The equatorial ridges of Pan & Atlas:

Terminal accretionary ornaments?

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ABSTRACT

In the outer regions of Saturn's main rings, strong tidal forces balance gravitational accretion processes. Thus, unusual phenomena may be expected there. The Cassini spacecraft has recently revealed the strange shape of two small satellites, Pan and Atlas, located in this region. Never–before-seen equatorial ridges give them a surprising "flying saucer" shape. The ballistic impact of ring particles onto the equatorial surfaces of already formed bodies embedded in the rings may explain the formation of the ridges. This ridge formation process is in good agreement with detailed Cassini imaging observations showing strong differences between rough polar and smooth equatorial terrains. The Pan and Atlas ridges are km-thick "ring-particle piles" formed after the satellites themselves and the ring's flattening but before the depletion of ring material from their surroundings.

In images collected by the Voyager spacecraft in the early 1980s, two small satellites were discovered orbiting inside Saturn's Roche zone[1,2]. Pan is located in the A ring's Encke Gap at 133,600 km from Saturn's center and Atlas orbits at 137,700 km from Saturn's center, just outside Saturn's A ring. The Cassini spacecraft has recently resolved them both, allowing precise measures of sizes and shapes (fig. 1). Their shapes are close to oblate ellipsoids. In particular, the moons are close to the size of the Hills sphere (also called the Roche lobe) of the moon[3], with equatorial radii of 16.5 and ~19.5 km, and polar radii of ~10.5 km and 9 km for Pan and Atlas, respectively[3]. More unexpectedly, both have a unique and unexplained feature: a prominent equatorial ridge. These ridges are roughly symmetric about the bodies' equators and give them the appearance of "flying saucers." Assuming that Pan and Atlas are synchronous rotators[4], consistent with Cassini images taken at several different times, Pan's ridge extends from -15° to +15° latitude (± ~5°) and apparently entirely encircles the satellite. Atlas' ridge extends from -30° to +30° latitude (± 10°) on the trailing side whereas on the leading side the ridge is much less prominent, with a modest depression on the leading side near the equator[3].

Recent work[5] has shown that a fast rotation may explain the diamond shape of the near earth asteroid 1999 KW4 because of the balance of the centrifugal and gravity forces at the asteroid's equator. To explain Pan and Atlas' shape with the same mechanism, their rotation periods should be respectively of 5h30 and 4h50. This is much shorter than their actual synchronous rotation periods of 14h and 14h30 respectively. In addition, tidal stress, which is an efficient mechanism to deform a body, especially so close to Saturn, would elongate a synchronously rotating body in the radial direction[6] rather than create an equatorial ridge. So neither centrifugal nor tidal forces seem adequate to explain the presence of these extended ridges.

A number of circumstances led us to investigate a different scenario for the creation of the ridges on Pan and Atlas: (1) Contrary to other resolved satellites, Pan and Atlas are embedded in Saturn's rings; (2) The ridges are equatorial and precisely in the same plane as Saturn's rings; (3) The vertical motion of Atlas (and perhaps Pan) through the rings is approximately equal to the vertical extent of the ridges[7]; (4) the total volume of the ridges is only approximately 10 to 25% of the bodies' volume[3]. Therefore, we have explored the possibility that the ridges are made of ring particles captured via ballistic transport onto the surface of a pre-existing body embedded in the rings. We start with a primordial body with an ellipsoidal shape initially free of any equatorial ridge – a "naked ellipsoid". In this scenario, a ridge would be simply an "equatorial-ornament" accumulated onto the body's surface as a later stage in the accretion process. This model is quantified and constrained by the following estimates and numerical simulations.

A simple calculation shows that the model is, to first order, in good agreement with observations. For a satellite with an orbital inclination i, semi-major axis a_s, and radius r, the latitudinal extension of the intersection of the ring-plane with the body's surface is $L=sin^{-1}(ia_s/r)$, assuming a vertical thickness h of the rings much smaller than the satellite radius, r, which is consistent with observations and models[8,9]. Ring-particles may collide between latitudes –L and +L on the satellite's surface. Using the Pan and Atlas' average radii[3] and their last published inclinations (0.001° and 0.003° respectively[7]), we get respectively L= ±12° and L= ±28°, in good agreement with observations. Atlas'inclination is likely resulting from Prometheus gravitational perturbations[4,7]. An unpublished estimate (R. Jacobson, private communication) suggests a 3 times smaller inclination, thus decreasing L in the same proportions. If this is true, this suggests a ridge formation scenario where Pan was initially on a more inclined orbit, typical of several other small Saturn's moons[7], and a damping of Pan's inclination by a dissipative mechanism like collisions or tidal friction.

To simulate the fall of ring particles onto the surface of Pan and Atlas, a numerical dynamical computer code[10] is used in which the orbits of Pan, Atlas and 10^4 massless test particles are integrated, accounting for Saturn's J2 and J4 gravitational moments[11]. The Pan and Atlas precursors have shapes similar to their actual ones but with equatorial radii smaller by ~10% to account for the initial absence of the ridges. Synchronous rotation is assumed. The test particles are initially gathered into a thin ring with vertical thickness h=250 m so that $h/r \ll 1$ at the beginning of the simulation. Locations of impacts at the surface of the satellites are detected and located in the satellite's east-longitude and latitude system (fig.2). Our simulations show that the large majority of impacts happen in a shorter time (~ 1.5×10^4 orbits) than the gravitational stirring time (about 4×10^4 orbits). It is why we have not taken into account collisions between ring particles. Indeed, collisional stirring between particles on nearly circular and coplanar orbits can only scatter them on distances of the order of their size, which is negligable compared to the satellite radius.

As expected, simulations show that impacts are concentrated near the equator (fig. 2), with typical latitudinal ranges ±10° for Pan and ±30° for Atlas, in excellent agreement with the observations (fig. 1a and 1b) and the above analytical estimate. Note that impacts on Atlas' surface near its leading (270° longitude) and trailing points (90° longitude) show a wider spread in latitude, approaching ±50°: this is a consequence of Atlas' much flatter shape compared to Pan. Surprisingly ring-particles' distribution of impacts appears to be strongly segregated: particles with initial semi-major axes inward of their respective satellite ("inner particles") and those outward of the satellite ("outer particles") impact on different hemispheres (crosses and open diamonds in fig. 2). For Pan, inner particles impact on the hemisphere facing Saturn and outer particles impact the hemisphere opposite to Saturn. For Atlas, the distributions are shifted by 90° compared to Pan: inner particles collide on the leading-hemisphere and outer particles collide on the trailing-hemisphere.

These different distributions are likely the consequences of the satellites' different eccentricities ($3.5x10^{-5}$ and $1.2x10^{-3}$ for Pan and Atlas respectively[7]). An orbital eccentricity e implies a radial excursion $\Delta r = \pm a_s e$. For Pan, $\Delta r = \pm 5$ km, which is much smaller than the Pans' Hills radius of 19.5 km. (The Hills sphere or Roche lobe is the size of the satellite's gravitational cross-section.) Conversely, the Atlas' radial excursion is ±165 km, which is much larger that its Hill radius of 23 km. Thus, different accretion processes must be considered for the two satellites, i.e. a low velocity scenario for Pan and a high velocity one for Atlas.

In order to reach Pan's surface, classical celestial mechanics[6] tells us that low-relative-velocity ring particles must pass through the L1 or L2 Lagrange points, which behave as gates for the Hills sphere. Inner particles must flow through the L1 point facing the sub-Saturn point, and outer particles flow through the L2 Lagrange point, facing the anti-Saturn point[6]. Once a particle penetrates Pan's Hills sphere, its trajectory has no space in which to randomize because the satellite almost fills all the space inside the Hills sphere[3]. As a result, the particle impacts Pan's surface almost immediately after passing the Lagrange point. This explains the segregation between the two hemispheres seen in the model results (top of fig.3), and also explains the observation that its equatorial ridge encircles both hemispheres: Pan accretes material coming from both sides of its orbit.

Atlas, on the other hand, has a large eccentricity. Thus, in the local rotating frame, Atlas makes a clockwise elliptical epicycle with a 2:1 ratio[6] with its radial excursion Δr extending much beyond its Roche lobe. In the inner portion of the epicycle in which $r_s<a_s$, (where r_s is the instantaneous satellite's distance to Saturn), Atlas orbits at a higher velocity than the local Keplerian velocity, so inner particles are accreted onto Atlas' leading hemisphere. Conversely, on the outer portion of its epicycle ($r_s>a_s$), Atlas orbits at a lower velocity than the local Keplerian velocity, so outer particles are accreted on the trailing hemisphere only. Due to high encounter velocities, incoming ring particles can cross Atlas' Roche lobe at any location and are not compelled to pass through the L1 and L2 points (bottom of fig.3). This peculiar local dynamics may explain the differences observed between the trailing and leading sides of Atlas [3]: Atlas may have accreted material coming preferentially from outside its orbit rather than from inside, which may result in a less prominent bulge on the leading hemisphere[3].

Therefore Pan and Atlas may have formed in two steps: an early stage in which a primordial body formed with roughly the current ellipsoidal shape but without an equatorial ridge, and a secondary stage in which the equatorial ridge accreted from material coming from the rings. As a consequence, visible differences between polar and equatorial terrains may be expected. This prediction has been confirmed by a June 13th 2007 high-resolution Cassini image[3] of Atlas' southern hemisphere (fig.1c). It clearly shows two different types of terrains: high-latitude regions (>40° south latitude) with a rough surface texture at spatial scales of a kilometer, and equatorial regions (<30° south latitude) with a very smooth surface and no visible structure down to pixel resolution (320 m). A smooth surface is compatible with an accumulation of ring–particles since the particle size distribution of Saturn's rings is known to be dominated by centimeter to meter sized particles[12], much below the Cassini's cameras resolution.

In order to have ridges confined to the equator, the incoming material must remain on very low inclination orbits ($<2\times10^{-3}$°) in spite of the efficient satellite's gravitational stirring[13]. So for the ring material to approach the satellites while remaining on low-inclination orbits it requires either (i) a rapid accretion of the ridges or (ii) the presence of a dissipative environment in order to damp inclinations of incoming particles. In addition, considerations of the minimum satellite mass for gap opening[3] show that Pan, and maybe Atlas, may have opened a gap before reaching their present size. So ridge accretion may have happened after the start of the gap opening and before the emptying of the satellites' surroundings. This suggests that a transition phase could have existed, like for giant-planet formation in the protoplanetary disk: while a gap is already opened, the young satellite could be fed by an accretion disk flowing from the gap's edges through its Lagrange points. In such an accretion disk, inclinations are damped by collisions in agreement with the second condition. If needed, dissipative collisions would also provide an efficient mechanism to lower Pan's inclination. Conversely, Atlas' inclination, being gravitationally forced by Prometheus[7], remains non zero

Voyager[2] and Cassini images[14] show the presence of tenuous ring material in the Pan and Atlas regions, and we examine whether or not it this material could be accumulated onto the ridges. Our simulations show (fig. SOM1) on the one hand that the material in the ringlet close to Pan is prevented from reaching Pan's surface because it is on horseshoe orbits while Pan is on a nearly circular orbit. On the other hand, due to Atlas' substantial inclination, the surrounding material is vertically stirred rapidly (fig. SOM2) and is prevented from accumulating specifically at Atlas's equator. So a recent accretion of ridges from the tenuous ring material in the Encke gap surrounding Pan or from the material near Atlas is unlikely

These results, together with other evidence collected by Cassini[3] suggest a relative chronology for the formation of Saturn's rings and the ridges of Pan and Atlas. The process by which Saturn's rings formed is still open to discussion and it is not known if the rings are made of primitive material initially located within Saturn's Roche zone at the time of Saturn's formation, or if they resulted from a primordial catastrophic fragmentation[14,15] or if both mechanisms have been at work. However, if a catastrophic breakup of a larger body happened, the cores of Pan and Atlas would have been among the largest fragments, orbiting initially on inclined and eccentric orbit. Then, a two step process may have occurred: before the flattening of the rings, these shards accreted a shell of debris coming from the surrounding disk giving them their low density and overall Roche lobe size[3]. Once the debris disk flattened into a thin ring system due to dissipative collisions, ring material accreted at the satellites' equator as outlined herein, forming today's ridges as observed by Cassini.

A different -but less probable- scenario would have Pan and Atlas dynamically captured inside a ring system already formed. Then, they would have cleared a gap on their orbit, accumulating material onto their equator forming their spectacular ridges. The sizes of Pan and Atlas, minus their ridges[3], do fit with a ring particle size distribution[14], which perhaps makes this sequence unnecessary, but we find no definitive barrier to capture, since small bodies about the size of Pan and Atlas are abundant in the outer solar System.

In conclusion, the different shapes of the equatorial ridges of Pan and Atlas are matched by dynamical expectations given their different orbits within the ring system, and images show strong evidence that Atlas is a two-component object. Along with other findings[3], these objects appear to have acquired their shapes in several phases, so that today's ridges are possibly kilometer thick piles of ring particles lying over a pre-existing body.

These ridges may be also of interest for planetary formation: they could be considered as "fossilized" accretion disks that once may have surrounded Pan and Atlas, like small-scale versions of the planetary sub-nebulas that once surrounded the giant planets. Such fossilized disks may result from two extremes characteristics of small satellites in planetary rings compared to planets in proto-planetary disks: (i) in rings, the ratio of the disk's thickness to the satellite's size is much smaller than unity so that material flows towards the satellite's equator (ii) in rings, it has been found that these satellites completely fill their Hills spheres[3] so that the trapped material is squeezed at the body's surface and accumulates immediately.

Thus, the outer region of Saturn's rings may be considered as a small-scale and in-situ laboratory in which to investigate fundamental planetary accretion processes. This study illustrates also that rings and small moons cannot be studied separately: they are part of a unique "ecosystem".

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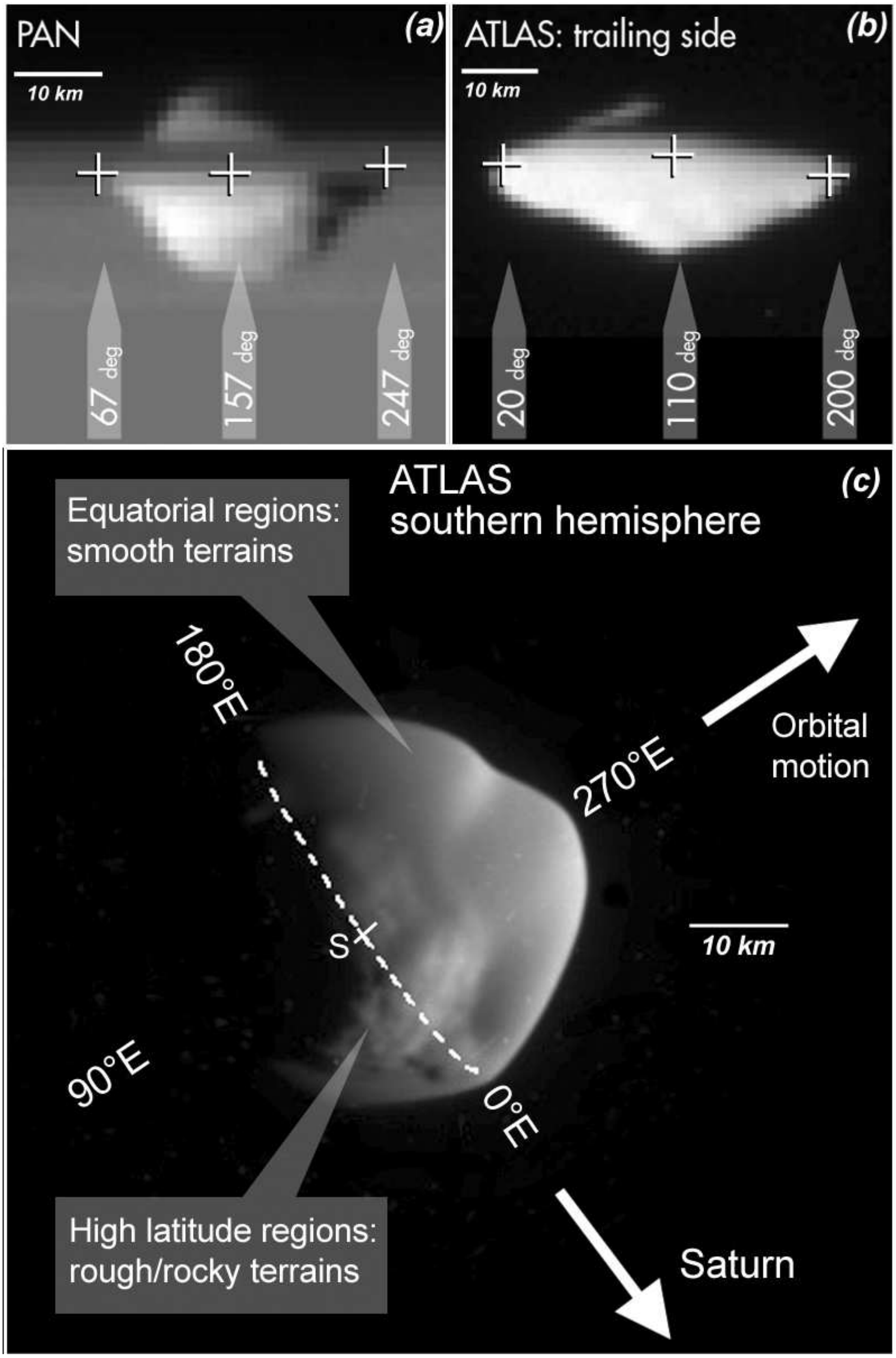

Figure 1: Cassini Narrow Angle Camera (NAC) images. (a): Pan embedded in the Encke gap at resolution of 1.3 km/pixel, crosses are located on the body's equator with their corresponding longitude. (b): Atlas's trailing side with resolution 1.05 km/pixel. (c): High resolution image of Atlas obtained on June 13th 2007 with 320m/pixel resolution : the South Pole is designated by an "S", the dashed-line is the frontier between the leading and trailing sides. Polar regions clearly show a rough and maybe rocky texture, while intermediate latitude and equatorial regions are very smooth, with no bedrock, sustaining the model of ring-particles accreted at the satellite's equator in a two steps process (see text). We use an east-longitude system, in which longitudes 0°, 90°, 180°, 270° correspond to the sub-Saturn points, trailing points, anti-Saturn points, leading points at the satellite's surface respectively. White spot are cosmic-rays.

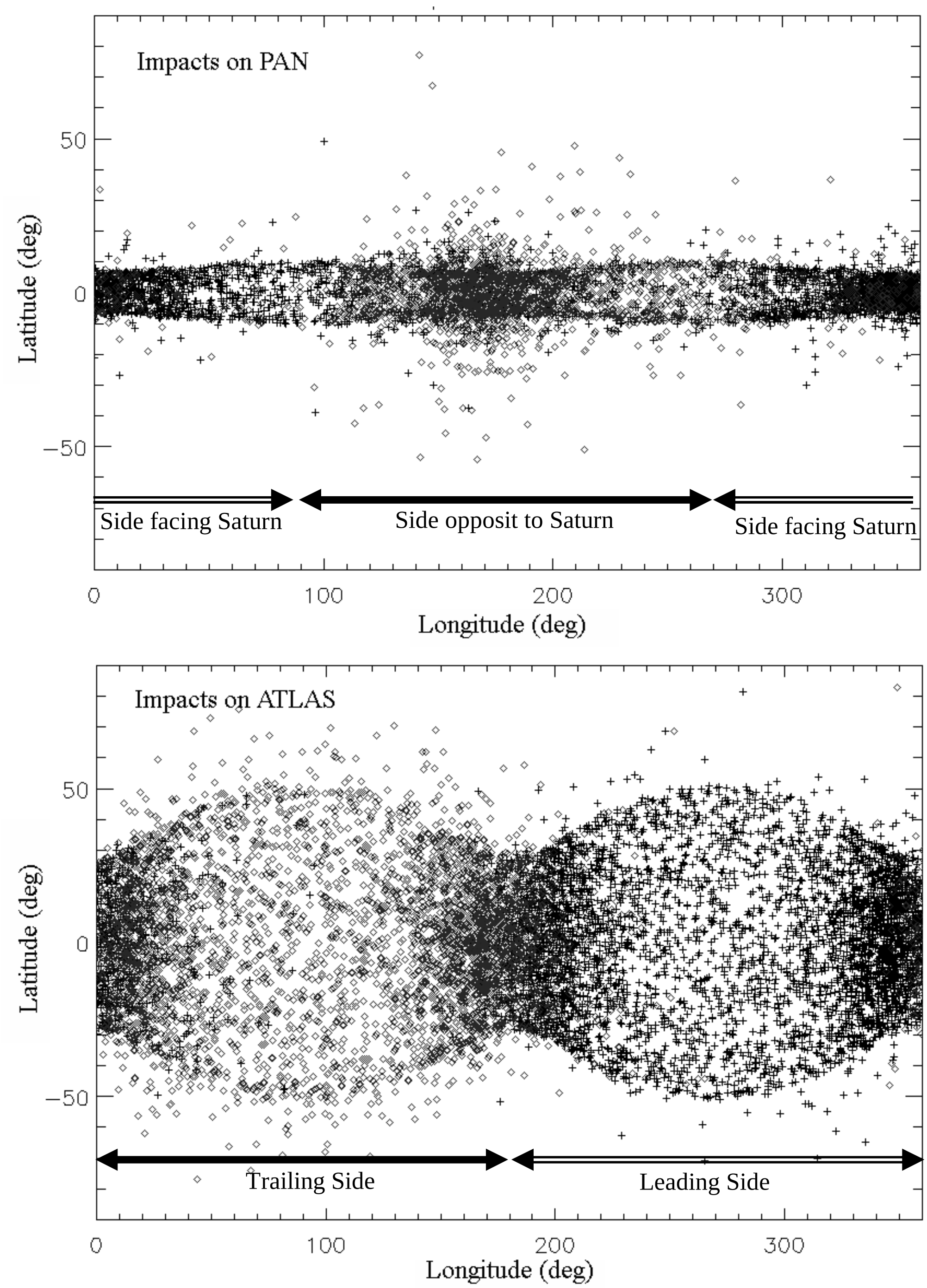

Figure 2: Impacts locations at the surface of Pan (top) and Atlas (bottom), as simulated by our numerical model. Each point shows one impact between a ring particle and the satellite. Open diamonds are for ring particles initially exterior to the satellite's orbit, and black crosses are for particles initially interior to the satellite's orbit. We use an east-longitude system. The simulation for Pan generates a narrow ridge encircling the body, as seen in the observations. The simulation for Atlas generates the wider ridge observed on that body (see fig. 1).

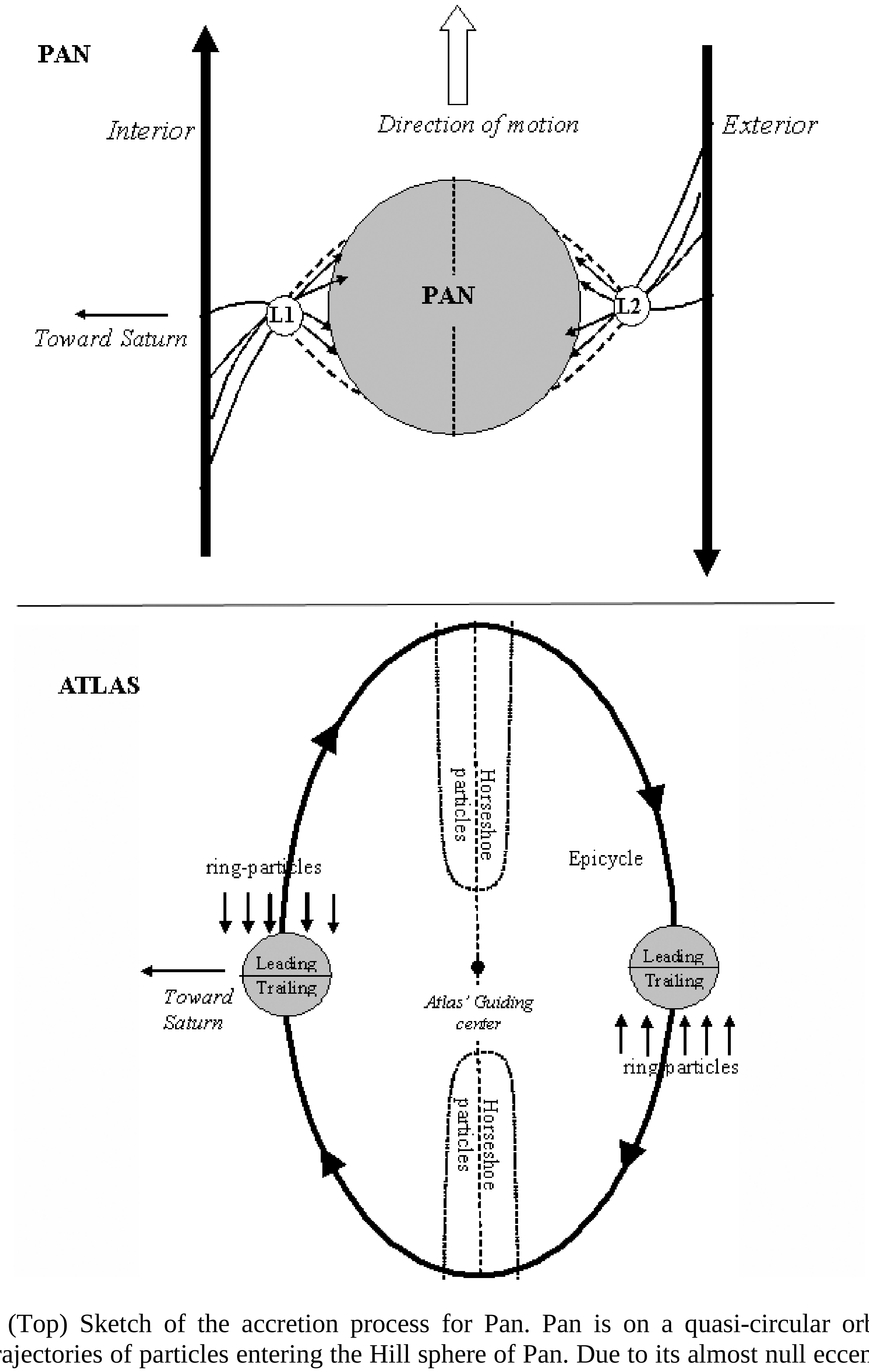

Figure 3: (Top) Sketch of the accretion process for Pan. Pan is on a quasi-circular orbit. Arrows indicate trajectories of particles entering the Hill sphere of Pan. Due to its almost null eccentricity, Pan is fixed, and as a consequence particles coming from in interior of the orbit (left portion) enter through the L1 Lagrange point and impact around the sub-Saturn point, while particles coming from outside's the satellite's orbit (right portion) enter through the L2 point and impact near the anti-Saturn point. (Bottom) Sketch of the accretion process for Atlas. Atlas is on an eccentric orbit and describes an elliptical epicycle around its guiding center, much larger than Atlas' physical size (r~20km). On the inner part of the epicycle (left), the satellite accretes material onto its leading side, while on the outer part (right), the satellite accretes material on its trailing side.

SUPPLEMENTARY ONLINE MATERIAL

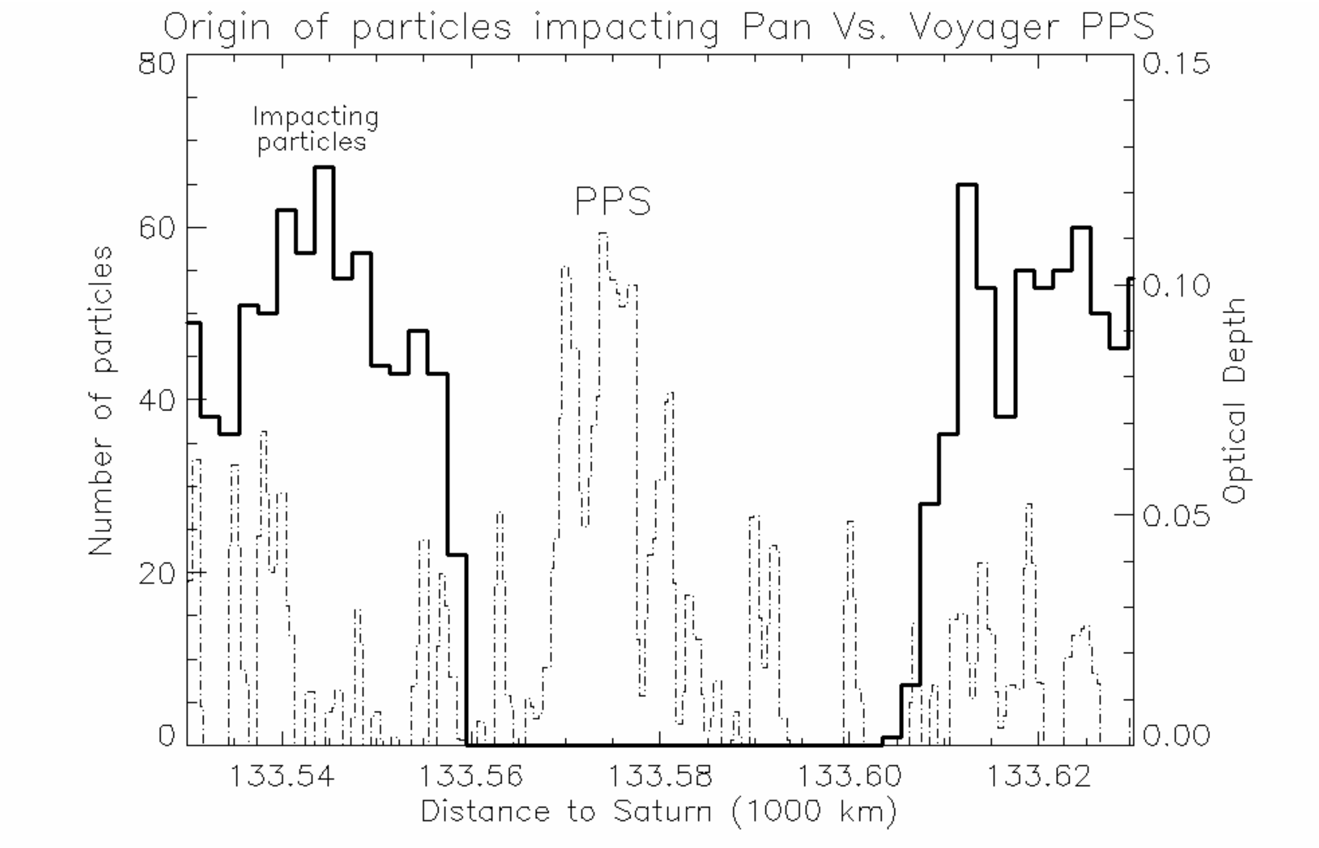

Figure SOM.1: Bold line: histogram of the initial location of particles impacting Pan in numerical simulations (left scale). In dashed-dotted line: local optical depth from Voyager data[2] (right scale). Pan is located at 133584 km[7]. Higher optical depth regions correspond to ringlets observed in the Encke division. Comparison of both graph shows that material from the central ringlet is in a region where no accretion on Pan's surface happen: indeed this material seem trapped on tadpole and horseshoe orbits while the satellite is on an almost circular orbit.

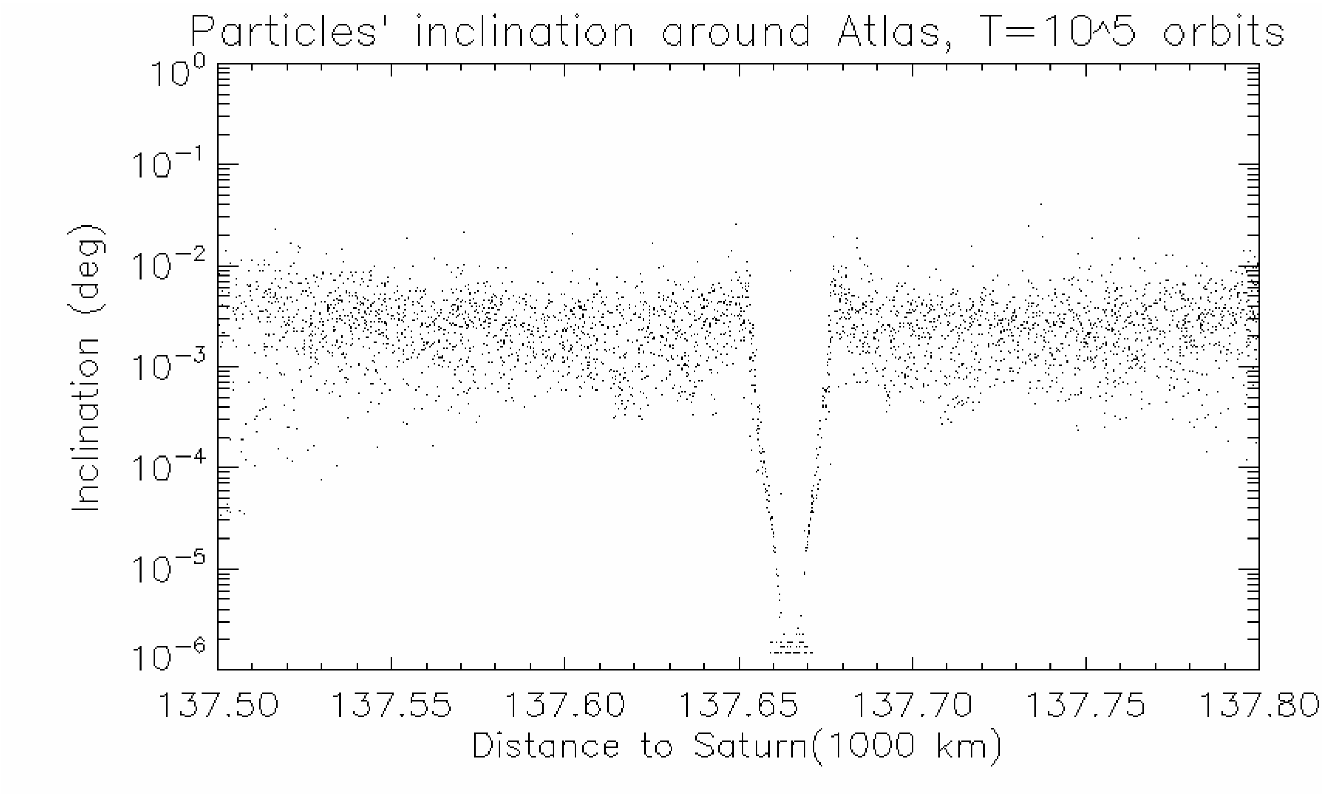

Fig. SOM2 : Particles' inclinations around Atlas after 10^5 orbits. Atlas is located at 137,665km[7]. To reach the Atlas' ridge, a particle must be on an inclination smaller than 0.002°. Initial inclinations are bout 10^{-6} °.