THE ASTRONOMICAL JOURNAL VOLUME 90, NUMBER 9 SEPTEMBER 1985

THE PASSAGE OF A "NEMESIS"-LIKE OBJECT THROUGH THE PLANETARY SYSTEM

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Received 19 March 1985; revised: 21 May 1985

ABSTRACT

The probability that passing stars could have perturbed the hypothetical stellar companion, Nemesis, into an orbit that penetrates the planetary system is about 15%. The planetary orbits crossed by Nemesis would become highly eccentric, and some would even become hyperbolic. If Nemesis ejects Jupiter from the solar system, the semimajor axis of the orbit of Nemesis would shrink down to a few hundred AU. The probability of any object in the inner edge of the Oort cloud at a semimajor axis of 2×10^4 AU having passed inside the orbit of Saturn is about 80%. The apparent lack of damage to the planetary orbits implies a low probability of there being any objects more massive than 0.02 $M_\odot$ in the inner edge of the Oort comet cloud. However, several objects less massive than 0.01 $M_\odot$ or 10 Jupiter masses could pass through the planetary system from the Oort cloud without causing any significant damage to the planetary orbits. The lack of damage to the planetary system also requires that no black dwarf more massive than 0.05 $M_\odot$ has entered the planetary system from interstellar space.

I. INTRODUCTION

Two groups have recently suggested that the Sun may have a low-mass stellar or black dwarf companion, Nemesis, with an orbital period of 26 Myr (Davis, Hut, and Muller 1984; Whitmire and Jackson 1984). They note that the perihelion passage of Nemesis through the inner comet cloud postulated by Hills (1981) would cause an intense comet shower to enter the inner planetary system. Some comets hit the Earth, causing severe environmental stress. They propose that these induced comet showers are responsible for the periodic extinctions suggested by the data of Raup and Sepkoski (1984).

As noted by Hills (1984a), there is a nonnegligible probability of Nemesis actually entering the planetary system as a result of eccentricity changes induced by passing stars. Nemesis lies in the outer edge of the Oort comet cloud at a semimajor axis of 9×10^4 AU. Any similar objects lying in the inner edge of the clasical Oort cloud at a semimajor axis of 2×10^4 AU would have a much higher probability of entering the planetary system.

Bahcall and Soneira (1981) found that about 15% of the stars they observed towards the Galactic pole have nuclear-powered companions (stars) at projected separations of the order of 0.1 pc = 2×10^4 AU. Latham *et al.* (1984) have confirmed that many of these pairs are physically connected systems. This suggests that there may be nonnuclear burning companions (black dwarfs) below the Kumar (1963) limit of 0.07 $M_\odot$ at this separation around many other stars including, perhaps, the Sun. Davidson (1975) discussed the difficulties of detecting such an object in a distant orbit around the Sun. Nemesis may be an example of such an object. The minimum mass of Nemesis needed to perturb the inner cloud enough to produce the postulated death showers is about 0.01 $M_\odot$ (Hills 1984a). In the current paper, I use computer simulations to investigate the potential damage caused by the passage of a Nemesis-like object through the planetary system. I use these computer results and the apparent lack of damage to the planetary orbits to place limits on the number and masses of any other black dwarfs (or large planets) within the Oort cloud.

The possible existence of black dwarfs in the Oort cloud raises the possibility that they may be quite common. In particular, could they be responsible for the missing mass in the solar neighborhood? Bahcall *et al.* (1985) find that the missing-mass objects must be less massive than 2 $M_\odot$. I investigate possible constraints on interstellar black dwarfs required by the observed lack of damage to the planetary orbits.

In the first part of Sec. II, I determine the probability that a solar companion such as Nemesis has entered the planetary system during the lifetime of the solar system. In the second part of this section, I determine this probability for unbound interstellar intruders. In Sec. III, I present the results of computer simulations between the Sun-planet system and black-dwarf intruders from the Oort cloud and from interstellar space. In Sec. IV, I use the results of Secs. II and III to place limits on the number of massive black dwarfs in the Oort cloud and in interstellar space.

II. ENCOUNTER PROBABILITIES

a) Objects in the Oort Cloud

We will first find the probability that a given object in the Oort cloud has entered the planetary system. This discussion is based on the work given in Hills (1981, 1984a). The equations given in the current paper are derived in these earlier papers.

Objects in the Oort cloud are severely perturbed by passing stars. As a result, their orbital eccentricities should follow the distribution dictated by statistical equilibrium. In this case, the probability of a given object having an orbital eccentricity greater than e is given by

$$P_e = (1 - e^2). \tag{1}$$

The probability of an object with semimajor axis a having a perihelion distance of q or less is then given by

$$P_q = \frac{2q}{a}\left(1 - \frac{q}{2a}\right) \simeq \frac{2q}{a}, \tag{2}$$

for $q \ll a$.

Long-period comets which cross within the orbit of Jupiter tend to be ejected into hyperbolic orbits. As shown by Hills (1981), the classical Oort or steady-state comet cloud exists for comets with semimajor axes $a > a_c = 2\times10^4$ AU as the result of the perturbations by passing stars being great enough and frequent enough per orbital revolution for these comets that the mean change in their pericenter distance q

exceeds the orbital semimajor axis of Jupiter, which is 5 AU. The rate at which these comets enter the planetary system is only limited by the size of the loss cone given by Eq. (2). The stellar perturbations deflect a constant stream of new comets (and possibly other objects) from the classical Oort cloud into orbits which take them within the orbit of Jupiter. Comets in the inner cloud ($a < 2\times10^4$ AU) only enter the planetary system in intense showers that persist for a relatively brief time (about one orbital period) after the close passage of a stellar intruder (Hills 1981).

The probability per orbital revolution that a given Oort cloud object of semimajor axis a enters the planetary system in an orbit with a pericenter distance q or less is given by Eq. (2). After N orbital revolutions, the integrated probability that the object has passed within distance q of the Sun is given by

$$P_N = (1 - P_q)^N = 1 - \left(1 - \frac{2q}{a}\right)^N. \tag{3}$$

If the age of the solar system is $\tau_s = 4.6$ Gyr, then for the case where the companion is much less massive than the Sun, Kepler's Third Law gives the number of revolutions made during the age of the solar system as

$$N = \frac{\tau_s}{P} = \frac{\tau_s}{\dfrac{2\pi a^{3/2}}{[(GM_\odot)^{1/2}]}} = 1626\left(\frac{2\times10^4\ \mathrm{AU}}{a}\right)^{3/2}. \tag{4}$$

The probability that a given object in the Oort cloud will, within 4.6 Gyr, pass inside the orbit of Jupiter decreases rapidly with increasing semimajor axis. The probability decreases from $P_N = 56\%$ for $a = 2\times10^4$ AU to $P_N = 1.4\%$ for $a = 10^5$ AU.

The greatest probability of a long-period comet entering the planetary system occurs if it has a semimajor axis $a = a_c = 2\times10^4$ AU, the semimajor axis of comets at the inner edge of the Oort cloud. As we shall now show, the probability drops off almost as rapidly for $a < a_c$ as for $a > a_c$.

As discussed in Hills (1981), for the comets inside a_c, the mean elapsed time between stellar encounters capable of producing a perturbation in the pericenter distance equal or greater than $q = 5$ AU is much longer than one orbital period of these comets. The number of independent loss-cone fillings for these objects, i.e., the number of times they are put at risk of being perturbed by passing stars into an orbit that crosses inside the orbit of Jupiter is given by

$$N = 1626\left[\frac{a}{2\times10^4\ \mathrm{AU}}\right]^2. \tag{5}$$

We can still use Eq. (3) to solve for P_N for these objects if we use N as given by Eq. (5). For semimajor axis $a = 10^4$ AU, $P_N = 33\%$, and for $a = 10^3$ AU, $P_N = 4\%$. Here P_N decreases less rapidly for $a < a_c$ than it did for $a > a_c$ because the increasing size of the loss cone with decreasing a compensates, in part, for the long time between stellar encounters capable of filling the loss cone.

Comets and other objects with a semimajor axis $a \leqslant 500$ AU have probably never suffered a perturbation in their pericenter distances as large as their initial pericenter distances if these perturbations are due purely to passing stars. For practical purposes, we can consider their orbits to be frozen since formation.

If Nemesis exists, it would increase the probability of objects with $a < a_c$ entering the loss cone. Nemesis would perturb some of them into Jupiter-crossing orbits at each of its perihelian passages. Hills (1984a) finds that Nemesis would fill the loss cone of such comets (and other objects with $a < a_c$)if its mass is at least 0.01 $M_\odot$. In this case, the number of independent loss-cone fillings for these objects due to the perturbations of Nemesis is $N_{\rm Nem} = f_0 N_{\rm rev}$, where $N_{\rm rev}$ is the total number of orbital revolutions made by Nemesis (about 180 if it has always been at its present distance) and f_0 is the fraction of the time that the perihelion distance of Nemesis is small enough to fill the loss cones of these comets. To fill their loss cones, it has to pass within the semimajor axes of these comets if its mass $M_N = 0.01\ M_\odot$, and it has to pass closer than about 2.5 times their semimajor axes if $M_N = 0.05\ M_\odot$ (Hills 1984a). For comets with semimajor axis $a = 3000$ AU, Hills (1984a) finds that $f_0 = 0.15$ for $M_N = 0.015\ M_\odot$ and $f_0 = 0.40$ for $M_N = 0.20\ M_\odot$. In this case, $N_{\rm Nem} = 72$ for $M_N = 0.015\ M_\odot$ and $N_{\rm Nem} = 27$ for $M_N = 0.2\ M_\odot$, for comets with semimajor axes $a = 3000$ AU. The value of $N_{\rm Nem}$ for a low-mass Nemisis is about a factor of 3 larger than the value of N calculated on the basis of passing stars alone, and $N_{\rm Nem}$ is an order of magnitude greater than N for passing stars if Nemesis is as massive as 0.2 $M_\odot$. If Nemesis exists, then for comets with $a = 3000$ AU, the total number of independent loss-cone fillings resulting from passing stars and Nemesis combined must be at least four times larger than that due to passing stars alone.

b) *Interstellar Intruders*

If the space density of possible intruders is n and their average speed with respect to the Sun is V, then mean time between encounters in which the intruders have an impact parameter p or less with respect to the Sun is given by

$$\tau = \frac{1}{(\pi p^2) n V}. \tag{6}$$

The missing mass in the solar neighborhood corresponds to a mass density of $\rho = 0.1\ M_\odot/\mathrm{pc}^3$ (Bahcall 1984). If the average mass of the objects responsible for the missing mass is m, then the space density of these objects is

$$n = \frac{\rho}{m} = 10\ \mathrm{pc}^{-3}\left(\frac{0.01\ M_\odot}{m}\right). \tag{7}$$

The average number of intruders which have passed within impact parameter p of the Sun in its lifetime τ_s is given by

$$N_i = \frac{\tau_s}{\tau} = \frac{\tau_s}{\pi p^2 n V)^{-1}} = \left(\frac{p}{98\ \mathrm{AU}}\right)^2\left(\frac{0.01\ M_\odot}{m}\right)\left(\frac{V}{30\ \mathrm{km/s}}\right). \tag{8}$$

The closest approach $R_{\rm min}$ attained in an encounter in which the impact parameter is p is given by

$$R_{\rm min} = a_c\left\{\left[1 + \left(\frac{p}{a_c}\right)^2\right]^{1/2} - 1\right\} = p\left[\left(\frac{a_c}{p}\right)^2 + 1\right]^{1/2} - a_c. \tag{9}$$

Here $R_{\rm min} \simeq p - a_c$, for $p \gg a_c$, and $R_{\rm min} \simeq (a_c/2)(p/a_c)^2$ for $p \ll a_c$. The parameter

$$a_c \equiv \frac{G(M_\odot + m)}{\langle V^2\rangle} = 0.985\ \mathrm{AU}\left(\frac{M_\odot + m}{M_\odot}\right)\left(\frac{30\ \mathrm{km/s}}{V}\right)^2 \tag{10}$$

is the "accretion" radius which characterizes the strength of the gravitational focusing. For $p = 98$ AU, we find that $R_{\min} = 97$ AU. For the intruder to pass within the orbit of Jupiter requires that $R_{\min} = 5$ AU, which occurs when $p = 6$ AU.

The probability that at least one missing-mass object has passed within impact parameter p of the Sun is given by $P_p = (1 - e^{-N_i})$, where N_i is given by Eq. (8). For $n = 10$ pc^{-3} and $N_i \ll 1$, $P_p \cong N_i$. For impact parameter $p = 6$ AU, $P_p = 0.4\%$, while for $p = 40$ AU, $P_p = 17\%$. The probability that one of these missing-mass objects has passed inside the orbit of Jupiter or even Pluto is low unless their average mass is much less than 0.01 $M_\odot$.

III. COMPUTER SIMULATIONS

A large number of computer simulations were made of encounters between a planet-star system and intruders with masses comparable to that of a black dwarf or a massive planet. In these simulations, the mass M_p of the planet is taken to be 0.001 M_*, where M_* is the mass of the star which the planet orbits. This star-planet mass ratio is similar to that of the Sun-Jupiter system. In these simulations, the intruder mass is either (0.005 or 0.05) M_*. The calculations were made for various periastron distances of the intruder relative to the star. Two sets of impact velocities were used in these calculations to simulate objects entering the planetary system from both the Oort cloud and from interstellar space. Table I summarizes the results for an intruder from the Oort cloud (Oort cloud intruder), while Table II shows it for interstellar intruders. It is interesting to compare the results of Table II to the computer simulations of encounters between a star-planet system and a stellar intruder that is as massive as the home star of the planet (Hills 1984b).

The computer simulations used the computer code described in Hills (1983b). The code uses the Shampine-Gordon (1975) variable-order, variable-step-size integrator and the Heggie (1970) quasiregularization. If a temporarily bound triple system forms in the encounter, the integration continues until one of the three objects is thrown into either a hyperbolic orbit, or a bound orbit with a semimajor axis larger than 350 times that of the inner binary, or until 5×10^6 integration steps have been completed. A very high percentage of encounters with Oort cloud intruders produced very long-lived triple systems which persisted to the 5×10^6-step limit. The average computer time required per encounter was higher than in any of my earlier computer simulations. In contrast, the simulations of the encounters with the interstellar intruders were quite cheap because these high-velocity impacts produced only flyby encounters and formed no temporarily bound trinary systems.

Table I summarizes the results of the calculations for the Oort cloud objects. If an intruder enters the planetary system from the Oort cloud, its velocity is very nearly that of an object in a parabolic orbit. I have approximated the pre-encounter approach of an intruder from the Oort cloud by treating it as an object in a hyperbolic orbit with a velocity at infinity equal to 7.5×10^{-3} of the circular velocity of the planet. (For the Jupiter-Sun system, this corresponds to a velocity at infinity of 0.1 km/s.) This approximation allows the use of the massive computer code originally used to study

TABLE I. Planet-Nemesis interaction. Masses = (1 − 0.001) − 0.5; $V/V_{\rm orb} = 0.007\,505$.

$\frac{R_{\min}}{a_0}$	$\langle \Delta E/E_0 \rangle$	$\langle e \rangle$	P.E.	P_c	$(P_c)_{\rm long}$	$\frac{N_{\rm rev}}{N}$	N
0.00268	+0.137 ± 0.022	0.347 ± 0.072	0.208	0.60	0.49	11.9	47
0.067	+0.166 ± 0.023	0.359 ± 0.042	0.190	0.45	0.37	10.2	100
0.242	+0.126 ± 0.019	0.204 ± 0.028	0.024	0.47	0.41	1.83	71
0.386	+0.117 ± 0.034	0.252 ± 0.036	0.056	0.51	0.44	3.38	96
0.564	+0.081 ± 0.014	0.218 ± 0.033	0.077	0.57	0.50	3.32	130
0.604	+0.059 ± 0.013	0.146 ± 0.038	0.040	0.45	0.375	0.65	40
0.821	+0.114 ± 0.024	0.188 ± 0.037	0.093	0.49	0.46	1.80	100
1.073	+0.075 ± 0.012	0.167 ± 0.030	0.073	0.46	0.425	3.08	120
1.358	+0.045 ± 0.018	0.094 ± 0.025	0.038	0.50	0.48	0.61	100
1.481	+0.024 ± 0.003	0.053 ± 0.006	0.0052	0.48	0.48	0.84	365
1.419	+0.031 ± 0.004	0.067 ± 0.008	0.0105	0.47	0.46	0.66	350
1.676	+0.0104 ± 0.0020	0.0326 ± 0.0035	0.000	0.49	0.49	0.52	100
2.414	+0.0006 ± 0.0001	0.0119 ± 0.0005	0.000	0.13	0.11	0.16	350
3.285	-9×10^{-6} ± 2.4×10^{-5}	0.00245 ± 0.00008	0.00	0.00	0.00	0.00	350
4.29	$+2\times10^{-6}$ ± 5×10^{-6}	0.000696 ± 0.000036	0.000	0	0	0	100

PLANET - NEMESIS INTERACTION

Masses = (1 - 0.001) - 0.005; $V/V_{\rm orb}$ = 0.007505;

$\frac{R_{\min}}{a_0}$	$\langle \Delta E/E_0 \rangle$	$\langle e \rangle$	P.E.	P_c	$(P_c)_{\rm long}$	$\frac{N_{\rm rev}}{N}$	N
0.630	0.0129 ± 0.0037	0.0167 ± 0.0020	0.000	0.52	0.48	2.3	100
0.858	0.01475 ± 0.0036	0.0196 ± 0.0040	0.000	0.48	0.46	0.68	100
1.121	0.00609 ± 0.00218	0.0108 ± 0.0021	0.000	0.52	0.50	1.11	100
1.419	0.00210 ± 0.00049	0.0062 ± 0.0009	0.000	0.48	0.47	0.60	350
1.751	0.00078 ± 0.00007	0.00294 ± 0.00016	0.000	0.40	0.38	0.49	350

encounters between a binary star and a stellar intruder (Hills 1983b and the earlier papers cited therein). The full three-body integration began with the intruder at 10 times the semimajor axis of the planet.

The first column of Table I shows the closest-approach distance of the intruder to the central star in units of the initial semimajor axis of the planetary orbit. Column 2 shows the average change in the binding energy of the planetary orbit in units of its initial binding energy. The "errors" quoted are the standard "errors" of the mean. They are a consequence of the dependence of the results on the binary orbital phase and on the orientation of the binary with respect to the incoming intruder. The actual integration error was nil; e.g., the typical fractional change in the energy of the system due to integration errors was about 10^{-9} and the worst error after a maximum of 5×10^6 integration steps was about 10^{-5}. The next column gives the average eccentricity of the post-encounter orbit. The following column gives the probability of an exchange collision, the fraction of the completed encounters in which the intruder becomes bound to the star, while the planet is ejected into a hyperbolic orbit.

Column 5 gives the probability of capture P_c, the fraction of the encounters which lead to the formation of a temporarily bound trinary which persists long enough for the outer member of the trinary to make at least one revolution around the inner binary in an orbit with a semimajor axis at least 2.5 times larger than that of the inner orbit. Column 6 gives the probability of long-term capture $(P_c)_{\text{long}}$. This is the fraction of the encounters which had to be terminated before the breakup of the trinary system because either the outer member of the trinary went into an orbit with a semimajor axis more than 350 times larger than that of the inner binary or

TABLE II (a). Planet-interstellar intruder encounter. Masses = (1 − 0.001) − 0.005; $V/V_{\text{orb}} = 2.25$.

$\frac{p}{a_0}$	$\frac{R_{\text{min}}}{a_0}$	$\langle \Delta E/E_0 \rangle$	$\langle e \rangle$	P.D.	N
0.01	0.00025	−0.001269 ± 0.001347	0.03372 ± 0.000548	0.000	628
0.1	0.0238	−0.001987 ± 0.001995	0.02970 ± 0.000536	0.00159	628
0.2	0.0834	−0.001234 ± 0.001218	0.02334 ± 0.000534	0.000	379
0.3	0.1613	+0.000721 ± 0.000813	0.018213 ± 0.000511	0.000	628
0.4	0.2482	+0.000310 ± 0.000695	0.014987 ± 0.000481	0.000	628
0.5	0.3396	+0.000316 ± 0.000451	0.01170 ± 0.000285	0.000	628
0.6	0.4337	−0.000192 ± 0.000447	0.009915 ± 0.000361	0.000	628
0.7	0.5293	−0.000352 ± 0.000323	0.00848 ± 0.00034	0.000	628
0.8	0.6259	−0.000360 ± 0.000310	0.00746 ± 0.00026	0.000	628
0.9	0.7333	−0.000498 ± 0.000431	0.007139 ± 0.000425	0.000	628
1.0	0.8212	−0.000121 ± 0.000368	0.00658 ± 0.00037	0.000	628
1.1	0.9195	+0.000140 ± 0.000514	0.006433 ± 0.00052	0.00	628
1.2	1.018	+0.000292 ± 0.00040	0.005434 ± 0.000445	0.00	628
1.3	1.117	+0.000044 ± 0.000208	0.003788 ± 0.000185	0.00	628
1.4	1.216	+0.0000 ± 0.000151	0.002996 ± 0.000121	0.00	628
1.5	1.315	−0.000006 ± 0.000121	0.002476 ± 0.000091	0.00	628
1.6	1.414	−0.000005 ± 0.000100	0.002097 ± 0.000072	0.00	628

TABLE II (b). Jupiter-interstellar intruder encounter. Masses = (1 − 0.001) − 0.05; $V/V_{\text{orb}} = 2.25$.

$\frac{p}{a_0}$	$\frac{R_{\text{min}}}{a_0}$	$\langle \Delta E/E_0 \rangle$	$\langle e \rangle$	P.D.	N
0.01	0.00024	−0.0749 ± 0.0131	0.3291 ± 0.0057	0.00159	628
0.1	0.023	−0.0580 ± 0.0117	0.2856 ± 0.0051	0.00637	628
0.2	0.0808	−0.0321 ± 0.0092	0.2277 ± 0.0043	0.000	628
0.3	0.1574	−0.0191 ± 0.0071	0.1779 ± 0.0035	0.000	628
0.4	0.2433	−0.0104 ± 0.0062	0.1447 ± 0.0035	0.00159	628
0.5	0.3341	−0.00753 ± 0.00465	0.1152 ± 0.0025	0.00159	628
0.6	0.4276	−0.01005 ± 0.00419	0.09529 ± 0.0024	0.00318	628
0.7	0.5229	−0.0146 ± 0.0062	0.0850 ± 0.0039	0.00330	303
0.8	0.6193	−0.008876 ± 0.00308	0.07420 ± 0.00260	0.00	628
0.9	0.7164	−0.009203 ± 0.003576	0.06823 ± 0.00302	0.00159	628
1.0	0.8141	−0.008644 ± 0.003483	0.06334 ± 0.00315	0.00159	628
1.1	0.9122	−0.008028 ± 0.004321	0.0585 ± 0.0036	0.00318	628
1.2	1.0106	−0.00542 ± 0.00423	0.0502 ± 0.0034	0.00318	628
1.3	1.11	−0.00195 ± 0.00205	0.03806 ± 0.00184	0.000	628
1.4	1.208	−0.001216 ± 0.001496	0.0301 ± 0.0012	0.000	628
1.5	1.307	−0.000813 ± 0.00120	0.0248 ± 0.0009	0.000	628
1.6	1.406	−0.000554 ± 0.00100	0.0210 ± 0.0007	0.000	628

the system persisted to the 5×10^6-step limit.

Column 7 gives $(N_{\rm rev}/N)$, the average number of revolutions per encounter made by the outer member of a triple-body system before its dissociation or before the integration was terminated because the encounter led to long-term capture. Dividing this by P_c as given by Column 5 gives the average number of orbital revolutions made by the outer member of every triple-body system that forms in these encounters. If $(N_{\rm rev}/N)$ is large, the computer simulations become very costly. The last column gives the total number of encounters run at the given value of the impact parameter. The total number of encounters is much less than I like, but the great cost of these calculations prevented my doing any more. An exceptionally expensive series of encounters were the ones where $R_{\rm min}/a_0 = 0.067$ for an intruder with a mass of $0.05\ M_*$. These one hundred simulations took 19.5 hr of CDC 7600 time with eight of the encounters running to the 5×10^6-step limit. The outer member of the trinary was integrated for an average of ten revolutions per encounter, or about 23 revolutions for every triple-star system that formed. Some of these triple systems persisted for a time equivalent to more than 30 000 orbital revolutions of the original P-S system.

Table II shows the average results of encounters between the planet-star system and an interstellar intruder. The pre-encounter impact velocity of the intruder is 2.25 times the orbital velocity of the planet. For the Jupiter-Sun system, this corresponds to an intruder velocity of 30 km/s, which is typical of the solar neighborhood.

Column 1 of Table II shows the impact parameter in units of the semimajor axis of the binary. The next three columns are similar to those of Table I. Column 5 gives the probability of dissociation, P.D., the fraction of the encounters which lead to the dissociation of the planet-star system. The last column again gives the number of encounters run at each impact parameter. This is much larger than it was for the low-velocity encounters with the Oort-halo intruders because the calculations were much cheaper. The energies of these three-body systems are positive, so none of them produced bound trinary systems. All encounters were flyby. Likewise, none of the encounters led to an exchange collision in which the intruder is captured by the star and the planet is ejected into a hyperbolic orbit.

a) $\langle \Delta E/E_0 \rangle$

Figure 1 shows the average fractional increase in the binding energy $\langle \Delta E/E_0 \rangle$ of the P-S system when it is perturbed by an intruder from the Oort cloud. This is plotted as a function of the initial perihelion distance of the intruder. The intruders had masses of $M_i = (0.005 \text{ and } 0.05)\ M_*$. The values of $\langle \Delta E/E_0 \rangle$ for the lower-mass intruders have been scaled up by a factor of 10. The scatter in the results is large, but it is evident that $\langle \Delta E/E_0 \rangle$ is directly proportional to the mass of the intruder. The fact that $\langle \Delta E/E_0 \rangle$ is positive indicates that the P-S system shrinks when perturbed by Oort cloud intruders. If no exchange collision occurs, then the ratio of the mean semimajor axis after the encounter to that before the encounter is given by

$$\langle a_f/a \rangle = [1 + \langle \Delta E/E_0 \rangle]^{-1}. \tag{11}$$

From the data in Table II, we see that $\langle \Delta E/E_0 \rangle$ tends to be negative for encounters with interstellar intruders; i.e., the encounters tend to expand the planetary orbits. The amount of expansion is quite small compared to the amount of con-

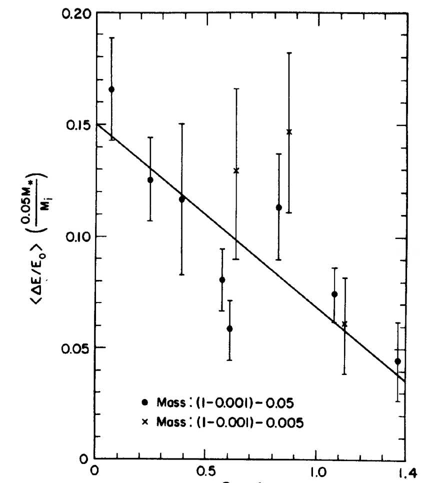

FIG. 1. Fractional change in the orbital binding energy of the planet-star system as a function of the perihelion distance of the Oort cloud intruder.

traction produced in encounters with low-velocity intruders from the Oort halo. Furthermore, the differential bias towards orbit expansion is very small compared to the average change in the orbit energy per encounter; i.e., the encounters with interstellar intruders produce a large random walk in binding energy with only a small bias towards orbital expansion. As a result, in the present study, the average change in orbital energy per encounter with a black dwarf intruder is much less well determined for interstellar intruders than for Oort cloud intruders, despite the much larger number of simulations made of encounters with interstellar intruders.

b) $\langle e \rangle$

Figure 2 shows the average post-encounter orbital eccentricity plotted as a function of the pre-encounter pericenter

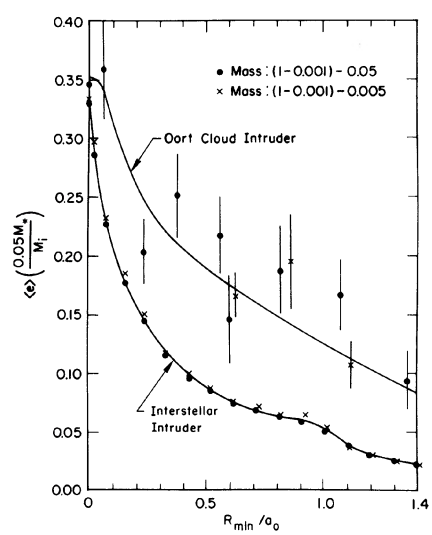

FIG. 2. Average post-encounter eccentricity of the planet-star system as a function of the closest approach of the intruder to the planet-star system.

approach distance R_{min} of the intruder.

The upper curve shows the results for low-velocity objects from the Oort halo, and the lower curve shows the results for the high-velocity intruders from interstellar space. The dots show the results for intruders having masses of 0.05 M_*, while the crosses show the results for intruder masses of 0.005 M_*. The results for intruder masses of 0.005 M_* have been scaled up by a factor of 10. It is evident from the plots that in the low-mass intruder limit the mean post-encounter orbital eccentricity is directly proportional to the mass of the intruder.

The change in the orbital eccentricity is approximately inversely proportional to the velocity of the intruder at its closest approach to the star. For encounter with $R_{min} \simeq a_0$, the pre-encounter semimajor axis of the planet, the $\langle e \rangle$ of the P-S system after an encounter with an Oort cloud intruder is about 2.4 times larger than for an encounter with an interstellar intruder. The value of 2.4 is also the inverse ratio of their velocities at closest approach. For $R_{min}/a_0 \ll 1$, the velocities of the intruders from both the Oort halo and from interstellar space are approximately equal to the parabolic velocity. In this limit, where the parabolic velocity at closest approach is much larger than the pre-encounter impact velocity of the interstellar intruder, the change in eccentricity produced by an interstellar intruder becomes comparable to that produced by an Oort cloud intruder having the same pericenter distance.

For $M_i = 0.05\ M_*$ and $R_{min} = a_0$, the average post-encounter orbital eccentricity is $e_f \sim 0.14$ for an Oort cloud intruder. If all planetary orbits were that eccentric, the increased gravitational interaction among the planets would greatly increase the probability of the dynamical evolution of the planets degenerating into the type of meleé shown in the simulations given in Hills (1970), with some of the planets actually being ejected from the solar system by their mutual interactions. It is evident from the lack of damage to the planetary orbits that no Oort cloud object as massive as 0.05 M_* has passed through the planetary system since the dissipation of the solar nebula. Because the change in the eccentricity is proportional to the intruder mass M_i, any intrusions of objects from the Oort cloud having masses less than about 0.02 $M_* = 20$ Jupiter masses would not have produced a noticeable effect on the orbits of the planets. One or two such intruders could pass through the planetary system and not noticeably perturb the present orbits of the planets (unless an intruder happened to make an improbably close encounter with one of the planets, or unless its perihelion distance R_{min} was very much less than the semimajor axes of the planets).

Considering the data on post-encounter eccentricities given in Table II, it is evident from the low eccentricities of the planets that no interstellar intruder as massive as $\simeq 0.05\ M_\odot$ has passed through the planetary system.

c) P. E.

The fourth column of Table I gives the probability of an exchange collision with intruders from the Oort halo. There were no exchange collisions with interstellar intruders, and there were no exchanges with low-mass Oort halo intruders with $M_i = 0.005\ M_*$. In an exchange collision, the planet is kicked into a hyperbolic orbit and the intruder is captured into a highly eccentric orbit with a semimajor axis of a few hundred AU. Because of the small number of cases run, these data are coarse. The probability of exchange for intruders with $M_i = 0.05\ M_*$ and pericenter distances $R_{min} \leqslant 1.1\ a_0$ is about $\langle \text{P. E.} \rangle = 0.079$ when the average is weighted by the number of cases run in each series of encounters. It drops off quickly beyond $R_{min} = 1.1\ a_0$. In statistical equilibrium, each value of R_{min} is equally probable for an object in the Oort cloud if R_{min} is much less than the semimajor axis of such an object, as is the case (Hills 1981).

Consider an object of mass 0.05 M_* and semimajor axis a in the Oort cloud. The probability per orbital period that it passes within a distance q of the Sun is given by Eq. (2). The probability per orbital period that it undergoes an exchange collision with a planet of semimajor axis a_0 is then given approximately by

$$P_{exch} = 0.079\left[\frac{2(1.1a_0)}{a}\right] = 0.174\left[\frac{a_0}{a}\right]. \tag{12}$$

Here we have used the result that the average exchange probability, $\langle \text{P. E.} \rangle$, is 0.079 for $q < 1.1a_0$. The probability that an exchange has taken place after N passages through the planetary system is given by

$$P_N = 1 - (1 - P_{exch})^N. \tag{13}$$

If $P_N \ll 1$, then

$$\begin{aligned} P_N &= 0.174\ N\left(\frac{a_0}{a}\right) \\ &= \frac{0.174\ \tau_s (GM_\odot)^{1/2}}{2\pi a^{3/2}}\left(\frac{a_0}{a}\right) \\ &= \frac{0.0277\ \tau_s (GM_\odot)^{1/2} a_0}{a^{5/2}}. \end{aligned} \tag{14}$$

The smallest semimajor axis of objects in the classical steady-state Oort cloud is $a = 2 \times 10^4$ AU.

When an exchange occurs, the planet is usually hurled into an orbit that is barely hyperbolic. Its velocity at infinity is small compared to its orbital velocity, so the post-encounter orbital binding energy of the captured intruder is approximately that of the planet prior to the encounter. As a result, the post-encounter semimajor axis a_f of the intruder is trivially related to the pre-encounter semimajor axis a_0 of the planet by the equation

$$\frac{a_f}{a_0} = \frac{M_i}{M_p}, \tag{15}$$

where M_p is the mass of the planet and M_i is the mass of the intruder. If an Oort cloud object (e.g., Nemesis) with a mass (say) of 0.05 $M_\odot$ should replace Jupiter, which has a mass $M_p = 10^{-3}\ M_\odot$, than the post-encounter semimajor axis of this intruder would be about 260 AU.

If the intruder is much more massive than the planet it replaces, the planet can give the intruder very little orbital angular momentum. As a result, the post-encounter pericenter distance of the captured intruder will be about the same as it was before the encounter. This leaves the captive intruder in a highly eccentric orbit; e.g., if $a_f = 260$ AU and $R_{min} = 5$ AU, then $e_i = 0.98$.

d) P_c

Encounters between interstellar intruders and the P-S system are too energetic to allow the formation of temporarily bound triple-star systems. All such encounters are flybys. However, intruders from the Oort cloud are quite easily captured into temporarily bound short-period orbits. The value of P_c given in Table I is the probability of forming a triple-star system that lasts long enough for the outer member of the trinary to make at least one complete revolution around the inner binary in an orbit having a semimajor axis greater than 2.5 times that of the inner binary.

We see from Table I that for $R_{\min} \lesssim 2.0\, a_0$ about half the encounters with Oort cloud intruders produce temporary trinary systems. These intruders enter the planetary system at nearly the parabolic speed. The energy transfer with the planet can either increase the orbital energy of the intruder so it is thrown into a hyperbolic orbit, or it can decrease its orbital energy so it becomes more strongly bound to the Sun-planet system. There is a nearly 50% chance of the latter occurrence for close encounters. If the intruder is captured and a temporary trinary system forms, the orbital period of the intruder is usually much longer than that of the P-S system. This difference in orbital periods produces great computational difficulty because the average orbital period of the outer member of the trinary and, subsequently, the orbital decay time is several times larger than the orbital period of the inner binary.

The next column gives $(P_c)_{\rm long}$, the probability of long-term capture, which is the fraction of the encounters that are terminated because the outer member of the trinary is either thrown into a long-period orbit with a semimajor axis exceeding 350 times that of the inner binary, or the orbital integration was not completed after 5×10^6 integration steps. We see that most trinaries which form in these encounters are long term by these criteria. Such a propensity for long-lived trinaries has not occurred before in this series of computer experiments.

The next column gives $N_{\rm rev}/N$, the average number of revolutions made by the outer number of the trinary systems per encounter prior to the dissolution of the system of the termination of the orbital integration. Since about half of the encounters produce trinaries, the number of revolutions made per trinary is about twice $N_{\rm rev}/N$.

IV. DISCUSSION

We have found that any object in an orbit near the inner edge of the Oort cloud at a semimajor axis of $a_c = 2 \times 10^4$ AU will almost surely have entered the planetary system at some time during the past 4.6 Gyr as a result of the gravitational perturbations by passing stars. However, the observed low eccentricity of the planetary orbits virtually rules out any object more massive than 0.02 $M_\odot$ having passed through the planetary system. We conclude from the lack of damage to the planetary orbits that it is extremely unlikely that any object more massive than 0.02 $M_\odot$ dwells in an orbit with a semimajor axis in the range $a \simeq (0.5-2)\, a_c \simeq (10\,000–40\,000)$ AU.

We may further rule out the existence of any massive object in an orbit with semimajor axes less than a_c from the absence of a steady stream of long-period comets with semimajor axes less than 2×10^4 AU. Any object more massive than 0.01 $M_\odot$ in such an orbit would constantly refill the loss cone of these comets so a steady stream of them would enter the planetary system (Hills 1984a). However, the inner edge of the steady-state Oort comet cloud is just where it should be if it were determined by the rate at which passing stars in the solar neighborhood make close passages with the Sun (Hills 1981). This rules out any object more massive than 0.01 $M_\odot$ in the inner comet cloud, where $a < a_c$.

If Nemesis exists, it may have profoundly affected the outer part of the planetary system by perturbing any planet initially beyond Pluto into an orbit of high eccentricity and large inclination to the ecliptic. If such a planet were as massive as Jupiter, it is likely that it would have suffered an exchange collision with Nemesis so that Nemesis would now be locked into a relatively short period with a semimajor axis less than 10^3 AU and a pericenter distance on the order of the original pre-encounter semimajor axis of the massive planet. The absence of the intense comet showers that such a massive black dwarf would produce rules out such an exchange collision having occurred.

I dedicate this paper to the memory of my friend and former colleague, L. Wayne Fullerton (Deceased December 24, 1984, Houston, Texas).

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