THE SCATTERED DISK POPULATION AND THE OORT CLOUD

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Abstract. The trans-Neptunian belt has been subject to a strong depletion that has reduced its primordial population by a factor of one hundred over the solar system's age. One by-product of such a depletion process is the existence of a scattered disk population in transit from the belt to other places, such as the Jupiter zone, the Oort cloud or interstellar space. We have integrated the orbits of the scattered disk objects (SDOs) so far discovered by 2500 Myr to study their dynamical time scales and the probability of falling in each of the end states mentioned above, paying special attention to their contribution to the Oort cloud. We found that their dynamical half-time is close to 2.5 Gyr and that about one third of the SDOs end up in the Oort cloud.

1. Introduction

There has been a long discussion on where comets originated and on whether there are intrinsic physical differences that reflect different formation distances from the Sun. In particular, the trans-Neptunian (TN) belt has been proposed as the source region of Jupiter family (JF) comets (Fernández, 1980; Duncan et al., 1988). The delivery of comets from the TN belt to the inner planetary region requires the presence of a transient population of bodies whose orbits have been removed from the TN belt. This conjecture received observational confirmation with the discovery of the *Centaurs*, whose orbits lie in the region of the Jovian planets, (2060) Chiron being the first of this class discovered in 1977 (Kowal, 1989). It was also expected that bodies scattered outwards to the region beyond the TN belt moving on very eccentric orbits and with perihelia beyond Neptune's orbit would be found. Object 1996 TL_{66}, discovered by Luu et al. (1997), was the first of this class of *Scattered Disk Objects* (SDOs). SDOs are usually defined as those with perihelion distances $q > 30$ AU and semimajor axes $a > 50$ AU. From numerical integrations over 4 billion yr, Duncan and Levison (1997) were able to reproduce such a scattered disk from TN objects (TNOs) strongly perturbed by close encounters with Neptune.

The sample of discovered SDOs has now increased to nearly 70 objects. The results from different surveys allowed Trujillo et al. (2001) to estimate the popula-

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tion of SDOs with radius $R > 50$ km at 3×10^4 bodies and a total mass of 0.05 $M_\oplus$, if a differential power-law size distribution of exponent $q = -4$ is assumed. An independent survey conducted by Larsen et al. (2001) led to the discovery of 5 Centaurs/SDOs and another two recoveries. From this survey they estimate a population of 70 SDOs brighter than red magnitude $m_R = 21.5$. Applying appropriate bias corrections for distance in the detection probability, the estimated total population is in good agreement with that derived by Trujillo et al. (2001). If we assume that the differential size distribution keeps the same exponent $q = -4$ down to typical comet radius $R = 1$ km, the total poplation of SDOs is estimated to be:

$$N(R > 1 \text{ km}) = 8 \times 10^9 \tag{1}$$

Such a population is large enough to be the source region of JF comets (Trujillo et al., 2001). Since such bodies can diffuse either to the planetary region or to large heliocentric distances, it may also also be a potential source of Oort cloud comets. This is what we analyze in this paper.

2. The Numerical Method

We numerically integrated the orbits of 76 SDOs (that included a few objects with $q < 30$ AU) taken from the Minor Planet Center's Web site: http://cfa-www.harvard.edu/iau/Ephemerides/Distant/Soft00Distant.txt. The numerical integration was performed with our numerical code EVORB that includes a Bulirsch-Stoer routine for the computation of every close encounter between a test body and a planet within 3 Hill radius. A detailed report about the accuracy of the integrator can be found in Fernández et al. (2002). In this case, the dynamical model includes the Sun and the four giant planets in a barycentric reference frame, and we used an integration step of 0.25 yr.

The SDOs (assumed to be massless) were integrated for 2.5 Gyr, but the integration was terminated if one of the following end states occurred:

1. Collision onto a planet or onto the Sun.
2. Reaching the region interior to the orbit of Jupiter, in which case it can be either ejected or transfer to a JF comet orbit in a very short time scale.
3. Reaching a distance of 20,000 AU from the Sun still in a barycentric elliptical orbit. In this case we consider that the body is stored in the Oort cloud.
4. Hyperbolic ejection to interstellar space.

We elaborated a simple program to automatically detect objects in mean motion resonances. For each object the program computes the critical angles for all the first, second and third order eccentricity-type mean motion resonances and also for some inclination-type ones. If a specific critical angle shows a nonuniform distribution between 0 and 360 degrees, the program looks at the semimajor axis of the body's orbit. In case it is close to the theoretical value of the resonance corresponding to this critical angle, it will be indicated as a potential resonance. In this way we detected 3 objects (2000 SR_{331}, 2000 FE_8 and 2001 KC_{77}) that spend all the time librating in the 2:5 mean motion resonance with Neptune, 2 objects (2000 SS_{331}, 2001 KV_{76}) that initially are librating in the 1:3 resonance and then escape from the resonance and one object (2002 CZ_{248}) which is temporarily captured in the 1:2 resonance. The 2:5 resonance seems to be a very stable orbital state, even for high eccentricities such as for 2000 SR_{331} ($e \sim 0.44$).

3. The Results

Figure 1 shows the end states of our sample of SDOs plotted as a function of time. The three most common end states: capture within Jupiter's region, hyperbolic ejection or transfer to the Oort cloud, are more or less evenly distributed, although with a slight predominace of the Oort cloud. From the original sample of 76 bodies, a little more than half (39) were lost after 2.5 Gyr, which indicates that the dynamical half-life is just about our integration time.

Figures 2 and 3 show the evolution of three objects from our sample that had different end states. Object 2001 QX_{322} ended up in the Jupiter's region after suffering several close encounters with Neptune, Uranus, Saturn, and finally Jupiter (close encounters with any of the Jovian planets are indicated in the upper panel, where the numbers 5 ... 8 stand for Jupiter ... Neptune respectively). We can see in the plot that at the very end of its evolution the object becomes a Centaur.

Object 2002 TC_{302} ends up in the Oort cloud. It starts up its evolution with a perihelion distance $q = 28.04$ AU, i.e. strictly speaking it is not a SDO, but afterwards it raises its perihelion to about 32 AU and it keeps oscillating at both sides of Neptune's orbit. The body has many encounters with Neptune, though its high inclination ($\sim 40°$) prevents them from being too frequent. The body's semimajor axis diffuses under the gravitational influence of Neptune until it reaches the Oort cloud.

Object 2000 SR_{331} is an interesting example among the survivors, since its initial perihelion distance is only $q = 31.14$ AU. Yet it remains locked in the 2:5 mean motion resonance with Neptune that prevents close encounters with this planet.

4. Discussion

Our results show that the dynamical half-time of the sample of SDOs studied is $\sim$ 2.5 Gyr. We should bear in mind that this is a biased sample, since there is a growing difficulty of detecting objects with larger semimajor axes. We found that roughly one third of the bodies end up in the Oort cloud. We can roughly estimate

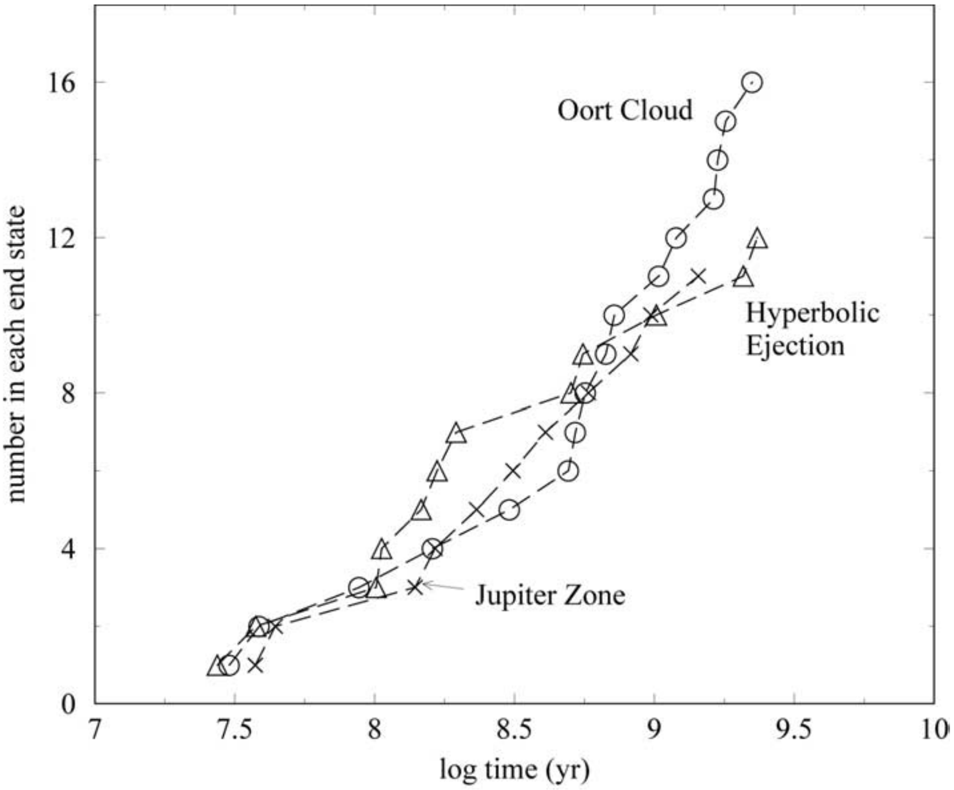

Figure 1. The end states found for our sample of SDOs integrated for 2.5 Gyr.

the transfer rate to the Oort cloud, bearing in mind that the total population of SDOs with radii $R > 1$ km is 8×10^9 by means of the following expression:

$$I_{SDO} = \frac{N_{SDO} \times f}{\tau} \sim 2.4 \text{ yr}^{-1} \tag{2}$$

where $f \sim 0.3$ is the fraction of SDOs that reach the Oort cloud, and $\tau \sim 10^9$ yr is the typical dynamical time scale for reaching the Oort cloud.

Therefore, about two objects per year reach the Oort cloud. If we assume that the supply of SDOs has been constant during the solar system's age, the total supply would be $\sim 10^{10}$ bodies. But considering that the TN population could have been about two orders of magnitude larger at the beginnings of the solar system, the value estimated above is actually a lower limit. Therefore, JF comets and at least some LP comets might have the same source region in the TN belt, but following different dynamical paths.

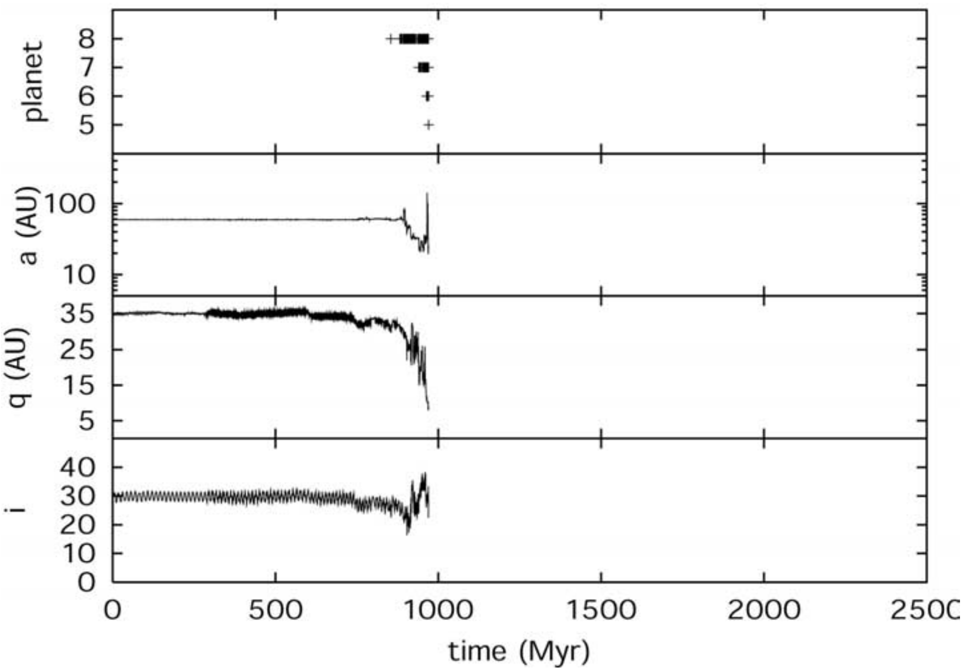

Figure 2. Dynamical evolution of the SDO 2001 QX_{322} that ends up captured by Jupiter.

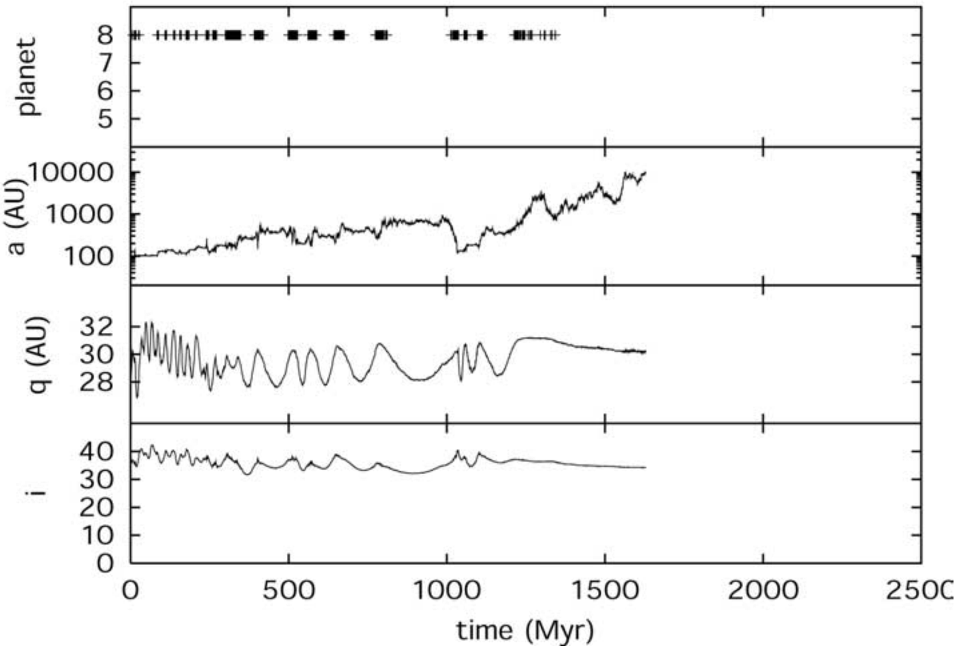

Figure 3. Dynamical evolution of the SDO 2002 TC_{302} that ends up in the Oort cloud.

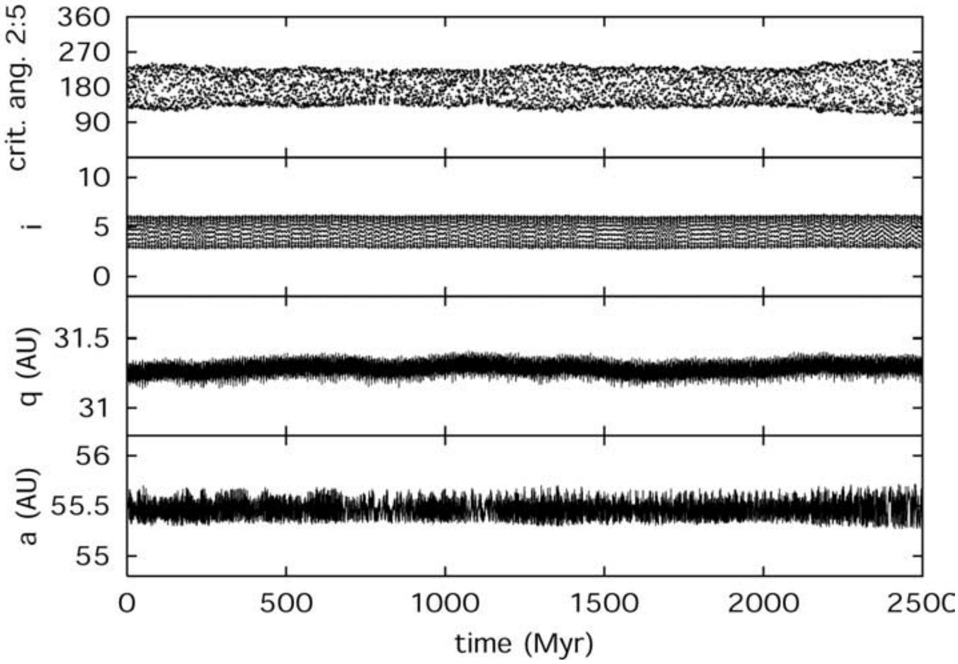

Figure 4. Dynamical evolution of the SDO 2000 SR_{331} that remains during the whole period of integration trapped in the 2:5 resonance.

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