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Assessing the contribution of centaur impacts to ice giant luminosities

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ABSTRACT

Voyager 2 observations revealed that Neptune's internal luminosity is an order of magnitude higher than that of Uranus. If the two planets have similar interior structures and cooling histories, Neptune's luminosity can only be explained by invoking some energy source beyond gravitational contraction. This paper investigates whether centaur impacts could provide the energy necessary to produce Neptune's luminosity. The major findings are (1) that impacts on both Uranus and Neptune are too infrequent to provide luminosities of order Neptune's observed value, even for optimistic impact-rate estimates and (2) that Uranus and Neptune rarely have significantly different impact-generated luminosities at any given time. Uranus and Neptune most likely have structural differences that force them to cool and contract at different rates.

1. Introduction

While the ice giants may have similar interior structures (e.g. Podolak et al., 1995; Fortney and Nettelmann, 2010), their internal luminosities differ by a factor of 10. From Voyager 2 IRIS radiometer observations, Pearl and Conrath (1991) calculated an internal luminosity of $\log L/L_\odot = -11.024$ for Neptune, while Pearl et al. (1990) found an internal luminosity of $\log L/L_\odot = -12.054$ for Uranus. The $2.7 M_\oplus$ mass difference between the two planets is not enough to explain the luminosity difference: the internal power generated per unit mass is 3.22×10^{-7} erg g^{-1} s^{-1} for Neptune and 3.92×10^{-8} erg g^{-1} s^{-1} for Uranus (Pearl et al., 1990; Pearl and Conrath, 1991). Multiple theories explaining the energy balance of the ice giants have been put forward, including stable stratification in Uranus' interior (Podolak et al., 1990), early and efficient heat transport by baroclinic instability in Uranus (Holme and Ingersoll, 1994), and efficient capture of strongly interacting dark matter by Neptune (Mitra, 2004; Adler, 2009).

One energy source that has not been investigated in connection with ice giant energy balance is impact heating. Given a sufficient supply of centaurs,[1] impacts onto Neptune could be frequent enough to boost Neptune's luminosity to observed values. Indeed, meteoroid impacts onto the Moon generate flashes of optical light, first observed by Dunham et al. (1999). Energy deposited in ice giant atmospheres by centaurs that penetrate the photosphere would not be released instantly to space, as in the case of lunar meteoroid flashes, but would instead be radiated away on a ~100-year timescale (Conrath et al., 1990). This paper explores the possibility that centaur impacts may contribute significantly to ice giant luminosities.

The investigation begins with an order-of-magnitude calculation of the typical centaur size required to produce Neptune's luminosity with impacts alone, treating impacts as a steady-state process. Next, we explore different impact rates and break the steady-state assumption, treating impacts as a stochastic process. Section 3 contains estimates of the total number of centaurs, which we use as a scaling factor for published impact rates. Section 4 describes a Monte Carlo approach to computing a cumulative probability distribution of planet luminosity. Results and conclusions are presented in Section 5.

2. Impact-induced luminosity: Order-of-magnitude estimate

To get a basic idea of how much impacts contribute to ice giant luminosities, we assign a constant value $\dot{M}$ to each planet's accretion rate and assume a constant accretion-generated luminosity. The impact-generated luminosity is then

$$L_{\rm imp} = \frac{GM\dot{M}}{R}, \quad (1)$$

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[1] While we use the word "Centaur" loosely to describe any object that may impact Uranus or Neptune, Jewitt (2009) defines centaurs as comets whose dynamics are controlled by perihelion and/or aphelion interactions with giant planets, such that perihelia q and semimajor axes a are in the range $5.2 < (q, a) < 30.0$ AU. The Minor Planet Center website, minorplanetcenter.net/blog/asteroid-classification-i-dynamics/, defines a centaur as an asteroid with $q > 5.2$ AU and $a < 30.0$ AU.

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where M is the planet mass and R is the planet radius. Equating L_{imp} with Neptune's present luminosity requires $\dot{M} = 4 \times 10^{17}$ g yr^{-1}. Based on simulations of diffusion from the Kuiper Belt to the inner Solar System, Levison and Duncan (1997) found that comets impact Uranus and Neptune slightly more than once per thousand years. To deliver the average $\dot{M}$ quoted above, most of the impacting centaurs with a density of $\sim$1 g cm^{-3} would have to have radii over 40 km. Such a large average centaur size can be ruled out by crater observations; for example, Stern and McKinnon (2000) calculated that the largest craters detected on Triton were created by impactors with radii of 1–5.5 km. The occultation surveys of Roques et al. (2006) and Schlichting et al. (2009, 2012) also indicate a centaur/Kuiper Belt Object size distribution heavily biased toward sub-kilometer bodies.

In the steady-state scenario where L_{imp} is constant and the Levison and Duncan (1997) impact rate applies, impacts clearly cannot drive Neptune's internal heating. Explaining Neptune's luminosity with impacts alone requires one of two scenarios: (1) a substantially higher impact rate, which is possible if Levison and Duncan (1997) underestimated the total number of centaurs; or (2) a recent giant impact that has driven Neptune's luminosity to an above-equilibrium value. The rest of this paper examines scenarios (1) and (2).

3. Total number and size distribution of centaurs

Determining the frequency and energy of impacts on ice giants requires knowing both the total number of centaurs and their size distribution. The number of centaur detections is too small to reconstruct a size distribution based on observations alone: only 7 centaurs met the "secure orbit" standards used by the Deep Ecliptic Survey team to compute a debiased H-magnitude distribution (Adams et al., 2014). Fortunately, centaurs have short dynamical lifetimes, so their size distribution is a relic of their source population. The cold Kuiper Belt (e.g. Holman and Wisdom, 1993; Levison and Duncan, 1997; Fraser et al., 2010; Volk and Malhotra, 2011), the Neptune Trojans (Horner and Lykawka, 2010), the inner Oort cloud (Emel'yanenko et al., 2005; Kaib et al., 2009; Brasser et al., 2012; Volk and Malhotra, 2013; de la Fuente Marcos and de la Fuente Marcos, 2014; Fouchard et al., 2014), the Plutinos (Morbidelli, 1997; di Sisto et al., 2010), and the scattered disk (di Sisto and Brunini, 2007; Volk and Malhotra, 2008, 2013) could all be centaur sources. However, no empirical information exists on the size distribution of objects in the Oort cloud, and Fraser et al. (2010) find that the scattered disk is not populous enough to explain the observed influx of comets into the inner Solar System. Doressoundiram et al. (2005) also show that centaur colors are not consistent with an origin in the scattered disk. Moreover, Schlichting et al. (2013) show that the cold Kuiper Belt and scattered disk objects have size distributions that follow the same functional form, only with different maximum sizes. Calculations presented here are based on the cold Kuiper Belt size spectrum of Schlichting et al. (2013), which is a close match to the size spectrum of Saturnian satellite impactors inferred from the cratering record (Minton et al., 2012). Schlichting et al. (2013) used a combination of theoretical coagulation models, occultation surveys, and observations of large KBOs to constrain the size spectrum.

The first estimate of the total number of centaurs comes from the simulations of Tiscareno and Malhotra (2003), who investigated the dynamical evolution of the observed centaurs over 100 Myr. The top panel of Fig. 1 shows their computed time-averaged eccentricity distribution. Tiscareno and Malhotra (2003) also estimated the detection fraction of centaurs as a function of eccentricity, which is reproduced in the bottom panel of Fig. 1. The detection fraction estimate holds for centaurs with $R \geqslant 30$ km. Multiplying the eccentricity distribution with a fit to the detectability function (black line in the bottom panel of Fig. 1) and summing over the 0–1 eccentricity range yields an estimate of $f_{det} = 3.7\%$ for the fraction of centaurs with $R \geqslant 30$ km that have been detected. The total number of large centaurs with $R \geqslant 30$ km is then is $\sim N_{obs}/f_{det}$, where $N_{obs} = 53$ is the number of centaurs that had been discovered when the Tiscareno and Malhotra (2003) calculations were performed.

The next step in determining the total number of centaurs is to find the radius of the largest centaur. For $R \geqslant 30$ km,

$$N_{\geqslant}(R) = \frac{N_0}{\zeta - 1}\left(\frac{R}{R_0}\right)^{1-\zeta}. \quad (2)$$

In Eq. (2), $N_{\geqslant}(R_{max}) = 1, N_{\geqslant}(30\text{ km}) = N_{obs}/f_{det} = 1432$, and $\zeta = 4$ (e.g. Trujillo et al., 2001; Fraser et al., 2008; Minton et al., 2012; Schlichting et al., 2013), so that $R_{max} = 338$ km. An estimate of the total number of centaurs then follows, given an analytical form for the differential size distribution dN/dR. Schlichting et al. (2013) find a KBO size distribution of the form $dN/dR \propto R^{-\zeta}$, where $\zeta = 2$ for $10\text{ km} \leqslant R \leqslant 30$ km; $\zeta = 5.8$ for $2\text{ km} \leqslant R \leqslant 10$ km; and $\zeta = 2.5$ for $0.1\text{ km} \leqslant R \leqslant 2$ km. We set a lower limit of $R = 1$ km to the size of centaurs considered here, which is justified because the mass contained in the smallest bodies is negligible unless $\zeta \geqslant 4$. The Schlichting et al. (2013) conclusion that $\zeta < 4$ for the smallest bodies is supported by sky brightness measurements, which rule out $\zeta \geqslant 3.4$ for $R < 1$ km (Kenyon and Windhorst, 2001; Ichikawa and Fukugita, 2011). The size distribution computed based on the Tiscareno and Malhotra (2003) maximum centaur-size estimate contains 2.8×10^7 comets with $R \geqslant 1$ km, and is shown in the top panel of Fig. 2 (red curve). The distribution agrees well with the results of Sheppard et al. (2000), who predict about 100 centaurs with radii above 50 km. However, the number of small bodies is an order of magnitude lower than the di Sisto and Brunini (2007) estimate of $\sim 2.8 \times 10^8$ centaurs with radii above 1 km.

Other estimates of the total number of centaurs come from radius measurements of centaurs and KBOs. The most conservative estimates come from assuming that Chariklo, the largest observed centaur, is in fact the largest centaur in the Solar System. (It is highly likely that the largest centaur has not been observed, given that the detection probability is extremely low for even moderately eccentric orbits.) Chariklo radius estimates range between 118 km and 151 km (Fornasier, 2013; Stansberry et al., 2008; Groussin et al., 2004; Altenhoff et al., 2001; Jewitt and Kalas, 1998). The green and black curves in Fig. 2 show size distributions where the largest body takes on the maximum and minimum observational estimates of Chariklo's radius, respectively. Finally, Fig. 2 shows a size distribution that is optimistic about the size of the largest body, with $R_{max} = 458.5$ km, the maximum measured radius of the Plutino Orcus (blue curve). Larger TNOs such as Quaoar and Pluto have higher densities that suggest differentiation, whereas Orcus' bulk density is more consistent with the undifferentiated comet population. It is plausible, then, that Orcus represents a transition object between Kuiper Belt comets/centaurs and true dwarf planets. Note that this "optimistic" size distribution predicts only a factor of 2.5 more centaurs than using the Tiscareno and Malhotra (2003) results, but brings the number of small bodies closer to the predictions of di Sisto and Brunini (2007).

The bottom panel of Fig. 2 shows the cumulative mass function $M_{<}(R)$, the mass of centaurs with radii less than a given value. For each size distribution from the top of Fig. 2, three possible centaur densities are considered. The highest density is the maximum inferred value for Orcus (1.53 g cm^{-3}, Stansberry et al. (2012), dashed lines). The solid lines show mass functions with the bulk