the excess prograde candidates are real objects. This team failed to detect objects in the second field. However, the background in this field was brighter than in the first and thus the limiting magnitude in the second field was smaller ($V = 27.7$ compared to 28.6 in the first). Since the brightest objects that they discovered in the first field was $V = 27.9$, it is not surprising that they did not discover objects in the second. Thus, the lack of detections cannot in any way be construed to invalidate the detections in the first field. However, the detection is still controversial, and the issue will not be resolved until deeper HST observations are obtained (currently scheduled for the summer of 1997). Given the character of the observations in the first field, it was not possible to determine the orbits of any of these candidate objects. Therefore, we will not be able to make use of these observations in our discussion of the dynamical structure of the Kuiper belt in the following sections.

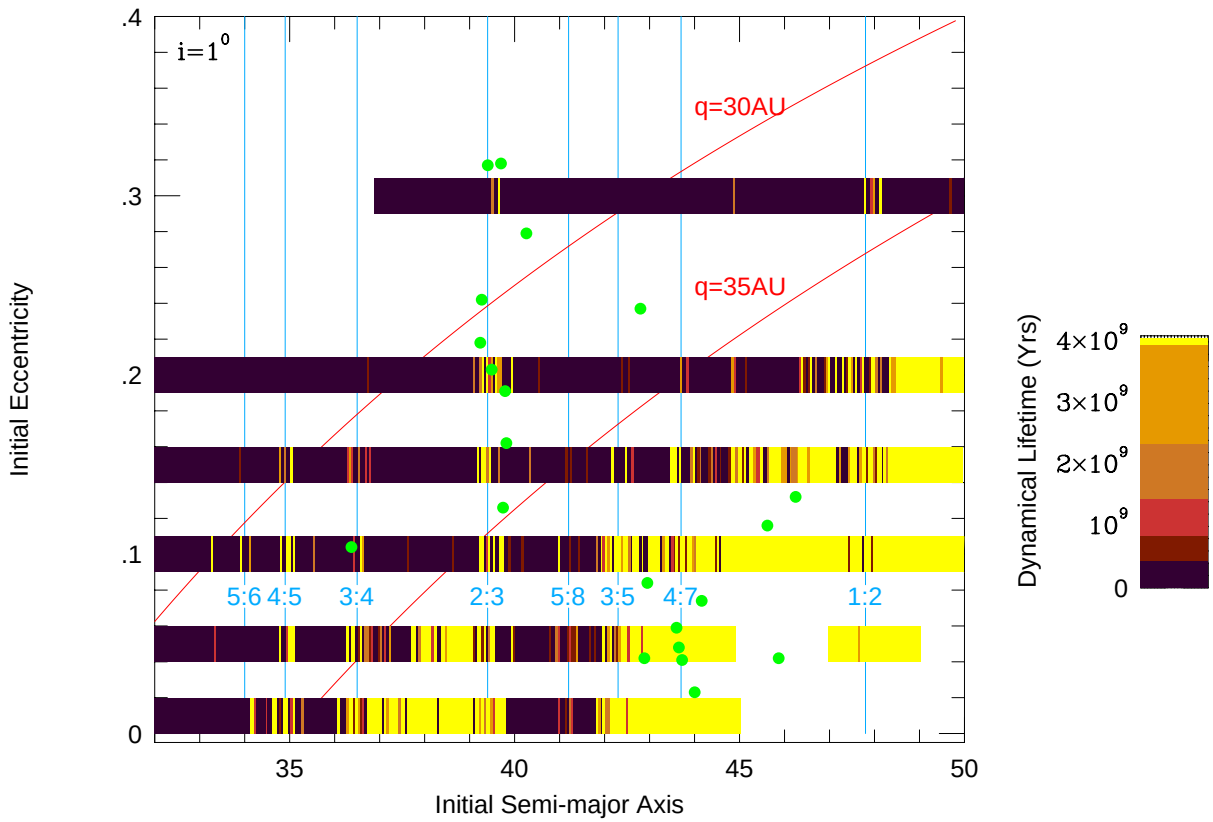

Figure 1 — The dynamical lifetime for test particles in the Kuiper belt derived from Duncan et al.'s (1995) 4×10^9 year integrations. Each particle is represented by a narrow vertical strip of color, the center of which is located at the particle's initial eccentricity and semimajor axis (initial inclination = 1°). The color of each strip represents the dynamical lifetime of the particle. Strips colored yellow represent objects that survive for the length of the integration, 4×10^9 years. Dark regions are particularly unstable on these timescales. The green dots represent the location of the orbits for the known Kuiper belt objects, as determined by Marsden. For reference, the locations of the important Neptune mean motion resonances are shown in blue and two curves of constant perihelion distance, q, are shown in red.

THE LONG-TERM STABILITY OF ORBITS IN THE KUIPER BELT

The first detailed studies of the stability of orbits in the Kuiper belt was by Torbett (1989) and Torbett & Smoluchowski (1990), who showed that low inclination orbits beyond Neptune are chaotic with Lyapunov times less than 10^6 years if their perihelion distances are between 30 and 45 AU. Gladman & Duncan (1990) integrated 20 particles initially on circular orbits between 30

the main secular resonances. In addition, there is a region ($36\,AU \lesssim a \lesssim \sim 39\,AU$ with $i \lesssim 15°$ and $e \lesssim 0.05$) which is dynamically stable for the age of the solar system. The observations to date indicate that this region is unpopulated. Therefore, there are clearly discrepancies between the observed orbital element distribution in the Kuiper belt and that predicted by dynamical erosion of the planets in their current configuration.

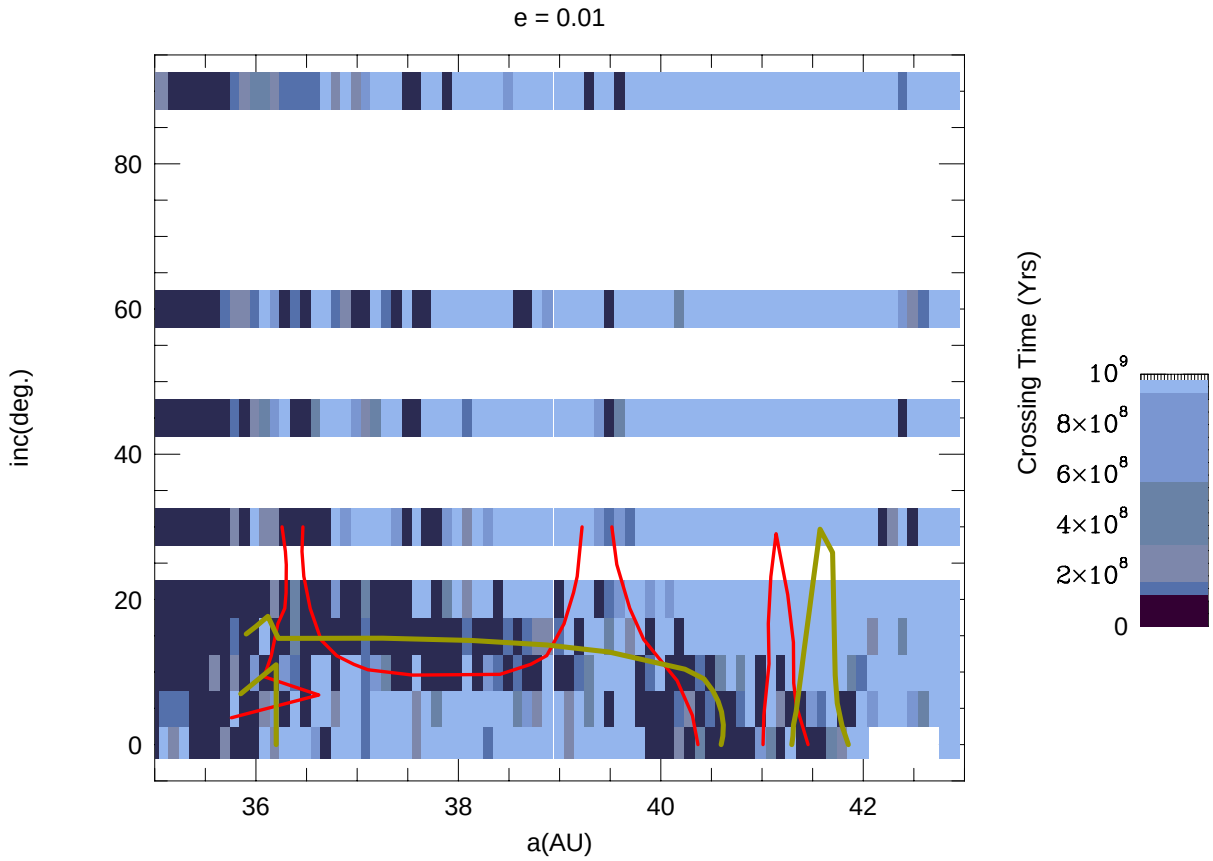

Figure 2 — The dynamical lifetime for test particles with initial eccentricity = 0.01 derived from Duncan et al.'s (1995) 10^9 year integrations. This plot is similar to Figure 1 except that a different color table was used for the solid bars. In addition, the red and yellow curves show the locations of Neptune longitude of perihelion secular resonances (ν_8) and the Neptune longitude of the ascending node secular resonances (ν_{18}), respectively, as determined by Knežević et al. (1991). The green lines show the location of the important Neptune mean motion resonances.

If these distinct classes of Kuiper belt orbits persist and the unpopulated region remains unpopulated as new objects are discovered and as better orbits are determined, then some mechanism other than the long-term gravitational effects of the outer planets in their current configuration must have created them. Three mechanisms that may have accomplished this come to mind:

- The hypothetical early outward migration of Neptune would cause its mean motion resonances to sweep through this region thereby capturing most objects into these resonances (Malhotra 1995, Holman 1995). The idea is based on the results of Fernandez & Ip (1981) that show that Uranus and Neptune most likely migrated outward as they dynamically dispersed the planetesimals surrounding them. Uranus and Neptune evolved outward because they were much more likely to scatter objects down to Jupiter and Saturn, which removed them from the planetary system, than eject them from the planetary system (also see Levison & Duncan 1996). Malhotra (1995) showed that Kuiper belt objects are likely to have been captured in the mean motion resonances with Neptune if their initial eccentricities were small. After capture, the