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PHYSICS

Kinematic and Thermodynamic Properties of the Galaxy

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We present the first detailed physically-based thermodynamic model of the Galaxy as obtained from high-resolution kinematical data from the inner stellar halo. We interpret the observed distribution of Hyper Velocity Stars (HVS) as a physical manifestation of the Maxwell-Boltzmann (M-B) probability distribution expected for a fully virialized galactic system existing in quasi-equilibrium with its surroundings. The conventional view is that the HVS sample originates from chance gravitational encounters that have attained enough speed to escape the Galaxy. We counter that the HVS population is created by thermodynamic effects and link the observed mid-disk velocity peak with the M-B most probable velocity VPeak ≈ Vmp=432 km/s. Most of the HVS population originates at the Galactic virialization radius of 23 kpc with the current observed sample reproducing the M-B distribution with fidelity.

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INTRODUCTION

Hyper Velocity Stars (HVS) have become a valuable tool to constrain the total dynamic mass of the Milky Way. We investigate a thermodynamic origin for the HVS population and compare it against popular ejection (slingshot) mechanisms. We perform a combined analysis (HVS sample and stellar halo kinematics) and comfortably fit a Maxwell-Boltzmann distribution to these data sets, a result consistent with virialized Galaxy models. In this paper, we advance a physically-based approach conveniently termed the Rotation Curve-Spin Parameter (RC-SP) model to distinguish it from ΛCDM.

THE VIRIAL GALAXY

The RC-SP solution employs a baryonic-based interpretation based on the spin parameter equation, and includes angular momentum and total energy associated with the Galactic "state" (Peebles 1971) (La Fortune 2016). In addition to obtaining galactic dynamics from extended rotation velocity profiles, this paper strengthens the RC-SP model via precision measures of inner stellar halo component dispersion velocities and HVS "escape velocity" analysis. The RC-SP approach is based on two classical equations, the Virial Theorem and Newton's second law for circular motion. The Virial Theorem is expressed below and includes the constraint which limits the theorem to isolated, self-gravitating systems in "equilibrium" and is equally applicable to dark matter halos or baryonic disks. Only two parameters are required to determine the global "system" properties of galaxies, RVirial and VEsc (where RVirial ≈ RDisk):

$$M_{Dyn} \equiv M_{DM} \cong \frac{R_{Virial}\, V_{Esc}^{2}}{G};\ with\ PE = 2KE$$

Although Newtonian dynamics ensures VCirc = VEsc/√2 at RVirial, it cannot provide a defined VCirc profile as a function of radius. ΛCDM theory removes this difficulty as dark matter halos conveniently have constant VCirc (flat virial halo rotation) permitting use of Newton's second law for circular motion:

$$M_{DM} = \frac{R_{Virial}\, V_{Virial}^{2}}{G}\ ;\ with\ V_{Virial} \equiv V_{Circ} = constant$$

This substitution effectively decouples galactic VEsc (and by association, VCirc) from any significant baryonic influence. Rather than constraining VCirc to a theoretical value throughout RVirial, we treat VCirc as a *direct observable,* now possible with the availability of accurate component velocities measured between 6 and 30 kpc, a region spanning both the inner and outer Galactic disks (King III 2015). In following sections we explore the implications of non-flat circular velocity against the latest, most sophisticated ΛCDM simulations. We leverage the unbound Hyper Velocity Star (HVS) population to estimate Galactic VEsc and provide a physical (classical) origin and explanation for King's recently discovered kinematic feature.

GALACTIC ROTATION – RC-SP VERSUS ΛCDM MODELS

In this section, we examine a well-cited rotation curve from Bhattacharjee augmented with data from Bajkova and Bobylev. This composite rotation curve is reproduced in Figure 2. Included are three ΛCDM models, labeled 1, 2, and 3 from the original figure (Bajkova 2016). The RC-SP Galactic rotation curve fit is shown by the black dash. This curve fit is based on observed velocities within the disk (R≤40 kpc) and the Keplerian decline beyond. Into the original figure, we have inserted a model of King's velocity peak (gray dash) where observations are entirely missing. As shown below, all three ΛCDM rotation curves smoothly span this range, perhaps unaware of the recent discovery of this kinematic feature.

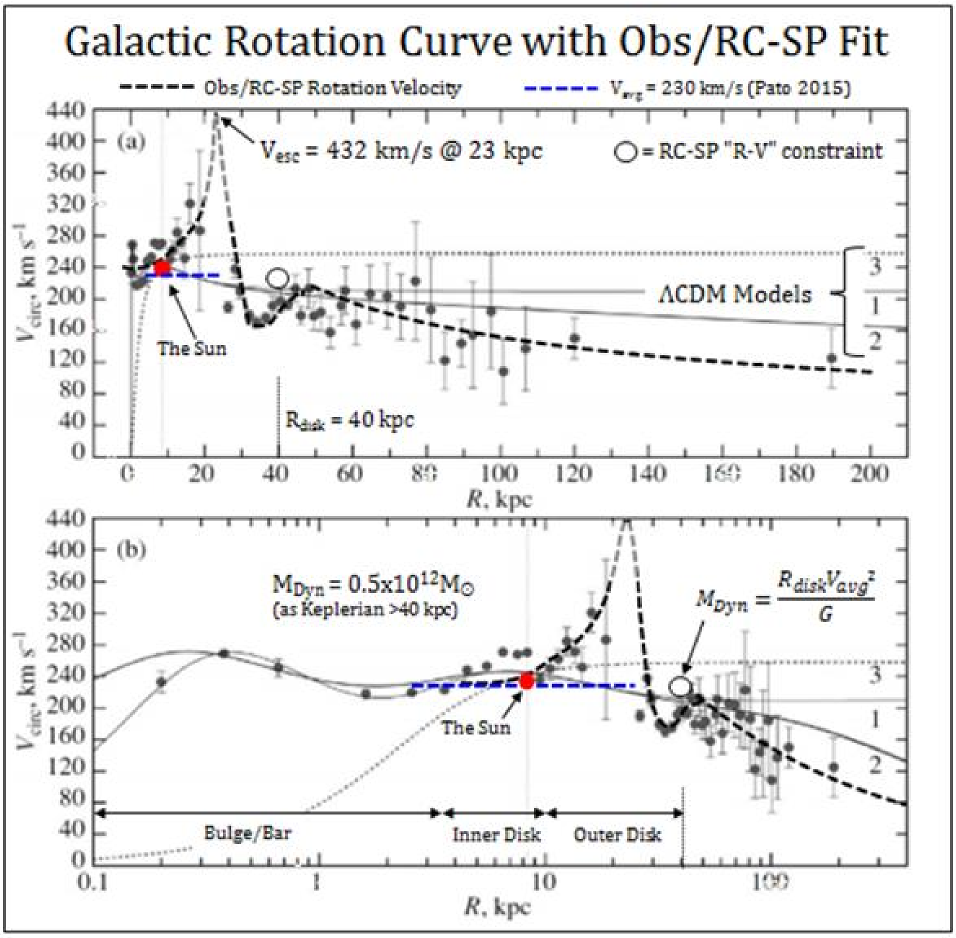

Figure 1: Galactic rotation curve from Bhattacharjee, Bobylev and Bajkova. Panel (a) illustrates the Obs/RC-SP integrated rotation profile (black dash). Prominent kinematic features include a spike in rotation to escape velocity (gray dashed) and a Keplerian decline beyond the Galactic disk. ΛCDM models are identified 1, 2 and 3 (see Bajkova ref. for details). Panel (b) is a semi-log version of panel (a). This view provides the specific R-V combination (open circle) corresponding to the RC-SP Galactic dynamic mass. This mass is obtained from the fit (Keplerian decline) beyond 40 kpc. The average rotation velocity (blue dash) and the Sun's velocity and position (red dot) is provided for reference. Image source – Fig.1 (Bajkova 2016)

In the above figure, all three ΛCDM models conflict with the Galaxy data especially at outer radii where it is evident that a conventional Keplerian decline provides a better fit than the flat rotation prediction (Sofue 2015) (Huang 2016). The gray dashed curve in the region of Bajkova's missing data is based on a recently measured kinematical feature in the inner stellar halo. We challenge the notion this feature is a perturbative/ transient halo artifact, contending it is long-lived and thermodynamic in origin.

OBSERVED KINEMATICS OF THE GALACTIC STELLAR HALO

The kinematics of the stellar halo serves as a sensitive probe of Galactic dynamics especially within ΛCDM cosmology where the stellar and dark matter halos share the same space. We examine in detail the properties of the stellar halo recently obtained from King's high precision component velocity dispersion survey spanning 6 to 30 kpc.

Our focus is a previously identified kinematic feature termed the "tangential dip." New observations have resulted in this dip becoming a significant trough, creating more tension between galactic kinematics and ΛCDM and MOND model expectations. The main take-away is that this this stellar feature should not be discounted or ignored within any truly accurate model of the Galaxy.

Figure 2 shows King's component velocity dispersion results (R, φ, and θ). We have annotated King's data with isotropic dispersion (black dash) corresponding to a central baryonic mass MBar = 0.085×10^{12}MΘ and average Galactic rotation velocity (blue dash). The lower right-hand panel provides the anisotropy coefficient β, demonstrating the extremity of this "dip" that translates to high velocity circular orbits.

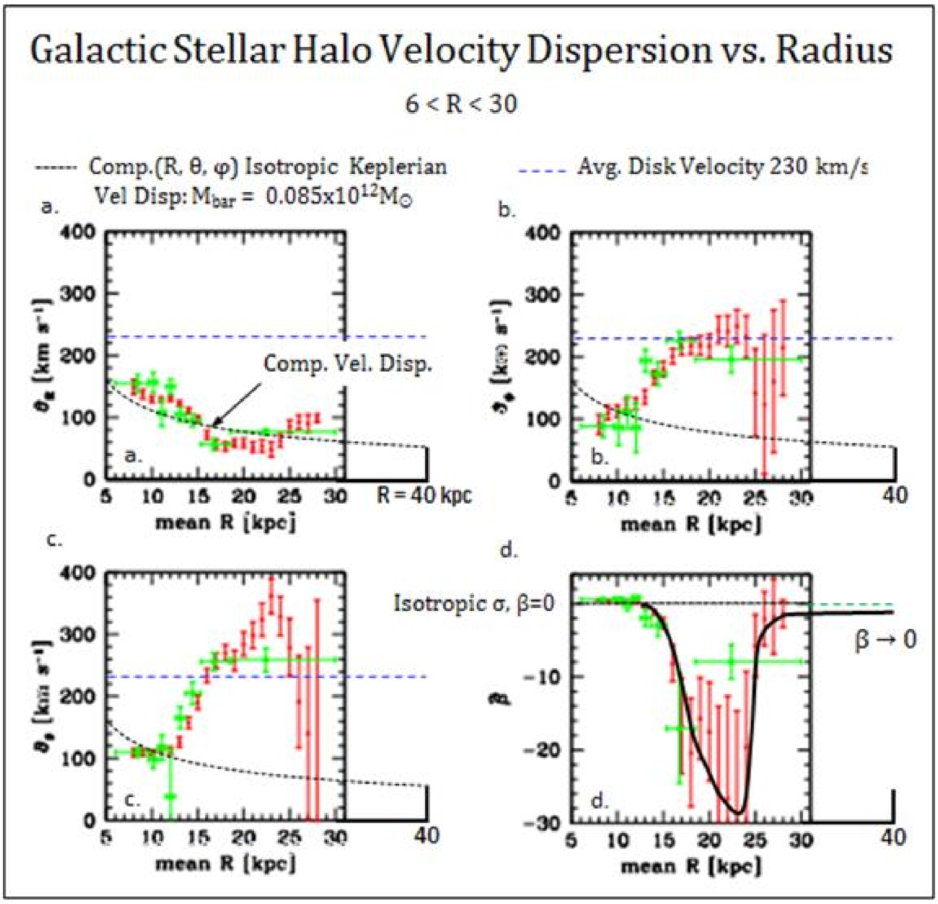

Figure 2: a., b., and c. panels provide observed velocity dispersions for radial, polar and azimuthal components. Included with the original data is the MW average disk rotation velocity VCirc = 230 km/s (blue dash) and the isotropic baryonic 'point mass' curve (black dash). In the

lower right panel, Extreme depression in anisotropy coefficient, $\beta = [1-(\sigma\theta^2+\sigma\varphi^2)/2\sigma R^2]$ denotes a spike in highly tangential orbits near mid-disk. To date, this kinematic substructure has not been incorporated into ΛCDM models of the Galaxy. Image source - Fig. 10 (King III 2015)

The dynamic mass distribution within the Galaxy is roughly traced as the net positive difference in velocity between the baryonic isotropic curve (black dash) and particular dispersion components. We find very little velocity support from the radial, with azimuthal and vertical components being dominant. This particular kinematic substructure cannot be reproduced within the context of the theoretical properties of dark matter halos.

In the next section, we next construct a dynamical model that relies on this complex but subtle kinematic substructure. We combine King's results with those obtained from Hyper Velocity Star (HVS) surveys to construct a physically consistent (kinematical, dynamical, and thermodynamical) model of the Galaxy. Note we emphasis a single RC-SP Galaxy model based on *observation* rather than simulation ad hoc "best fits."

HYPER VELOCITY STAR ORBITAL PARAMETERS

In this section, we advance a thermodynamic origin for the observed population distribution of Hypervelocity Stars (HVS). This unbound stellar population of stars is receiving attention as a method to quantify the dynamic (or dark matter halo) mass of the Galaxy. Currently, the HVS population is thought to acquire extreme velocities through intense gravitational ejection mechanisms deep inside the Galactic core (Tauris 2015) (Fragione 2016a) (Rossi 2016) (Fragione 2016b). Dynamic masses obtained by ejection mechanisms rely on "chance" encounters (constrained to the Galactic center) and complex three-body gravitational interactions to obtain a HVS model population. Figure 3 shows the HVS sample space against four dark matter halo mass models (see inset). In this figure, Fragione regarded stars VObs >275 km/s as "unbound" and a HVS candidate. To this original figure, we include King's summed component velocities in quadrature (blue dash) with its measured peak velocity of 432 km/s at 23 kpc. Just beyond the peak, we find Galactic velocities plunge into a conventional Keplerian decline beyond the baryonic disk equivalent to MDyn = 0.5 $\times 10^{12}$Mʘ and not the excessively high dark matter halo masses depicted.

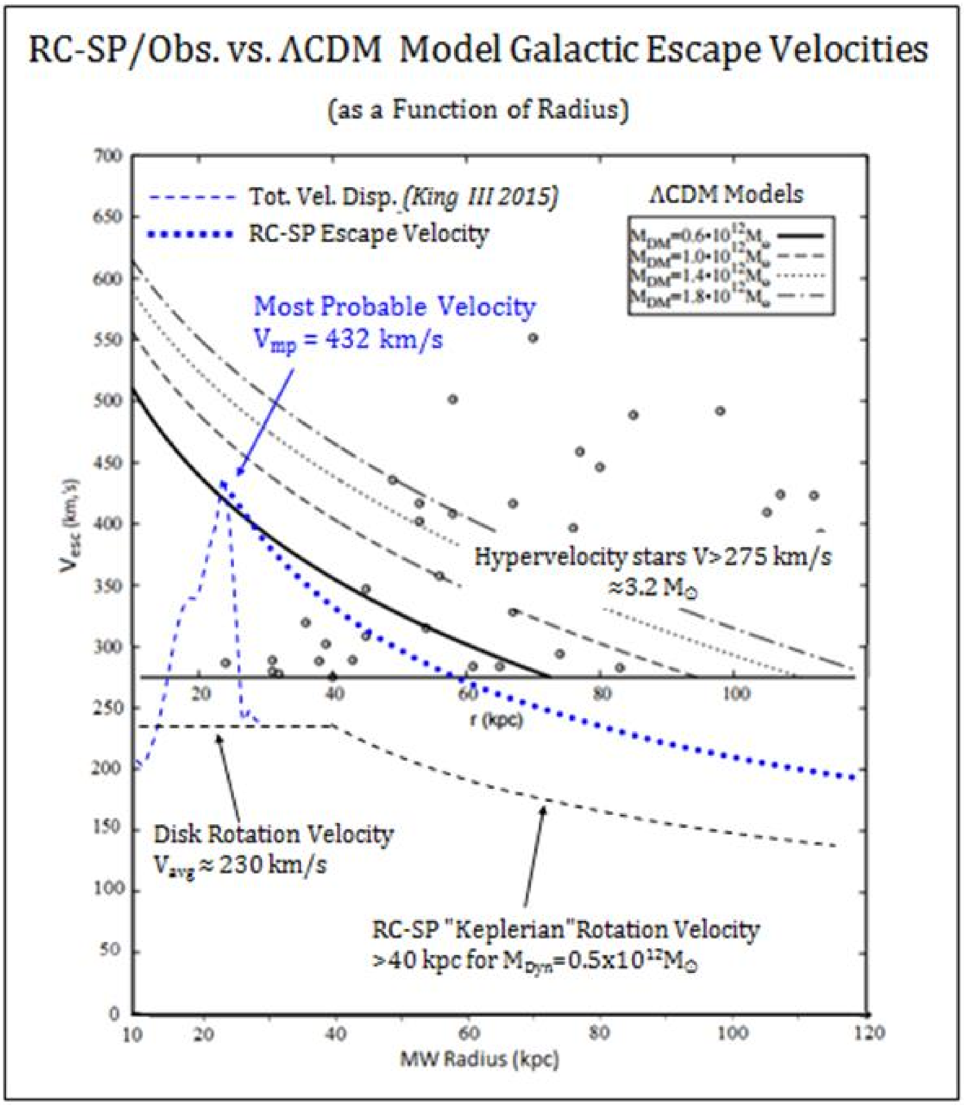

Figure 3: Hypervelocity star sample population R-V space for the MW compared against RC-SP radial escape velocity profile (bold blue dotted) and four dark matter halo models from Fragione (various black - see inset for details). King III quadrature summed velocity dispersion components (blue dashed spike).As the MW is a virialized system, we assign the MW's 432 km/s peak as the Maxwell-Boltzmann "most probable" velocity. RC-SP parameterized average disk and Keplerian decline (both black dashed) as labeled. Image source – Fig 2 (Fragione 2016a)

The above figure highlights an issue which has been plaguing ΛCDM cosmology since inception, the tremendous insensitivity between halo properties and observation. Due to this lack of connection and high uncertainty between the dark matter and baryonic constituents, a particular halo model with a halo mass between 1.2 – 1.7 x10^{12}Mʘ could only be "favored" over the others. In effect, halo mass uncertainty is equivalent to the RC-SP dynamic mass of the entire Galaxy. From Figure 3, we certainly observe a link between VPeak at 23 kpc as the virial radius of origin for the HVS population. As such, the HVS sample should be distributed based on thermodynamic considerations. The next step is to assign a *physical mechanism* responsible for this particular profile for the HVS sample population – the Maxwell-Boltzmann probability distribution.

A THERMODYNAMIC SOLUTION TO EXPLAIN HVS SAMPLE/POPULATION STATISTICS

In this section we focus on the Maxwell-Boltzmann form and define peak velocity equivalent to the most probable velocity Vmp = 432 km/s within the distribution with (Wu 2014):

$$x = \frac{V}{V_{mp}}; \quad P(x) = \frac{4}{\sqrt{\pi}} x^2 e^{-x^2}$$

Figure 5 below compares Rossi's expectation for the HVS velocity distributions (red dash and solid black) based on the gravitational ejection model. As it appears, the dearth of data beyond the peak indicates a narrow distribution at high velocities directly attributable to the very deep gravitational well of the dark matter halo. The M-B distribution (blue dash) shows a significant high velocity tail should be present.

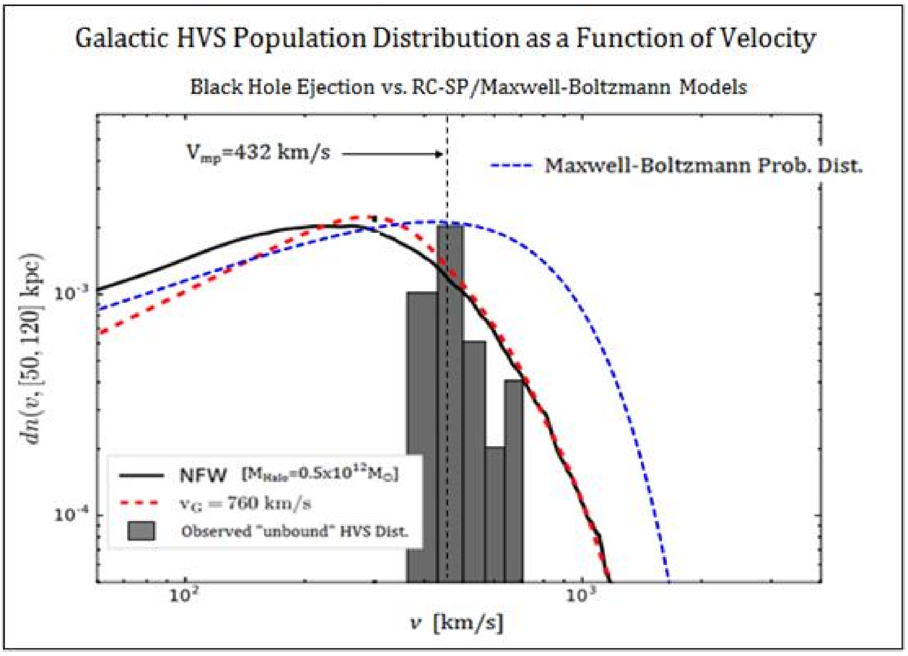

Figure 4: HVS probability density functions per black hole ejection schemes (solid black and red dash). Observed "unbound" late B-star (~3.5 MΘ) HVS distribution (gray histograms) from Brown 2014. The alternative RC-SP/Maxwell-Boltzmann probability distribution (blue dash) is based on most probable velocity Vmp=432 km/s (black dash) with arbitrary vertical scale. Image source - Fig. 3 (Rossi 2016)

As shown above, Rossi contends that the linear decline in HVS distribution in the low velocity tail is expected. We find the M-B distribution (blue dash) in this region is actually more linear than either ejection model, but no true discrimination between models is possible < 432 kms^{-1}.

At the high velocity end of the distribution, Rossi contends the steep decline in the model is real with HVS becoming increasing rare at higher velocities. We contend it is the high velocity tail of the HVS distribution that distinguishes the M-B solution over chance gravitational encounters. In Figure 6 below, we expand the HVS sample distribution beyond ≈400 km/s by including lower stellar mass G/K dwarfs (Tauris 2015). In the figure below, the absence of HVS < 350 km/s is due to arbitrary truncation of the data.

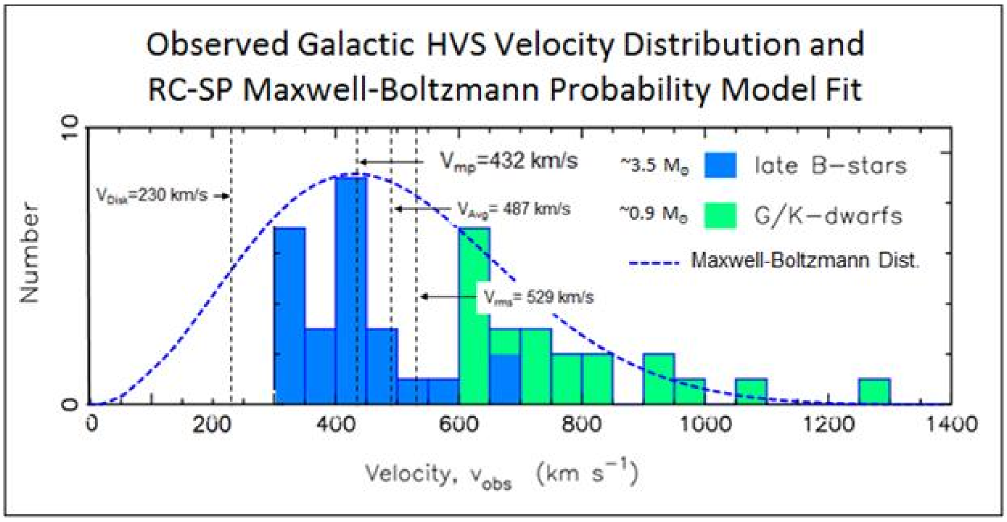

Figure 5: Velocity distribution of HVS late B-type (blue histograms) and G/K-dwarfs (green histograms) with respect to the Galactic rest frame. The combined data traces the M-B probability distribution (blue dash) for a most probable velocity, Vmp= 432 km/s. The M-B vertical scale is matched to the data for comparative purposes. The M-B average velocity is VAvg = 487 km/s and root-mean-squared Vrms=529 km/s. This latter value is near the oft cited global Galactic escape velocity of 550 km/s. Image source - Fig. 1 (Tauris 2015)

We find HVS stellar mass tracks well with the M-B solution, with lighter G/K dwarfs exhibit greater net velocity than heavier late B-stars, accurately tracing the overall M-B distribution and the magnitude of escape velocities in relation to King's velocity dispersion results. Of course, the stellar universal Initial Mass Function (IMF) needs to be considered as it directly influences the mass of the star that could become a HVS candidate, i.e., the IMF exhibits a peak in stellar mass between 0.2Mʘ to 4Mʘ (Baldry 2003) (Offner 2014). We would expect the M-B distribution would become fully "occupied" but this (to date) is not the case. Either the missing data is due to severe under-sampling or a more subtle effect not yet fully understood.

This thermodynamic interpretation is physically consistent with a virialized, quasi- equilibrium system in highly ordered motion (Struck 2016). Struck interpreted this ordered motion as "free energy" that will be thermalized in the future. We contend ordered galactic motion is "potential energy" contributing to total dynamic mass today.

CONCLUSIONS

Recent data suggests the Galaxy is an open thermodynamic "system" in quasi-equilibrium with its external "surroundings." Under this model, we employ observed kinematics of the inner stellar halo and the latest sampling of Hyper Velocity Stars to indicate a thermodynamic origin without imposing any deviation from classical mechanics. Thanks to the Winnower for open access publishing, the research community and private communication that make this information available to the larger audience. This paper is dedicated to my dad.

APPENDIX – KING'S STELLAR INNER HALO VELOCITY DISPERSION

Radius (kpc)	σ_R	σ_θ	σ_ϕ	σ_{Tot}
1	- -	- -	- -	- -
2	- -			- -
3	- -			- -
4	- -	- -	- -	- -
5	150	110	80	202
6	150	110	85	205
7	150	110	90	207
8	150	110	100	211
9	140	110	110	209
10	135	110	115	209
11	125	110	120	205
12	125	110	140	218
13	120	120	160	233
14	115	150	175	258
15	100	190	190	287
16	80	230	200	315
17	50	250	215	334
18	50	260	215	341
19	50	260	215	341
20	50	280	220	360
21	50	295	240	384
22	50	320	240	403
23	50	360	245	438
24	60	320	230	399
25	80	280	140	323
26	90	190	120	242
27	92	140	185	250
28	94	130	180	241
29	96	120	188	243
30	98	115	140	206

$$\sigma_{Total} = \sqrt{\sigma_R^2 + \sigma_\theta^2 + \sigma_\phi^2}$$

[1] *component values manually obtained from Fig. 10 (King III 2015)*

BIBLIOGRAPHY

Bajkova, A.T., Bobylev, V.V. "Rotation Curve and Mass Distribution in the Galaxy from the Velocities of Objects at Distances up to 200 kpc." *arXiv*, Jul 27, 2016: http://arxiv.org/pdf/1607.08050v1.pdf.

Baldry, I., K., Glazebrook, K. "CONSTRAINTS ON A UNIVERSAL STELLAR INITIAL MASS FUNCTION FROM ULTRAVIOLET TO NEAR-INFRARED GALAXY LUMINOSITY DENSITIES." *The Astrophysical Jounal, 593:258-271*, Aug 23, 2003: http://iopscience.iop.org/article/10.1086/376502/pdf.

Fragione, G., Capuzzo-Dolcetta, R., Kroupa, P. "Hypervelocity stars from young stellar clusters in the Galactic Centre." *arXiv*, Sep 17, 2016b: https://arxiv.org/pdf/1609.05305v1.pdf.

Fragione, G., Loeb, A. "Constraining Milky Way mass with Hypervelocity Stars." *arXiv*, Aug 4, 2016a: http://arxiv.org/pdf/1608.01517v1.pdf.

Huang, Y., Liu, X.-W., Yuan, M.-S. et al. "The Milky Way's rotation curve out to 100 kpc and its constraint on." *arXiv*, Apr 5, 2016: http://arxiv.org/pdf/1604.01216v1.pdf.

King III, C., Brown W.R., Geller, M.J., Kenyon, S.J. "STELLAR VELOCITY DISPERION AND ANISOTROPY OF THE MILKY WAY INNER HALO." *The Astrophysical Journal, 813:89*, Nov 10, 2015: http://iopscience.iop.org/article/10.1088/0004-637X/813/2/89/pdf.

La Fortune, J.M. "The Baryonic Tully-Fisher Relationship: Empirical Evidence for a Baryonic Solution to the Galactic "Missing Mass" Problem." *The Winnower*, Jul 15, 2016: https://thewinnower.com/papers/4963-the-baryonic-tully-fisher-relationship-empirical-evidence-for-a-baryonic-solution-to-the-galactic-missing-mass-problem.

Offner, S.S.R, Clark, P.C., Hennebelle, P., et al. "The Origin and Universality of the Stellar Initial Mass Function." *arXiv*, May 19, 2014: https://arxiv.org/pdf/1312.5326v4.pdf.

Peebles, P.J.E. "Rotation of Galaxies and the Gravitational Instability Picture." *A&A, 11, 377-386*, Dec 1970 rec'd 23, 1971: http://articles.adsabs.harvard.edu/cgi-bin/nph-iarticle_query?1971A%26A....11..377P&defaultprint=YES&filetype=.pdf.

Rossi, E.M., Marchetti, T., Cacciato, M., Kuiack, K., Sari, R. "Joint constraints on the Galactic dark matter halo and Galactic Centre from hypervelocity stars." *arXiv*, Aug 5, 2016: https://arxiv.org/pdf/1608.02000v1.pdf.

Sofue, Y. "Dark Halos of M31 and the Milky Way." *arXiv*, Apr 12, 2015: https://arxiv.org/pdf/1504.05368.pdf.

Struck, C., Elmegren, B.G. "Near-exponential surface densities as hydrostatic, nonequilibrium profiles in galaxy discs." *arXiv*, Sep 28, 2016: https://arxiv.org/pdf/1609.08957v1.pdf.

Tauris, T.M. "Maximum speed of hypervelocity stars ejected from binaries." *MNRAS 448, 1 L6-L10*, Mar 21, 2015: http://mnrasl.oxfordjournals.org/content/448/1/L6.short.

Wu, Y-C., Y. "An Exploration of the Limits of the Maxwell-Boltzmann Distribution." *arXiv*, Oct 25, 2014: http://arxiv.org/pdf/1410.6965.pdf.