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GALACTIC HALO STARS IN PHASE SPACE: A HINT OF SATELLITE ACCRETION?

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ABSTRACT

The present-day chemical and dynamical properties of the Milky Way bear the imprint of the Galaxy's formation and evolutionary history. One of the most enduring and critical debates surrounding Galactic evolution is that regarding the competition between "satellite accretion" and "monolithic collapse"; the apparent strong correlation between orbital eccentricity and metallicity of halo stars was originally used as supporting evidence for the latter. While modern-day unbiased samples no longer support the claims for a significant correlation, recent evidence has been presented by Chiba & Beers for the existence of a minor population of high-eccentricity metal-deficient halo stars. It has been suggested that these stars represent the signature of a rapid (if minor) collapse phase in the Galaxy's history. Employing velocity and integrals of motion phase-space projections of these stars, coupled with a series of *N*-body/smoothed particle hydrodynamic chemodynamical simulations, we suggest that an alternative mechanism for creating such stars may be the recent accretion of a polar orbit dwarf galaxy.

Subject headings: galaxies: evolution — galaxies: formation — Galaxy: halo

1. INTRODUCTION

The "monolithic collapse" versus "satellite accretion" debate surrounding galaxy formation is a classic one. The former was best expressed by Eggen, Lynden-Bell, & Sandage (1962, hereafter ELS); supporting evidence for the ELS picture came from the apparent correlation between the eccentricity (ϵ) and the metallicity of halo stars. In contrast, by using a large and reliable set of data for halo objects chosen without kinematic bias, Chiba & Beers (2000, hereafter CB00) found no strong correlation between ϵ and metallicity. Bekki & Chiba (2000) showed that this lack of correlation is naturally explained by hierarchical clustering scenarios of galaxy formation. CB00 did, however, identify a concentration of stars of $\epsilon \sim 0.9$ and [Fe/H] ~ -1.7 and suggested that this population of stars formed from infalling gas during an early stage our Galaxy's formation, in a manner similar to an ELS collapse.

Current cosmological theories of structure formation have more in common with accretion-style scenarios, such as that envisioned by Searle & Zinn (1978). Evidence in support of satellite accretion during our Galaxy's formation can be found in the observations of considerable substructure in the halo (e.g., Ibata, Gilmore, & Irwin 1994; Majewski, Munn, & Hawley 1996; Helmi et al. 1999; CB00). Helmi & White (1999, hereafter HW99) noted that satellites disrupted several billions years ago will not retain the spatial correlations required to allow identification. However, they showed that the trail of stars left by a disrupted dwarf satellite will retain strong correlations in velocity space. Furthermore, the integrals of motion (E, L, L_z) are conserved quantities and should evolve only slightly within the relatively stable potential of a galaxy after its halo is virialized. This space of adiabatic invariants is a natural space to search for signatures of an accretion event (e.g., Helmi & de Zeeuw 2000, hereafter HZ00).

We were motivated to run a grid of chemodynamical simulations with the intention of contrasting the effects of the two collapse scenarios on the evolution of the Milky Way. The two models described here vary primarily in their degree of clustering, and we examine the properties of the resulting simulated galaxies in order to uncover present-day "signatures" of the models' initial conditions and evolution.

Details of our code and the models used in this study are provided in § 2. In § 3, we present the evolution and clustering histories of the simulated galaxies. We focus on the ϵ-distribution of our simulated galaxies' halo stars and on the comparison with observations. Tracing the evolution of stars originating in recently accreted satellite galaxies provides a clue to the source of high-ϵ halo stars. We next show that such stars occupy restricted regions of phase space, a signature of common ancestry. Similar analysis of the CB00 data set shows that the identified "clump" of high-ϵ low-metallicity halo stars occupies a similar restricted region of phase space. The implications for theories of galaxy formation and their observational signatures are discussed in § 4.

2. THE CODE AND MODEL

Our Galactic chemodynamical code (GCD+) models self-consistently the effects of gravity, gasdynamics, radiative cooling, and star formation. Type Ia and Type II supernova feedback is included, and the instantaneous chemical recycling approximation is relaxed. Details of GCD+ can be found in Kawata & Gibson (2003) and Kawata (2001).

The semicosmological version of GCD+ used here is based on the galaxy formation model of Katz & Gunn (1991). The initial condition is an isolated sphere of dark matter and gas, onto which small-scale density fluctuations are superposed, parameterized by σ_8. These perturbations are the seeds for local collapse and subsequent star formation. Solid-body rotation corresponding to a spin parameter λ is imparted to the initial sphere. For the flat cold dark matter (CDM) model described here, the relevant parameters include $\Omega_0 = 1$, $H_0 = 50$ km s^{-1} Mpc^{-1}, the total mass (5×10^{11} $M_\odot$), the baryon fraction ($\Omega_b = 0.1$), and the spin parameter ($\lambda = 0.0675$). We employed 38,911 dark matter and 38,911 gas/star particles, making the resolution of this study comparable to other recent studies of disk galaxy formation (e.g., Abadi, Navarro, & Steinmetz 2003). The two models described here differ only in the value of σ_8. In model 1 (M1), $\sigma_8 = 0.5$, as favored in standard CDM ($\Omega_0 = 1$) cosmology. In model 2 (M2), we explore the use of

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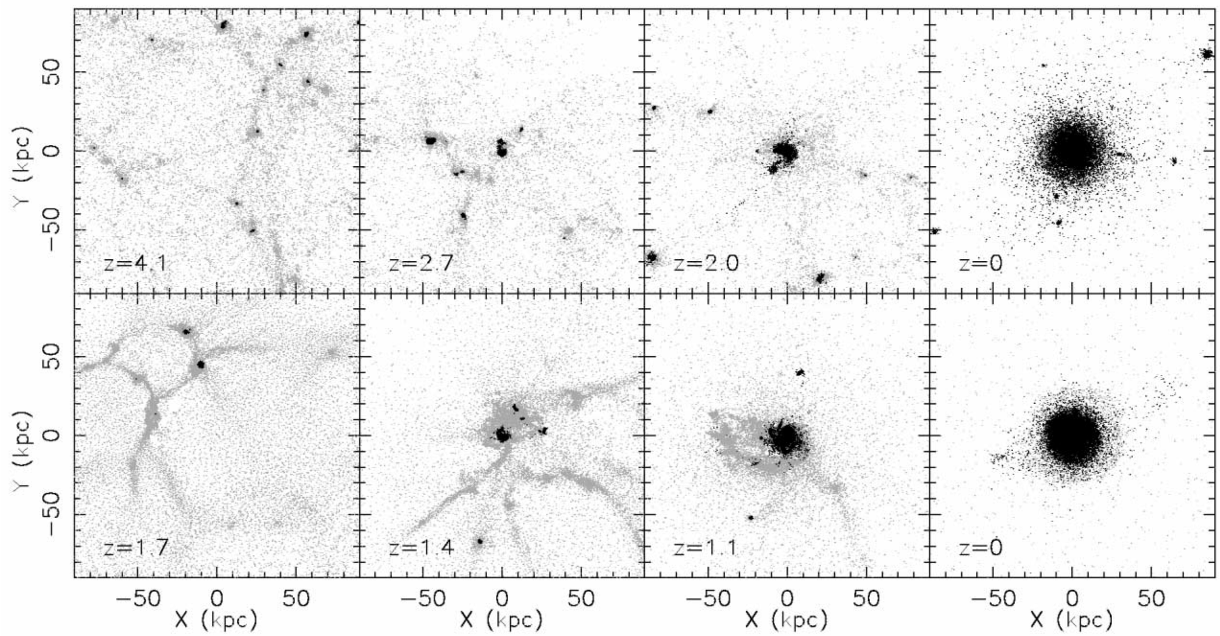

FIG. 1.—*X*-*Y* plots of M1 (*upper panels*) and M2. The *Z*-axis is defined to be the initial axis of rotation. The gray (black) dots represent gas (star) particles. Epochs are chosen (with redshifts labeled) so that roughly the same stellar mass is present in the corresponding upper and lower panels. Gas collapse and star formation are more centralized in M2.

a smaller value for σ_8 of 0.04, a value that results in a more rapid, dissipative, collapse.

3. RESULTS

Figure 1 illustrates the evolutionary histories of the two models. M1 demonstrates classical hierarchical clustering: gas collapses into the local dense regions seeded by the initial small-scale perturbation, with star formation occurring subsequently in these overdense regions. Stars continue to form in subclumps as well as in the central region as a disk galaxy is built up. We see less clumping in M2, with gas streaming homogeneously toward the center of the galactic potential, resulting in most of the star formation occurring in the central regions.

We analyzed the bulk properties of our simulation at $z = 0$ and confirmed that they were consistent with the simulations of Katz (1992), Steinmetz & Muller (1995), Berczik (1999), and Bekki & Chiba (2001). The predicted surface density profiles, metallicity gradients, specific angular momenta of gas and stars, and rotation curves for our models did not differ significantly from previous studies or between our own two models. We suffer from the same overcooling problem encountered in earlier studies (White & Frenk 1991). This results in too high rates of star production at early epochs, overly rapid metal enrichment, and a halo metallicity distribution function (MDF) peaked approximately 1 dex higher than that observed (Ryan & Norris 1991). The field of MDFs is the subject of a future, lengthier analysis, but we do note that this offset in the halo MDF peak does not impact on our analysis here (we can still adopt a differential metallicity cut to delineate between the halo and thin disk in our simulation). We did find a difference in the orbital ϵ-distribution of the simulated solar neighborhood halo stars of the two models. After Bekki & Chiba (2000), individual stellar eccentricities were calculated by allowing the orbits of star particles to evolve for 1.8 Gyr under the gravitational potential of the simulated disk galaxy achieved at $z = 0$. Eccentricities were then derived using $\epsilon = (R_{\rm apo} - R_{\rm peri})/(R_{\rm apo} + R_{\rm peri})$, where $R_{\rm apo}$ ($R_{\rm peri}$) is the apogalactic (perigalactic) distance from the center of the simulated galaxy. Halo stars are defined to be simulated star particles with [Fe/H] < -0.6. Due to the higher-than-expected absolute value for the halo MDF (alluded to earlier), this metallicity cut may lead to an underestimate of the halo population, but the final halo "sample" is representative.

The dotted (dashed) line of the histogram in Figure 2*a* shows the ϵ-distribution of halo star particles in the solar circle of M1 (M2). The solar circle is defined as an annulus of the galactic disk,[3] bounded by 5 kpc $< R_{XY} <$ 12 kpc and $|Z| <$ 2 kpc, where Z is the rotation axis and R$R_{XY} = \sqrt{(X^2 + Y^2)}$. Each bin shows the fraction of such star particles lying in a given ϵ-range. Also shown (*solid line*) is the observational constraint from CB00. M1 produced a greater number of high-ϵ ($\epsilon > 0.8$) solar circle halo stars and is in better agreement with observation.

Considering the analysis of ELS, whose rapid collapse model resulted in highly eccentric halo stars, it was not unreasonable to expect that the more dissipative, "monolithic" nature of the collapse of M2 would result in a higher number of high-ϵ halo stars. This prompted a more detailed examination of the collapse time of M2. Using analysis of the evolution of top-hat overdensities with the collapse redshift $z_c = 1.75$, which we adopt (Padmanabhan 1993), the collapse timescale $t_{\rm coll}$ of M2 is estimated to be ∼1.4 Gyr, thus not satisfying the conditions originally proposed by ELS ($t_{\rm coll} \ll t_{\rm sf}$, where $t_{\rm sf}$ is the star formation timescale). While encompassing the spirit of ELS within the current cosmological paradigm, M2 should not be considered an exact analog of the ELS rapid collapse scenario.

Since the difference between M1 and M2 is in the clustering

[3] The volume of our "solar circle" is roughly an order of magnitude larger than the analog employed in the CB00 data set. We have ensured that this apparent volume "mismatch" does not impact on our results by testing for sensitivity to azimuthal variations within the annulus by subdividing the simulated data set into random octiles. The phase-space effects described are robust to this azimuthal subdividing.

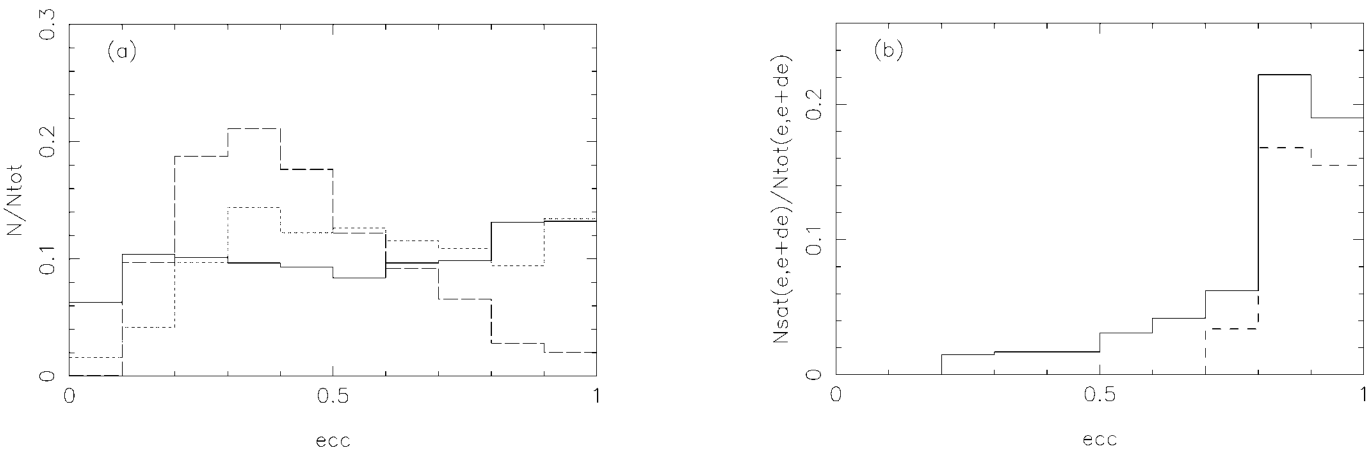

FIG. 2.—(*a*) Present-day ϵ-distribution of halo stars at the solar circle for our two models: The dotted (dashed) line represents M1 (M2). The solid line corresponds to the observational data set of CB00. M1 leads to a greater number of high-ϵ halo stars in the solar circle. (*b*) The solid line shows the ϵ-distribution of solar circle halo stars that were in satellites at redshift $z = 0.46$. The dashed line shows stars originating from a single such satellite (S1). The *y*-axis is normalized by the total number of star particles in each ϵ-bin (from panel *a*).

history, our result suggests that the Milky Way may have experienced significant clustering processes during its formation. To clarify this hypothesis, we examine the specific accretion history of each model, tracing the ϵ-distribution functions for the stars associated with each disrupted satellite. In M1, we identify two satellites at $z = 0.46$ that have merged into the halo of the host galaxy by $z = 0$. These are the final significant merger events in the simulated galaxy's formation. The largest such dwarf galaxy (hereafter S1), with a stellar mass of $\sim 10^9\ M_\odot$, was on a precessing polar orbit.[4] By $z = 0.26$, tidal forces had begun stripping stars from S1, and by $z = 0$, its stars were spread effectively throughout the halo.

The histogram of Figure 2*b* shows the ϵ-distribution of solar circle halo stars that originated in the satellites identified at $z = 0.46$. The *y*-axis is normalized by the total number of solar circle halo stars in each ϵ-bin. The dashed line represents those stars from S1. We notice that the majority of these halo stars are of high ϵ and that S1 in particular contributes ∼20% of all high-ϵ halo stars in the solar circle at $z = 0$.

In Figure 3, we plot the phase-space distributions of solar circle stars of M1. Figures 3*a*–3*c* show velocity directed radially away from the galactic center $V_{\rm rad}$ versus rotational velocity in the plane of the disk V_ϕ; velocity out of the plane V_z versus V_ϕ; and $V_{\rm rad}$ versus V_z. Figure 3*d* plots the integrals of motion, i.e., the projected angular momentum L_z versus the absolute value of the energy ($|E|$). Stars originating in S1 are marked as open circles. We see that such stars occupy a restricted region of phase space. It is worth noting that these results are qualitatively similar to those of HW99 and HZ00, both of which follow (at higher spatial resolution) the accretion of stars in a *static* potential, in which little disruption to the adiabatic invariants would be expected. Thus, our study confirms that these results hold when the formation processes of the galaxy are self-consistently simulated, and hence the potential in which the satellite is disrupted is dynamic. In fact, our final velocity phase-space distribution (Figs. 3*a*–3*c*) is reminiscent of the one in Figure 5 of HW99, bearing in mind that most of our stellar orbits will be at intermediate points between their pericenter and apocenter. Furthermore, the distribution of the disrupted stars in integrals of motion space (Fig. 3*d*) is in good qualitative agreement with those for the satellites in Figure 7 of HZ00.

Motivated by the high ϵ seen in the accreted satellite stars (Fig. 2*b*), we examined the phase-space distribution of the clump of high-ϵ metal-deficient halo stars identified by CB00. Figure 4 shows the sample of CB00 stars within 2.5 kpc of the Sun with $[{\rm Fe/H}] \leq -1$, plotted in the same phase-space projections as the simulated data in Figure 3. Highlighted by open circles are stars with $\epsilon > 0.8$ and $-2.0 < [{\rm Fe/H}] < -1.4$. A wider range of energies is seen in the observed data set, in comparison with the simulations shown in Figure 3*d*. The latter indicate that recently accreted satellite stars will be of higher energy (lower $|E|$) on average than halo field stars, since their stellar orbits will be less bound. We thus make an arbitrary cut in energy in order to separate the field stars from those we suspect come from an accreted satellite, and the new subset of stars are marked by filled circles. We notice immediately that these stars are more tightly confined in phase space and closely resemble the distribution of the accreted satellite in our simulation.

4. DISCUSSION

We have simulated self-consistently two models of the formation of a Milky Way–like galaxy using our *N*-body/smoothed particle hydrodynamic chemodynamical code GCD+. The models differ only in the amplitude of small-scale density perturbations σ_8 incorporated into the initial conditions. This results in different merging histories, which we then use to search for distinctive present-day chemical and kinematical signatures of the simulated galaxies' early formation epochs. In M1, stars form in local dense regions of gas, seeded by a value of σ_8 comparable to current CDM orthodoxy. The galaxy subsequently builds up via a series of mergers in the manner of standard hierarchical structure formation scenarios. A low value of σ_8 in M2 resulted in a more dissipative collapse of the baryonic matter, with star formation occurring predominantly in the galaxy's central regions. Both models result in disk galaxies with remarkably similar qualities; M1, however, produces a greater number of high-eccentricity halo stars and, in this

[4] The stellar mass of the satellite appears too large considering the inferred mass of the Galaxy's stellar halo (e.g., Morrison 1993). However, the *fractional* contribution of S1 to the simulated halo (∼10%) is reasonable, even if the *absolute* mass is overestimated. This overestimation is an artifact of the overcooling problem alluded to earlier and does not impact on the phase-space conclusions described here.

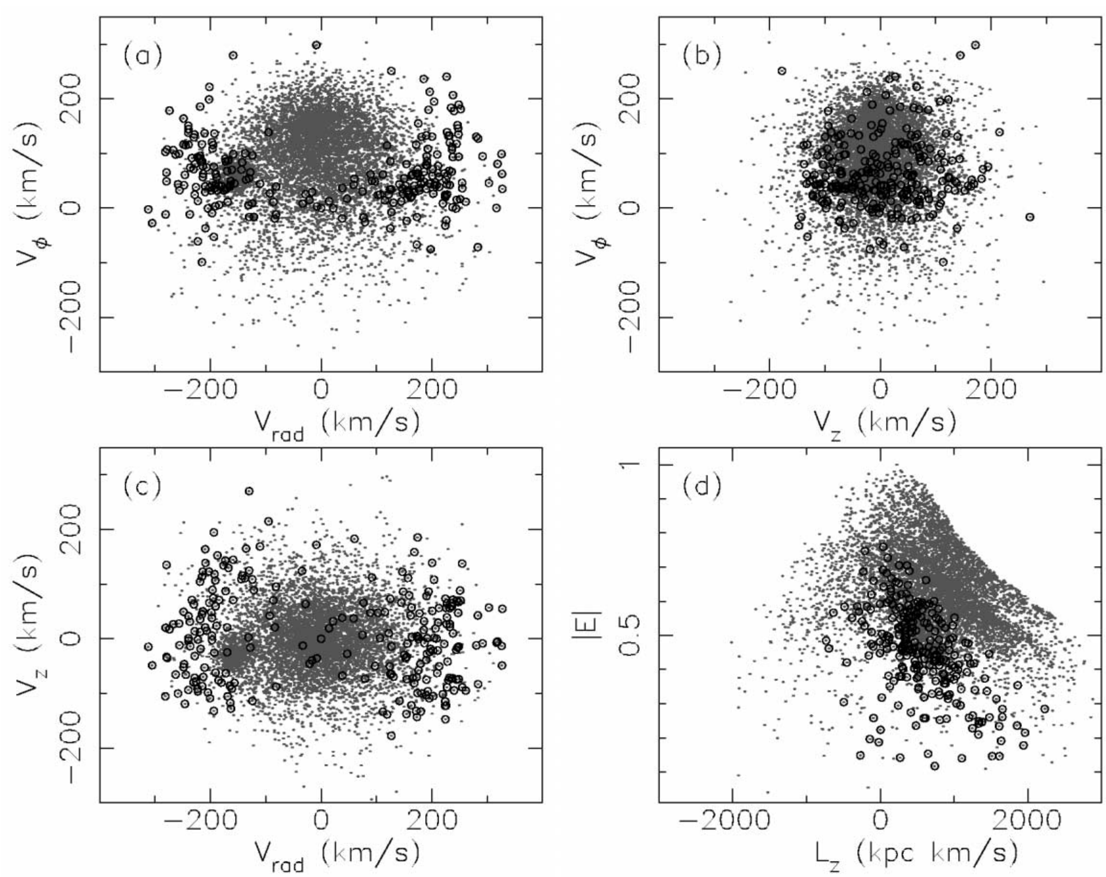

FIG. 3.—(*a–c*) Velocity-space projections of the present-day solar circle stars of M1. The open circles denote the subset of stars originating in S1. (*d*) Distribution for the same stars in integrals of motion space; i.e., the absolute value of the total energy ($|E|$) vs. the projected angular momentum (L_z).

regard, is in better agreement with the observational data set of CB00. By tracing the merging histories of satellites in M1, it becomes apparent that a significant number of high-ϵ halo stars originated in accreted dwarf galaxies. In fact, almost 20% of high-ϵ halo stars located in the solar circle originated in one satellite, of stellar mass $\sim 10^9\ M_\odot$, which was on a precessing polar orbit and was accreted over the past ∼5 Gyr.

Thus, our simulation suggests that stars from an accreted satellite that was on a polar orbit can form part of the galaxy's halo and that such stars have highly eccentric orbits. Originating in accreted polar satellites, these stars would not gain the angular momentum induced by the tidal torque of the external gravitational field that results in the rotation of the disk component of the galaxy. Such stars will fall toward the center of the galactic potential and end up on highly eccentric orbits.

The existence of an apparent correlation between metallicity and ϵ in halo stars was taken by ELS to be a sign of a rapid collapse driving the formation of the Galaxy. Our study suggests that another way of creating such high-ϵ halo stars is through the recent accretion of polar orbit satellites. Furthermore, dwarf galaxies of stellar mass $\sim 10^9\ M_\odot$ typically have appropriate average metallicities to be the source of this group of stars with [Fe/H] ~ -1.7 (e.g., Mateo 1998). Velocity phase space and the space of adiabatic invariants are where we would expect substructure within the halo caused by past merging to be apparent. The distribution in such space of an accreted satellite of our simulated galaxy resembles that of previous studies that traced the disruption of dwarf galaxies in static potentials. The greater dispersion in the distributions of our simulation can most likely be attributed to the dynamic nature of the potential in our full simulation of Galactic evolution, eroding the invariance of the integrals of motion. The identified concentration of high-ϵ low-metallicity halo stars from CB00 occupy a similar restricted region of phase space to the simulated accreted satellite.

The suggestion that this concentration of stars in the ϵ-metallicity plot is caused by satellite accretion has also been noted by Dinescu (2002). In the metallicity range $-2.0 <$ [Fe/H] < -1.5 of the CB00 data, Dinescu notes an excess of stars in retrograde orbits with rotational velocities $V_\phi \sim -30$ km s^{-1} from that expected from a "pure" halo. She identifies these stars as candidates for having been torn from the system that once contained ω Centauri; ω Cen is believed to be the nucleus of a disrupted, accreted dwarf galaxy (e.g., Lee et al. 1999), is in a retrograde orbit, and has an orbital ϵ of ∼0.67. Using a simple disruption model, Dinescu showed that the tidal streams tend to have higher orbital ϵ than the disrupted satellite does. Along with the mean metallicity of ω Cen being [Fe/H] $= -1.6$, the inference is that the clump of high-ϵ halo stars identified in CB00 contains a significant number of stars that have been tidally stripped from ω Cen. Our simulations provide a degree of support for this hypothesis. Taking those stars with $L_z < 0$ in Figure 4*d*, we see a clump of stars with intermediate energies and $L_z \sim -400$ kpc km s^{-1}. These stars are identified in all phase-space plots by filled circles; we see that the distribution becomes more restricted in each velocity-space dimension and that there is greater concord with HW99's idealized satellite accretion studies.

The key question that we wish to address remains: *What are the implications for the competing galaxy formation para-*

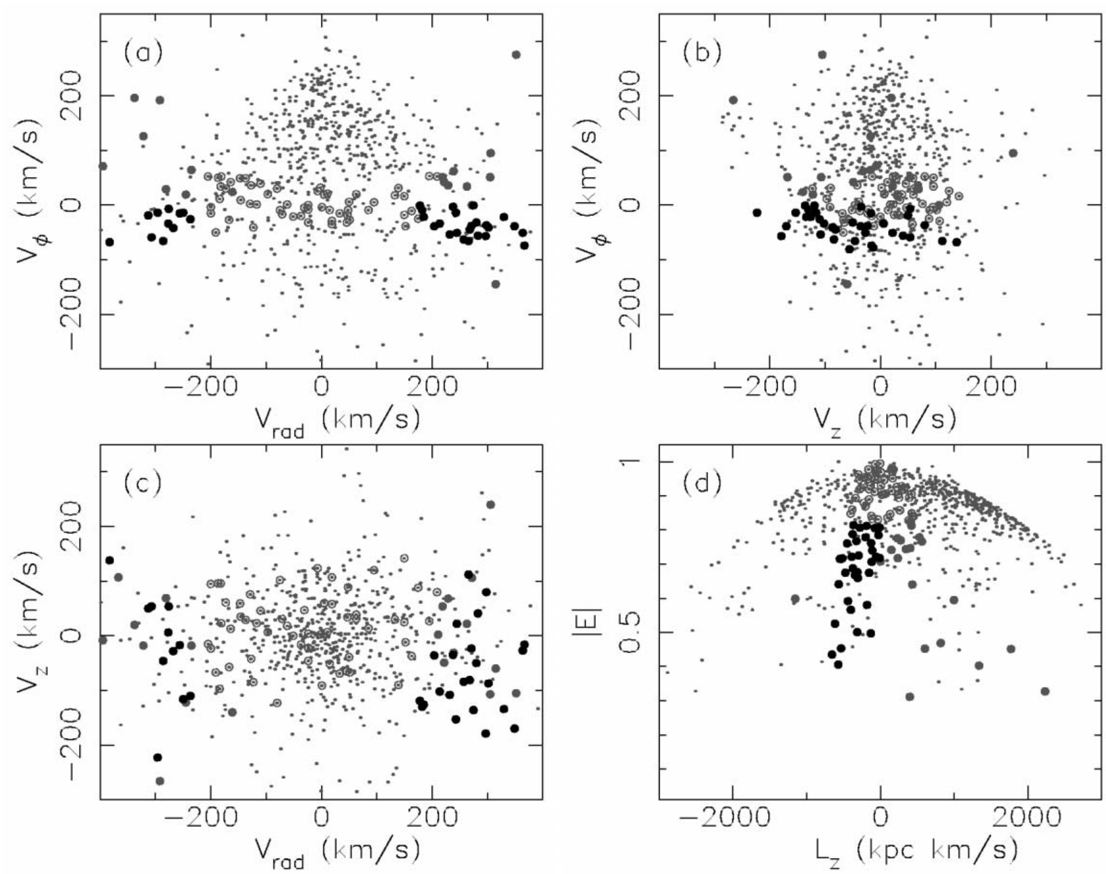

Fig. 4.—Velocity and integrals of motion phase space for the 729 CB00 stars within 2.5 kpc of the Sun with $[Fe/H] < -1$. (*a–c*) Velocity space; (*d*) energy vs. projected angular momentum. Stars with $0.8 < \epsilon < 1.0$ and $-2.0 < [Fe/H] < -1.4$ are represented as open circles. The filled gray circles denote stars of high energy; the filled black circles correspond to high-energy stars with -800 kpc km s$^{-1} < L_z < 0$ kpc km s^{-1}.

digms? A brief response is as follows: CB00 observationally found no correlation between eccentricity and metallicity for halo stars near the Sun, obviating the need for a "rapid collapse" picture of Galaxy formation. However, CB00 do interpret a clump of high-eccentricity low-metallicity stars in this observational plane in terms of ELS, i.e., as a relic of a rapid collapse phase. Our simulations suggest that an equally plausible origin for this clump is the recent accretion of a polar orbit satellite in the Galactic halo.

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