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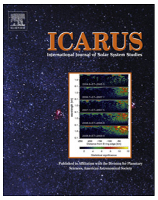

Do Centaurs preserve their source inclinations?

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ABSTRACT

The Centaurs are a population of small, planet-crossing objects in the outer Solar System. They are dynamically short-lived and represent the transition population between the Kuiper belt and the Jupiter family short-period comets. Dynamical models and observations of the physical properties of the Centaurs indicate that they may have multiple source populations in the trans-Neptunian region. It has been suggested that the inclination distribution of the Centaurs may be useful in distinguishing amongst these source regions. The Centaurs, however, undergo many close encounters with the giant planets during their orbital evolution; here we show that these encounters can substantially determine the inclination distribution of the Centaurs. Almost any plausible initial inclination distribution of a Kuiper belt source results in Centaurs having inclinations peaked near 10–20°. Our studies also find that the Kuiper belt is an extremely unlikely source of the retrograde Centaur that has been observed.

1. Introduction

The group of minor planets known as Centaurs represent the dynamical link between the reservoirs of icy objects in the outer Solar System and the short-period Jupiter family comets in the inner Solar System. Because the orbits of the Centaurs cross those of the outer planets, Centaurs are dynamically short-lived. Tiscareno and Malhotra (2003) numerically integrated the orbits of 53 observed Centaurs and found that their median dynamical lifetime was only 9 Myr. This means that there must exist a long-lived source for this transient population. Attempts to identify the Centaur sources have largely focused on dynamical models of the potential source regions. Early studies to identify a source region for the short period comets suggested that the long period comets (originating from the nearly isotropic distant Oort Cloud) could be captured into short period orbits by means of planetary perturbations, and that the higher capture probabilities at low inclinations could explain the prograde, low inclinations of the short period comets (Everhart, 1972). But Fernandez (1980) and Duncan et al. (1988) showed that Everhart's mechanism is a very inefficient way to produce Centaurs and short period comets from Oort Cloud comets, suggesting that a more proximate, lower-inclination population just beyond Neptune would be a more likely source region. With the subsequent discovery of the Kuiper Belt and its complex dynamical structure, recent studies have focused on the dynamical subclasses of the Kuiper belt as the sources that resupply the Centaurs and the Jupiter family comets: Levison and Duncan (1997), Volk and Malhotra (2008) and Di Sisto and Brunini (2007) modeled the scattered disk source; Di Sisto et al. (2010) and Morbidelli (1997) modeled the Plutinos (objects in the 3:2 mean motion resonance with Neptune) as a source of the short period comets; the Trojan populations of Neptune and/or Jupiter (objects in the 1:1 mean motion resonance with Neptune or Jupiter) were studied by Horner and Lykawka (2010) and Horner and Wyn Evans (2006). The Oort cloud has also been revisited as a possible source (Emel'yanenko et al., 2005; Brasser et al., 2012). These models have identified dynamical pathways as well as the flux per unit source population from each source, but it remains unclear which, if any, source population dominates the flux of new Centaurs. We do not yet have strong enough observational estimates of the number of small, comet-sized (1–10 km) bodies in each of the proposed source regions to be able to estimate the absolute number of new Centaurs and/or Jupiter family comets from each region (Bernstein et al., 2004; Duncan and Levison, 1997; Volk and Malhotra, 2008; Fraser et al., 2010).

Another approach is to examine the dynamical and/or physical properties of the observed Centaurs and compare them to the same properties in the source region. Because the Centaurs have orbits that are much more favorable for observations than the orbits of trans-Neptunian objects (TNOs), they have been the subject of several spectroscopic and photometric studies (Tegler et al. (2008) and references therein, Barucci et al. (2011)). Interestingly, the Centaurs have a bimodal color distribution (Tegler et al., 2008), which was not found in the early studies of (brighter, larger) TNOs. New studies indicate that the color distribution of TNOs is size dependent and that a bimodal color distribution occurs in the population of smaller, dynamically excited TNOs (Fraser and Brown, 2012; Peixinho et al., 2012). These observations give us some clues about the origins of the Centaurs, but there are not yet large enough

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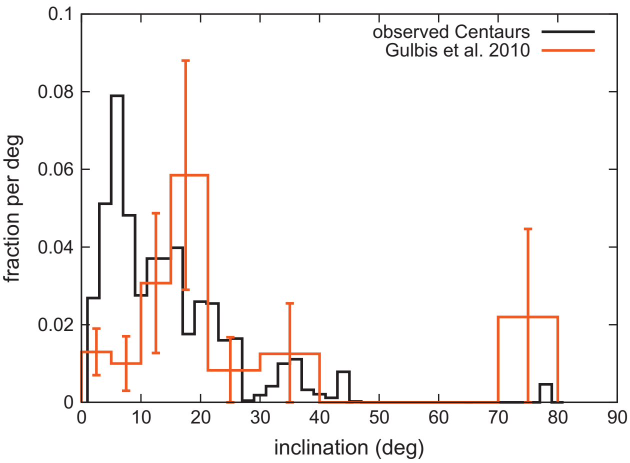

Fig. 1. The inclination distribution of the observed Centaurs (data from the Minor Planet Center website) and the debiased inclination distribution for the Centaurs from the Deep Ecliptic Survey (Gulbis et al., 2010).

sample sizes to draw any firm conclusions. Furthermore, due to the inherent faintness of TNOs as observed from Earth, it is unclear that we will be able to observe sufficient numbers of smaller, Centaur-sized TNOs in the near future to improve this state.

The dynamical properties of the Centaurs might be a possible way of identifying the sources. The dynamics of the observed Centaurs have been modeled by Tiscareno and Malhotra (2003) and Bailey and Malhotra (2009); their orbital evolution is dominated by chaotic diffusion and the frequent close encounters with the outer planets, which cause their orbital elements to evolve rapidly. It has been suggested (e.g. Gulbis et al. (2010)) that, despite their strongly chaotic evolution, the orbital inclinations of the Centaurs might preserve memory of their source regions. There are currently sufficient observations of TNOs to identify several dynamical subclasses and to calculate inclination distributions separately for the classical Kuiper belt, the scattered disk, and the resonant populations (Brown, 2001; Elliot et al., 2005; Gulbis et al., 2010). The inclination distribution of the Centaurs is less well defined due to the relatively small number, 108, of observed Centaurs.[1] The observed inclination distribution of these objects is shown in Fig. 1 along with the debiased inclination distribution from the Deep Ecliptic Survey (Gulbis et al., 2010). If the Centaurs' inclination distribution does retain some memory of the source region's inclination distribution, that could be an important means for linking the Centaurs to a particular dynamical subclass of the Kuiper belt or to the Oort cloud.

In this work, we investigate the extent to which inclinations of Centaurs may preserve the inclination distribution of their sources. We present the results of numerical simulations of hypothetical Centaurs generated from the Kuiper belt subclasses. We follow the orbital evolution of these hypothetical Centaurs until they either transition onto inner Solar System orbits or they are ejected from the giant planet region. During this evolution, our simulated Centaurs experience many close encounters with the four outer planets, each of which induces some change in the orbital elements of the Centaurs. We use these simulations to calculate the average outcomes of planetary encounters, including the average change in a Centaur's inclination as a function of close encounter distance. Using these average encounter outcomes, along with statistics about close encounter frequency as a function of encounter distance and the dynamical lifetimes of Centaurs, we compute the dynamically evolved inclination distribution expected of Centaurs as a function of the initial inclination distribution of the source population. We then discuss the implications of these results for identifying the dominant Centaur source(s).

2. Numerical simulations

To explore the evolution of inclinations in the Centaur region, we performed a numerical integration of test particles entering the planet-crossing region from a trans-Neptunian source region. We chose source region parameters based on the classical Kuiper belt (CKB) and the scattered disk (SD) because these dynamical classes are widely regarded as the most likely sources of the Centaurs (Levison and Duncan, 1997; Di Sisto and Brunini, 2007; Volk and Malhotra, 2008; Lowry et al., 2008). This numerical simulation is not meant to be exactly representative of either the CKB or the SD, but is rather an exploration of the parameter space of these populations. To that end, our test particles uniformly cover the following ranges in semimajor axis (a), perihelion distance (q), mean anomaly (M), argument of perihelion (ω), and longitude of ascending node (Ω):

- $40\ \mathrm{AU} \leqslant a \leqslant 80\ \mathrm{AU}$
- $30\ \mathrm{AU} \leqslant q \leqslant 32\ \mathrm{AU}$
- $0 \leqslant M, \Omega, \omega < 2\pi$.

To explore a large range in inclination, the test particles were divided into 24 inclination bins (200 test particles per bin) with the following bin widths:

- 1° for $0^\circ \leqslant i < 10^\circ$
- 2° for $10^\circ \leqslant i < 30^\circ$
- 5° for $30^\circ \leqslant i < 50^\circ$

and inclinations were assigned uniformly within each bin. The choice to limit perihelion distances to the 30–32 AU range was made to manage computational time. Test particles with these q values will either enter the Centaur population (which we define as $5 < q < 30$ AU) or be ejected from the Solar System early in the simulation, minimizing the necessary total length of the simulation. In previous scattered disk simulations (Volk and Malhotra, 2008), we found that the inclination distribution is preserved as test particles evolve from $q > 33$ AU to $q \sim 30$ where they start to have close encounters with Neptune; the test particles' inclinations on our initially nearly Neptune-crossing orbits are a good representation of their larger q source region inclinations. We limit the initial semimajor axes to <80 AU to conserve computational time because test particles starting at larger values of a will take longer to evolve onto Centaur-like orbits. We show later in this section that the dynamical properties we are interested in do not depend on this limit in a.

The integration was performed using the swift_rmvs3 code in the SWIFT software package,[2] which is capable of integrating test particles through arbitrarily close encounters with the massive planets. For each simulation we include the four outer planets and the Sun as massive bodies (the Sun's mass is augmented with the mass of the terrestrial planets), and the hypothetical Centaurs are included as massless test particles. We use a step size of one year, and we remove test particles if they achieve a heliocentric distance inside Jupiter's orbit or beyond 1000 AU, or if they impact one of the giant planets. The inner boundary of the simulation was chosen to conserve computational time; following test particles into the inner Solar System would require the inclusion of the terrestrial planets and the use of a much shorter integration step size. This choice means

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[1] http://www.minorplanetcenter.net/iau/lists/t_centaurs.html.

[2] http://www.boulder.swri.edu/~hal/swift.html (Levison and Duncan, 1994).