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Naturally Occurring Selection Effects on the Terrestrial Accretion of Interplanetary Dust Particles

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Abstract. Interplanetary dust particles deposited in the Earth's atmosphere (IDPs) are an important source of extraterrestrial material. The origin of these particles, whether asteroidal or cometary, is a dispute that can be resolved into two separate questions. What are the fractions of the asteroidal and cometary components of the zodiacal cloud? And what fraction of each component is captured by the Earth? Evidence from the structure of the zodiacal cloud, particularly the dust bands and the Earth's resonant circumsolar ring, indicate that about one third of the cloud is asteroidal while two thirds is cometary. The geometry of capture is such that low eccentricity (e), low inclination (I) particles will be preferentially captured over high e, I particles. Two known abundant sources of low e, I particles are the asteroidal families Themis and Koronis, as witnessed by the associated zodiacal dust bands. We show that capture rates of particles from these two families achieve dominance over every other source. This leads to the result that particles from Themis and Koronis may account for over half of all deposited IDPs and that very few of the IDPs deposited in the Earth's atmosphere are of cometary origin. Furthermore, there are dynamical arguments which suggest that the accretion rate of Themis and Koronis dust particles varies with time. Two perodicities occur, a seasonal variation with a period of six months and a long-term variation with a period near 10^5 years. The amplitude and period of this long-term variation is supported by measurements of extraterrestrial ^{3}He found in deep-sea sediments.

1. Source Contributions to Atmospheric IDPs

Modelling of the IRAS dust bands indicates that they are related to the prominent asteroid families Themis, Koronis and possibly Eos and that dust in the bands constitutes 5-10% of the zodiacal cloud (Dermott *et al.* 1994a), rougly evenly split between the low latitude Themis & Koronis bands and the high latitude bands. Modelling of the circumsolar ring indicates that dust from the asteroid belt may account for 30% of the zodiacal cloud (Dermott *et al.* 1994b),

n_{com}/n_{ast}	$n_{tk} = 5\%$ S_{com}	S_{nf}	S_{tk}	$n_{tk} = 2\%$ S_{com}	S_{nf}	S_{tk}
80/20	7%	25%	68%	11%	47%	42%
70/30	5%	37%	58%	7%	59%	34%
50/50	3%	51%	46%	4%	72%	24%
30/70	1%	61%	38%	2%	80%	18%
20/80	<1%	65%	34%	<1%	82%	17%

Table 1. Dust particle source contribution to the zodiacal cloud (n_{com}, n_{ast}, n_{tk}) and resulting contribution to deposited IDPs (S_{com}, S_{nf}, S_{tk}). Dust particles from all asteroids combined are labeled *ast*, Themis and Koronis particles are labeled *tk*, asteroidal particles not originating in the Themis or Koronis families are labeled *nf*, and particles having cometary origins are labeled *com*. For example, in a zodiacal cloud with 30% asteroidal dust (n_{com}/n_{ast} = 70/30) and with the Themis and Koronis dust bands contributing 5% of the total surface area (n_{tk} = 5%) more than half of all deposited IDPs will be from the Koronis and Themis families (S_{tk} = 58%).

the remainder presumably being cometary and interstellar in origin. It should be noted however that this asterodial contribution of 30% is highly controversial.

An important source of extraterrestrial material is the collections of interplanetary dust particles recovered from the Earth's atmosphere (IDPs). However, the origin of the dust in these collections, whether asteroidal or cometary, is a matter of dispute. Studying the capture probabilities of dust particles from various proposed sources may help to resolve this controversy. The geometry of capture is such that low eccentricity (e), low inclination (I) particles will be preferentially captured by the Earth over high e, I particles. This has been pointed out by Flynn (1990). Two known abundant sources of low e, I particles are the asteroid families Themis and Koronis, as witnessed by the dust bands associated with them. Because of their much smaller ecliptic inclinations ($\leq 2°$), capture rates for particles from the asteroid families Themis and Koronis achieve dominance over every other source. This naturally occurring selection effect leads to the result that very few IDPs in the atmosphere are of cometary origin and that dust from Themis and Koronis, while constituting only 2-5% of the zodiacal cloud, can account for most of the atmospheric extraterrestrial material. Table 1 lists the contributions to atmospheric IDPs for three different sources based on their overall contributions to the zodiacal cloud. Collections of IDPs taken from the stratosphere should be heavily biased in favor of particles from these two asteroid families Themis and Koronis. Indeed, analysis of NASA's IDP collections shows that the compositional diversity of the particles is surprisingly narrow, consistent with the particles being derived mainly from one or two asteroid families (Flynn 1995). We are currently unable to seperate the contributions of Themis from those of Koronis.

2. Seasonal Variations in Accretion of IDPs

The orbit of a dust particle can be completely characterized by a set of five orbital elements. These elements can be thought of as being the vectorial sum of two components - the proper and the forced elements. Proper elements represent

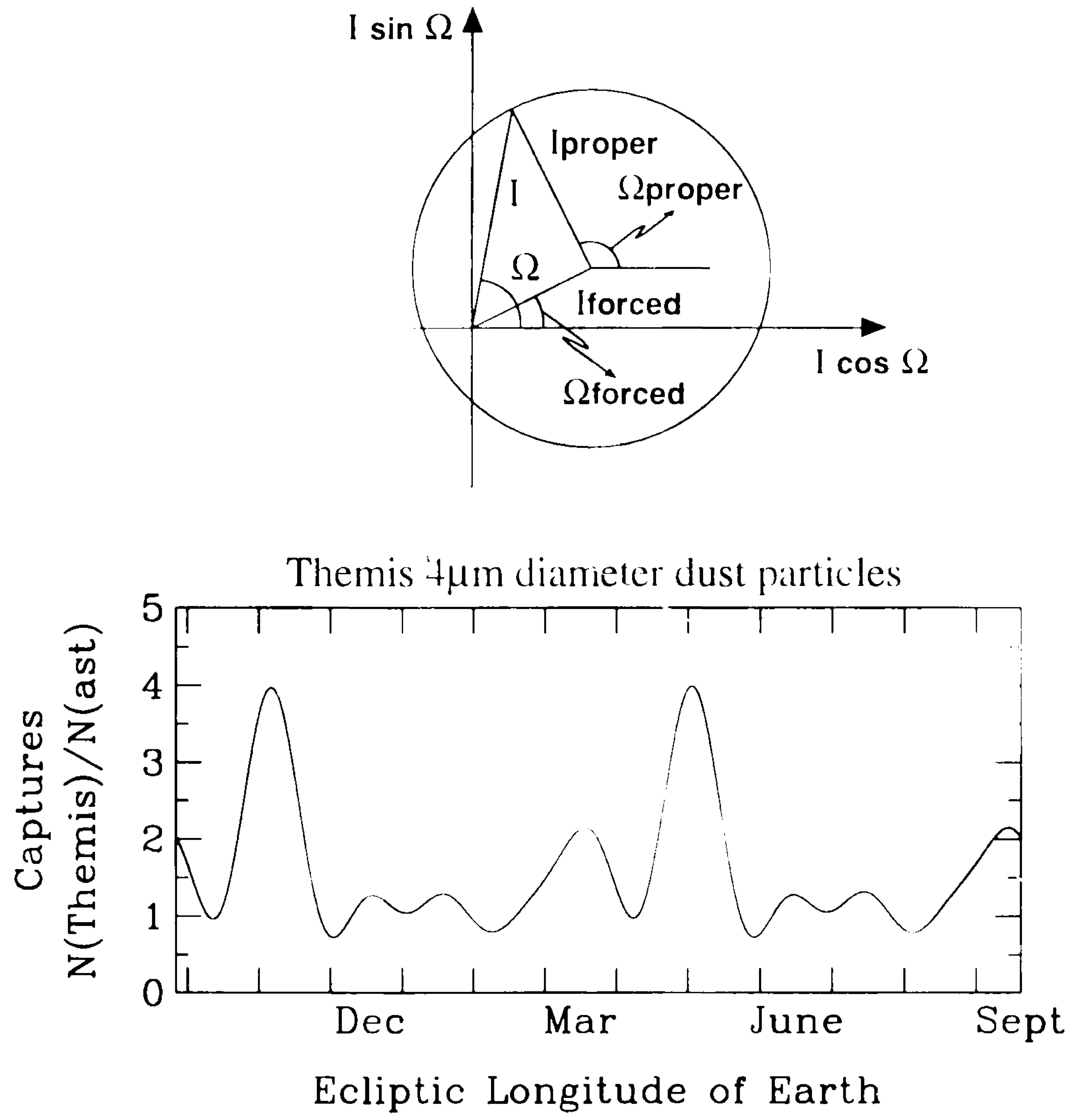

Figure 1: The top schematic demonstrates the idea of proper and forced inclination interference. When both ascending and descending ecliptic nodes are considered (bottom) the capture rate exhibits two periods of enhancement relative to the background asteroidal particles (shown here for 4 μm diameter $\rho = 2.5$ $g\ cm^{-3}$ Themis particles).

an "average" characteristic motion in the sense that they result from an elimination of short-period perturbations. Forced elements arise from the long-term periodic gravitational perturbations primarily due to the action of the Jovian planets. Particles whose origins lie within the Themis and Koronis families share a common proper inclination but have randomly distributed proper ascending nodes, thus forming a circle when plotted in $(I\cos\Omega, I\sin\Omega)$ space (See Figure 1). Taking into consideration the forced ascending node then reveals an interesting effect if the forced and proper inclinations are comparable, which is the case for Themis and Koronis particles. For a range of proper ascending node the forced and proper inclinations add *constructively* and result in a total inclination double that of the proper. For another range of proper ascending node the two inclinations add *destructively*, resulting in a total inclination very nearly zero. This interference pattern introduces systematically varying total inclinations of the particles as a function of their nodes (See Figure 1). Since the capture rate is so strongly dependent on inclination and capture can occur only at the ecliptic nodes this suggests that there exists a seasonal variation in the number of Themis and Koronis particles deposited in the Earth's atmosphere. By numerically simulating the migration of particles from these source families to the inner Solar System it is possible to predict the phase and amplitude of the seasonal variation. Figure 1 shows the predicted variation in the number of 4 μm Themis particles captured relative to background asteroidal particles, for which the capture rate is constant

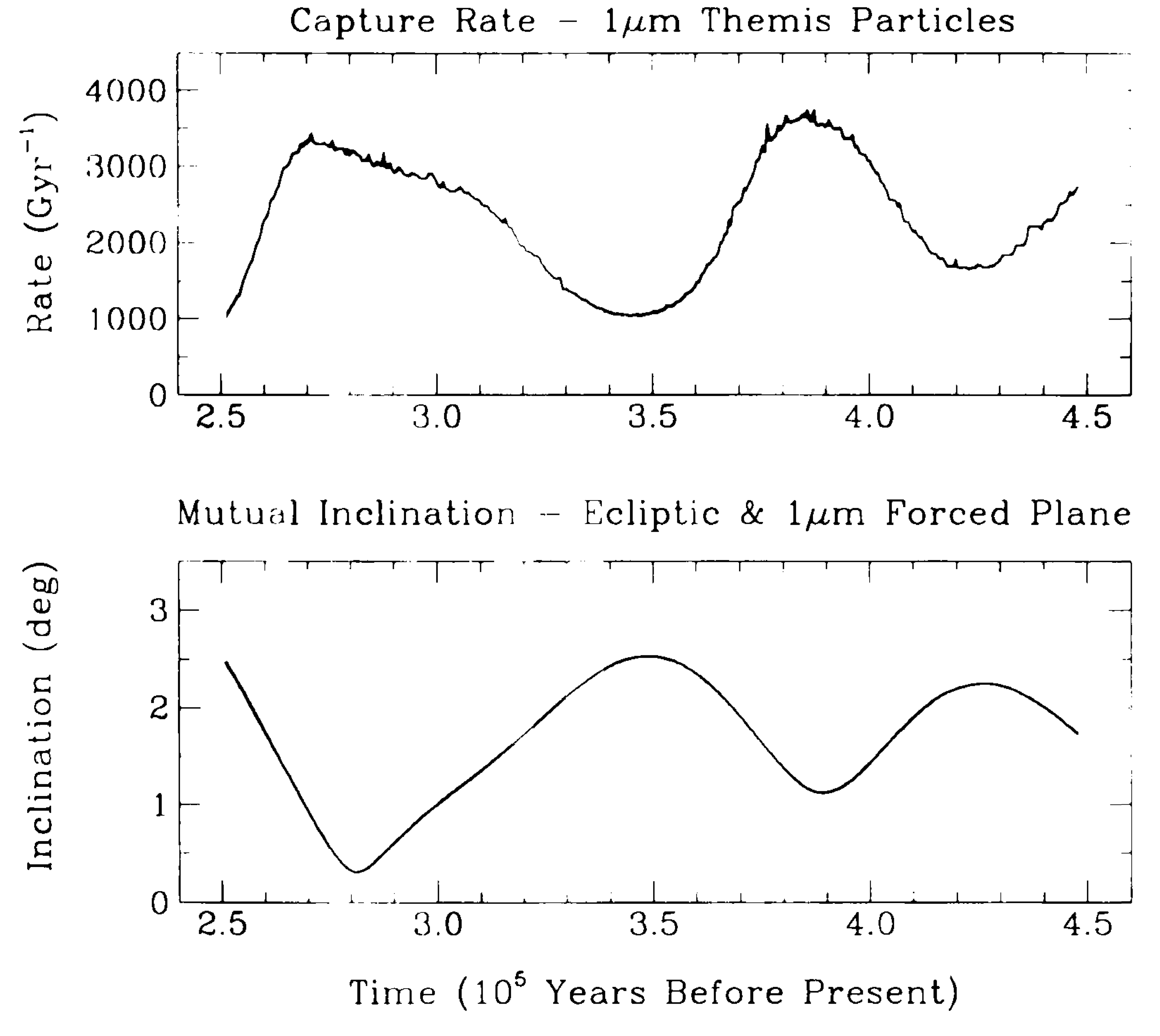

Figure 2: Variation of the capture rate (top) due to the changing mutual inclination (bottom) between the ecliptic at date and the forced plane of symmetry of 1 μm diameter Themis dust particles ($\rho = 2.5$ $g\ cm^{-3}$) reaching 1 AU at date.

3. Long-term Variations in Accretion of IDPs

The strong dependence of the capture probability on the mutual inclination between the Earth's orbit and the dust particle orbits suggests that there will be variations in the terrestrial accretion rate due to secular changes in the inclination of the Earth's orbit. For the period spanning 250 to 450 thousand years ago we have numerically simulated the evolution of waves of 1 μm diameter Themis dust particles from their source in the asteroid belt to $1AU$ The mutual inclination between the forced plane of symmetry of these waves and the ecliptic at date is plotted in Figure 2. The "Time" axis indicates the time in the past when the mean semi-major axis of the particles in each wave was equal to $1AU$ The amplitude and period of this long-term variation in the dust accretion rate is supported by measurements of extraterrestrial ^{3}He found in deep-sea sediments (Farley 1995).

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