# EXPOSURE OF THE CASSINI SPACECRAFT TO HORSESHOE AND TADPOLE HAZARD ZONES

*A.A. Wolf* and D. Seal**

Regions of stability along the orbital paths of Saturn's satellites have been shown to exist, These regions have been called "horseshoes" and "tadpoles" due to their characteristic shapes. Particles in these regions can be trapped by the gravitational interactions of Saturn and the satellites. Although it is not known to what extent particles may have accumulated in these regions, the presence of trapped particles might be a hazard to the Cassini spacecraft during the satellite tour. The regions associated with the inner icy satellites (Mimas, Enceladus, Tethys, Dione, and Rhea) are of particular concern because they are within Saturn's E ring. This work quantifies the spacecraft's exposure to these regions. Our principal objectives are to determine the amount of time the spacecraft is exposed to horseshoe and tadpole regions during several sample tours, to find methods of reducing exposure time and consider effects these methods might have on science return or operational considerations, and to estimate how much time can be spent in various regions without incurring unacceptable risk.

The existence of these regions is derived from analysis of the restricted 3-body problem. For each individual Saturnian satellite, we consider a system of three bodies: a major body (Saturn), a minor body (the satellite, assumed to move about Saturn in a near circular orbit) and a nearly massless object (debris, spacecraft, etc.) whose gravity does <u>not</u> affect the motions of the two major players.

The major and minor bodies move about the system's barycenter. The massless body must lie outside boundaries called "zero-velocity contours", which depend on the value of the constant of integration C in the Jacobi integral. Figure 1 shows zero-velocity contours for the Sun-Jupiter system, which assume characteristic "horseshoe" and "tadpole" shapes in the region near Jupiter's orbit (but away from Jupiter itself). With decreasing C, the tadpoles shrink until local minima are reached at the L4 and L5 Lagrangian points. Zero-velocity contours are explained in greater detail in References 1, 2, and 3.

A particle placed at L4 or L5 with zero velocity (in the rotating frame) stays there, because no resultant force acts on it. A small displacement (or the addition of a small velocity) causes the particle to librate in the vicinity of the point. If $m_1 > 25 m_2$ (as is the case for Saturn and all its satellites), this libration is stable (i.e., the particle will not depart the vicinity of the L4 or L5 point). The particle's path closely corresponds to the shape of its associated zero-velocity curve (Reference 3, 4). A "clear zone" exists in the vicinity of the satellite at the open end of the horseshoe which is continuously cleared of possible Saturnian system debris by "chaotic" particle motion.

Nature displays examples of captured objects in such regions, the most famous being the "Trojan Satellites" of Jupiter which orbit in the vicinity of the L4 and L5 points of the Jupiter/Sun system. Figure 2 graphically depicts this tadpole capture phenomenon, plotted by Dr. D. Bender (Ref. 5). There are at present 184 Trojan asteroids known. Three examples of L4 /L5-type debris were discovered in the Saturnian system during the Voyager I flyby (Ref. 6): one each at the L4 and L5 points of Tethys, and one at the L4 point of Dione.

---

*Member of Technical Staff, Jet Propulsion Laboratory, California Institute of Technology

Fig. 1: Zero-velocity contours in the Sun-Jupiter system

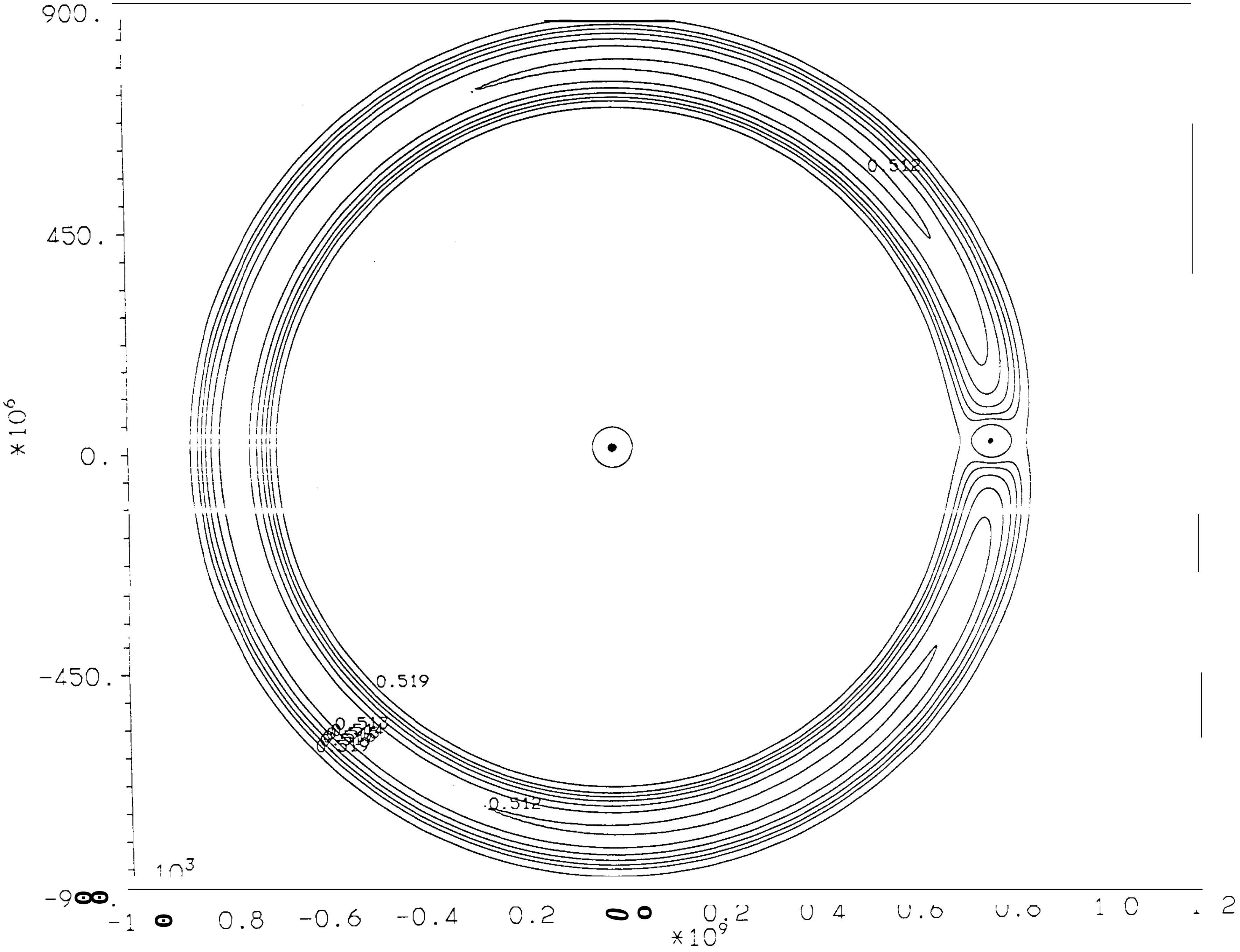
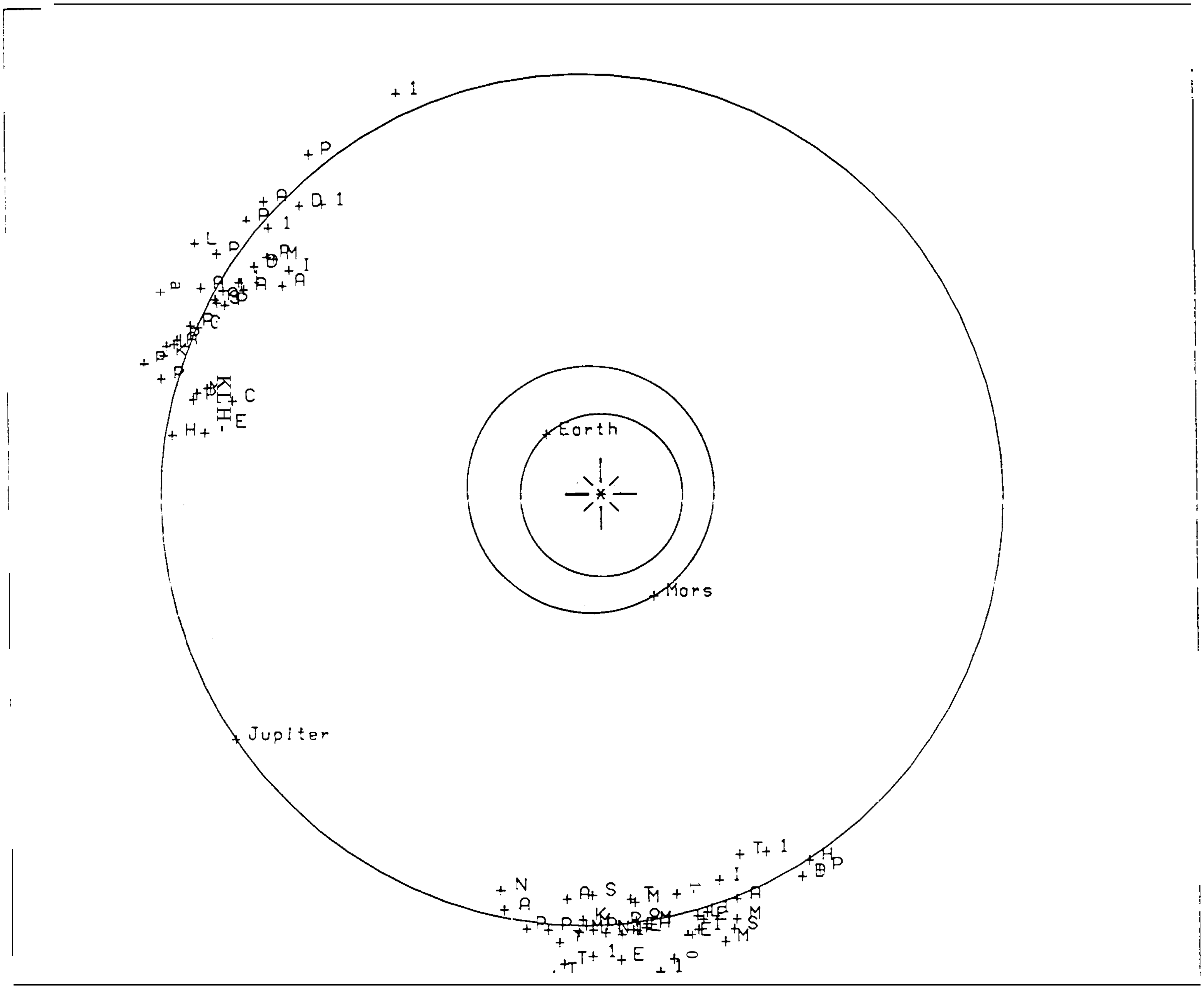


Fig. 2: The orbit of Jupiter + 80 Trojans (epoch: February 1, 1994)



We employed the STOUR computer program (used in the initial stages of tour design at JPL) to evaluate six sample tours for exposure 10 horseshoe! and tadpole regions. These tours illustrate several strategies which are under discussion for incorporation into the final Cassini tour trajectory. A summary Of horseshoe and tadpole exposure times obtained from STOUR (shown in hours) for each of the six sample tours by satellite is shown in Table 1. Mimas' zones are not penetrated at all. Enceladus' horseshoe is penetrated only in tour 1, for 18 minutes; its tadpole is not penetrated at all. This is because the periapse of the spacecraft's orbit rarely dips below the orbits of either of these two satellites.

## Table 1: Horseshoe and tadpole crossing durations (in hours) by satellite

***HORSESHOES***

| | Mimas | Enceladus | Tethys | Dione | Rhea | TOTAL ICY SATS | Titan | TOTAL ALL SATS |
|---|---|---|---|---|---|---|---|---|
| Tour 1 | 0.00 | 0.29 | 8.43 | 6.71 | 13.23 | 28.67 | 204.11 | 232.79 |
| Tour 2 | 0.00 | 0.00 | 0.44 | 4.50 | 6.96 | 11.90 | 76.79 | 88.69 |
| Tour 3 | 0.00 | 0.00 | 0.44 | 3.90 | 6.31 | 10.65 | 195.03 | 205.68 |
| Tour 4 | 0.00 | 0.00 | 0.00 | 5.68 | 9.98 | 15.67 | 109.94 | 125.61 |
| Tour 5 | 0.00 | 0.00 | 5.17 | 3.74 | 11.59 | 20.50 | 170.37 | 190.87 |
| Tour 6 | 0.00 | 0.00 | 1.82 | 1.77 | 3.61 | 7.20 | 218.72 | 225.92 |

***TADPOLES***

| | Mimas | Enceladus | Tethys | Dione | Rhea | TOTAL ICY SATS | Titan | TOTAL ALL SATS |
|---|---|---|---|---|---|---|---|---|
| Tour 1 | 0.00 | 0.00 | 0.08 | 0.19 | 1.07 | 1.35 | 40.17 | 41.52 |
| Tour 2 | 0.00 | 0.00 | 0.04 | 0.03 | 0.22 | 0.30 | 6.71 | 7.01 |
| Tour 3 | 0.00 | 0.00 | 0.04 | 0.00 | 0.19 | 0.23 | 25.28 | 25.51 |
| Tour 4 | 0.00 | 0.00 | 0.00 | 0.04 | 0.32 | 0.36 | 14.27 | 14.63 |
| Tour 5 | 0.00 | 0.00 | 0.17 | 0.09 | 0.34 | 0.59 | 17.40 | 17.99 |
| Tour 6 | 0.00 | 0.00 | 0.04 | 0.00 | 0.00 | 0.04 | 45.01 | 45.05 |

The spacecraft spends roughly an order of magnitude more time in Titan's hazard zones' than in those of the inner icy satellites. The ultimate reason for this is that the great majority of satellite flybys in any Cassini tour are Titan flybys, because Titan is the only Saturnian satellite massive enough to provide the gravitational assist needed to control the spacecraft's orbit. Because the spacecraft is always either coming from or going to a Titan flyby (or both), one of the two nodal crossings on every orbit must occur at the orbital radius of Titan. Crossings of Titan's orbit occur on every revolution, whether or not Titan is nearby at the time. In what may seem a paradox, crossings of Titan's hazard zones occur on revolutions which do *not* contain Titan flybys. On revolutions containing Titan flybys, the spacecraft passes close enough to Titan to be in the clear zone, and no hazard zone passage occurs. Although Titan is outside the E-ring (our main area of concern), further analysis or efforts at observation should be undertaken to ascertain the presence or absence of particles in Titan's zones due to the large amount of time spent in them.

Exposure to the hazard zones of the inner icy satellites is greatest at low inclinations and rarely occurs at inclinations above a few degrees. This is because the radii of the hazard zones are small. An inclination of a few degrees displaces the spacecraft vertically out of the zones unless one of the two nodal crossings (the points where the spacecraft crosses the equatorial plane) occurs at the orbital distance of one of the satellites. The hazard zones are located near the satellites' orbit planes, which are close to Saturn's equator. If a nodal crossing does occur at the orbital distance of one of the satellites, a horseshoe passage occurs regardless of inclination unless the spacecraft is close enough to the satellite to be in its clear zone.

Given that one node always occurs at Titan's orbit, it is possible to calculate the spacecraft's distance from Saturn at the other node for any combination of period and periapse radius. We can use this information to avoid combinations of period and periapse which place a node at the orbital radius of one of the inner icy satellites, which allows us to use inclination to stay out of these zones entirely.

Crossings of the hazard zones of Titan, unlike those of the inner satellites, occur at high as well as low inclinations. This is because one of the two nodal crossings on every orbit must occur at the orbital radius of Titan (regardless of inclination), for reasons previously discussed.

If the transfer angle is other than 180 or 360 deg., any ballistic (zero ΔV) trajectory between the two Titan flybys must have a near-equatorial inclination. However, higher inclinations are available between such flybys with the addition of a maneuver. For example, let us assume we know of a particular ballistic, near-equatorial transfer orbit departing Titan at time t1 and arriving at t2, with period P, whose transfer angle is not nearly 180 or 360 deg. Let's say we want to depart at t1 and arrive at t2 with a higher inclination than the ballistic trajectory allows. We can depart Titan at t1 on an orbit with period P but at the higher inclination. We can then use a maneuver near apoapse to change the orbital plane, targeting to Titan for an arrival at t2. Maneuvers like these are often referred to as "broken plane" maneuvers. In practice, we might allow the departure and/or arrival times to change slightly in order to minimize AV. A maneuver of -40-50 m/s is needed to avoid the inner icy satellites' horseshoes (or -10 m/s to avoid tadpoles only) on each leg containing a periapse passage.

It is not always possible to avoid Titan's horseshoes. Crossings which occur at low inclinations can be avoided using broken-plane maneuvers of about 60 m/s each. (Titan's horseshoe is wider than those of the icy satellites, hence the larger AV. ) However, it is possible to avoid some crossings of Titan's tadpoles. Resonance of the spacecraft's orbital period with that of Titan gives rise to a regularity in the occurrence of Titan tadpole crossings. If we refrain from using certain resonances, we can avoid crossing Titan's orbit in the tadpole regions.

Estimates are provided of the AV cost of adding broken-plane maneuvers to avoid the inner icy satellites' hazard zones for the entire tour, and for portions of the tour. These can be examined in light of rough estimates of the risk to the orbiter from damaging or degrading particle impact during various portions of the mission, which we also provide. Risk estimates are made using models of particulate mass distribution adopted from N. Divine's extensive work at JPL (References 7 and 8). These models are based primarily on imaging data from Earth at Saturn's ring plane crossings in 1980 and data from the Voyager 1 and 2 flybys in 1980 and 1981. Several distributions are considered, from "nominal" conditions to more conservative worst-case estimates, where macroscopic particles dominate the population of particulate matter. These models are used in conjunction with the STOUR data on zone crossing times and durations to compute fluences of various particle sizes for the Cassini spacecraft. Of primary interest are the larger particles of 10-3 to 10-2 grams or more which can pierce critical spacecraft surfaces such as propellant tanks and the electronic bus. Less massive particles are of interest in surface degradation and measurement by science instruments.

## REFERENCES

1. Roy, A. E., *Orbital **Motion.*** 1978, Halstead Press, New York.

2. Szebehely, v., *Theory* of Orbits - *The Restricted Problem of Three Bodies.* 1967, Academic Press, New York.

3. Dermott, S.F. , and Murray, C. D., The Dynamics of Tadpole and Horseshoe Orbits (2 parts). *Icarus* **48, 1-11 and 12-22, 1981**

4. Zhao, Z-Y., and Liu, L., The Stable Regions of the Triangular Libration Points of the Planets. *Icarus* 100, 136-142, 1992

**5.** Bender, D.F., "Relative Motion Among the Trojan Asteroids", Paper #DPS 31. 13-P, presented at the DPS conference, Washington, D. C., Ott/Nov, 1994

6. Seidelmann, P. K., Barrington, R. S., and Szebehely, V., Dynamics of Saturn's E Ring. *Icarus* 58, 169-177, 1984

**7.** Divine, N., "Risk Analysis for Saturn Ring Particles Impacting the Cassini Orbiter, " JPL IOM 5217-89-153, October 2, 1989

8. Divine, N., "Particle Distributions in the Orbits of Five Saturn Satellites, " JPL IOM 5217-90-129, October 9, 1990