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THE EFFECT OF NEPTUNE'S ACCRETION ON PLUTO AND THE PLUTINOS

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ABSTRACT

The peculiar relationship of Pluto to Neptune, its resonances and high eccentricity and inclination, have led to the theory that the relationship arose from the migration of the outer planets, particularly the outward migration of Neptune, during the early solar system. In support of this scenario is the fact that the formation of Neptune at its current location would have been complicated by long dynamical times and low densities in the solar nebula. Here we address the following questions: Though the formation of Neptune at its current location seems unfavorable, are there dynamical obstacles to the capture of Pluto and the Plutinos under this scenario? Or are there features of the Neptune-Pluto system that would allow us to preclude this possibility of Neptune forming near its current orbit? Levison & Stern have examined the effect of the purely gravitational interactions of the giant planets on Pluto and concluded that the most important dynamical aspects of the Neptune-Pluto system could be reproduced. The exception was the amplitude of the 3 : 2 resonant argument, which was found to be too large in their model. We performed simulations of the outer solar system that included a slowly accreting Neptune and found that the efficiency of capture of dynamically cold particles into the 3 : 2 resonance was increased by a factor of 3, and that the resonant argument was substantially decreased. However, further dissipation is still required to match all aspects of the Plutino population and to produce truly Pluto-like orbits. Given that cold initial conditions did not reproduce the observations completely, simulations of initially dynamically hot particles near the 3 : 2 resonance with Neptune were also examined. These results, though resulting from seemingly ad hoc starting conditions, are reported as they produce remarkably good matches with both the Plutino population and Pluto's own orbit, including all three of its known resonances. These simulations reveal that Pluto could have arisen from an initially low-e ($\sim$0) but high-i ($\sim 25°$) orbit, both a clue to its origin and an illustration of the difficulty in understanding Pluto's current orbital configuration.

Key words: Kuiper belt — planets and satellites: individual (Neptune, Pluto) — solar system: formation

1. INTRODUCTION

The present dynamical relationship of the Neptune-Pluto system is fascinating on the one hand but, on the other, perplexing and intricate. How could this complex but exquisitely sensitive gravitational orchestration of the Pluto system have taken place? During the past several years, some exciting insights have been achieved into the array of factors that may have played significant roles in leaving it in its present configuration. The (irreversible) outward migration of the giant planets and Pluto (Fernández & Ip 1984; Malhotra 1993, 1996) could have played an important part in the process. (Other relevant references can be found in these papers, as well as in references to follow.) Numerical experiments have borne this out: the expansion of Neptune's orbit has been found able to capture initially nonresonant objects into the 3 : 2 resonance while at the same time increasing both their eccentricity and inclination (Hahn & Malhotra 1999). This work showed how Pluto could find itself in the basic 3 : 2 resonance with Neptune, while increasing its orbital inclination. There was, however, no discussion of any other resonances, either of the Kozai (Williams & Benson 1971) or the superresonance (Milani, Nobili, & Carpino 1989; Wan, Huang, & Innanen 2001).

In addition, Levison & Stern (1995) showed that many of the aspects of the Neptune-Pluto system could be explained more simply by the purely gravitational interactions between Pluto and the giant planets. No migration is required in this model, though it assumes Pluto happened to be initially near the 3 : 2 resonance, which the migration scenario does not require. The most important features of the Neptune-Pluto system could be reproduced by Levison & Stern's model, but the match was not exact. In particular, the 3 : 2 resonant amplitude was invariably found to be too high.

In this paper, the nonmigratory scenario examined by Levison & Stern (1995) will be revisited with the addition of another factor: the growth of Neptune's mass as it undergoes its primordial accretion. It will be shown that this modification to the model can produce more efficient capture into the 3 : 2 resonance and at smaller resonant amplitudes, thus producing orbits that are more Pluto-like.

In order to do this simulation in the simplest possible way, we have used as a working hypothesis that the current configuration of the giant planets is essentially constant, with just the mass of Neptune changing with time. This has been done to isolate the effects of the changing Neptunian mass, without prejudice to other effects among the giant planets.

It is well known that there are problems with the hypothesis that Neptune accreted at its current position. There may not be enough time to form this massive planet at such a large heliocentric distance, owing to the long dynamical times and low density of material in the solar nebula (e.g., Kokubo & Ida 2000; Levison & Stewart 2001). Alternatives to in situ accretion have been proposed, such as the formation of the proto-Neptune in the Jupiter-Saturn region, from which it was subsequently ejected (Thommes, Duncan, & Levison 1999). Any substantial migration of the outer planets would also invalidate our assumptions. However, Neptune's formation remains an important part of the puzzle of the outer solar system, and an exploration of the effects of its possible in situ accretion seems in order.

These questions remain: Can we exclude the possibility that Neptune accreted at its current location? Is there some feature of the Neptune-Pluto system that is incompatible with this alternative? We attempt to answer part of these questions by examining whether or not (1) Pluto and (2) the Plutinos could be captured by this process. The three known resonances in which Pluto currently resides provide a sensitive standard against which individual simulated capture events can be examined. In addition, the Plutino population is sufficiently large (41 multiopposition bodies are considered here) to provide a statistical sample against which to compare simulations. We will see that the slow accretion of Neptune can capture particles into orbits like those of Pluto and the Plutinos, though a capture into all three resonances is quite rare. We leave a more complete scenario, incorporating both accretion and migration effects, for future investigations.

2. METHODS

In the simulations presented here, the Sun, the four giant planets, and Pluto feel each other's mutual gravitational perturbations, along with a set of test particles that interact with the six massive bodies but not with each other. Numerical integrations were performed with a Wisdom-Holman style mapping (Wisdom & Holman 1991; Kinoshita, Yoshida, & Nakai 1991). The time step was chosen to be 200 days in order to provide sufficient resolution (>20 steps per orbit) of Jupiter's motion. At Neptune and Pluto, respectively, this translates to roughly 300 and 450 steps per orbit. Unless otherwise noted, the data are recorded at a sampling interval Δ of 5×10^4 yr. The Nyquist critical frequency $1/(2\Delta)$ then sets the highest frequencies that can be reliably determined from this output and corresponds to a period of 0.1 Myr, more than adequate for most of the resonances of interest. This also corresponds to the low-pass filter used by Milani et al. (1989, hereafter MNC89) in their analysis of the LONGSTOP 1B results.

The simulations are monitored at each time step for a close approach between Neptune and Pluto and stopped when their mutual distance is less than twice Neptune's instantaneous Hill radius $R_{\rm Hill} = a[mM_{\rm N}/(3\,M_{\odot})]^{1/3}$, where $m = 1$ when Neptune is at its current mass, $M_{\rm N}$. This conservative value of $2R_{\rm Hill}$ is chosen to help ensure that close approaches are detected, in particular at low m, where Neptune's Hill sphere is smaller.

Long-term integrations of the solar system are accompanied by well-known problems, not the least of which is that the outer planets have been found to be chaotic on timescales of 20 Myr (Sussman & Wisdom 1992). However, our study exceeds this timescale only by a small factor and is concerned primarily with the qualitative aspects of the motion, and not the precise positions of the bodies themselves.

The variation of Neptune's mass was accomplished simply by monotonically modifying its numerical value slightly at intervals within the simulation (i.e., adiabatically) while at the same time recomputing any relevant quantities (e.g., Jacobi coordinates). This breaks the symplecticity of the algorithm, but the accretion process itself is inherently nonconservative. Testing of the algorithm was done by comparing its results with analytic secular theory (see § 2.2) with good results.

2.1. *Resonant Arguments and Timescales*

Resonances are characterized by the libration of a critical argument, the latter being a linear combination (with integer coefficients) of the angular variables. The critical arguments relevant to a particular problem correspond to terms in the Fourier expansion of the disturbing function with nonzero coefficients and are determined from d'Alembert's rules. Following MNC89, we will consider the critical arguments of the Sun-Neptune-Pluto system that are of order 2 or less in the eccentricities and inclinations, and that contain the term $3\lambda_{\rm P} - 2\lambda_{\rm N}$ where λ is the mean longitude of a planet. These terms are really only of special interest insofar as the 3 : 2 mean motion resonance is maintained; however, we will see that this is the case for almost all values of the mass of Neptune considered here.

The critical arguments are not all independent, and we choose the same set of four arguments as MNC89 as our basis. These arguments are

$$\theta_1 = 3\lambda_P - 2\lambda_N - \varpi_P\ , \quad \theta_2 = \varpi_P - \varpi_N\ , \qquad (1)$$

$$\theta_3 = 2(\varpi_P - \Omega_p) = 2\omega_P\ , \quad \theta_4 = \Omega_N - \Omega_P\ . \qquad (2)$$

The fast frequencies related to the mean motions are thus conveniently contained in θ_1, with the other arguments describing the slower ones. Note that libration in θ_1 corresponds to the 3 : 2 mean motion resonance, in θ_2 to the ν_8, in θ_3 to the Kozai resonance, and in θ_4 to the ν_{18} resonance.

The precessional motions of the outer solar system have periods typically of hundreds of thousands to millions of years. The slowest frequency of particular interest is that of the 1 : 1 superresonance, with a period of 34.5 Myr (MNC89). The growth timescale of Neptune is unknown, though current thinking on the rate of dissipation of the solar nebula puts an upper limit in the vicinity of 10^7 yr, assuming slow planet growth based on a core accretion model of giant planet formation (Levy 1985; Wetherill 1990; Lissauer 1993; Pollack et al. 1996). A study of the formation of the outer planets by Pollack et al. (1996) did not study Neptune itself but extrapolated from Uranus to a total formation time of 4–37 Myr.

Thus, the timescales of interest here are from a few times 10^5 to over 10^7 yr, and our choices of sampling interval and integration length were made on this basis. The sampling interval of 5×10^4 yr was chosen to filter out motions with periods shorter than 10^5 yr. The 50 Myr timescale for the growth of Neptune's mass used was chosen both to be adiabatic as regards the oscillations of interest and to match the actual growth timescale of Neptune itself under a slow accretion scenario. Though Pollack et al. found that both Jupiter and Saturn may have grown very quickly during their final "runaway" gas accretion phases, the low ratio of gas to metals in Uranus and Neptune makes it unlikely that they underwent a similarly large rapid (and hence non-adiabatic) final mass increase due to runaway gas accretion. However, more rapid accretion and other models such as the formation of Neptune from a small number of relatively large protoplanets (e.g., Brunini & Fernández 1999) or by gravitational instability in the solar nebula (Cameron 1978; Cameron, DeCampli, & Bodenheimer 1982; Boss 1997) also deserve investigation.

The boundary of a resonance in phase space (or in this case in parameter space, since Neptune's mass m is varied) is where its argument switches to circulation. This criterion is straightforward to apply in the cases of the 3 : 2 and Kozai resonances, but is less so for the 1 : 1 superresonance. This resonance involves two of the secular frequencies of the system, both of which change slowly as Neptune's mass is varied, making the transition to circulation a slow one and hence difficult to detect over the timescale of our simulations. The criterion of Wan et al. (2001) is used, taking the superresonance to be broken when the two frequencies differ by more than 2%, which amounts to a 10° phase difference over our 50 Myr integrations.

2.2. *Testing*

By way of an initial comparison, a 50 Myr simulation using the LONGSTOP 1B (MNC89; Nobili, Milani, & Carpino 1989) initial conditions was performed, with Neptune's mass fixed at its current value. The LONGSTOP 1B simulations spanned 100 Myr; though longer simulations of the outer solar system have been performed, most notably by the Digital Orrery (Applegate et al. 1986; Sussman & Wisdom 1988) and by Wisdom & Holman (1991) and Kinoshita & Nakai (1996), these results were substantially consistent with those of MNC89. However, these data provide a more extensive examination of the frequencies of the outer solar system and hence provide an easier basis for comparison with our results.

In our simulations, the secular frequencies of the outer solar system are well reproduced. Our (absolute) values[1] are $g_5 = 4''.259$ yr^{-1}, $g_7 = 3''.091$ yr^{-1}, $f_7 = 2''.987$ yr^{-1}, $g_8 = 0''.649$ yr^{-1}, and $f_8 = 0''.675$ yr^{-1}. These values all match those of LONGSTOP 1B within our frequency resolution, namely, $\pm 1/50$ Myr $= 0''.026$ yr^{-1}.

The values expected for g_6 and f_6 ($\sim 25''$ yr^{-1}) and f_5 ($\sim 0''$ yr^{-1}) are outside the range that can be resolved with our data output rate and were not measured. We confirm the result of Milani & Nobili (1985), who found that the perihelion of Uranus is locked to that of Jupiter ($\dot{\varpi}_7 \approx \dot{\varpi}_5$).

[1] We use the notation g_i and f_i for the frequencies associated with e-ϖ and i-Ω, respectively (e.g., Murray & Dermott 1999), while MNC89 used g_i and s_i.

3. STABILITY DURING ACCRETION

Though unlikely, it is possible that a lower Neptune mass could destabilize the solar system, with the lightened Neptune itself the most likely victim. Such an occurrence would invalidate our model, and so it was investigated in some detail. A simulation is considered in which the outer planets, including Pluto, are present and the mass of Neptune is *decreased*. At intervals, the coordinates and velocities of all particles, as well as the mass of Neptune, are recorded. From these new initial conditions, the simulations are later restarted at the lower but now fixed value of Neptune's mass, to check their stability.

These tests serve a twofold purpose. First, a comparison of these numerical results with secular theory provides us with confidence that the algorithm is working correctly. Secondly, it provides us with a chance to look for less-than-obvious instability in the accreting system, which might either be important to understanding the process in our own solar system or reveal a flaw in our adopted model.

Qualitatively, the effect of a less massive Neptune on the outer planets was found to be small. There are moderate (20%–50%) decreases in the oscillations of the inclination of Jupiter, Saturn, and Uranus, the latter also showing a decreased oscillation in eccentricity. This can be interpreted simply as a lowering of the secular perturbations due to Neptune. The semimajor axes of the planets maintain the low-amplitude oscillations they show in the current solar system. The orbit of Neptune itself is largely unaffected, the most prominent effect being a slight increase in the oscillation of its inclination at very low m.

Though a smaller Neptune has little qualitative effect on the outer solar system, the secular frequencies g_i and f_i change slightly. This is reflected by a change in the rates of precession of their respective ϖ_i and Ω_i. However, the precession rates, though usually dominated by one particular eigenfrequency, involve all the others. We obtain the correct frequency from our numerical simulations by extracting the line with the most power in a fast Fourier transform (FFT) of the time series of Ω and ϖ for each planet. The exception is the perihelion of Uranus, which is locked to that of Jupiter (Milani & Nobili 1985), and as a result the g_7 eigenfrequency appears rather as the second strongest line in the FFT of ϖ_7, after g_5. The frequencies obtained are plotted in Figure 1.

The secular frequencies of the outer solar system are largely unaffected by a change in Neptune's mass. The frequencies associated with Uranus see the largest change, with g_7 and f_7 decreasing slowly and linearly with Neptune's mass. It is not unexpected that the largest effect would be seen in Uranus, the lightest and nearest to Neptune of the outer planets. A calculation of the secular frequencies of the outer solar system using first-order theory (e.g., Murray & Dermott 1999) confirms this. The analytically derived eigenfrequencies of the system are consistent within the frequency resolution of those obtained in our simulations.

Our simulations also measure the Lyapunov time of the system using the tangent-map technique (Mikkola & Innanen 1999); however, we see no clear signs of chaos. We observe hints of the 20 Myr chaos that has previously been reported (Sussman & Wisdom 1988), but the length of our integrations exceeds this timescale only by a modest amount. In fact, our data do not permit the measurement of a Lyapunov exponent unless its timescale is on the order of a few million years or less. Though there are a few values

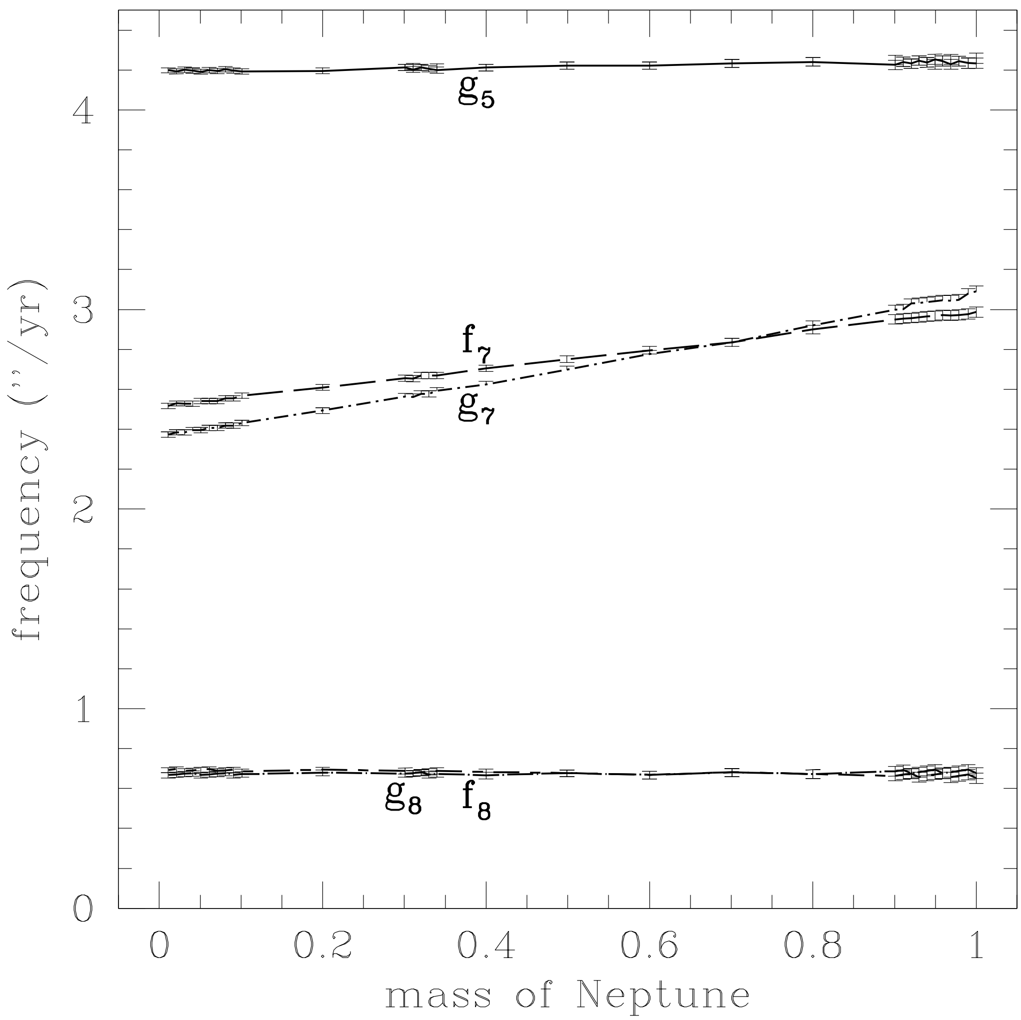

FIG. 1.—Synthetic secular frequencies of the outer planets as a function of Neptune's mass. Data points are plotted at the values of Neptune's mass m examined, with error bars indicating the frequency resolution.

of m for which the plots of the Lyapunov exponent show some signs of longer timescale chaos, particularly near $m = 0.3$ and $m = 0.9$, there are no indications of strong instability there. These results thus provide no surprises and bolster our confidence in the algorithm.

3.1. *Pluto*

The effect of Neptune's mass on Pluto rather than on the other Jovian planets is of primary interest here. Insofar as the accretion process is reversed by these tests, it provides a glimpse of the effect of Neptune's accretion on Pluto. However, though we have seen a certain degree of consistency in the behavior of Pluto as Neptune's mass is decreased, it is not always qualitatively the same between slightly different code implementations and initial conditions (i.e., the DE405 ephemeris [Standish 1998] vs. LONGSTOP 1B). This, together with the known chaotic nature of Pluto's orbit (Sussman & Wisdom 1988), leads us to be cautious in drawing conclusions here. However, we will outline a few observations.

As the mass of Neptune decreases, the 1 : 1 superresonance disappears first. The critical argument begins what appears to be a very slow circulation even when m is reduced to 0.99 and is broken by the criterion of Wan et al. (2001) (see § 2.1) at $m \gtrsim 0.95$. The Kozai resonance is more problematic: it usually maintains a fairly steady amplitude of libration before disappearing at $m \approx 0.3$, but it may go into circulation as early as $m = 0.9$. The 3 : 2 mean motion resonance consistently persists the longest, its amplitude of oscillation (following Levison & Stern 1995, we call this A_δ) increasing smoothly from its current value of 80° up to 180° as Neptune's mass is decreased to 2%–3% of its current value, at which point the resonance is broken and the resonant argument θ_1 begins to circulate. Thus the 3 : 2 resonance is found to be insensitive to m, the 1 : 1 superresonance is at the other extreme, and the Kozai resonance is somewhere between these two.

4. SIMULATIONS

Though there seem to be no serious instabilities associated with the growth scenario examined here, could this growth have resulted in the capture of Pluto? Or, given that Pluto is perhaps the largest of a population of similar objects, how do the properties of Plutinos captured under this model compare with those observed?

A disk of cold planetesimals in the vicinity of the 3 : 2 resonance were simulated under the proposed accretion scenario. Once accretion is complete, the Plutinos evolve under the gravitational effects of the (full-mass) giant planets. Levison & Stern (1995) showed these to be significant and able on their own to produce orbits similar to (though not precisely matching) those of the Plutinos. Thus, our interest here lies primarily in comparing the results of an accretion-initiated scenario with one that is purely gravitational, though comparisons with observed Plutinos will also be made. It will be shown that a significantly better match to some aspects of the Plutino distribution can be achieved through the addition of accretion to the models.

Simulations were run of 500 test particles spread evenly in 38.75 AU $< a <$ 40.25 AU. The remaining elements were chosen from a uniform random distribution with $0 < e < 0.01$ and $0° < i < 1°$ relative to the invariable plane and the longitude of the ascending node Ω, the argument of perihelion ω and the mean anomaly in 0°–360°. This set of initial conditions represents a cold primordial population of bodies in the vicinity of the 3 : 2 resonance. The mass of Neptune was increased linearly from a fraction $m = 0.01$ to $m = 1$ (i.e., its current value) over 50 Myr, and then the simulation continued at constant mass for another 50 Myr. These simulations include the effects of the giant planets on themselves and on all test particles at all times but do not include Pluto.

Of the 500 particles, 223 did not last the full 100 Myr but were ejected or suffered a close encounter with Neptune. Of the 277 remaining at the end of 100 Myr, 64 were in the 3 : 2 mean motion resonance, with others showing transitions through it. Those particles considered to be in resonance must have been librating for at least 25 Myr at the end of the simulation.

A plot of the final e and i for these objects is in Figure 2*a*. These values are averages taken over the final 5 Myr in order to remove secular effects. Values near those of Pluto can be obtained.

Capture into the 3 : 2 resonance with Neptune is not sufficient for stability on gigayear timescales (Levison & Stern 1995; Morbidelli 1997): the amplitude of the resonant argument is also a factor. Figure 3*a* plots A_δ for the particles over the last 25 Myr during the time Neptune was at full mass. The distribution peaks around 120°, and the minimum value is 84° near Pluto's value of 80° (MNC89; Levison & Stern 1995). We note, however, that Pluto's libration amplitude (in the real solar system) may have changed from its original value through thousands of millions of years of gravitational interactions with the other bodies in the 3 : 2 resonance (Nesvorný, Roig, & Ferraz-Mello 2000), an effect that would take place on a much longer timescale and which is not modeled here.

A low amplitude of the critical argument A_δ enhances stability. Though they considered the amplitude of the Kozai argument as well, Levison & Stern (1995) found that particles in the 3 : 2 resonance with amplitude of less than 120° or so remained stable over the age of the solar system. Thirty-seven of the 64 particles in the 3 : 2 resonance, or 58%, fall into that category here.

Capture into the 3 : 2 resonance via accretion produces a somewhat lower value of the resonant argument than capture purely by a massive Neptune. Though capture into a Pluto-like orbit can be made by a full-mass Neptune (Levison & Stern 1995), the amplitude of the 3 : 2 resonance was invariably too high (i.e., A_δ greater than 100°, while Pluto's value is 80°). In the accretion scenario modeled here, 11 particles, or 17% of the resonant particles, have $A_\delta < 100°$. Given that Levison & Stern (1995) have shown that most of the aspects of Pluto-like orbits with the exception of a sufficiently low A_δ can be reproduced purely by gravitational effects, this may be the most interesting aspect of the addition of accretion to such a model.

In a minimum-mass solar nebula where the surface density of solids $\Sigma = 30[a/(1\ \mathrm{AU})]^{-1.5}$ g cm^{-2} (Hayashi 1981; Kenyon 2002) in the outer solar system, the surface density

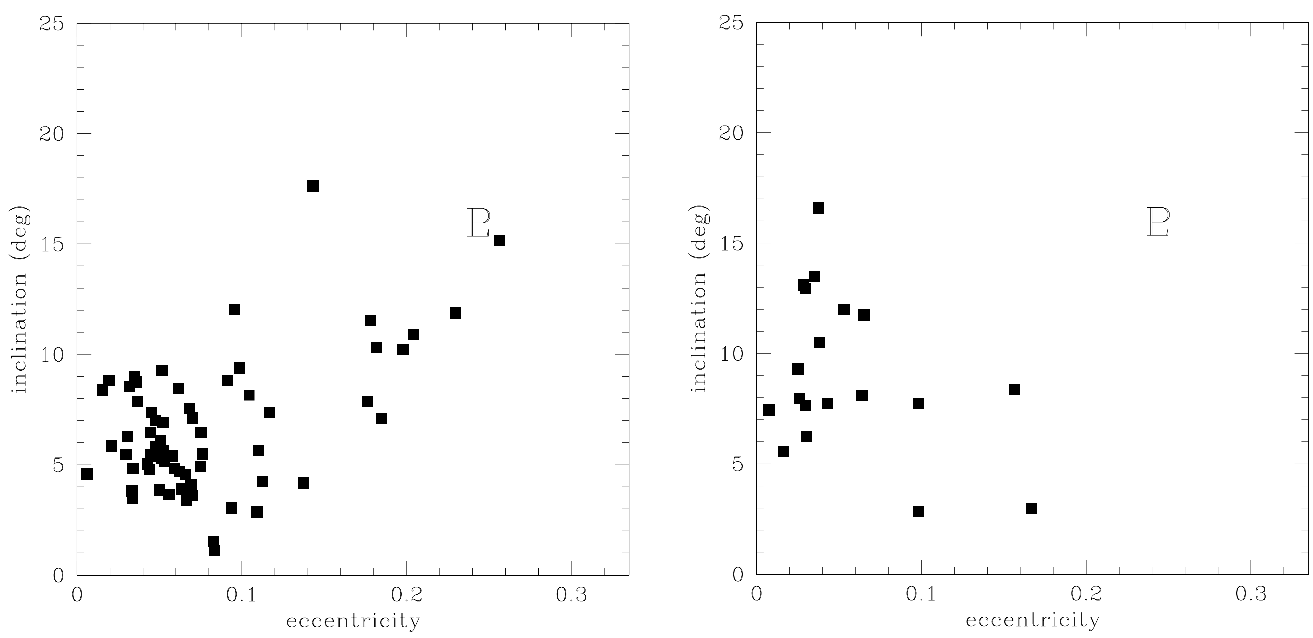

FIG. 2*a* FIG. 2*b*

FIG. 2.—Plot of the final e and i for the simulated particles captured into the 3 : 2 resonance for the runs (*a*) with and (*b*) without accretion

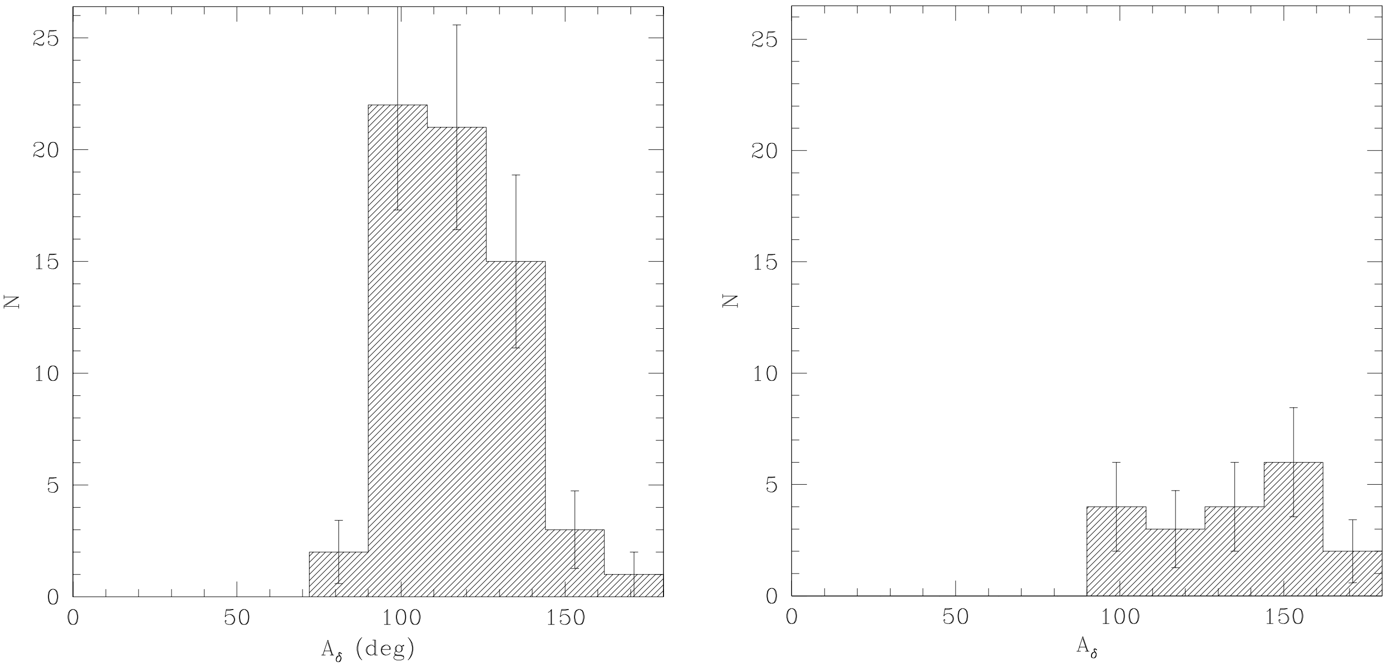

FIG. 3*a* FIG. 3*b*

FIG. 3.—Distribution of A_δ for the runs (*a*) with and (*b*) without accretion. The error bars are $\sqrt{N}$.

at the 3 : 2 resonance is $\Sigma = 0.12$ g cm^{-2}, or about 5×10^{27} g or $\sim$0.8 $M_\oplus$ in the annulus between 39 and 39.75 AU. Given the average capture efficiency of $64/250 \approx 0.26$ from 39 to 39.75 AU seen here, we would expect a mass of 0.2 $M_\oplus$ in the 3 : 2 resonance. Assuming only 37 of the 64 bodies captured into the 3 : 2 resonance have sufficiently low A_δ to be stable reduces the initial mass of Plutinos estimated from these simulations to 0.12 $M_\oplus$. This is high given that the *total* current mass of the Kuiper belt is estimated at 0.04–0.26 $M_\oplus$ (Jewitt, Luu, & Trujillo 1998; Chiang & Brown 1999; Gladman et al. 2001), with the newer estimates on the lower side.

However, continued loss of bodies from the 3 : 2 resonance, especially those in the peak of the distribution with $A_\delta \sim 120°$ (Fig. 3*a*), is probable. There may be other processes eroding the Kuiper belt as well. One possibility, proposed by Petit, Morbidelli, & Valsecchi (1999), is that Neptune-scattered planetesimals may have ejected many bodies from the Kuiper belt while exciting the orbits of those that remained. As well, gravitational interactions between Pluto and the Plutinos may erode the population of smaller bodies over time (Yu & Tremaine 1999; Nesvorný et al. 2000), though not all investigators agree (Petit et al. 1999).

Of the 64 particles captured into 3 : 2 resonance, 10 displayed transient passages through the Kozai resonance or slow circulation near it, but none were distinctly trapped there over the final 50 Myr of the simulations. This does not necessarily mean that the accretion scenario examined here could not have produced Pluto. Levison & Stern (1995) showed that particles in Pluto's vicinity could end up in the Kozai resonance owing purely to the continuing gravitational effects of the giant planets acting on timescales much longer than those examined here. Thus the simple influence of the giant planets themselves or other unmodeled dissipative effects may have placed Pluto into the Kozai resonance after accretion was complete. However, it does appear that the growth scenario examined here, while reducing A_δ, does not specially favor the Kozai resonance. Also, no particles were found in the 1 : 1 superresonance; our experiments seem to indicate that capture into the Kozai resonance is a necessary precondition for the superresonance.

Though the accretion model can produce relatively low amplitude values of the 3 : 2 resonant argument and orbits with *e*- and *i*-values comparable to those of Pluto, these two conditions seem to be anticorrelated (Fig. 4). Particles with *e* and *i* near Pluto's values are produced, as are some with A_δ near that of Pluto, but these are not the same particles. Again, the particles will continue to evolve on longer timescales and thus have not yet reached their final state, but this situation makes Pluto's orbit even more puzzling.

In order to confirm that the difference in the resonant amplitudes is not simply due to our use of a different integrator than used by Levison & Stern (1995), these 500 particles were simulated again, this time without any growth, in the presence of all the giant planets including a full-mass Neptune, for 50 Myr. Using the same criterion as earlier, only 19 of the particles were in resonance for the final 25 Myr of the simulations. The median A_δ was 142°, versus 116° for those produced by the accretion scenario. Plots of A_δ for these particles are in Figure 3*b*. Thus, accretion seems to both favor the capture of Plutinos and produce smaller A_δ, though the results do not otherwise differ dramatically from the purely gravitational scenario of Levison & Stern (1995).

A plot of the average values of *e* and *i* at the end of the nonaccretion simulations are in Figure 2*b*. The lack of points near Pluto's position in *e*-*i* space may simply indicate poor statistics. Levison & Stern (1995) found that particles could remain in nearly circular, uninclined orbits for long periods (up to 5×10^8 yr) before jumping to a Neptune-crossing orbit. Thus, low-(*e*, *i*) particles

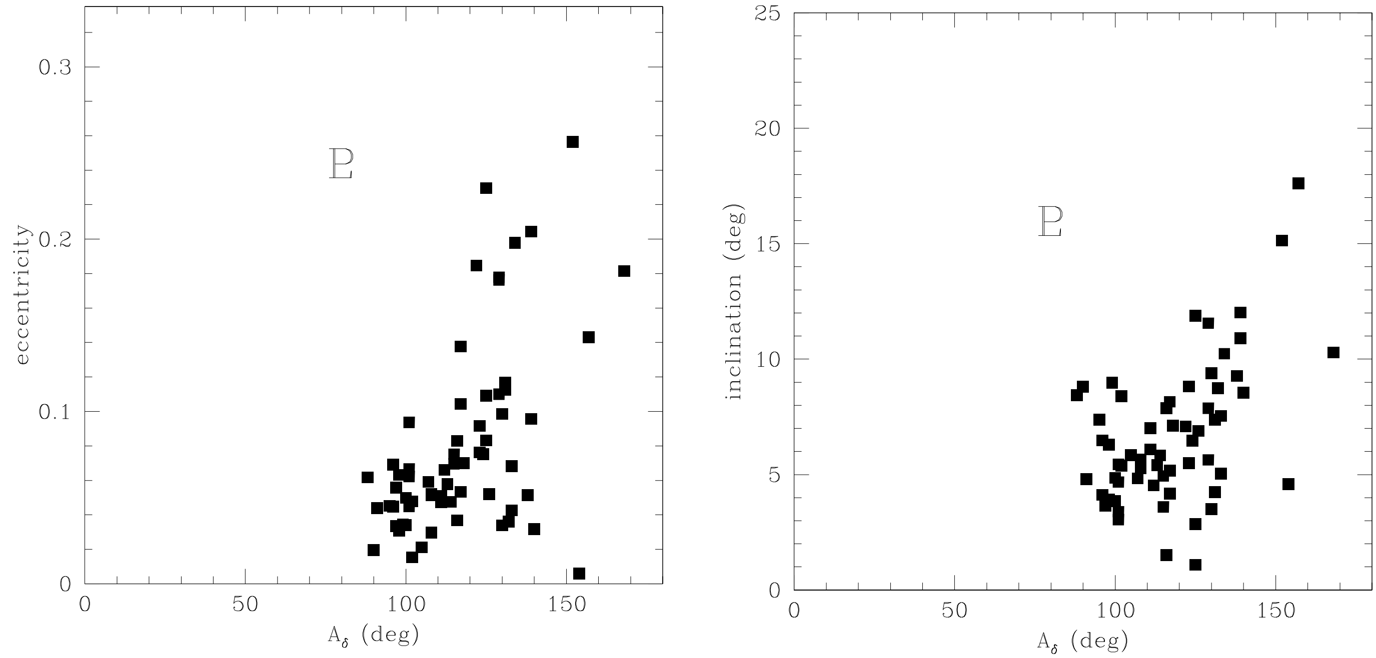

FIG. 4*a* FIG. 4*b*

FIG. 4.—A_δ vs. *e* and *i* for the simulations with accretion

may eventually move to more Pluto-like orbits even in the absence of accretion, but accretion populates this area more quickly.

Figure 5 displays plots of *e* and *i* versus A_δ for the non-accretion case. Again, the particles with the most Pluto-like *e* and *i* are found to have larger (i.e., less Pluto-like) A_δ. However, Pluto is only one of a number of bodies trapped in the 3 : 2 resonance, and it is exceptional in at least one way (i.e., it is the most massive). A fairer comparison requires that the other Plutinos be considered.

In order to do so, the evolution of 41 known bodies near Pluto's orbit were simulated for 50 Myr together with the four giant planets, with the purpose of comparing their current resonant amplitudes with those produced by our slow accretion-capture scenario. The elements for these bodies were obtained from the Minor Planet Center Web site, and only bodies seen for two or more oppositions were simulated. By this procedure we have attempted to obtain a sufficiently numerous sample of objects with the best-determined orbits. This allows us to make a comparison

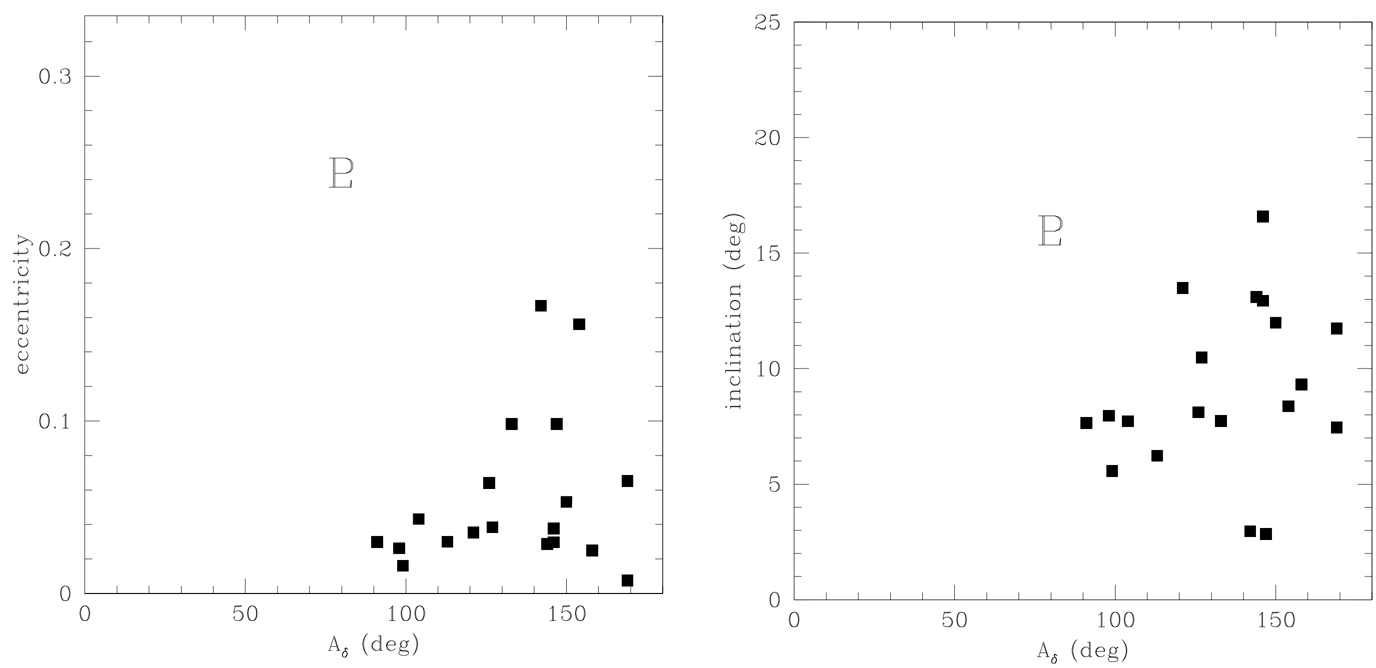

FIG. 5.—A_δ vs. *e* and *i* for the simulations without accretion

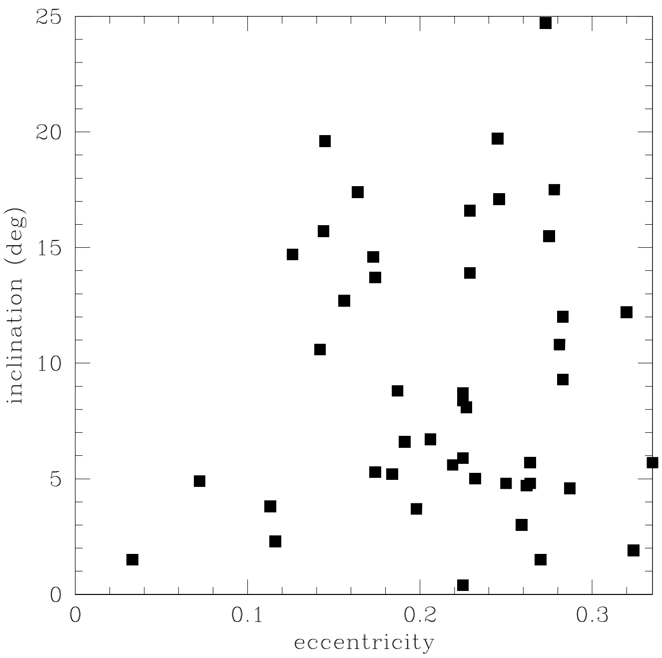

FIG. 6.—Eccentricity and inclination of 41 known Plutinos

between our hypothesis and observations. Nevertheless, one recognizes two primary concerns. First, our simulations are quite short, and Levison & Stern (1995) have shown (as mentioned earlier) that particles in the 3 : 2 resonance continue to evolve significantly on longer timescales. Secondly, observational biases skew the sample of known Plutinos, and the orbital elements of some of these objects remain uncertain as well. As a result, conclusions must be drawn with care.

The integration algorithm used in simulating the known Plutinos was the same as used before, but with the mass of Neptune held constant at its current value, and planetary elements were derived from the DE405 ephemeris (Standish 1998). A plot of e versus i for the known Plutinos is presented in Figure 6. The accretion scenario better matches the wide spread of the observed sample than the no-accretion case (Fig. 2) but is biased toward substantially lower e and i than the observed sample.

High-i KBOs will be less efficiently detected by surveys concentrating near the ecliptic. However, when Brown (2001) debiased the inclinations of the Plutinos, the resulting distribution did not differ strongly from that observed. The difference between the observed and accretion results is thus significant. Low-e objects may also be underrepresented, as low-perihelion objects are the brightest and most easily detected. The difference in the e-distributions is thus harder to assess. Nevertheless, the e- and i-distributions from the accretion simulations are not dramatically inconsistent with observations.

A histogram of the amplitude of the 3 : 2 resonance A_δ obtained for the known Plutinos is shown in Figure 7a. The values are distributed at $A_\delta < 150°$, with only three at $A_\delta > 120°$. The Plutinos show smaller values of the 3 : 2 resonant argument A_δ than either the accretion or no-accretion scenarios can produce (Fig. 3). The accretion-based simulations do, however, show markedly lower values of A_δ, which Levison & Stern (1995) found to be the primary discrepancy between purely gravitational models and observations. It thus seems that though accretion may provide part of the solution by ensuring lower values of A_δ and hence enhanced stability at early times, it cannot completely explain the low values of the 3 : 2 resonant argument currently observed. We follow Levison & Stern (1995) in concluding that further systemic dissipation is required.

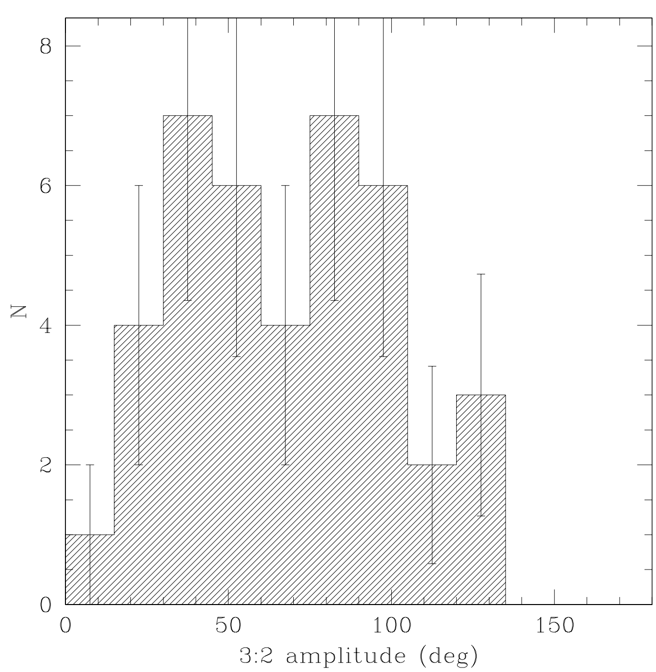

FIG. 7a

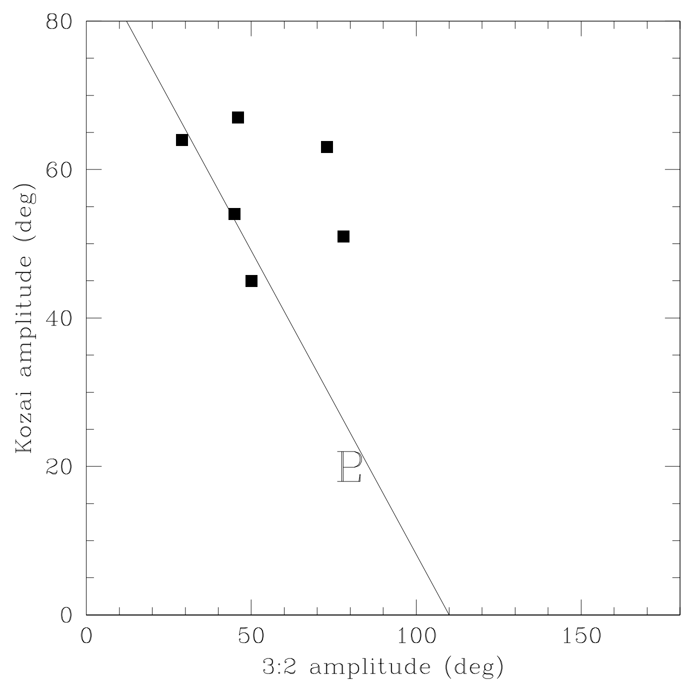

FIG. 7b

FIG. 7.—Distribution of A_δ and a plot of A_δ vs. A_ω for 41 known Plutinos

For completeness, a plot of A_δ versus A_ω for the Plutinos is provided in Figure 7*b*. Few Plutinos (seven, one off the plot) are in the Kozai resonance, and none are in the superresonance, confirming the result of Wan & Huang (2001). We note that only one object, and that not in the Kozai resonance, was found to be in ν_{18} (θ_4) resonance. Those observed Plutinos in the Kozai resonance have A_ω much larger than Pluto itself. As a result, few fall within the stability limit of Levison & Stern (1995). Thus, the Plutinos may represent the last survivors of a primordial population, as proposed by Morbidelli (1997). However, other factors, most notably uncertainties in the orbital elements, may be at work, so we look to future discoveries and continuing refinements of the orbits of Plutinos to bring this matter into clearer focus.

5. HOT INITIAL CONDITIONS

It is generally assumed that dissipation within the solar nebula would result in any solid material initially settling into the invariable plane (or rather the local Laplace plane, but these coincide in the uniform disk assumed to have preceded the formation of the planets). There is no compelling reason known at this time to believe that things might have been otherwise. However, in order to examine whether other initial conditions might result in captures better matching the observed Plutinos, simulations were run of 1000 test particles with elements chosen from a uniform random distribution with 38 AU $< a <$ 41 AU, $0 < e < 0.3$, and $0^\circ < i < 25^\circ$ and the longitude of the ascending node Ω, the argument of perihelion ω, and the mean anomaly in 0°–360°. This extremely hot Kuiper belt is implausible, but an examination of nonstandard initial conditions seems reasonable given the difficulty in reproducing Pluto's orbit from more traditional ones.

The mass of Neptune was increased from 1% to 100% of its current value over 50 Myr, and then the simulation continued at constant mass for another 50 Myr, as before. Of the 1000 particles, 644 did not last 100 Myr but were ejected or suffered a close encounter with Neptune. Of the 356 remaining at the end of 100 Myr, 66 were in the 3 : 2 mean motion resonance continuously during the final 25 Myr.

Capture into the 3 : 2 resonance takes place from across the range of *e* and *i* examined here without substantial bias. A plot of *e* versus *i* for these objects is in Figure 8.

Of immediate interest is Figure 9*a*, in which A_δ is plotted for the particles over the final 50 Myr of the simulations. The distribution peaks around 115°, but there are many particles at, or even below, Pluto's value of about 80°. Fifty-two of the 66 particles have $A_\delta < 120^\circ$ and 20 have A_δ less than 80°. One particle, indicated by the triangle, was captured into an oscillation of ω around 180°.[2]

More of them have very small A_δ than for the initially cold populations (Fig. 3). The histogram is quite similar to that of the known Plutinos (Fig. 7*a*), though small number statistics makes a detailed comparison difficult. A plot of the amplitude of the 3 : 2 resonance versus that of the Kozai is presented in Figure 9*b*. The particles are in some cases below

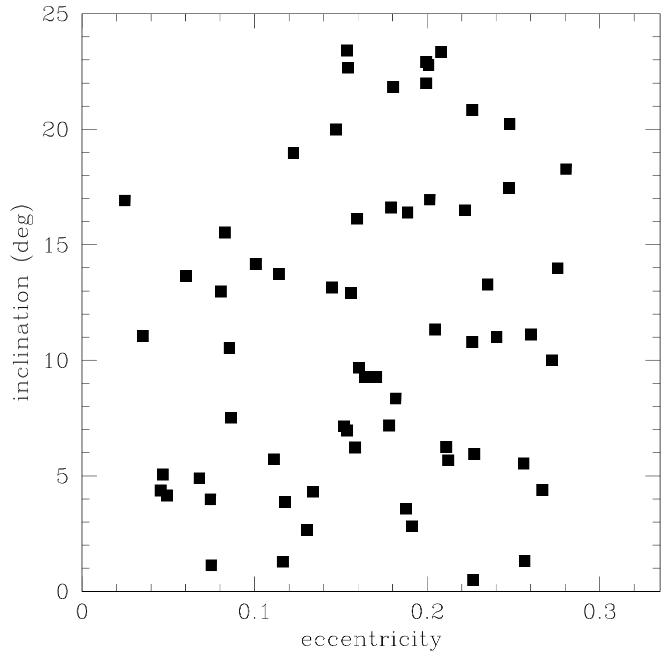

FIG. 8.—Plot of the final *e* and *i* for the simulated particles with hot initial conditions captured into the 3 : 2 resonance.

the stability boundary of Levison & Stern (1995), though none quite have the low A_ω of Pluto's current orbit. The ratio of particles in the 3 : 2 resonance versus the Kozai is 18%, very close to the 7/41, or 17%, seen in the observed sample. The distributions of A_δ and A_ω of the known Plutinos (Fig. 7*b*) are also grossly consistent with these results, especially if bodies with larger A_δ are more likely to have become unstable over the age of the solar system. The relationship between A_δ and *e* and *i*, shown in Figure 10, also easily allows for Pluto-like values in all three, unlike that for the initially cold population. Though there is no obvious reason to expect the initially hot Kuiper belt examined here, the much improved match with the resulting Plutino population indicates that further research into this possibility is warranted.

One particle in these simulations ended up on a very Pluto-like orbit, being captured into all three resonances; it is circled in Figure 9*b*. Several of the other particles in the Kozai resonance showed very slow circulation in the resonant argument of the superresonance, indicating they were close to it. However, this one particle, which we call "α," is particularly striking. It ends up near Pluto's current values of *a*, *e*, and *i* and is in all three of Pluto's resonances.

Though the set of initial conditions used in this case seems implausible, the resemblance of the results to the current Plutinos and the generation of a remarkably Pluto-like orbit leads one to further questions. The initial conditions used are broad enough to include the orbits of just about all the observed Plutinos. Do these hot initial conditions simply populate the most stable regions of the phase space right from the start, or is there more to it?

The initial and final *e* and *i* of the 12 test particles that end up in the Kozai resonance are shown in Figure 11. The one that also ends up in the 1 : 1 superresonance (α) is indicated by the solid arrow. The current (averaged) position of Pluto is shown by the symbol. The particles show relatively little change in *i* but often evolve

[2] In its simplest form, the Kozai resonance allows only libration around a fixed point with $\omega = 90^\circ$ or $\omega = 270^\circ$; however, libration around $\omega = 180^\circ$ is possible under certain conditions (Michel & Thomas 1996; Thomas & Morbidelli 1996).

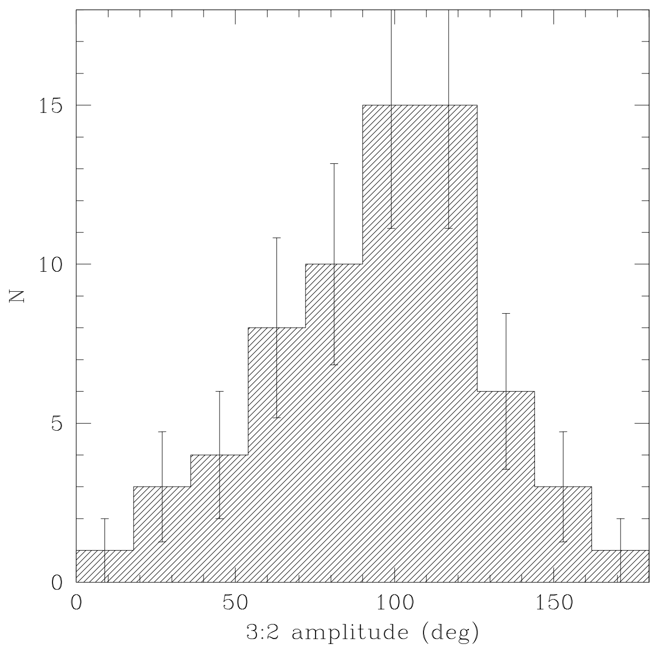

Fig. 9*a*

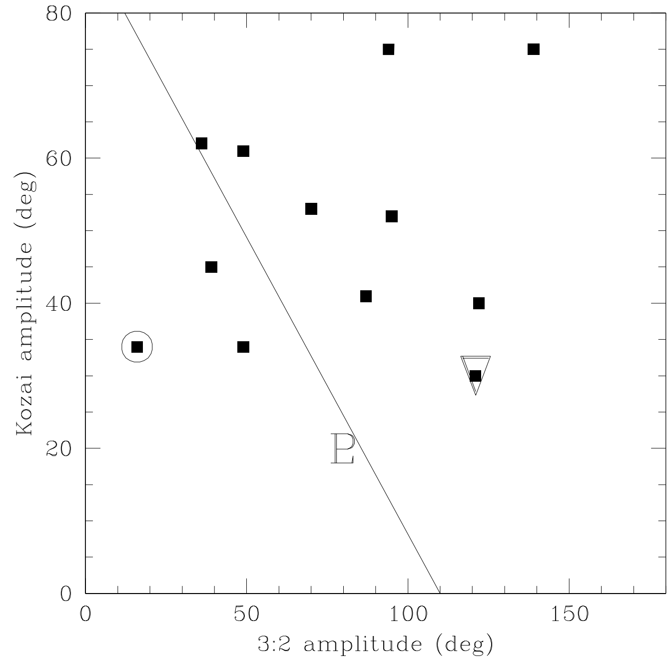

Fig. 9*b*

Fig. 9.—(*a*) Histogram of the amplitude A_δ of the resonant argument of the 3 : 2 resonance produced from dynamically hot initial conditions, with $\sqrt{N}$ error bars. (*b*) A_δ vs. A_ω for the 12 particles in both the 3 : 2 and Kozai resonances. The circle indicates the one in the 1 : 1 superresonance as well. The inverted triangle is a particle trapped in Kozai resonance about $\omega = 180°$ instead of the usual 90° or 270°. Pluto's averaged position is indicated by its symbol. The line represents the stability boundary of Levison & Stern (1995).

substantially in *e*. Such captures can occur from initial inclinations as low as 5°. The final positions cluster around the centre of the Kozai resonance within the 3 : 2 resonance as mapped out (in their Fig. 5) by Morbidelli, Thomas, & Moons (1995). Thus, the hot initial conditions chosen can evolve fairly quickly toward Pluto-like orbits but do not simply originate there.

The "α" particle illustrates this clearly. It starts at very low *e* (=0.015), though at substantial *i*. It shows a large, smooth increase in eccentricity, and does not get to high *e* simply through a lucky scattering event off Neptune. It also has the smallest libration amplitudes in both the 3 : 2 and Kozai resonant arguments and ends up in the superresonance; it thus represents an intriguing special case. The

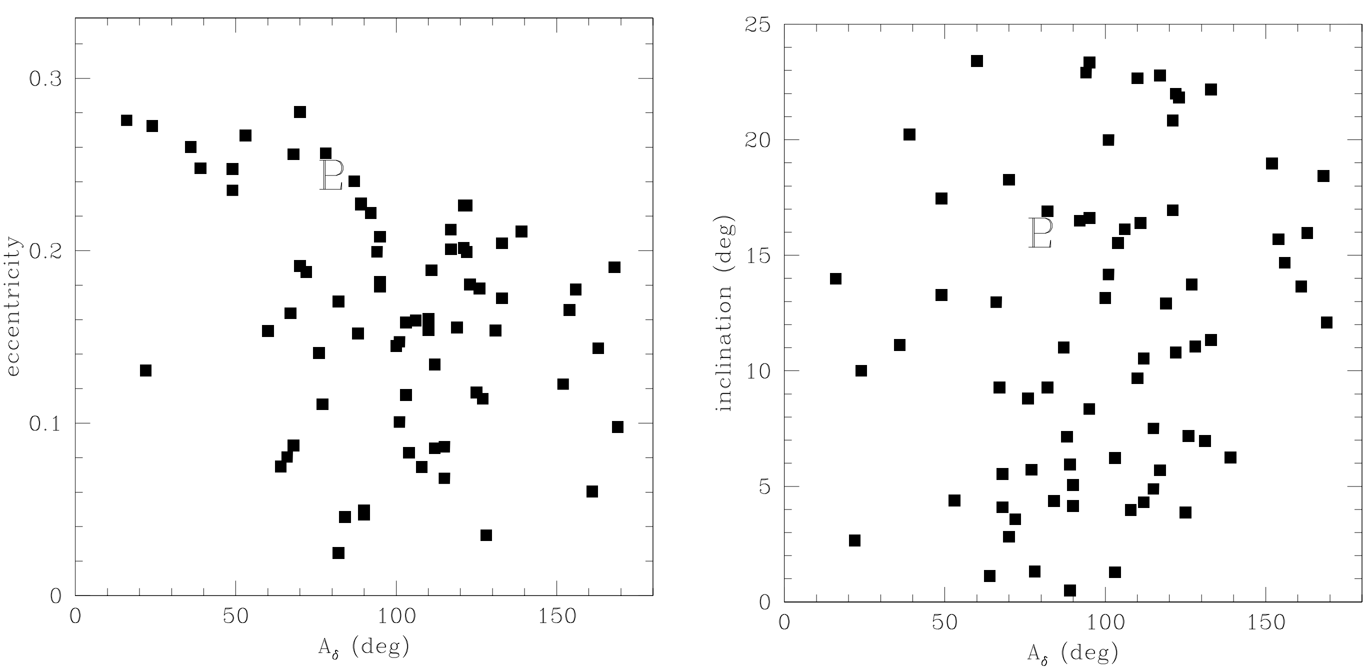

Fig. 10.—Value of A_δ vs. *e* and *i* for the simulations with accretion and dynamically hot initial conditions

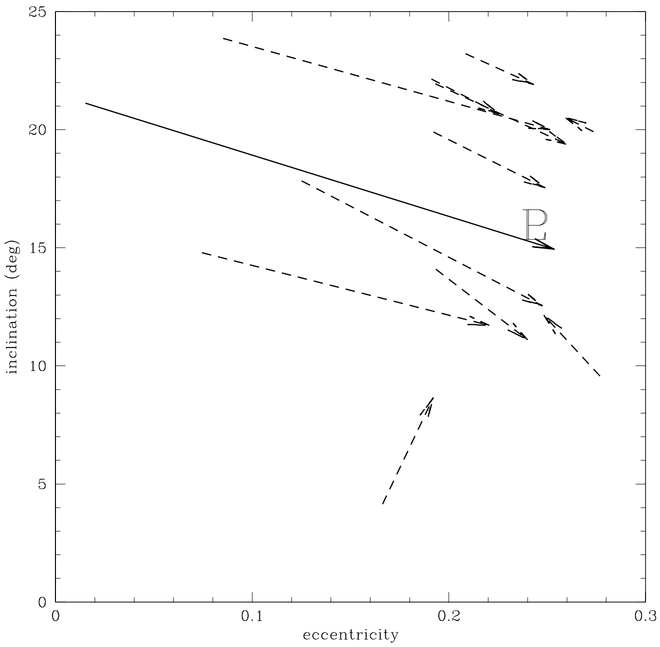

FIG. 11.—Initial and final eccentricities and inclinations for particles captured into both the 3 : 2 and Kozai resonances from dynamically hot initial conditions (*arrows*). The solid arrow indicates the particle that is captured into the 1 : 1 superresonance as well.

orbital evolution of this particle is presented in Figure 12. The increase in Neptune's mass occurs during the first 50 Myr, and then it is held constant for the second half. The increase in e, coupled with a smaller decrease in i, occurs during the accretion phase and levels out afterward. This particle does not show this behavior in the simulations where Neptune's mass is simply held constant, indicating that accretion is at work. A difficulty with this as a proposed origin for Pluto is that particle originates at an i even larger than Pluto's current value, a starting point that is not easy to explain.

In order to investigate this particle further, 100 particles were simulated with the same growth scenario with initial conditions in the vicinity of the α particle, namely, $a \in [39, 39.75\ \mathrm{AU}]$, $e \in [0, 0.04]$, and $i \in [20°, 22°]$. Many of these were pushed up to high e at nearly constant i, but only one of these entered all three resonances in a truly Pluto-like orbit. It also had a very low $A_\delta = 26°$ and $A_\omega = 43°$, which enhance stability, though these resonant amplitudes do not precisely match Pluto's. Thus it seems possible for high-i, low-e orbits to produce remarkably Pluto-like orbits via accretion. However, we conclude that such an origin for Pluto is unlikely for two reasons. First, how can an initially high-i orbit for Pluto be explained? And second, given such an orbit, Pluto would still have had to thread the needle to reach its current orbit. Nevertheless, the model does have the advantages of not requiring any further dissipative processes to produce Pluto's orbit. However, the value of accretion in explaining the Plutinos seems primarily to be the production of low resonant amplitudes in the 3 : 2 resonance.

6. CONCLUSIONS

A hypothetical case in which Neptune slowly accretes mass while on its current orbit has been examined. Under this assumption, the three known resonances of Pluto become important at very different values of Neptune's mass. No instability in the solar system is observed during the process of Neptune's growth to its current mass.

In simulations of dynamically cold test particles near Pluto's orbit, we found that the capture of Plutinos into the 3 : 2 resonance happens quite naturally and occurs from orbits that are not initially Neptune-crossing (but become so later, the particles being protected by the 3 : 2 resonance at that point), as was found by Levison & Stern (1995) for models that did not include accretion. However, accretion models have substantially increased capture efficiencies into the 3 : 2 resonance, and the resonant arguments of the captured Plutinos were smaller and their e and i were higher, and thus the final orbits were more Pluto-like than those produced without it. Given that Levison & Stern (1995) found that all the important features of the Neptune-Pluto system could be produced by simple gravitational interactions between the outer planets acting over gigayear timescales with the exception of sufficiently low A_δ, this may be the most important contribution of accretion to such a model. Though the reasons for the differences have not been investigated thoroughly here, it seems logical that the slow growth of Neptune produces a more nearly adiabatic change in the system than the effectively sudden introduction of a full-grown Neptune at $t = 0$, thus reducing the overall perturbations on the test particles.

However, accretion acting on initially dynamically cold particles cannot produce 3 : 2 resonant amplitudes as low as those seen in the observed Plutino population. Thus, we concur with Levison & Stern (1995) that if such capture is what took place in our own solar system, additional subsequent dissipation would be required.

Simulations of dynamically hot bodies near the 3 : 2 resonance can, however, produce distributions that better match those of the observed Plutinos. Low-amplitude librations of the critical argument of the 3 : 2 resonance are naturally produced. Capture into orbits with resonant amplitudes of the 3 : 2 and Kozai resonances below the stability threshold of Levison & Stern (1995) can occur, and the distribution of amplitudes produced is comparable to that of the current observed Plutino population. The distributions of e and i of the simulated and observed populations are also consistent, though small numbers and the uncertain orbits of the observed population limit the comparison.

Capture into very Pluto-like orbits, including low amplitudes in A_δ and A_ω, as well as capture into the 1 : 1 superresonance, can also occur from the dynamically hot set of initial conditions. However, this is seen to take place from relatively high i (even higher than Pluto's current value) and only in rare cases, though from very low e. Capture of dynamically hot bodies into only the 3 : 2 and Kozai resonances, the most important in terms of protection, can occasionally be made from initial inclinations as low as 5°. The captured particles often evolve significantly in e and i, and so these results do not simply stem from the initial conditions populating the most Pluto-like regions of phase space at $t = 0$.

Though such a dynamically hot population reproduces the observed distributions well, it is not easy to understand how such conditions might have arisen. Neptune is the most likely body to stir up this region, but at the beginning of our scenario it had not yet reached a mass substantial enough to do so. Given the absence of a plausible reason for such

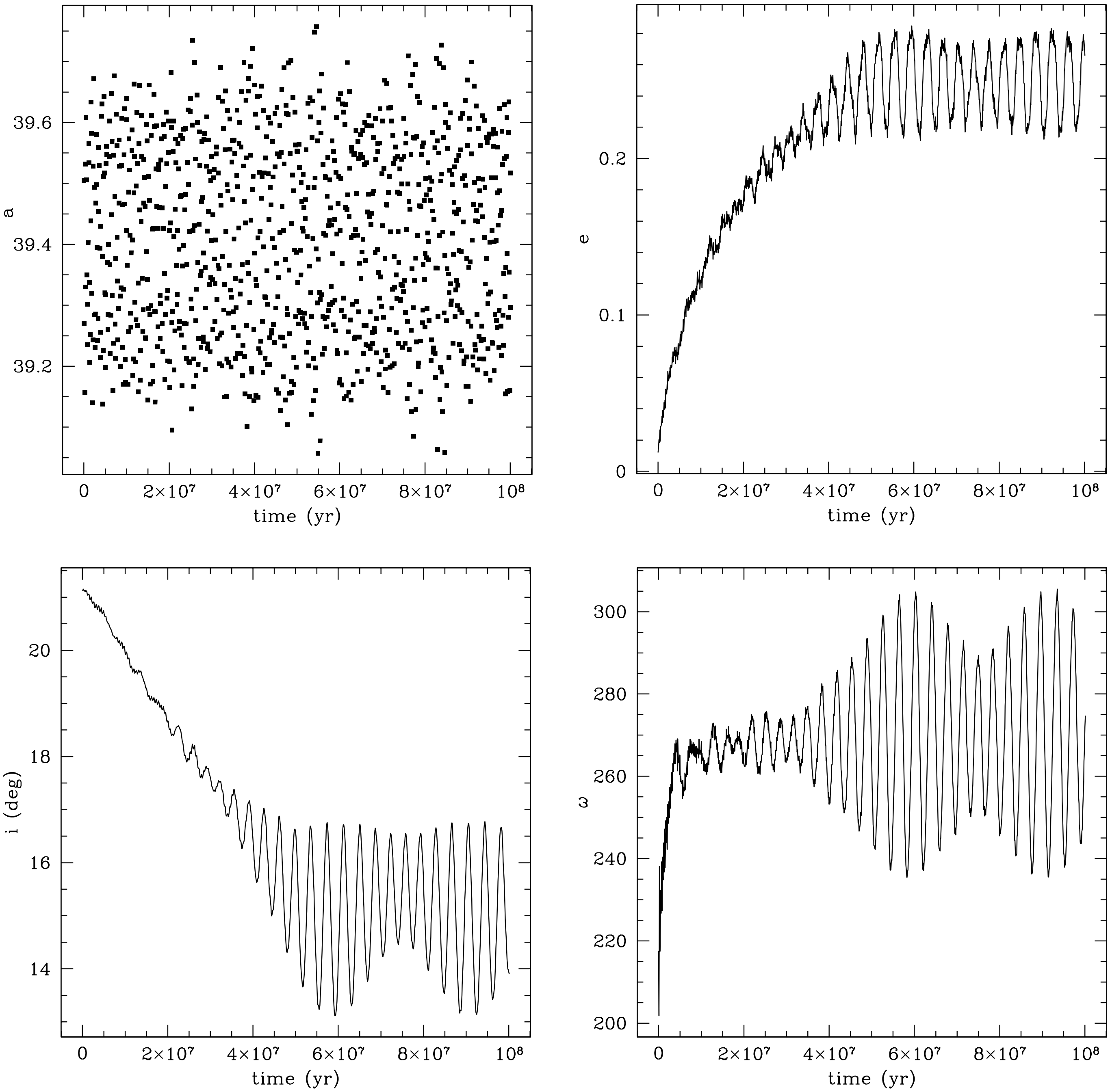

Fig. 12.—Evolution of a, e, i, and ω for the "α" particle, captured into all three resonances

dynamically hot initial conditions, we are at this time reluctant to conclude that these sorts of conditions did in fact exist in the early solar system.

Though there are no dynamical obstacles to the capture of Pluto or Plutinos by the accretion scenario presented here, the difficulties in growing Neptune at its current location (e.g., due to the long accretion timescales involved) remain, as does the question of how Pluto arrived at its current high inclination and with a semimajor axis within the 3 : 2 resonance. These latter parameters may well require the migration scenario. Finally, Neptune's own unusual satellite system (retrograde Triton, eccentric Nereid) reminds us that other events may have played significant roles in the system. However, the accretion process was certainly at work in the early solar system, and further investigation of Neptune's growth in the context of the formation of the Kuiper belt and the capture of Pluto and the Plutinos is warranted.

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