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THE GALACTIC ORBITS OF NEARBY UV CETI STARS

Christine Allen and Miguel A. Herrera

Instituto de Astronomía
Universidad Nacional Autónoma de México

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RESUMEN

Se han integrado numéricamente las órbitas galácticas de 93 estrellas UV Ceti del entorno solar. Las estrellas que estudiamos son las mismas para las cuales Poveda et al. (1996a) determinaron sus propiedades cinemáticas y sus edades. Todas ellas están situadas a menos de 25 pc del Sol ($\pi \geq 0.04''$), y los valores para sus distancias, movimientos propios y velocidades radiales se conocen bien (Gliese y Jahreiss 1991). Se utilizó el modelo para la masa galáctica de Allen y Santillán (1991), y se integraron las órbitas durante tiempos comparables a la edad del disco viejo. Se obtuvieron los parámetros orbitales. Todas las órbitas son regulares, y los valores obtenidos para sus parámetros son los característicos para la población clásica del disco delgado joven. La altura de escala que se encuentra para la muestra completa es de 115 pc. Sin embargo, los parámetros orbitales que se encuentran para los 7 objetos con características cinemáticas extremas, señalados por Poveda et al., son muy distintos de los del resto de las estrellas ráfaga; en particular, sus excentricidades orbitales son todas mayores que 0.3. La altura de escala para la muestra excluyendo a los objetos anómalos es de 105 pc. En consecuencia, proponemos que los objetos anómalos pertenecen al disco grueso, que puede ser caracterizado ya sea por $e \geq 0.3$ o por $|z_{\rm max}| > 400$ pc.

ABSTRACT

The galactic orbits of 93 UV Ceti stars of the solar neighborhood have been numerically integrated. The UV Ceti stars studied are those of the working list for which Poveda et al. (1996a) determined kinematic properties and ages. All stars are contained within 25 pc of the Sun ($\pi \geq 0.04''$), and values for their distances, proper motions and radial velocities are available for them (Gliese & Jahreiss 1991). The galactic potential model of Allen & Santillán (1991) was used, and the orbits were integrated for times similar to the age of the old disk. The galactic orbital parameters are obtained. The orbits are all regular, and the values found for the orbital parameters are similar to those characteristic of the classic young thin disk. The vertical scale height found for the whole sample is 115 pc. However, the orbital parameters found for the 7 objects with extreme kinematic characteristics recognized in Poveda et al. are markedly different from those of the rest of the flare stars; in particular, their orbital eccentricities are larger than 0.3. The vertical scale height of the sample excluding the anomalous objects is just 103 pc. Consequently, we propose that the anomalous objects belong to the thick disk, which may be characterized by either $e \geq 0.3$ or $|z_{\rm max}| > 400$ pc.

Key words: **GALAXY–KINEMATICS AND DYNAMICS — GALAXY– STRUCTURE — STARS– FLARE**

1. INTRODUCTION

The question of the age of the flash stars, and of their classic analog among stars of the solar vicinity, the flare or UV Ceti stars, has long been controversial, and is still not entirely settled. Early estimates of Haro & Chavira (1966) placed the ages of the oldest UV Ceti stars at 10^9 years, and their mean ages

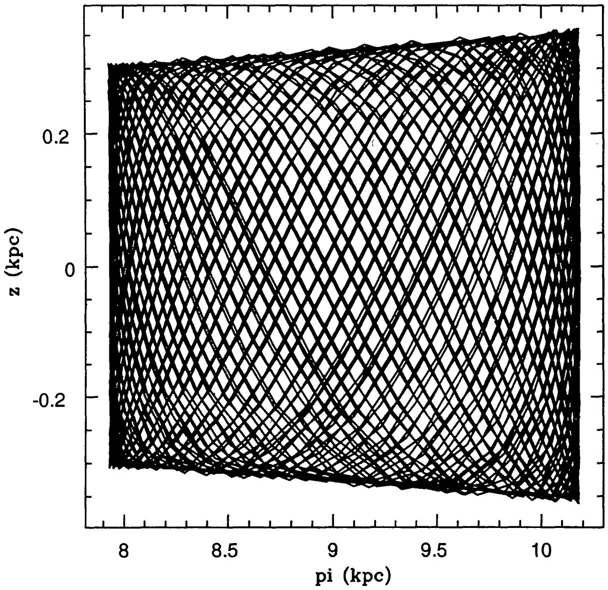


Fig. 1. The meridional orbit of a typical flare star, Gl 493.1.

at 4×10^8 years. These estimates conflicted with the result of Boesgaard & Hagen (1974) who found an age of about $3 - 4 \times 10^9$ years for α Centauri A and B, since Proxima, one of the best known flare stars, is a convincing member of the system. The ages of the flare stars were also studied by Kunkel (1975) and others, who found evidence indicating that some faint UV Ceti stars flare throughout the life of the Galaxy. More recently, Poveda et al. (1996a, hereinafter Paper I) determined the kinematic properties of the nearby UV Ceti stars and obtained for them mean ages of about 3×10^9 years. Specifically, it was found in Paper I that the kinematic properties of the nearby UV Ceti stars as a group are characterized by a total velocity dispersion of $\sigma = 30 \pm 3$ km s^{-1}, and most closely resemble those of main sequence stars of types F4 – F6 in the solar vicinity. For these stars, the estimated mean nuclear ages are about 3×10^9 years. With the assumption of a nearly constant rate of star formation in the galactic disk at least over the last 8×10^9 years, the ages of individual UV Ceti stars were found to span the interval from 0 to 6×10^9 years. These values for the ages of UV Ceti stars are quite consistent with the age determined by Boesgaard & Hagen (1974) for the α Centauri system, yet disagree with the ages estimated by Haro & Chavira (1966).

Paper I also showed that there are no significant differences in the velocity dispersions of the faint flare stars and those of the brighter ones. A comparison of the velocity dispersion of flare stars that are members of double and multiple systems with those that are single also showed no significant difference. However, a small number of flare stars exhibiting very discordant kinematics was found; these stars were interpreted as belonging to the thick disk or even halo population, because their large velocities cannot be due to the progressive acceleration mechanisms operating on disk stars; in other words, their large velocities must be primeval. The most extreme example is Gl 451B (Groombridge 1830B), whose visual companion is spectroscopically classified as a subdwarf; this system has a heliocentric space velocity of 304 km s^{-1}. Other examples, although less extreme, are Gl 166C, Gl 412B, Gl 424, and Gl 630.1A. Thus, a small group of apparently single, high velocity —and hence presumably very old— flare stars was found, whose persistent chromospheric activity poses a problem.

One conjecture explored to explain the group of very high velocity flare stars (Poveda, Allen, & Herrera 1996b) involves the occasional coalescence of the components of old contact binaries, which would produce in most cases a fully convective single star with high rotational velocity; such a star would become chromospherically active, with Hα emission, flare activity, etc., but with kinematic properties that would advertise its membership to an old population. Because of the loss of angular momentum through flare activity and stellar winds the fate of these short-period binaries would be to coalesce into a rejuvenated rapidly rotating single star. In fact, van't Veer & Maceroni (1989) have found the time-scale for coalescence of short period ($P < 4$ d) late type main

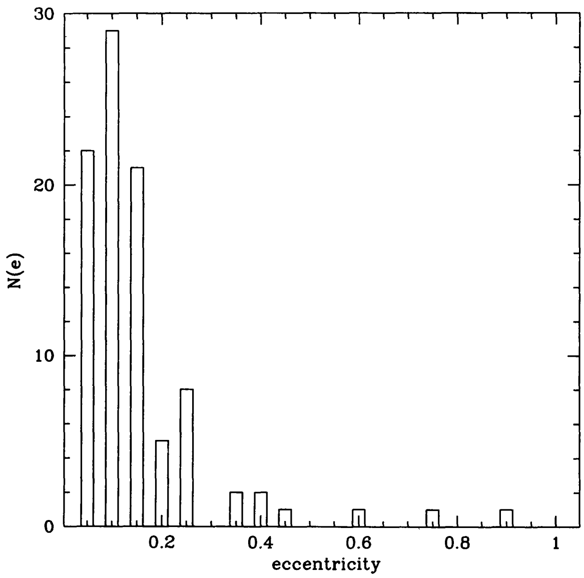


Fig. 2. Distribution of three-dimensional galactic orbital eccenticities for 93 nearby UV Ceti stars.

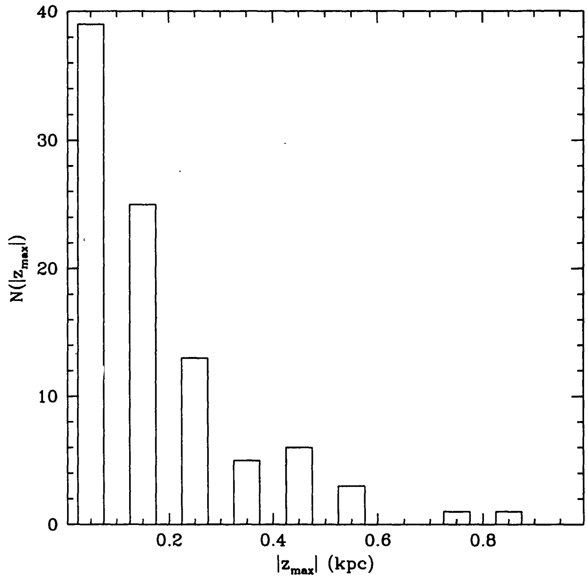


Fig. 3. Distribution of maximum $|z|$ values for the galactic orbits of 93 nearby UV Ceti stars.

sequence binaries to be about 7.5×10^8 years. If this scheme is approximately correct, we would expect to find a number of kinematically less extreme, binary precursors to the old single flare stars found. Poveda et al. (1996b) identified both these types, and gave lists of presumably already coalesced rejuvenated single stars, and of some close binaries which could be precursors of such rejuvenated stars. This interpretation hinges on the reliability of the kinematic properties of flare stars as age indicators, since for most of them no other alternatives exist. Thus, it is important to find confirming evidence of membership to a different population of the most extreme examples of flare stars, and of old age for their precursors.

In view of such complications, it seems worth while to compute the galactic orbits of nearby UV Ceti stars in order to compare them with those of disk population star samples of different ages. In particular, if we find the orbits of the seven extremely discordant stars to be clearly different from those of the ordinary disk stars, the interpretation of them as belonging to the thick disk will be strengthened. This approach is part of the more general problem of establishing the manner in which the mean orbital parameters vary as a function of stellar age, so as to have additional ways of estimating the ages of groups of stars (Allen & Schuster, in preparation).

2. THE GALACTIC ORBITS

The sample of stars considered in this study consists of the 93 nearby UV Ceti stars with known space motions contained in Table 1 of Paper I. For the numerical integration of the orbits the galactic mass model of Allen & Santillán (1991) was used. Although the model is quite simple, it represents well the observed data most directly related to the quantities that determine the galactic orbits. The model consists of three components: a central spherical mass distribution and a disk, both of the Miyamoto-Nagai form, and a massive spherical halo. The galactic parameters upon which the model is based are $R_0 = 8.5$ kpc, $V_0 = 220$ km s^{-1} and a total local mass density of $\rho = 0.15\ M_\odot$ pc^{-3}. The spherical halo is assumed to have an outer radius of 100 kpc. With such parameters the total mass of the model galaxy turns out to be $9 \times 10^{11}\ M_\odot$. The model potential is fully analytical, continuous, and with continuous derivatives; the density can be obtained from it in closed form, and it is positive everywhere; the mathematical simplicity of the model allows rapid, accurate, and reproducible numerical orbit integrations. The model has been used extensively to compute galactic orbits of a variety of objects (e.g., Carraro & Chiosi 1994; Dauphole & Colin 1995; Scholz et al. 1996). For our purpose, orbits of all nearby flare stars with sufficient kinematical data were integrated over times of 16 Gyr, an interval amply covering the ages of even the oldest galactic disk objects. The orbits were computed using a 7th order Runge-Kutta-Fehlberg integrator with automatic step-size control. The fractional errors in the energy at the end of each run were typically smaller than 10^{-6}, the errors in h, the z-component of the angular momentum were about an order of magnitude smaller. A representative meridional orbit, that of Gl 493.1, is shown in Figure 1.

The galactic orbital parameters found for the computed orbits of the 93 flare stars considered in this study are listed in Table 1. We can see at a glance that the great majority of flare stars do indeed show the kinematic properties of thin disk stars: they differ only slightly from circular orbits, and their excursions perpendicular to the galactic plane are small. Mean orbital parameters for the sample of 93 are listed in Table 2, first line. The results shown in Tables 1 and 2 are clearly compatible with the age estimates found in Paper I, in the sense that the nearby flare stars seem to be distributed like, and have the kinematics of, young thin disk stars. However, a closer inspection of the eccentricity histogram (Figure 2) shows a small group of discrepant stars. Indeed, although the numbers are not large, there is an indication of bimodality: there are 8 stars with $e \geq 0.3$; they are marked with an asterisk in Table 1. Figure 3 shows the distribution of $|z_{\rm max}|$, the maximum $|z|$ distances attained by the stars in their galactic orbits; this histogram is just what would be expected for a group of stars of the young thin disk.

Table 2 lists also mean orbital parameters for dif-

TABLE 1

GALACTIC PARAMETERS FOR 93 UV CETI STARS

Star	R_{min} (kpc)	R_{max} (kpc)	$\|z_{max}\|$ (kpc)	e	Star	R_{min} (kpc)	R_{max} (kpc)	$\|z_{max}\|$ (kpc)	e
Gl 15A	7.576	9.732	0.042	0.125	Gl 490A	7.663	8.514	0.033	0.053
Gl 15B	7.563	9.695	0.044	0.123	Gl 490B	7.701	8.517	0.075	0.050
Gl 22AC	5.870	9.451	0.129	0.234	Gl 493.1	7.931	0.186	0.360	0.124
Gl 29.1	8.183	9.026	0.174	0.049	Gl 494	7.563	8.930	0.032	0.083
Gl 48	6.202	9.377	0.049	0.204	Gl 516A	7.990	10.188	0.020	0.121
Gl 51	7.643	8.652	0.144	0.062	Gl 516B	7.988	10.190	0.018	0.121
Gl 54.1	8.277	9.758	0.214	0.082	Gl 517	8.022	8.996	0.158	0.057
Gl 65A	7.377	9.270	0.150	0.114	Gl 551	8.313	9.546	0.264	0.069
Gl 65B	7.368	9.299	0.188	0.116	Gl 569AB	8.349	10.155	0.107	0.098
Gl 82	7.899	8.508	0.006	0.037	Gl 616.2	6.802	9.857	0.267	0.183
Gl 83.1	5.820	8.646	0.136	0.195	Gl 630.1A*	2.683	9.584	0.307	0.562
Gl 103	7.165	8.631	0.330	0.093	Gl 644A	6.814	8.764	0.197	0.125
Gl 109	7.476	9.213	0.064	0.104	Gl 644B	6.814	8.764	0.197	0.125
Gl 113.1	8.168	8.546	0.063	0.023	Gl 644C	6.787	8.936	0.241	0.137
Gl 157B	8.452	9.532	0.188	0.060	Gl 669A	7.556	9.055	0.041	0.090
Gl 166C*	6.327	12.712	0.504	0.335	Gl 669B	7.543	9.054	0.039	0.091
Gl 171.2A	7.602	9.217	0.061	0.096	Gl 718	7.057	11.548	0.183	0.241
Gl 182	8.490	8.529	0.096	0.002	Gl 719	7.602	9.161	0.287	0.093
Gl 206	8.451	9.074	0.203	0.036	Gl 725A	8.137	9.002	0.463	0.051
Gl 207.1	8.488	8.967	0.261	0.027	Gl 725B	8.196	9.092	0.482	0.052
Gl 229	7.964	9.097	0.058	0.066	Gl 729	8.478	9.400	0.007	0.052
Gl 234A	7.553	8.521	0.128	0.060	Gl 735	8.491	8.673	0.006	0.011
Gl 234B	7.553	8.521	0.128	0.060	Gl 752B	7.227	10.744	0.022	0.196
Gl 268	7.345	9.272	0.013	0.116	Gl 781*	1.601	9.827	0.260	0.720
Gl 277A	8.511	8.741	0.171	0.013	Gl 791.2	8.203	9.416	0.104	0.069
Gl 277B	8.511	8.722	0.171	0.012	Gl 799A	8.474	8.496	0.012	0.001
Gl 278C	8.487	9.265	0.099	0.044	Gl 799B	8.462	8.520	0.019	0.003
Gl 285	7.623	8.612	0.032	0.061	Gl 803	8.217	8.512	0.010	0.018
GJ 1108	8.266	8.567	0.031	0.018	Gl 812A	6.289	9.311	0.289	0.194
GJ 1111	8.488	8.998	0.168	0.029	Gl 815A	6.992	8.549	0.516	0.100
GJ 1116A	8.381	10.977	0.460	0.134	Gl 815B	6.992	8.549	0.516	0.100
GJ 1116B	8.381	10.977	0.460	0.134	Gl 825	6.685	10.693	0.451	0.231
Gl 375	5.999	9.491	0.064	0.225	Gl 841A	7.625	8.528	0.272	0.056
GJ 2079	7.880	8.524	0.090	0.039	Gl 852A	7.918	12.728	0.434	0.233
Gl 388	8.442	8.926	0.121	0.028	Gl 860A	6.975	9.067	0.106	0.130
Gl 398	7.474	9.361	0.061	0.112	Gl 860B	7.057	9.087	0.106	0.126
Gl 406	6.278	8.595	0.136	0.156	Gl 866AB	7.475	11.309	0.890	0.204
Gl 412B*	6.170	13.839	0.252	0.383	Gl 867A	8.323	8.887	0.057	0.033
Gl 424*	6.004	14.001	0.081	0.400	Gl 867B	8.323	8.887	0.057	0.033
Gl 425A	7.990	9.600	0.108	0.092	Gl 873	8.107	10.321	0.073	0.120
Gl 425B	7.990	9.600	0.108	0.092	Gl 875.1	7.850	9.003	0.127	0.068
Gl 431*	8.264	17.422	0.346	0.357	Gl 890	8.482	9.481	0.045	0.056
Gl 447	8.215	10.490	0.370	0.122	Gl 896A	8.445	9.033	0.008	0.034
Gl 451B*	1.448	20.259	0.213	0.867	Gl 896B	8.433	8.902	0.024	0.027
Gl 473A	7.800	9.184	0.014	0.081	Gl 899*	6.474	12.482	0.280	0.317
Gl 473B	7.800	9.184	0.014	0.081	Gl 908	5.188	8.510	0.777	0.243
Gl 487	8.346	8.550	0.077	0.012					

TABLE 2

MEAN ORBITAL PARAMETERS FOR DIFFERENT SUBGROUPS OF UV CETI STARS

Groups	R_{min} (kpc)	R_{max} (kpc)	$\|z_{max}\|$ (pc)	e
Full sample (93 stars)	7.46 ± 1.27	9.66 ± 1.77	175.7 ± 171.2	0.127 ± 0.139
Discrepant stars (7 stars)	4.64 ± 2.49	13.95 ± 3.57	291.7 ± 125.4	0.518 ± 0.191
Full sample minus 7 (86 stars)	7.69 ± 0.74	9.31 ± 0.86	166.3 ± 171.0	0.095 ± 0.067
Stars with $e \geq 0.3$ (8 stars)	4.87 ± 2.41	13.77 ± 3.38	290.3 ± 117.4	0.492 ± 0.190
Full sample minus 8 (85 stars)	7.70 ± 0.73	9.27 ± 0.79	165.0 ± 171.5	0.093 ± 0.062

ferent subsamples of UV Ceti stars. The second line displays values for the seven very discrepant stars, the next line for the remaining sample (86 stars). The fourth line contains values for the subsample of 8 stars that have eccentricities $e \geq 0.3$, corresponding to the minimum observed in the eccentricity distribution shown in Fig. 2; the next line displays values for the remaining sample (85 stars). Table 2 is a clear evidence that there are indeed two groups of flare stars with significantly different kinematics, and hence orbital parameters. We propose to identify the sample of 85 stars with the conventional young population I flare stars, and the group of 8 stars with $e \geq 0.3$ as a subgroup belonging to the thick disk population, whose persistent flare activity clearly merits further study (Poveda et al. 1996b). Note that 7 out of these 8 stars are precisely the 7 stars identified in Paper I because of their extreme kinematics. In Paper I, Gl 899 was not excluded because, solely on the basis of its U, V, W space velocity components, it was conservatively regarded as a marginal case. The information provided by the full galactic orbit, in particular, the eccentricity of this system, clearly places it among the thick disk population. Note also that these stars have mean values of $|z_{max}|$ significantly larger than the remaining stars.

It is interesting to compare the orbital properties of nearby UV Ceti stars with those of other groups of disk stars. A particularly valuable study of galactic disk stars is that of Edvardsson et al. (1993). These authors have undertaken to study the galactic disk by obtaining extensive and accurate photometric and spectroscopic observations for a carefully selected group of nearby field F and G stars. Detailed chemical abundances, as well as distances and individual ages are obtained for these stars. Their galactic orbital parameters, which were computed with a simple galactic mass model, are also given. An interesting feature of this study is that the sample of stars was selected according to photometric parameters, and therefore is not kinematically biased.

Edvardsson et al. do not list proper motions and radial velocities for their stars, so a recomputation of their galactic orbits is not easily feasible. However, we were able to obtain up-to-date kinematical data for the subgroup of 25 stars with the largest values of orbital eccentricities or $|z_{max}|$ (Kinman 1996, private communication) and we computed their galactic orbits. For these stars, any differences between the galactic model used by Edvardsson et al. and ours, as well as those arising from different definitions of the eccentricities, should be most noticeable. Our results for the galactic orbital parameters of those stars are found to differ little from those given by Edvardsson et al. (see Figures 4 and 5), in spite of the fact that these authors list the planar eccentricity instead of the 3-dimensional one, and in spite of the differences of galactic models and constants. The smallest differences occur in the eccentricities. The $|z_{max}|$ values of Edvardsson et al. were found to be systematically smaller than ours, a consequence of the larger mass concentration on the galactic plane adopted by these authors. However, the differences are not large as long as we deal with $|z_{max}|$ smaller than about 800 pc. The small differences found lead us to conclude that we can safely use the values listed by Edvardsson et al., as we do in the following.

Firstly, for the purpose of comparing velocity dispersions of young disk stars and flare stars, we divided the Edvardsson et al. stars in six age groups,

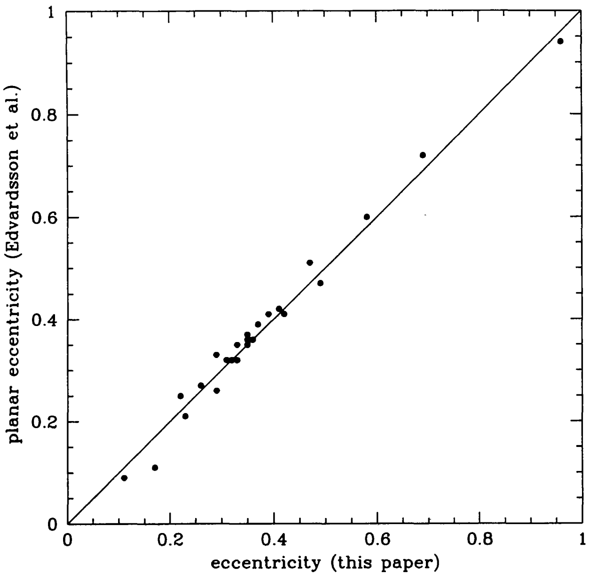


Fig. 4. Comparison of galactic orbital eccentricities obtained with two different mass models.

each comprising 30 or 31 stars. If we now consider the group of the 30 youngest stars we find that the mean age of this group of stars is 2.2 Gyr, and that their total velocity dispersion is 30 km s^{-1}. If we go to an even younger sample, so as to obtain a mean age of 2.0 Gyr the total velocity dispersion is reduced to 28 km s^{-1} (and the number of stars is reduced to 22). These results agree very well with the values found in Paper I for the velocity dispersions of the nearby flare stars. It is gratifying to find essentially the same results for an entirely different group of stars than those of Gliese's catalogue, upon which our previous velocity dispersion estimates and age determinations were based.

Revised ages for the sample of stars of Edvardsson et al. have recently been published by Ng & Bertelli (1998). The most reliable ages given by these authors are based on Hipparcos parallaxes (their Tables 7 and 8), and these also show the smallest discrepancies from the ages obtained by Edvardsson et al. In order to assess the influence of the uncertainties of the ages as given by different sets of isochrones and fitting procedures, we have recomputed velocity dispersions for the nearby flare stars, but now regrouping them according to the revised ages of Ng & Bertelli, and restricting the analysis only to those ages flagged with 6 or 7 in their Tables 7 and 8, which indicate the most reliable fits. The total number of stars with such ages is now 143. Again, we divided this sample into 6 age groups, each comprising now 23 or 24 stars. The mean age of the youngest group of stars is now 1.62 Gyr, and the total velocity dispersion of this group is 30.3 km s^{-1}. The revised ages for the nearby flare stars are thus reduced to about 1.6 Gyr, making them somewhat younger than we had previously estimated.

To further carry out our comparison, we list in Table 3 the mean values for the orbital parameters for six age groups of the stars of Edvardsson et al. It is easily seen that the mean orbital parameters of our flare stars most closely resemble those of the youngest group of Edvardsson et al. stars, which was found to have a mean age of 2.2 Gyr. Although the values found show a considerable dispersion, our group of discrepant flare stars ($e \geq 0.3$) most closely resembles the two oldest groups of stars of the Edvardsson et al. sample, which, as we shall presently argue, probably contain a large fraction of thick disk stars.

The same analysis was repeated using the revised ages of Ng & Bertelli (1998), as described earlier. Our results are listed in Table 4. A comparison with Table 3 shows a smoother trend in the variation of the mean orbital parameters, especially $|z_{\max}|$, as a function of age. Note that since the oldest —and hence most extreme— stars in the Edvardsson et al. sample do not have reliable ages as determined by Ng & Bertelli, the mean values of the orbital parameters of the oldest groups are now less extreme, in spite of the fact that individual ages of stars older than about 9 Gyr tend to be larger in Ng & Bertelly than in Edvardsson et al. Thus, the group of 8 flare stars with $e \geq 0.3$ would now appear to be slightly older than the oldest comparison group, which has an age of 12.4 Gyr. The comparison of Tables 3 and 4 al-

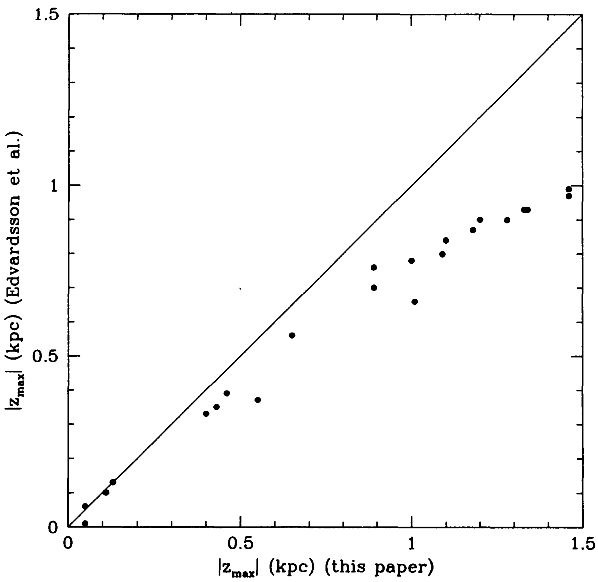


Fig. 5. Comparison of values of $|z_{\max}|$ obtained with two different galactic mass models.

TABLE 3

MEAN ORBITAL PARAMETERS FOR GROUPS OF STARS OF DIFFERENT AGES (EDVARDSSON ET AL.)

	R_{min} (kpc)	R_{max} (kpc)	$\|z_{max}\|$ (pc)	Mean Age (Gyr)	e
Group 1	7.13	8.68	88.0	2.20	0.099
(30 stars)	± 0.55	± 0.48	± 66.0	± 0.41	± 0.034
Group 2	7.01	9.18	206.3	3.32	0.133
(30 stars)	± 0.72	± 1.17	± 189.0	± 0.22	± 0.051
Group 3	6.80	9.06	116.0	4.39	0.140
(30 stars)	± 0.87	± 1.22	± 87.9	± 0.38	± 0.068
Group 4	6.79	9.07	228.0	6.24	0.146
(30 stars)	± 0.94	± 0.79	± 204.2	± 0.76	± 0.069
Group 5	6.41	9.45	224.8	9.52	0.193
(31 stars)	± 1.18	± 1.55	± 246.3	± 1.46	± 0.098
Group 6	4.96	8.99	605.8	14.16	0.319
(31 stars)	± 2.01	± 0.88	± 948.4	± 1.80	± 0.187

TABLE 4

MEAN ORBITAL PARAMETERS FOR GROUPS OF STARS OF DIFFERENT AGES (NG & BERTELLI)

	R_{min} (kpc)	R_{max} (kpc)	$\|z_{max}\|$ (pc)	Mean Age (Gyr)	e
Group 1	7.23	8.79	90.4	1.55	0.097
(24 stars)	± 0.57	± 0.58	± 80.0	± 0.43	± 0.033
Group 2	7.02	8.81	155.0	2.48	0.113
(24 stars)	± 0.65	± 0.83	± 124.4	± 0.30	± 0.045
Group 3	6.92	9.06	178.3	3.52	0.135
(24 stars)	± 0.80	± 0.87	± 108.4	± 0.34	± 0.054
Group 4	6.92	9.43	189.5	5.77	0.151
(24 stars)	± 0.97	± 1.33	± 208.5	± 0.65	± 0.070
Group 5	6.72	9.25	198.8	7.74	0.159
(24 stars)	± 1.11	± 1.30	± 208.1	± 0.57	± 0.088
Group 6	5.81	9.14	312.6	12.43	0.238
(23 stars)	± 1.68	± 1.25	± 257.6	± 2.28	± 0.152

lows us to better assess the uncertainties inherent to even the best current dating methods, as well as the corresponding mean orbital characteristics. In conclusion, the group of nearby flare stars would appear to have a mean age of $1.6-2.0$ Gyr, and the group of flare stars with $e \geq 0.3$ would seem to be older than $12-14$ Gyr.

Figure 6 is a plot of galactic orbital eccentricity versus age for the 182 stars of the galactic disk studied by Edvardsson et al. The figure shows that in

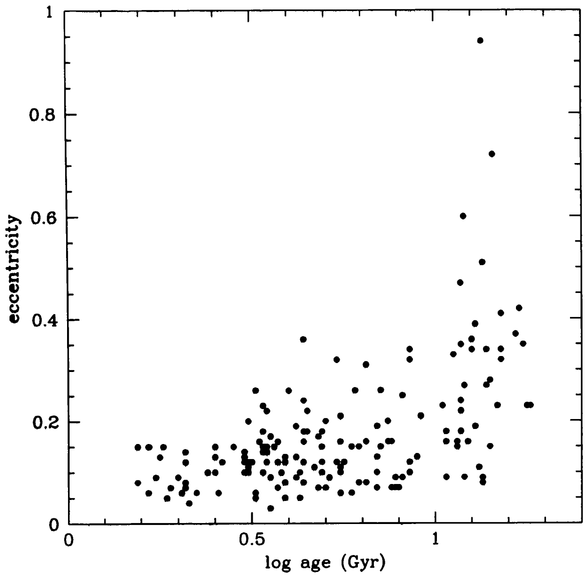


Fig. 6. Galactic orbital eccentricities versus ages for 182 disk stars from Edvardsson et al. (1993).

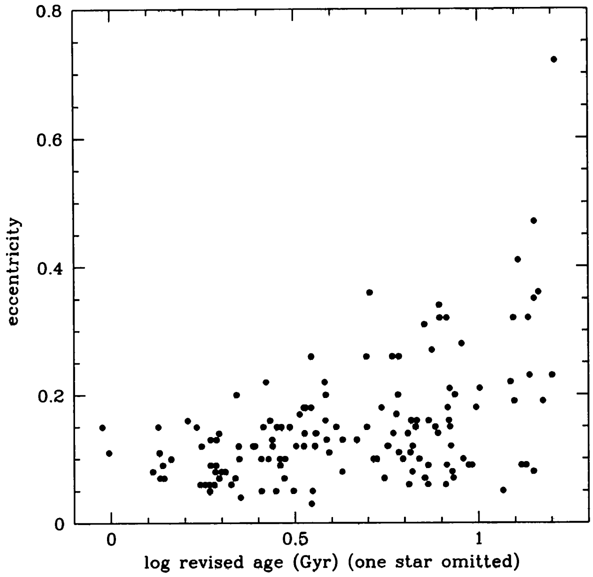


Fig. 7. Galactic orbital eccentricities versus ages for 143 disk stars having reliable ages according to Ng & Bertelli (1998).

order to find a significant number of stars with eccentricities larger than 0.3, it is necessary to go to ages greater than about 9 Gyr. The large spread of eccentricities that sets on abruptly at ages of about 10 Gyr can be interpreted as an indication that these older star groups contain a significant admixture of thick disk stars. This again is consistent with our previous identification of the 7 or indeed 8 very discrepant stars as having an origin distinct from that of the old thin disk. Figure 7 plots the eccentricities versus the ages taken from Ng & Bertelli (1998). The same trend is observed, setting on about 2.5 Gyr later, but as explained before, the oldest stars are now absent from the plot. Both plots would seem to indicate that the formation of the thick disk stopped about 10 – 12 Gyr ago.

It has been pointed out by Kunkel (1975), among other authors, that the galactic orbital eccentricities could be taken as a measure of age. Kunkel plots values of eccentricity, e, versus visual absolute magnitude, M_v, for a variety of stars; he states that the flare stars are contained in a region bounded by an envelope extending from low eccentricities and $M_v = 7$ to about $M_v = 11$ and $e = 0.4$, and concludes that flare stars occur at all ages, up to the age of the galactic disk. Kunkel used very rough estimates of the orbital eccentricities for his sample stars, namely those given by Woolley et al. (1970), and as far as we are aware, did not have control groups of stars with independently determined ages to quantify his statements. Our values for the orbital eccentricities, coming as they do from a numerical integration

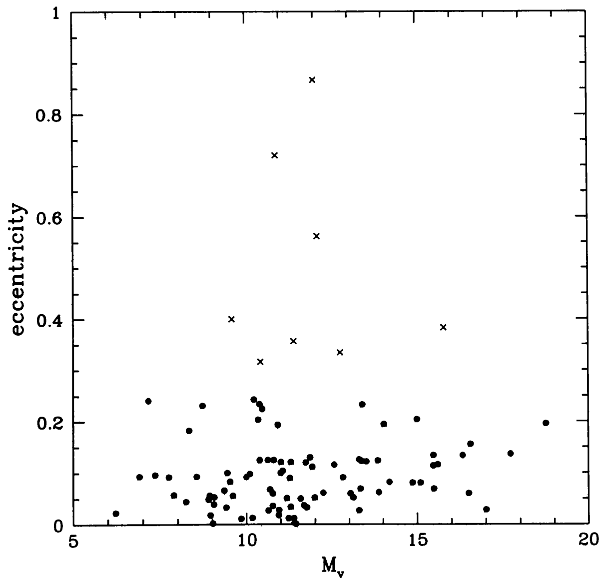
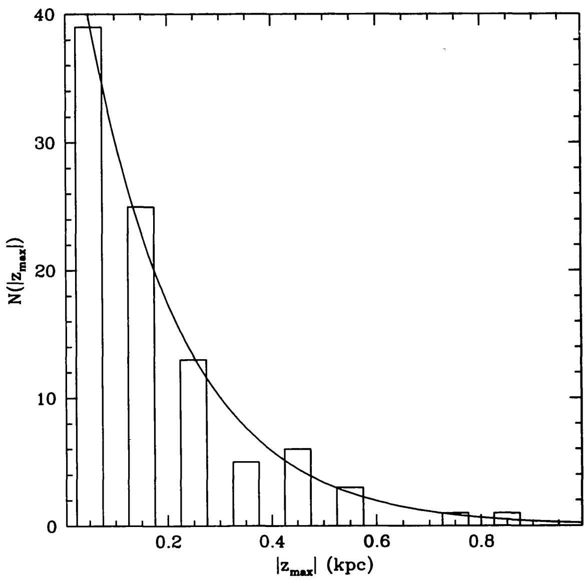


Fig. 8. Galactic orbital eccentricities versus absolute visual magnitudes for 93 nearby UV Ceti stars.

of the galactic orbits in a realistic potential, should be more reliable. Figure 8 shows the same plot for our group of nearby UV Ceti stars. While we find no stars of bright magnitudes and high eccentricities there are also no faint stars with high eccentricities. This absence of correlation between absolute magnitude and eccentricity becomes still more obvious if we disregard the 8 stars with $e \geq 0.3$ (plotted as crosses in Figure 8). If we assume that galactic orbital eccentricity is roughly correlated with age for objects of the classic thin disk, then we must conclude that indeed the flare phase is significantly shorter than the age of the galactic disk, except for a few anomalous cases. This result agrees with the findings of Paper I; since it was obtained by a completely different procedure, it can be regarded as a confirmation of the short duration of the flare stage.



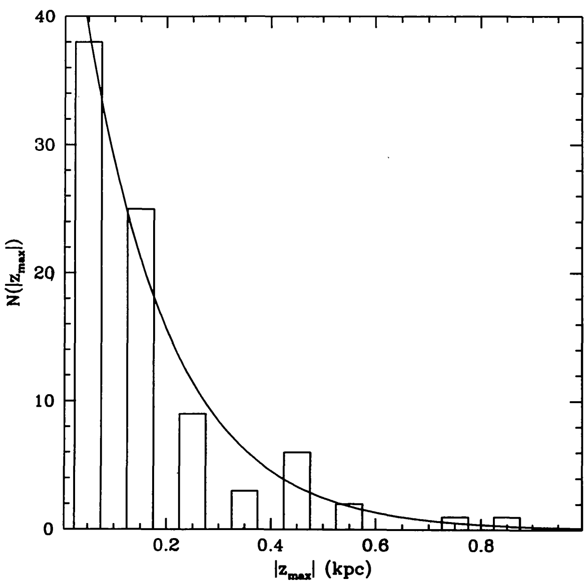


Fig. 9*a*). Histogram of $|z_{\rm max}|$ for 93 nearby UV Ceti stars. The solid line is an exponential fit. *b*). Histogram of $|z_{\rm max}|$ for 85 stars with $e < 0.3$. The solid line is again an exponential fit.

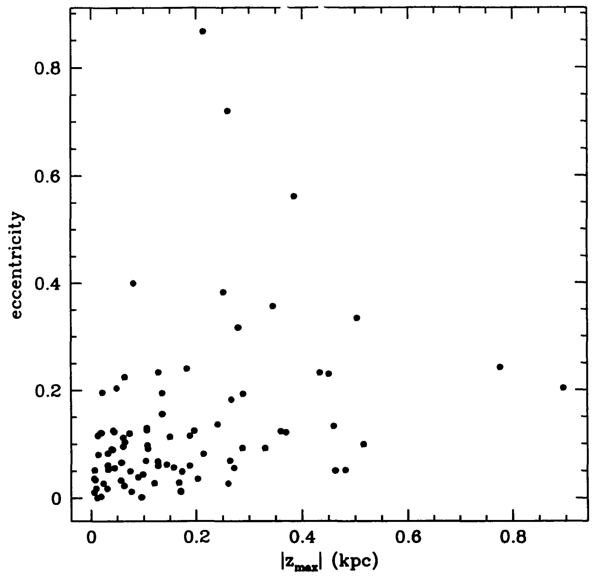


Fig. 10. Galactic orbital eccentricity versus $|z_{\rm max}|$ for 93 nearby UV Ceti stars.

Another point deserving attention is related to multiplicity among the stars of highest eccentricity. There is ample evidence that only very close companions may affect the chromospheric activity of their partners, so we shall consider only spectroscopic or eclipsing binarity. It turns out that 4 out of the 8 stars with $e \geq 0.3$ are known spectroscopic binaries, while among the remaining 85 stars only 8 have close companions. The numbers are too small to draw any firm conclusions, but they certainly agree with our previous suggestion (Poveda et al. 1996b) that the chromospherically active phase is prolongued by the presence of close companions.

A further interesting result concerns $|z_{\rm max}|$. We can use the distribution of $|z_{\rm max}|$ to derive an approximate scale height for our group of flare stars. To do this, we first note that the distribution of $|z_{\rm max}|$ is closely represented by an exponential law, with a scale height of 183 pc for the whole sample (Figure 9*a*), and of 163 pc for the 85 low-eccentricity stars (see Figure 9*b*). If we now assume that stars describe harmonic oscillations in z (a very good approximation for the low-eccentricity stars), then their average heights are $0.63|z_{\rm max}|$. Therefore, the scale height of the group of 85 flare stars with $e < 0.3$ is 103 pc, just the value expected for the thin disk stars. On the other hand, one would expect a correlation between the $|z_{\rm max}|$ and the galactic orbital eccentricities (Wielen 1977). Figure 10 shows, however, no obvious trend for our group of flare stars.

3. CONCLUSIONS

A comparison of the velocity dispersions of nearby flare stars with those of the Edvardsson et al. catalogue which has no kinematic bias shows excellent agreement with the results obtained in Paper I. The groups of disk stars most closely resembling the velocity dispersion of nearby UV Ceti stars have mean ages of 2 to 2.2 Gyr. Using the revised ages recently obtained by Ng & Bertelli on the basis of Hipparcos parallaxes lowers the estimated ages to about 1.6 Gyr.

The galactic orbital properties of nearby flare stars place the great majority of them among the young thin disk population.

The group of stars with eccentricities larger than 0.3 contains all 7 stars that were found to be extremely discrepant in our previous study, and therefore, excluded on the grounds that such extreme motions were primeval. The group of 8 flare stars with $e \geq 0.3$ is estimated to be older than about 12 Gyr.

The scale height of the full sample is 115 pc, and that of the 85 stars with $e < 0.3$ is 103 pc.

The group of UV Ceti stars with $|z_{\rm max}|$ greater than 400 pc contains 11 stars. We propose to ascribe to the thick disk population all those stars with either $e \geq 0.3$ or $|z_{\rm max}| > 400$ pc.

Among the disk stars of the Edvardsson et al. catalogue, it is necessary to go to ages greater than about 9 Gyr in order to find a significant number of stars with $e \geq 0.3$. The eccentricities begin to spread to values close to 1 at ages of about 10 Gyr (or to 12.5 Gyr if the revised ages of Ng & Bertelli are used). The onset of the large spread in eccentricities is quite abrupt, and suggests that thick disk stars are present in significant numbers among the older Edvardsson et al. stars.

The identification made in Paper I of the 7 discrepant stars as belonging to the thick disk population and owing their kinematics not to progressive acceleration but to their genesis is confirmed. One additional star, previously considered a marginal case, is clearly to be included among the group of discrepant stars. On the basis of orbital parameters, in particular, the eccentricities, we propose to differentiate disk from thick disk stars according to whether they have $e < 0.3$ or $e \geq 0.3$. Combined with other criteria based on kinematics and chemical abundances, the galactic orbits should allow a much better understanding of the differences between stellar populations in the Galaxy.

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Christine Allen and Miguel A. Herrera: Instituto de Astronomía, UNAM, Apartado Postal 70-264, 04510 México, D.F., México (chris@astroscu.unam.mx; mike@astroscu.unam.mx).