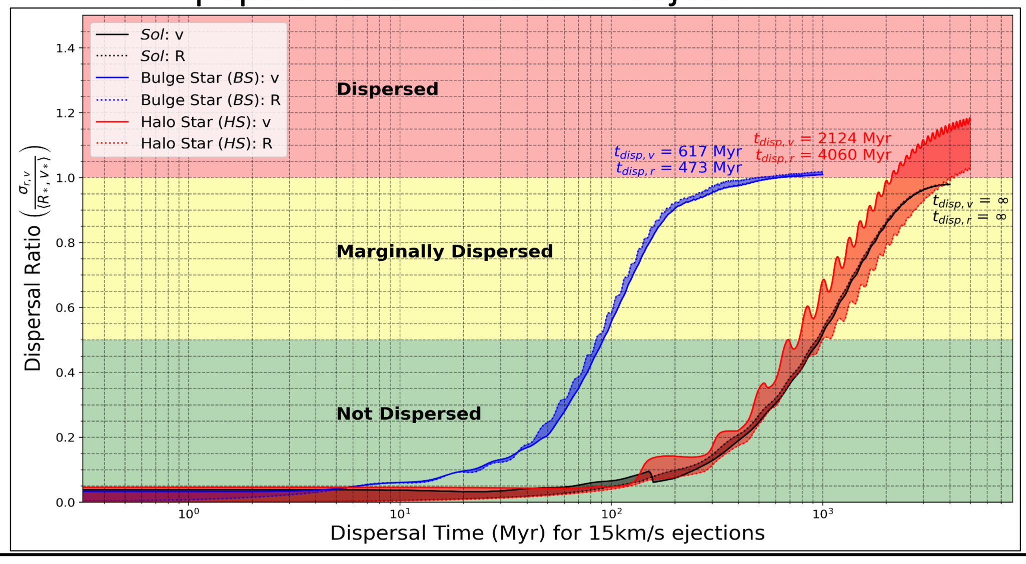
Halo Star (*HS*)



HS's orbit about the Galactic Centre projected on the *xy*, and *yz* planes.

HS ejects 50,000 particles and is advanced 5 Gyr with a time step of 4000 yr. We see development and dispersal times of the same order of magnitude, meaning that coherent streams are not likely in the halo, at least not at these ejection speeds. Material ejected from halo stars quickly becomes a part of the background population of interstellar objects.





View the full animations here!

Conclusions

This work examines the basic evolution of galactic meteoroid streams originating from disk, bulge and halo stars. Time scales needed for the development of Galaxy-spanning meteoroid streams, as well as for their dispersal, are determined. For disk stars, their cloud of ejected particles develops in a manner analogous to what is seen for cometary-produced meteoroid streams in the Solar System.

Implications

For near-circular orbits in the disk, coherent meteoroid streams can be long lived. Mismatched galactic frequencies, κ and ν, result in a variety of different radial and vertical oscillatory periods and create a banded structure within the stream. Material ejected in the distant past can return to the vicinity of its origin system and could in principle even be observed as an "interstellar" visitor.

Bulge and halo star systems primarily contribute to the "sporadic" population of interstellar objects.

Future Work

Though the flux of interstellar material into our Solar System may be low, it is not zero. And as global observational capabilities grow, the number of known interstellar objects will only increase, particularly with new large-scale surveys like the Vera C. Rubin Observatory coming online. This work is only a very early step in understanding what will undoubtedly become a rich field of exploration in the near-future.

Acknowledgements: This work was supported in part by the NASA Meteoroid Environment Office under Cooperative Agreement No. 80NSSC21M0073, and by the Natural Sciences and Engineering Research Council of Canada (NSERC) Discovery Grant program (grant No. RGPIN-2018-05659). This research has made use of the SIMBAD database, operated at CDS, Strasbourg, France.