Close encounters with giant planets
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Abstract:
We study the outcome of small bodies, called planetesimals, after close encounters with the giant planets during a simulation of the early evolution of the Solar System. We separate the planetesimals by those which were ejected from the Solar System and those which remained after one billion years. The surviving objects are further broken down into KBO’s (Kuiper Belt Objects) and OCO’s (Oort Cloud Objects) depending on the area in which they end the simulation. We find that KBO’s, OCO’s and ejected particles with lower densities have roughly the same chance of being tidally disrupted, or torn apart, during their close encounters. Differences are seen with planetesimals of higher densities, as KBO’s were tidally disrupted 0.486% of the time, OCO’s 0.047% of the time, and ejected particles 1.3% of the time.

Our Solar System:

Figure 1: Simplified model of our Solar System (not drawn to scale). The Kuiper Belt exists from the edge of Neptune at around 30 AU to 50 AU (1 AU being the distance from the Sun and the Earth). The Oort Cloud is an extremely distant region in our Solar System with the inner edge estimated at about 2,000-5,000 AU from the Sun.

There are many models that describe the evolution of the Solar System; for this experiment we analyze simulations based on the Nice Model. The Nice Model is a model which asserts that the giant planets (Jupiter, Saturn, Uranus and Neptune) formed in a much more compact configuration than the present-day configuration. The addition of a fifth or sixth (usually ice) giant planet has also been studied in these simulations. The planets are surrounded by a disk of small bodies called planetesimals, that formed from dust, ice and other materials, in a region now called the Kuiper Belt.

The gravitational interactions the small bodies had amongst themselves caused the disk to spread out, eventually leading to the interactions between the objects and Neptune’s orbit. This planet-planetesimal interaction leads to two main outcomes: the objects being scattered outward (to enter the Oort Cloud or be completely ejected) or scattered inward (toward an interaction with Uranus). A similar process occurs for the rest of the giants, including the additional ice giant(s).

Outcomes of Close Encounters:

Figure 2: Close encounters between the small bodies and the giant planets have two main outcomes: (a) they can be scattered outward into the Oort Cloud/completely ejected from the Solar System or (b) they can be scattered inward towards the next innermost giant planet.

The planetesimals are more likely to be scattered inward because it takes less energy to "pass off" the objects to the next planet than to eject them outwards.

Figure 3: If the small bodies reach Jupiter, the last giant planet before the terrestrial planets (Mercury, Venus, Earth and Mars), Jupiter will usually eject them from the Solar System.

Jupiter’s tendency to eject the planetesimals from the system results in a net loss of angular momentum. Consequently, Jupiter migrates inwards towards the sun. Saturn, Uranus, Neptune and the additional ice giant(s) gain angular momentum (from scattering particles inward) and migrate outwards.

Figure 4: Closest and farthest distances (AU) of the five giant planets vs. Time (years) for one simulation.

Third Outcome?
Every time an object encounters a giant planet, there is a third possibility: the planetesimal can be tidally disrupted- torn apart into hundreds or thousands of pieces. Each planet has a specific tidal disruption radius; if the object passes within that radius it will be broken apart.

Surviving Particles:

Figure 5: Cumulative distribution plot of the surviving planetesimals’ closest approaches to the giant planets for (a) objects the end up in the Kuiper Belt and (b) objects that end up in the Oort Cloud. The density of the particles is assumed to be 1.0g/cm³. All objects enveloped in red pass too close and get torn apart.

Ejected Particles:

Figure 6: Cumulative distribution plot of the ejected planetesimals’ closest approaches to the giant planets for objects with density 1.0g/cm³. All planetesimals enveloped in red pass too close and get torn apart.

Conclusion:
• At lower densities, the likelihood of an object being broken apart is not drastically different:
  • KBO: 0.919%
  • Oort: 0.488%
  • Ejected: 0.588%
• At higher densities, likelihood differs:
  • KBO: 0.488%
  • Oort: 0.047%
  • Ejected: 1.3%