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Simulating observable comets

III. Real stellar perturbers of the Oort cloud and their output

P. A. Dybczyński

Astronomical Observatory of the A. Mickiewicz University, Słoneczna 36, 60-286 Poznań, Poland
e-mail: dybol@amu.edu.pl

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ABSTRACT

Context. This is the third of a series of papers on simulating the mechanisms acting currently on the Oort cloud and producing the observed long-period comets.
Aims. In this paper we investigate the influence of current stellar perturbers on the Oort cloud of comets under the simultaneous galactic disk tide. We also analyse the past motion of the observed long-period comets under the same dynamical model to verify the widely used definition of dynamically new comets.
Methods. The action of nearby stars and the galactic disk tide on the Oort cloud was simulated. The original orbital elements of all 386 long-period comets of quality classes 1 and 2 were calculated, and their motion was followed numerically for one orbital revolution into the past, down to the previous perihelion. We also simulated the output of the close future pass of GJ 710 through the Oort cloud.
Results. The simulated flux of the observable comets resulting from the current stellar and galactic perturbations, as well as the distribution of perihelion direction, was obtained. The same data are presented for the future passage of GJ 710. A detailed description is given of the past evolution of aphelion and perihelion distances of the observed long-period comets.
Conclusions. We obtained no fingerprints of the stellar perturbations in the simulated flux and its directional structure. The mechanisms producing observable comets are highly dominated by galactic disk tide because all current stellar perturbers are too weak. Also the effect of the close passage of the star GJ 710 is very difficult to recognise on the background of the Galactic-driven observable comets. For the observed comets we found only 45 to be really dynamically "new" according to our definition based on the previous perihelion distance value.

Key words. comets: general – Oort cloud – solar system: general

1. Introduction

This is the last paper in a series presenting the methods and results of modeling the current source of the long-period comets. After the detailed analysis of stellar perturbations in Dybczyński (2002, the first paper of this series) and extensive investigation of the mutual action of stars and the Galactic disk tide in Dybczyński (2005, the second paper in this series), we search for real stellar perturbers, especially for stars that have passed or will pass closer than 5 pc from the Sun. A review of the previous results in this field can be found in the papers quoted above. The procedure for selecting such stars, as well as discussion of the completeness of our lists is described in Sect. 2. In Sect. 3 we describe the result of the Monte Carlo simulation of the simultaneous action of 21 current stellar perturbers and the Galactic disk tide on the Oort cloud. The detailed analysis of the past motion of the observed long-period comets within the same perturbational model is presented in Sect. 4. Implications for the proper distinction between dynamically "new" and "old" comets are also given. A simulation showing the results of the future close passage of GJ 710 is described in Sect. 5. Finally we summarise our conclusions in the last section.

2. Search for stellar perturbers of the Oort cloud

The essential starting point of our search should be a list of all stars with known positions, proper motions, parallaxes, and radial velocities. But such a list does not exist and is really hard to collect. We have prepared such a list with numerical data that is as precise as possible, based on the hitherto published catalogues.

2.1. High precision subset of the potential perturbers list

The obvious source for precise astrometric positions and parallaxes for a large number of stars is the HIPPARCOS catalogue (Perryman et al. 1997). We are however, interested not only in positions but also in space velocities of stars, so we need precise proper motions, too. It is a well-known fact that proper motions included in the HIPPARCOS catalogue are based on relatively short observational intervals, so it is not the best source of information about a star's movement when a long time prediction is needed. There have been several attempts to obtain better values for proper motions by combining the HIPPARCOS results with ground-based catalogues; see for example Urban et al. (1998); Høg et al. (2000b); Hoogerwerf & Blaauw (2000); Urban et al. (2000).

In our research we used the ARIHIP catalogue (Wielen et al. 2001) as the source for position and proper motions for the high precision subset of HIPPARCOS stars. This catalogue is a combination of the results of the HIPPARCOS astrometry space mission with the ground-based data. It contains 90 842 HIPPARCOS stars, 90 072 were identified in at least one ground-based catalogue, and for 770 stars the solution based only on the HIPPARCOS mission is presented. For all stars, instantaneous and long time mean proper motions are derived. For our purpose the "long-term prediction mode" (LTP) solution is the most promising source of positions, proper motions, and parallaxes. According to the authors, the ARIHIP mean errors of the proper motions in the long-term prediction mode are better by a factor of 1.6 than the corresponding error for the HIPPARCOS values.

Using a procedure similar to the one by García-Sánchez et al. (1999), namely assuming the radial velocity of 100 km s^{-1}, we searched the ARIHIP catalogue for potential visitors in the close solar neighbourhood in the last few and next few million years. We found 2122 stars that have approached or will approach the Sun to a distance closer than 5 pc with the assumed radial velocity. After an extensive search in the literature and in available catalogues, with a great help of the SIMBAD database system, we found radial velocities for 1295 stars on this list; for the remaining 827 stars, radial velocity seemed to have been unmeasured or unpublished. Using real radial velocities, we recalculated the heliocentric distances of the close approaches, obtaining a "high precision" list of 137 stars that have passed or will pass closer than 5 pc from the Sun. We included all stars listed in García-Sánchez et al. (2001) by definition. We used a straight line motion approximation, because this calculation is for selecting purpose only and we assumed relatively large threshold value of 5 pc for the minimal Sun – star distance to account for the inaccuracies of this approximation.

García-Sánchez et al. (2001) published a list of 156 stars that approach the Sun closer than 5 pc and 83 stars from their list are included in our high precision list. The rest (54 stars) are our new findings. Among the 83 stars in common, we confirmed the results of García-Sánchez et al. (2001) in 53 cases, while in 14 cases we obtained significantly different parameters of the approach, and finally we must exclude 16 stars because their miss-distance appeared to be larger than 5 pc. The differences come from more precise proper motions and/or from new, more precise radial velocity measurements. After close examination of this list we decided to exclude all stars with the parallax $\pi < 0\farcs015$, because such a small value generates unacceptably large estimated errors in the miss-distance or in the epoch of the approach. Finally our *high precision list* consists of 91 stars, including 53 confirmed, 14 recalculated and 24 new stars. The 5 pc threshold value is rather large from the point of view of stellar perturbations on the Oort cloud comets. In subsequent calculations we have taken only those stars into account with the estimated miss-distance smaller than 2.5 pc, which has shortened this list to 21 stars, including 5 new stars and 16 confirmed or improved. The list of these stars is presented in Table 1. Together with the HIPPARCOS number of the star, we included its common name as obtained from the SIMBAD database. We also present the parallax value from the ARIHIP catalogue and the radial velocity used in our calculations together with its source. The last column consists of flags marking the status of the star: new findings or confirmed/corrected previously published results.

2.2. Lower precision subset of potential perturbers

The rest of the HIPPARCOS stars (over 30 000), not included in the ARIHIP catalogue, were also searched for potential perturbers. In all possible cases we used positions and proper motions from the Tycho-2 catalogue (Høg et al. 2000a,b), which provided more accurate proper motions than the HIPPARCOS catalogue itself (Hoogerwerf & Blaauw 2000; Urban et al. 2000). Using the same procedure as described above, we obtained a list of 1305 stars with the estimated miss-distance below 5 pc for the assumed radial velocity of 100 km s^{-1}. Then, using all available sources, with a great help of the SIMBAD database system, we found radial velocity measurements for 757 stars. The rest of the 548 stars still await for radial velocity measurement or its publication.

Using real space velocities, 109 stars were found to pass closer to the Sun than 5 pc and 36 of them are our new findings. From the list published by García-Sánchez et al. (2001), 73 stars fell in this category (83 were included in the ARIHIP catalogue) and among them 38 were confirmed, 17 were corrected, 10 removed, and 8 included using earlier published values. Likewise we had to remove stars HIP 85605, HIP 86961, and HIP 86963 due to the erroneous parallax listed in the HIPPARCOS catalogue, later corrected by Fabricius & Makarov (2000). It is worth mentioning that by using the nominal HIPPARCOS parallax $\pi = 0\farcs203$ and $v_r = 21$ km s^{-1} for HIP 85605, one can obtain the Sun miss-distance less than 10 000 AU! In Table 2 we present only stars with the parallax $\pi > 0\farcs015$ and with the estimated miss-distance below 2.5 pc, with the one exception of Algol, whose large mass and low velocity suggests the possibility of a significant influence the Oort cloud comets. There are 25 stars in this list and 7 of them are new findings.

We also tried to extend our low-precision list with stars that were found in the latest edition of the Yale catalogue of trigonometrical parallaxes (van Altena et al. 1995) but omitted in HIPPARCOS. In the introduction to the Yale catalogue they say that there are approximately 2300 such stars. After careful filtering and various cross-reference examinations, we found only about 650 stars included both in Yale and Tycho-2 catalogues and not included in HIPPARCOS. Unfortunately, none of these stars approach the Sun closer than 5 pc, obviously taking only stars with known radial velocity into account.

Table 1. The "high precision" list of stars from the ARI_HIP catalogue that have approached or will approach the Sun closer than 2.5 pc. Only stars with parallax $\pi > 0.015$ arcsec are included. Estimated Sun miss-distances $D_{\min}$ and their uncertainties are expressed in parsecs, while moments of the closest approach $T_{\min}$ and their uncertainties are in millennia from the present epoch, parallaxes are in arc seconds and radial velocities and their uncertainties in km s^{-1}.

HIP	Name	$D_{\min}$	$\Delta D_{\min}$	$T_{\min}$	$\Delta T_{\min}$	π	V_r	ΔV_r[a]	Flag[b]
89825	GJ 710	0.209	0.136	+1361.30	58.38	0.052	–13.9	0.2 S	C
14754	GJ 127.1A	0.803	0.053	–149.13	0.67	0.099	+65.9	0.1 M	A
57544	GJ445	1.071	0.014	+45.35	0.12	0.186	–111.7	0.1 A	B
87937	Barnard's Star	1.146	0.007	+9.73	0.20	0.548	–110.8	1.0 H	B
27288	GJ 217.1	1.316	0.141	–822.51	107.61	0.046	+25.6	1.2 G	C
54035	GJ 411	1.444	0.005	+20.02	0.07	0.392	–84.7	0.1 N	B
26335	GJ 208	1.587	0.052	–495.18	6.57	0.088	+22.0	0.1 N	B
26624	HD 37594	1.725	0.574	–1801.42	309.02	0.024	+22.4	1.3 S	B
30344	HD 44821	1.852	0.457	–1987.48	79.35	0.034	+14.4	0.2 N	A
57548	GJ 447	1.901	0.019	+70.93	1.19	0.300	–31.1	0.2 A	B
92403	GJ 729	1.988	0.012	+153.02	2.99	0.336	–10.5	0.1 A	B
30067	HD 43947	1.998	0.192	–660.70	5.14	0.036	+40.5	0.1 A	B
27887	GJ2046	2.008	0.065	–402.52	6.80	0.078	+30.4	0.2 N	A
24186	GJ 191	2.148	0.007	–10.93	0.03	0.255	+245.2	0.1 A	A
20359	GJ 168	2.156	0.817	+386.92	3.45	0.032	–78.5	0.2 S	B
38228	HD 63433	2.183	0.296	+1328.27	27.52	0.046	–15.9	0.1 N	B
8709	GJ 3121	2.286	0.748	–237.17	23.04	0.063	+64.0	3.0 S	B
105766	GJ 4194	2.334	0.148	+324.52	2.44	0.039	–76.9	0.2 N	A
40501	GJ 2066	2.341	0.092	–134.46	1.19	0.109	+62.2	0.1 A	B
5643	GJ 54.1	2.425	0.075	–74.32	2.63	0.269	+28.1	0.1 A	B
103039	LP 816-60	2.485	0.135	–270.13	20.40	0.182	+15.8	0.6 S	B

[a] The source of the radial velocity is coded as follows: S = García-Sánchez et al. (1999), N = Nordström et al. (2004), A = Nidever et al. (2002), G = Grenier et al. (1999), H = Wielen et al. (2001), M = Maxted & Marsh (1999).
[b] Flag means: A = our new finding, B = confirmed, and C = corrected previous authors' findings.

A similar procedure was applied to non-HIPPARCOS stars with parallaxes listed in the Tycho-1 catalogue (ESA 1997) and known radial velocities. But these parallaxes appeared to be useless due to large errors. For example, we found a very interesting object, the star TYC 673-735-1 (HD 28309, BD+09 585, V* R Tau). Using the Tycho-1 parallax $\pi = 0\farcs145$ and a velocity $\upsilon = 32$ km s^{-1} we obtained a Sun miss-distance as small as 10 000 AU and a passage time of 2×10^5 years ago! However, after close examination it appeared that this was a variable star of Mira Ceti type and, according to its astrophysical characteristics, the real distance of this star must be significantly larger, say 0.43 kpc; see for example Szymczak et al. (1999).

2.3. The completeness of our search

The first obvious reason for the incompleteness of both our lists is the lack of radial velocities. As stated above, we only found velocity measurements for 61% of stars in the high precision list and for 58% of stars in the low precision list. This seems to be partially an observational selection effect caused by the fact that many observers are mainly interested in nearby stars so select large proper motion stars for their targets. While the implication that *large* $\mu \rightarrow$ *small distance* is generally a true one, not all nearby stars must have large proper motions. In contrast to the most common approach, in this paper we are interested in nearby stars with the smallest proper motions (due to the geometry of the problem) which might be the reason for the lack of data.

We called such stars the "*slow movers*" and attempted to encourage all observers to include them in their target lists for radial velocity measurements (Dybczynski & Kwiatkowski 2003). The "most promising" list of stars (from the point of view of this research) may be obtained when instead of 100 km s^{-1}, we assume a much smaller radial velocity, say 20 km s^{-1} and again estimate the Sun miss-distance for all stars. In 2003 we published the "most wanted" list of 13 stars from the ARIHIP catalogue. Four stars from that list (namely HIP 15929, HIP 30344, HIP 56798, and HIP 84263) have now had their radial velocity measured (Nordström et al. 2004). All of them have been confirmed as passing the Sun less than 5 pc; but only the star HIP 30344 has been included in the high precision list, while the remaining three have too large miss-distance uncertainties. The updated version of this list is presented in Table 3. The miss-distance $D_{\min}$ estimated from the straight line approximation for $\upsilon_r = 20$ km s^{-1} may be treated as the inverse of the "importance" of this particular star for our research.

We also prepared a similar list for the low precision subset. For the assumed radial velocity of 20 km s^{-1} we obtained a list of 45 stars with an estimated miss-distance lower than 3 pc. But during close examination of this list we had to exclude almost 70% of these stars: 11 have erroneously high parallaxes listed in the HIPPARCOS catalogue according to Fabricius & Makarov (2000), 2 (HIP 114110 and HIP114176) appeared to be fictitious points as stated in the general notes to the HIPPARCOS catalogue, 3 more are mentioned there as

Table 2. The "lower precision" list of stars from the HIPPARCOS catalogue (not included in the ARIHIP) that have approached or will approach the Sun closer than 2.5 pc. Only stars with parallax $\pi > 0.015$ arc sec are included. Symbol meaning and units are the same as in Table 1.

HIP[a]	Name	D_{min}	ΔD_{min}	T_{min}	ΔT_{min}	π	V_r	ΔV_r[b]	Flag[c]
93449 S	V* R CrA	0.542	2.621	+222.12	73.10	0.122	–36.0	5.0 R	A
71683 S	αCentauri A	0.925	0.005	+27.76	0.57	0.742	–25.1	0.3 N	C
71681 S	α Centauri B	0.975	0.015	+27.66	2.05	0.742	–22.7	1.0 S	C
70890 H	Proxima	0.954	0.036	+26.7	0.2	0.772	–21.7	1.8 S	D
12351 T	GJ 1049	1.466	3.106	–611.92	512.99	0.061	+26.2	10.0 S	B
31821 T	HD 47787	1.570	3.016	–2596.15	220.65	0.021	+18.3	0.2 N	A
54806 T	HD 97578	1.594	3.028	–1331.18	129.51	0.031	+23.5	1.0 B	A
110893 S	GJ 860A	1.607	0.035	+96.90	1.77	0.250	–33.9	0.1 A	B
100111 T	HD 351880	1.726	7.125	–942.37	71.45	0.040	+26.1	0.3 S	B
10332 T	V* UX Per	1.809	6.031	+1009.87	113.93	0.023	–41.5	2.0 R	A
26373 T	HD 37572	2.058	0.159	–719.36	11.42	0.042	+32.2	0.2 N	A
99461 T	GJ 783A	2.062	0.021	+40.42	0.13	0.165	–129.4	0.1 N	A
113421 T	HD 217107	2.118	0.134	+1361.44	25.24	0.051	–14.0	0.1 A	B
16537 T	GJ 144.0	2.171	0.011	–105.21	1.21	0.311	+16.3	0.1 A	C
22738 S	GJ 2036A	2.202	1.087	–261.97	137.86	0.089	+40.1	10.0 S	C
13772 T	GJ 120.1	2.230	0.801	–431.78	7.56	0.044	+50.4	0.2 N	C
86990 T	GJ 693	2.254	0.584	+41.98	14.00	0.172	–115.0	21.0 S	C
95326 S	CCDM-J19236-3911B	2.257	5.566	–342.58	113.83	0.078	+35.6	0.4 S	C
77257 T	GJ 598	2.260	0.079	+165.69	0.85	0.085	–66.8	0.1 N	C
13769 S	GJ 120.1C	2.271	0.576	–504.24	6.24	0.039	+49.5	0.2 A	C
83945 S	GJ 3991	2.286	0.869	+141.99	61.30	0.138	–45.0	10.0 S	C
32349 S	Sirius	2.299	0.066	+65.74	16.59	0.379	–9.4	1.5 S	C
93506 H	HD 176687	2.299	0.552	–1205.6	177.3	0.037	+22.0	3.7 B	D
98878 T	HD 190412	2.461	0.249	+591.11	80.62	0.030	–54.6	2.6 N	A
14576 S	Algol	2.655	2.438	–6896.00	2629.34	0.035	+4.0	0.7 S	C

[a] The letter after the HIPPARCOS number denotes the source of positions and proper motions: T = Tycho-2, S = Supplement-1 to Tycho-2, and H = HIPPARCOS.
[b] The source of the radial velocity is coded as in Table 1, with additional codes for B = Barbier-Brossat & Figon (2000) and R = Wilson (1953).
[c] The meaning of the Flag is: A = new star, B = corrected, C = confirmed result of previous authors, D = values copied from García-Sánchez et al. (2001) because no better data are available.

Table 3. The list of 9 "most wanted" stars from the high precision subset that have a Sun miss-distance D_{min} less than 3 pc for the assumed radial velocity $v_r = 20$ km s^{-1} only.

HIP	Star name	D_{min}[pc]	V [mag]	α_{2000}	δ_{2000}	Spectral type
24124	TYC-111-834-1	0.313	10.94	05 10 52.4	+06 16 28	–
30108	HD 43724	0.823	8.03	06 20 09.5	+46 38 49	G5
24600	HD 34353	1.495	9.58	05 16 36.5	–06 35 21	A2 IV/V
19527	HD 26439	1.605	8.50	04 11 00.5	+01 57 52	A9 V
29035	HD 233207	1.869	8.92	06 07 32.1	+51 57 32	G5
6935	HD 9176	2.432	8.90	01 29 23.2	–47 56 23	F5 IV/V
25469	HD 35716	2.643	8.51	05 26 48.1	+02 04 06	B8 V
112584	SAO 20251	2.761	9.12	22 48 07.6	+69 04 30	G0
38205	HD 65040	2.844	8.91	07 49 39.1	–74 38 15	F6 V

having large errors, 4 stars were excluded because they seem to be significantly more distant on the basis of their spectra (Gray et al. 2003), and finally we excluded 10 more stars due to their high parallax uncertainties. Thus the list of "most wanted" stars in the low precision subset consists of 15 stars and is presented in Table 4. Last four columns of Tables 3 and 4 consist of visual magnitude, position, and spectral type of the star for the convenience of the potential observer.

The next reason for the incompleteness of our search is the lack of parallax determinations. Again, "slow movers" seem to be badly represented in the sample of stars with a known parallax. From the statistics of nearby stars, it is estimated that we have not recognized over 30% of stars within 10 pc and over 60% within 25 pc (Henry et al. 2002; Costa & Méndez 2003). However, most (if not all) missing stars are faint, extremely low-mass dwarfs. Taking into account that a star with a mass of the order of 0.5 solar mass and travelling as close as 43 000 AU to the Sun very weakly influences the Oort cloud (see Sect. 5), probably all those missing stars are not important here.

There is yet another possibility that we have not recognized a massive perturber. A star that moves with the velocity of 20 km s^{-1} travels over 20 pc in one million years. As stated above we excluded from our lists all those stars with the

Table 4. The list of 15 "most wanted" stars from the lower precision subset, which have a Sun miss-distance $D_{\min}$ less than 3 pc for the assumed radial velocity of only $v_r = 20$ km s^{-1}.

HIP	Star name	$D_{\min}$[pc]	V[mag]	α_{2000}	δ_{2000}	Spectral type
109119	BD+09 4984B	0.235	9.74	22 06 11.8	+10 05 29	A2
34643	HD 56480	0.427	8.06	07 10 30.0	–72 20 34	A3m
69578	TYC-9005-226-1	1.209	12.0	14 14 30.7	–61 47 58	–
80242	CD-30 13092B	1.464	8.8	16 22 54.6	–31 04 38	F5
60104	CD-36 7775	1.931	10.21	12 19 36.1	–36 43 12	K5V
41487	HD 71292	2.020	8.7	08 27 39.0	+27 33 43	F2
21607	HD 29149	2.126	8.77	04 38 19.0	+53 47 03	F8
74387	HD 134557	2.448	7.91	15 12 04.3	–45 00 45	A0 IV
54298	CPD-52 4217B	2.498	10.2	11 06 30.6	–53 16 06	–
118182	BD+50 4201	2.619	11.0	23 58 22.7	+51 23 43	–
73529	HD 132952	2.679	9.85	15 01 45.2	+05 37 54	F8
108710	BD+45 3762	2.859	9.64	22 01 17.4	+46 21 06	K
85818	HD 158547	2.872	9.2	17 32 07.3	–44 19 19	B8/B9 V
97733	BD+30 3779C	2.935	9.48	19 51 41.3	+31 08 16	A5
18398	HD 24861	2.943	8.96	03 55 59.5	–29 48 38	K3/K4 III

distance greater than 66 pc ($\pi < 0\farcs015$) due to their high parallax uncertainties. It is thus possible that a star with large velocity have perturbed the Oort cloud comets recently and now is too far to be recognised. But again, such a star (due to its large velocity) would have little influence on the cloud, so this possibility does not seem to be very important for the completeness of our search; nevertheless, it still exists.

3. Simulated output of the recent stellar perturbers

From both lists presented in Tables 1 and 2, we selected stars that are currently closer than 2.5 pc from the Sun or have passed through this sphere in the last 10 mln years. We called these stars "*recent perturbers*". There are 21 such stars; the list is presented in Table 5. Four stars from Table 2, namely HIP 31821, HIP 54806, HIP 95326, and HIP 100111 are excluded from our final list of perturbers because of their large errors in parallax, exceeding 10%. Because the mass of the star is an important parameter when calculating the perturbation on the Oort cloud comet motion, we included the estimated masses of these stars.

At the beginning of our project we planned to search for comets made observable by a particular star, but it appeared that none of these stellar perturbers is powerful enough to produce observable comets in the absence of any other perturbing agent. Also close investigation of the simultaneous action of each particular star and the Galactic disk tide reveals no signs of the flux enhancement or perihelion distribution anisotropies. The reason is very simple: all 21 stellar perturbers that were found act extremely weakly on the Oort cloud comets due to their large miss-distance and small masses in most cases. The most massive stars, Algol and HD 176687, have proximity distances of 2.7 and 2.3 parsec (roughly 5×10^5 AU), respectively, while the outer limit for the Oort cloud comet heliocentric distance in our simulations is set to 2×10^5 AU.

In this situation, the long-standing problem of anisotropies in the aphelion direction distribution of long-period comets cannot be solved by attributing aphelion groupings to the recent stellar perturber action, such as proposed by Biermann et al. (1983) and Lüst (1984). Some other explanations have been proposed recently (Murray 1999; Matese & Lissauer 2002b), but in such investigations the effects of all possible biases should be included, as demonstrated by Horner & Evans (2002). In addition to that, a well-known directional asymmetry due to the action of the Galactic disk tide (the deficiency of the aphelion directions near the Galactic poles and equator), first discussed by Delsemme (1987) and fully confirmed in our simulations (see Figs. 1 and 4), should be taken into account.

Table 5. The list of 21 recent (and current) stellar perturbers of the Oort cometary cloud, in the order of their appearance in the vicinity of the Sun. We also present here their estimated masses (in solar masses).

HIP	Name	M_*	$D_{\min}$	$T_{\min}$
14576	Algol	5.8	2.655	–6896.00
30344	HD 44821	0.92	1.852	–1987.48
26624	HD 37594	1.5	1.725	–1801.42
93506	HD 176687	5.63	2.299	–1205.6
27288	GJ 217.1	2.0	1.316	–822.51
26373	HD 37572	0.76	2.058	–719.36
30067	HD 43947	0.94	1.998	–660.70
12351	GJ 1049	0.7	1.466	–611.92
13769	GJ 120.1C	0.1	2.271	–504.24
26335	GJ 208	0.7	1.587	–495.18
13772	GJ 120.1	1.0	2.230	–431.78
27887	GJ 2046	0.75	2.008	–402.52
22738	GJ 2036	0.5	2.202	–261.97
14754	GJ 127.1A	0.61	0.803	–149.13
16537	ε Eridani	0.85	2.171	–105.21
24186	Kapteyn's Star	0.281	2.148	–10.93
54035	GJ 411	0.464	1.444	+20.02
70890	Proxima	0.107	0.954	+26.70
71681	α Centauri B	0.916	0.975	+27.66
71683	α Centauri A	0.925	0.975	+27.76
32349	Sirius	2.5	2.299	+65.74

To investigate the overall influence of stars on the Oort cloud comets in the recent past and at present, we decided

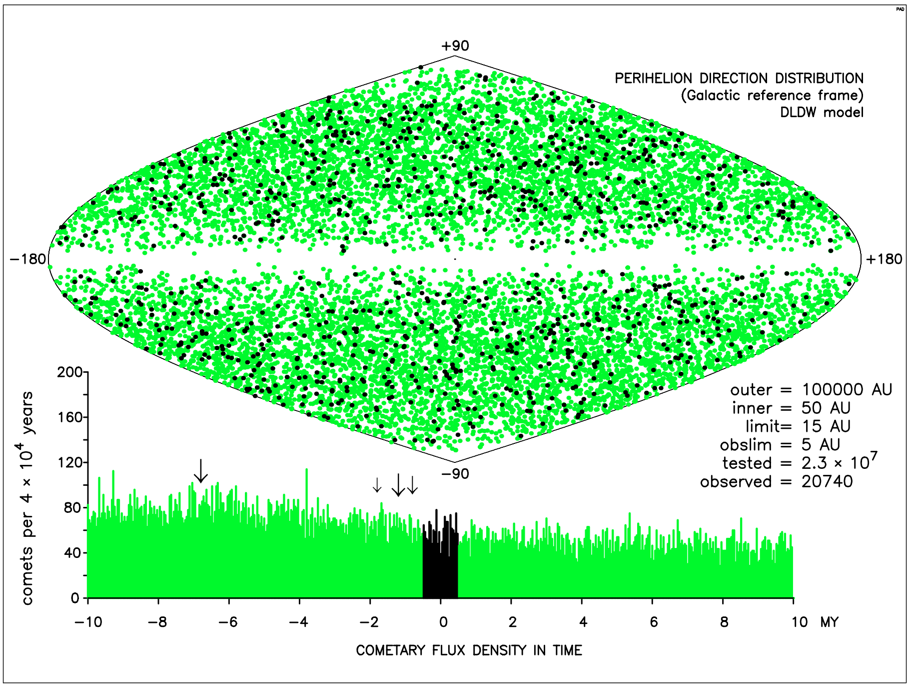

Fig. 1. The result of the numerical simulation of producing observable comets with galactic disk tide and 21 stellar perturbers from Table 5. The upper part of this figure describes the distribution of the perihelion directions of observable comets on the celestial sphere in the galactic reference frame. The DLDW model of the cloud was used here, and the main parameters of the simulation are presented in the lower right part of this plot. The lower part presents the obtained observable cometary influx versus time. Small arrows mark the passages of the four most massive perturbers. Black dots correspond to the observable comet perihelion passages during 1 mln years centred at the present epoch.

to perform a Monte Carlo simulation of the cumulative effect of all these 21 stellar perturbers and the galactic disk tide. Planetary perturbations were also included using the "*Solar System transparency coefficient*" approximation (Dybczyński 2004). The motion of 2.3×10^7 comets was numerically integrated for 20 mln years. During this simulation we recorded over 100 000 perihelion passages below 15 AU for 32 800 different comets. The results of this simulation are presented in Fig. 1. The time interval of this simulation spans 20 mln years and is centred at the present epoch. The upper part of Fig. 1 shows the distribution of the perihelion directions of potentially observable comets obtained in this simulation. Black dots represent the comets observable during the 1 mln year interval centred at the present epoch. The lower part of Fig. 1 presents the histogram of the cometary flux density and shows the number of the obtained observable comets per 10^4 years. Because the size of the cometary cloud taken into account in this simulation was only 2.3×10^7 comets, the flux should be rescaled to the population of 2×10^{12} when compared with the observed one. After rescaling we obtain approximately 100 comets with $q < 5$ AU per year. The slow decrease in the cometary flux is due to the removal by planetary perturbations and due to (very rare) collisions with the Sun.

Four massive perturber passages (Algol, HD 37594, HD 176687, and GJ 217.1) are marked with arrows (the size of the arrow roughly represents the mass of the perturber). It is evident that all 21 stellar perturbers included in this simulation do not produce any noticeable increase in the cometary flux or the perihelion directional distribution anisotropies. Again the miss-distances are too large for a significant increase in the flux, even for a large stellar mass. Figure 1 is very similar to the result for the galactic disk action in the absence of any stellar perturbations, obtained in Paper II (Fig. 1). On the basis of this result we can conclude that we are definitely not in a cometary shower at present.

4. The observed long-period comets and their dynamical history

With a set of 21 stellar perturbers, it is possible to investigate the past motion of all long-period comets under the influence of planets, galactic tide, and stellar perturbations. Such an investigation allows us (among others) to verify whether a particular comet has visited the observable region for the first time ("new" comet from the Oort cloud) or its previous perihelion passage was inside the region of planetary perturbations.

The calculation presented here was organized similarly to that described by Dybczyński (2001). There are two main differences: we used the latest Catalogue of Cometary Orbits (Marsden & Williams 2003), which increased the number of comets under consideration by 20%, and we included stellar perturbations into the dynamical model, which considerably increased the time needed to complete this calculation. The first step was to calculate the original orbital elements of all long-period comets included in the Marsden's catalogue. We use the term "original" in a standard way here, i.e. to denote orbits of comets before they enter the Planetary System, therefore free from the planetary perturbations. For details the reader is directed to our earlier papers. We limit our interest here to the comets of classes 1 and 2 (Marsden et al. 1978) to concentrate on 386 precise orbits. Next, for the elliptic comets that reached the distance of 250 AU from the Sun (308 in number), we follow their backward motion numerically one orbital revolution to the past under the simultaneous galactic and stellar perturbations. It should be stressed here that stellar perturbations were calculated with full precision by means of the N-body numerical integration, taking their mutual interactions into account. The result is generally similar to the one obtained by Dybczyński (2001). The action of the 21 stellar perturbers did not change cometary orbits significantly because none of the stars passed close enough to the Sun. In Table 6 we present a list

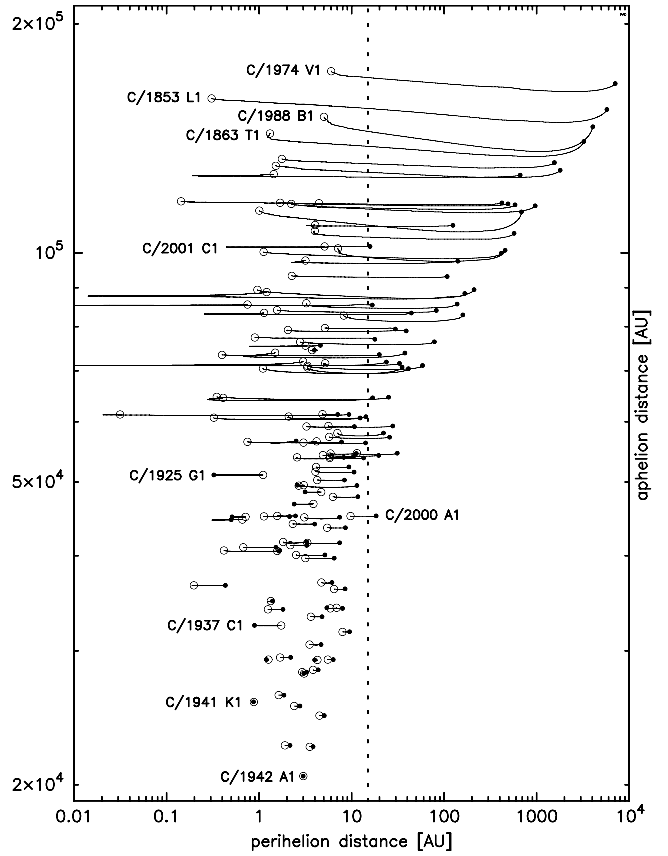

Fig. 2. The backward orbital evolution of 108 long-period comets under the influence of the Galactic disk tide and perturbations from 21 nearby stellar perturbers. Some comets mentioned in the text are given with their names.

Table 6. A list of 22 comets that changed their previous perihelion distance by more than 10% after including the perturbations from 21 nearby stellar perturbers. The $q_{\rm orig}$ and $Q_{\rm orig}$ are the original perihelion and aphelion distances, respectively; $q_{\rm gal}$ is the previous perihelion distance obtained only under the influence of the Galactic disk tide, while $q_{\rm pert}$ is obtained from the full dynamical model including 21 stellar perturbers.

Comet	$q_{\rm orig}$[AU]	$Q_{\rm orig}$[AU]	$q_{\rm gal}$[AU]	$q_{\rm pert}$[AU]
C/1896 V1	1.066	383 600	130.4	112.1
C/1916 G1	1.692	116 400	424.5	488.9
C/1921 E1	1.007	113 700	608.5	687.5
C/1922 U1	2.257	93 310	96.67	107.8
C/1925 G1	1.105	51 080	0.284	0.324
C/1932 M2	2.313	44 040	4.531	3.984
C/1935 Q1	4.034	108 800	104.1	124.8
C/1940 R2	0.364	2 969 000	4 204	653 300
C/1942 C1	1.441	126 900	546.5	661.7
C/1946 P1	1.129	45 050	2.475	2.133
C/1947 S1	0.749	85 540	13.77	16.72
C/1948 T1	3.261	59 140	11.8	10.67
C/1966 T1	0.417	40 640	1.869	1.68
C/1973 E1	0.143	116 900	366.5	421.7
C/1975 E1	1.206	88 840	148.2	166.9
C/1984 W2	4.005	106 900	489.9	570.5
C/1991 F2	1.513	130 200	1 604	1 794
C/1991 X2	0.197	36 580	0.512	0.431
C/1993 K1	4.845	61 400	6.291	7.082
C/1997 A1	3.163	97 720	124.1	140.8
C/1997 J2	3.051	49 520	2.96	2.593
C/2000 OF8	2.177	41 290	3.607	3.261

of 22 comets whose previous perihelion distance was changed by more than 10% by the stellar perturbers action.

All comets with the aphelion distance $Q_{\rm orig}$ < 20 000 AU did not change their orbit during one orbital period in the past. The past motion of comets with $Q_{\rm orig}$ > 200 000 AU, including C/1896 V1 and C/1940 R2 from Table 6, is highly inaccurate; these comets go too far from the Sun to be considered members of the Oort cloud. They are interstellar ones, or their available orbital data are not precise enough to predict their past motion.

The results for the comets that have 20 000 < $Q_{\rm orig}$ < 200 000 AU (108 in number) are presented in Fig. 2. It shows their orbital evolution in the $q \times Q$ plane. This plot was obtained as follows: starting from the original orbital elements we plot a small open circle; then in the course of the numerical integration, we plot a small dot after each integrator step; and finally (at previous perihelion) we plot a big dot. The dashed vertical line corresponds to the threshold value (15 AU) of the previous perihelion distance, proposed by Dybczyński (2001) as a definition of the dynamically "new" Oort cloud comet.

All comets presented in this figure are widely called dynamically "new" in the literature but it is evident that over half of them (64) have passed closer to the Sun than 15 AU at previous perihelion. In our opinion they should not be treated as "new". Some of them do not change their orbits at all (C/1942 A1 and C/1941 K1 for example), and some have even passed significantly closer to the Sun at their previous perihelion passage (C/1937 C1 and C/1925 G1 for example). While generally comets with large semi-major axes have changed their perihelion distances significantly, there are some exceptions; see the C/2001 C1 evolution for example. Looking at Fig. 2 one can conclude that almost all comets with $Q_{\rm orig}$ < 50 000 AU (and numerous with larger Q) have travelled among Solar System planets in the past.

According to our definition of the dynamically new Oort cloud comet (i.e. demanding that its previous perihelion distance was greater than 15 AU), there are only 45 dynamically "new" long period comets of classes 1 and 2, included in the latest Cometary Orbit Catalogue (Marsden & Williams 2003). We omitted here C/1896 V1, C/1940 R2, and C/1993 Q1 due to their highly uncertain semi-major axes.

There are numerous changes relative to Table 6 in Dybczyński (2001): 8 comets should be removed because their previous perihelion appeared to be smaller than 15 AU (C/1903 M1, C/1948 E1, C/1948 T1, C/1950 K1, C/1962 C1, C/1974 F1, C/1976 U1, and C/1990 M1), and 13 comets should be added (C/1999 J2, C/1999 K5, C/1999 U4, C/2000 A1, C/2001 C1, C/2001 G1, C/2001 K5, C/2001 Q4, C/2002 A3, C/2002 J5, C/2002 L9, C/2002 O7, and C/2003 A2). Comet C/1997 BA6 has also been removed from our list because its original orbit was hyperbolic. The complete list of the

Table 7. A list of 45 long-period comets that satisfy our definition of a dynamically "new" comet from the Oort cloud. The original perihelion and aphelion distances for each comet are listed ($q_{\rm orig}$ and $Q_{\rm orig}$, respectively), as well as the previous perihelion distance $q_{\rm previous}$ obtained with the full dynamical model (Galactic tide plus 21 stellar perturbers). All values are in AU.

Comet	$q_{\rm orig}$	$Q_{\rm orig}$	$q_{\rm previous}$	Comet	$q_{\rm orig}$	$Q_{\rm orig}$	$q_{\rm previous}$
C/1853 L1	0.306	159 600	5741	C/1978 R3	1.764	132 900	1560
C/1863 T1	1.313	143 600	3239	C/1979 M1	0.409	64 510	16.89
C/1902 R1	0.397	73 450	19.94	C/1984 W2	4.005	106 900	570.5
C/1902 X1	2.777	76 380	78.62	C/1987 W3	3.323	70 720	35.24
C/1906 E1	3.337	71 070	58.44	C/1988 B1	5.031	150 900	4037
C/1907 E1	2.051	79 200	38.94	C/1989 X1	0.348	64 680	25.09
C/1913 Y1	1.101	70 490	41.07	C/1991 F2	1.513	130 200	1794
C/1916 G1	1.692	116 400	488.9	C/1992 J1	3.000	72 000	23.8
C/1919 Q2	1.118	100 300	414.9	C/1997 A1	3.163	97 720	140.8
C/1921 E1	1.007	113 700	687.5	C/1999 J2	7.114	101 400	456.4
C/1922 U1	2.257	93 310	107.8	C/1999 K5	3.254	85 860	138.8
C/1925 W1	1.565	84 130	82.59	C/1999 U4	4.887	54 240	19.58
C/1935 Q1	4.034	108 800	124.8	C/2000 A1	9.741	45 100	18.38
C/1942 C1	1.441	126 900	661.7	C/2001 C1	5.110	102 000	15.86
C/1944 K2	2.226	116 000	962.4	C/2001 G1	8.239	82 760	158.9
C/1947 S1	0.749	85 540	16.72	C/2001 K5	5.190	71 600	33.02
C/1947 Y1	1.491	73 960	37.84	C/2001 Q4	0.960	89 420	210.3
C/1956 F1-A	4.437	116 200	582	C/2002 A3	5.143	79 680	29.7
C/1973 E1	0.143	116 900	421.7	C/2002 J5	5.725	57 310	25.71
C/1974 V1	6.016	173 300	7044	C/2002 L9	7.034	57 990	22.18
C/1975 E1	1.206	88 840	166.9	C/2002 O7	0.899	77 420	17.89
C/1978 A1	5.608	59 240	27.78	C/2003 A2	11.420	54 560	31.020
C/1978 H1	1.130	83 400	44.11				

dynamically new comets according to our definition is presented in Table 7.

5. Future close passage of GJ 710 and its effect on the Oort cloud

In the two lists presented in Tables 1 and 2, the closest passage is predicted for GJ 710. It will pass 0.2 pc from the Sun 1.3 mln years from now. This is the only star from both lists that can produce observable comets directly. We performed a Monte Carlo simulation to show the characteristics of the observable comets induced by such a close passage.

The results are presented in Fig. 3. In this simulation we excluded all comets observable without the stellar action, using so-called "dynamical filtering" (Dybczyński 2005). As a result, we obtain the distribution of the perihelion direction of the observable comets induced by the passage of GJ 710. It is easy to notice strong asymmetries in this distribution. Perihelion directions of comets observable in the first 2 mln years after the passage are highly concentrated along the heliocentric orbit of the star (dashed line) on both sides of its anti-perihelion direction (an empty circle). Due to the GJ 710 orbit orientation, they populate the normally empty region of the Galactic equator. The cometary flux histogram shows that the first comets can be expected some 700 thousand years after the passage, and the maximum of the flux will occur over 1 mln year later. We used a cometary cloud of 6.6×10^9 comets. After rescaling the flux for the cloud of 2×10^{12} comets we obtain the maximum flux of 3 comets per year. It should be stressed that we count here only those comets observable due to the passage of GJ710.

In Fig. 4 we present the results of a similar simulation but now comets observable without the stellar perturbation are not excluded. It is easy to note that almost all features visible in Fig. 3 are completely masked here by the vast majority of comets made observable by the Galactic tide alone. The only fingerprint of the GJ 710 passage is the slight overpopulation of black dots in the Galactic equatorial zone near the anti-perihelion of GJ 710 (small open circle). From the result presented in Fig. 3, one can estimate that the probability of being observed due to the GJ 710 passage is of the order of 5×10^{-6} for a single comet. It means that, among almost 43 000 observed perihelion passages of long-period comets presented in Fig. 4, only 675 come from the population described in Fig. 3.

The flux of observable comets presented in Fig. 4 reveals a very small increase due to the passage of GJ 710. Matese & Lissauer (2002a) estimated the increase in the flux for similar stellar passage on the level of 40%. From our simulation it appears that this increase is much smaller, only just a few percent. One of the reasons for this discrepancy is the fact that Matese & Lissauer (2002a) use averaged equations of cometary motion that overestimates the number of observable comets because the $q < OL$ condition is a necessary but not sufficient one for a comet to be observed. Here OL denotes the assumed observability limit. In many cases a comet is located near its aphelion during the minimum of the perihelion distance evolution, so it never comes closer than OL from the Sun. This effect is the main reason we do not use either averaged equations nor their analytical solutions in our calculations, as described in more detail by Dybczyński & Prętka (1997). This overestimation is

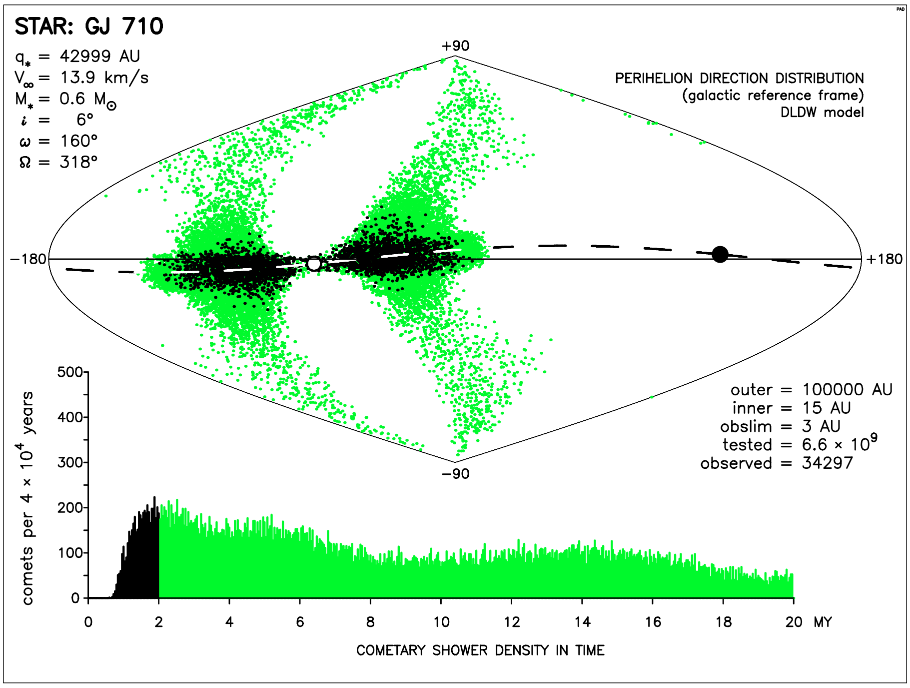

Fig. 3. The results of the numerical simulation of producing observable comets by the passage of GJ 710. All comets that can be observed without the stellar perturbation have been removed. The parameters of the star are presented in the upper left corner while the parameters of the simulation are shown in the lower right one. The DLDW model of the cloud was used. The projection of the GJ 710 heliocentric orbit is marked by the dashed line. The stellar perihelion is shown as a big, black dot, while the small open circle denotes its anti-perihelion direction. The observable comets influx starts 0.7 mln years after the stellar passage and gain its maximum 1 mln years later.

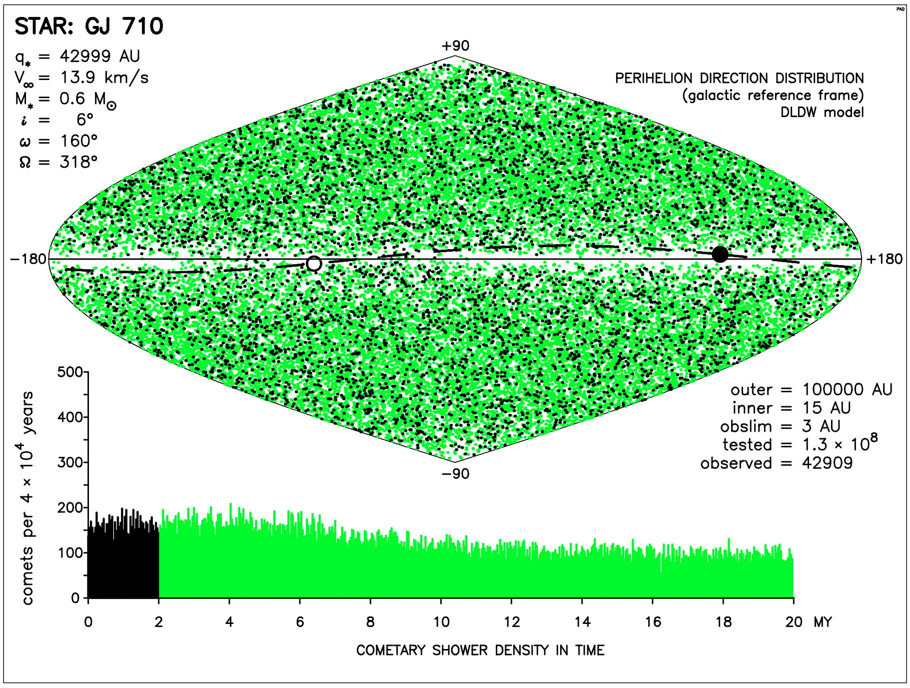

Fig. 4. The results of the numerical simulation of producing observable comets by the passage of GJ 710. Comets observable due to the galactic tide alone are not excluded here. As in the previous figure, the upper part describes the distribution of the perihelion directions of observable comets on the celestial sphere in the galactic reference frame. The DLDW model of the cloud was used here. The lower part presents the obtained observable cometary influx versus time. Comets that make their perihelion passage during the first 2 mln years after the star passage are marked by black dots, while the rest are in gray. The cloud population in this simulation is about one order smaller than presented in Fig. 3, because the calculation needed would be much more time-consuming.

more important for comets with large semi-major axes, because the time interval on which their perihelion distance is smaller than *OL* is much shorter than their orbital period. Another possible reason for the discrepancy mentioned above is the fact that Matese & Lissauer (2002a) investigated only those comets with $1/a < 7 \times 10^{-5}$, while in our simulation all semi-major axes are allowed. They also ignored planetary perturbations, while in our simulation the observable population of comets is systematically depleted by planets and collisions with the Sun.

6. Conclusions

We have searched for real stellar perturbers in the most precise recent stellar catalogues. We obtained a more reliable list of potential perturbers by using more precise proper motions and more numerous radial velocity measurements. In this way the number of stars visiting (in past or in future) the 5 pc vicinity of the Sun is increased by some 50%. The list of those passages closer than 2.5 pc, presented in Tables 1 and 2 is increased by 40% compared to the previously published data.

From this list we selected 21 stars that are recent or current perturbers of the Oort cloud. This list of perturbers seems to be quite complete considering the strength of the stellar action. Unfortunately, none of these perturbers is powerful enough to directly produce observable comets from the cloud. As a result we can conclude that any perihelion direction groupings found by previous authors in the observed long-period comets sample should be attributed to some other effect, not to the recent stellar perturbation.

We simulated the action of 21 stellar perturbers, as well as Galactic and planetary perturbations on the cometary cloud, to investigate an observable comet sample. From the result we can conclude that the simultaneous action of all mentioned perturbers does not reveal any peculiarities both in the cometary flux and in their perihelion direction distribution. In short: currently Galactic tide definitely dominates as a mechanism for producing observable comets from the Oort cloud.

We used the same list of 21 stellar perturbers to investigate the past motion of the observed long-period comets included in the latest edition of the Catalogue of Cometary Orbits. We included 308 elliptic comets of classes 1 and 2 in our investigation, calculated their original elements, and followed their past motion for one orbital period under the influence of Galactic tide and simultaneous perturbations from 21 nearby stars. According to our definition, we found that only 45 comets can be treated as "dynamically new", as the rest passed closer than 15 AU at their previous perihelion. As a general, simplified rule one can assume, that dynamically new comets should have semi-major axes that are greater than 25 000 AU instead of the 10 000 AU hitherto adopted widely, but there are some exceptions. The possible special significance of semimajor axes greater than 25 000 AU as defining dynamically new comets was hinted at by Marsden & Sekanina (1973) in their investigation of "original" orbits of comets.

There is only one star in our lists that can penetrate the Oort cloud, namely GJ 710. We performed a Monte Carlo simulation of the simultaneous action of this star passage and the Galactic disk tide on the cometary cloud. The sample of simulated observable comets resulting from that event was studied in detail. In particular we obtained a very small observable comet flux increase on the level of only few percent. The anisotropy in the perihelion direction distribution is also very difficult to observe due to the dominating role of the Galactic tide.

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