GRAVITY FIELDS AND INTERIORS OF THE SATURNIAN SATELLITES

THIRD ANNUAL MEETING OF THE ASIA-OCEANIA GEOSCIENCES SOCIETY
SINGAPORE, JULY 10-14, 2006

N.J. Rappaport[1], J.W. Armstrong[1], S.W. Asmar[1], L. Iess[2], P. Tortora[3], L. Somenzi[2], F. Zingoni[2]

Presented by Sami Asmar

1. Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California, USA
2. Universita’ La Sapienza, Rome, Italy
3. Universita’ di Bologna, Forly, Italy

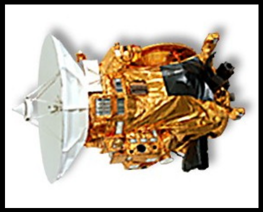
CASSINI RADIO SCIENCE TEAM
GRAVITY SCIENCE OBJECTIVES

- Mass and density of icy satellites
- Quadrupole field of Titan and Rhea
- Dynamic Love number of Titan
- Moment of inertia of Titan (in collaboration with the Radar Team)
- Gravity field of Saturn

Proposed measurements for the extended tour:

- Quadrupole field of Enceladus
- More accurate measurement of Titan k_2
- Local gravity/topography correlations for Iapetus
- Verification/disproof of “Pioneer anomaly”

MEASUREMENT METHOD AND DATA SET



Gravity field parameters determined by means of Doppler measurements over multiple segments across flyby. Several arcs can be used.

Velocity change across flyby: $\Delta v \approx \frac{GM}{b^2}\frac{b}{v}$

Measurement accuracy at 1000 s :

$\Delta f/f = 3\ 10^{-12}$ (solar conjunctions)
$\Delta f/f = 3\ 10^{-14}$ (solar oppositions, 4.5 μm/s)

The 34m beam waveguide tracking station DSS 25, NASA's Deep Space Network, Goldstone, California

The Advanced Media Calibration System for tropospheric dry and wet path delay corrections.

DYNAMICAL MODEL

- Gravitational accelerations from all the bodies of the Saturnian system.
- Non-gravitational accelerations:
  - RTG (fixed in S/C frame, mostly radial, 5×10^{-12} km/s^{2}.
  - Solar radiation pressure (included but very small).
  - Short arc technique in which the arc contains no maneuvers.
- Solve-for parameters:
  - The initial states of the satellite and Cassini
  - The satellite's GM
  - The satellite's J_2 and C_{22} if data were acquired at closest approach

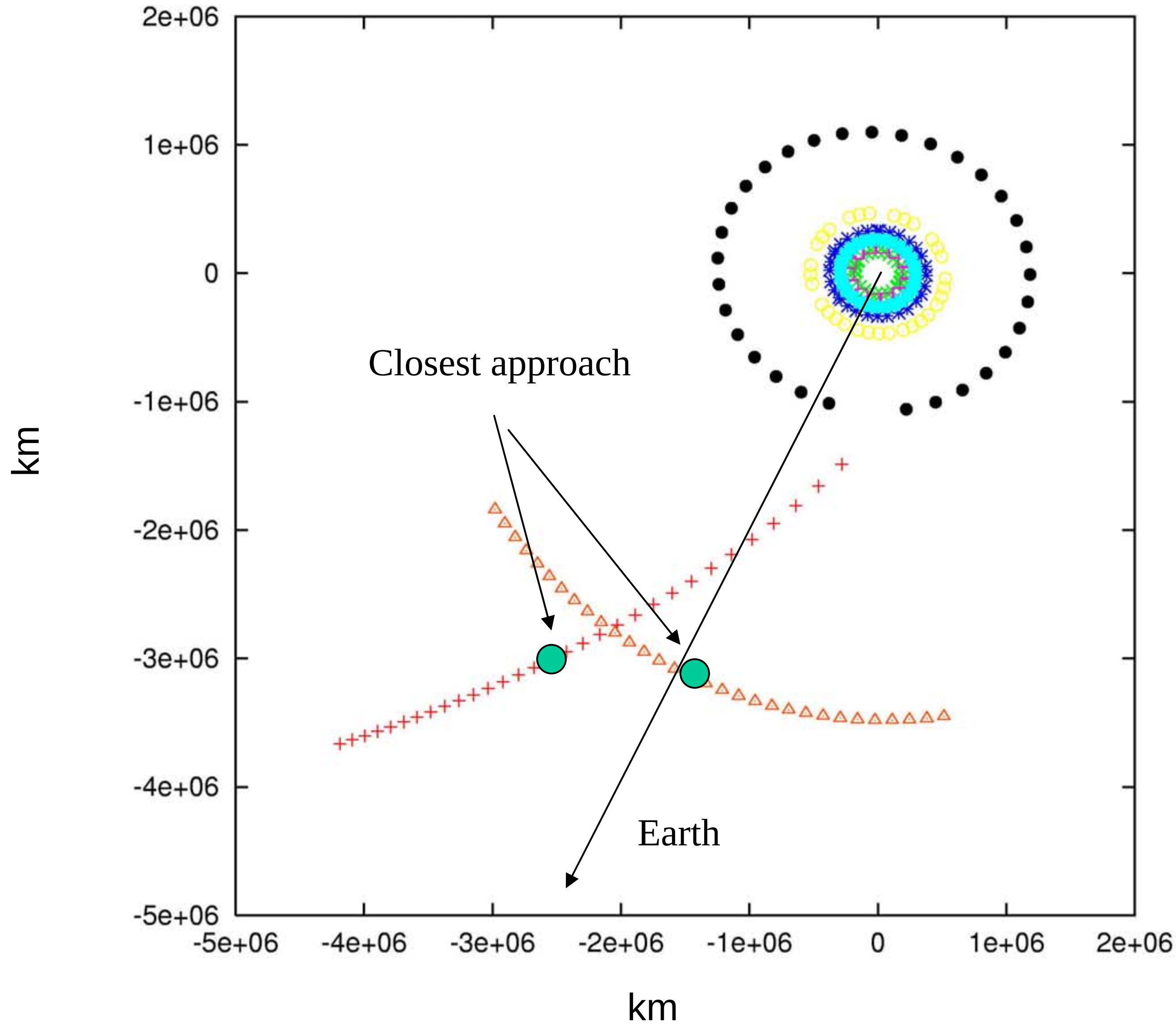
RESULTS FOR PHOEBE

- Flyby occurred on June 14, 2004.
- Altitude was 2000 km.
- Optical navigation data were used to improve our knowledge of the spacecraft orbit with respect to Phoebe.
- GM = 0.5517 +/- 0.0007 km^3/s^2
- With a mean radius of 107.3 km, this mass implies a density of 1.59 g/cm^3.
- This corresponds to a silicate mass fraction of 0.58 to 0.63.
- Phoebe is most probably a captured satellite, maybe a Kuiper Belt object.

IAPETUS MASS DETERMINATION

- There were two Iapetus flybys: The first one on October 17, 2004.
  - The distance was 1.1 million km.
  - The SEP angle was 87°.
  - The relative velocity was 3.7 km/s.
- The second flyby was on December 31, 2004.
  - The distance was 12300 km.
  - The SEP angle was 165°
  - The relative velocity was 2.0 km/s

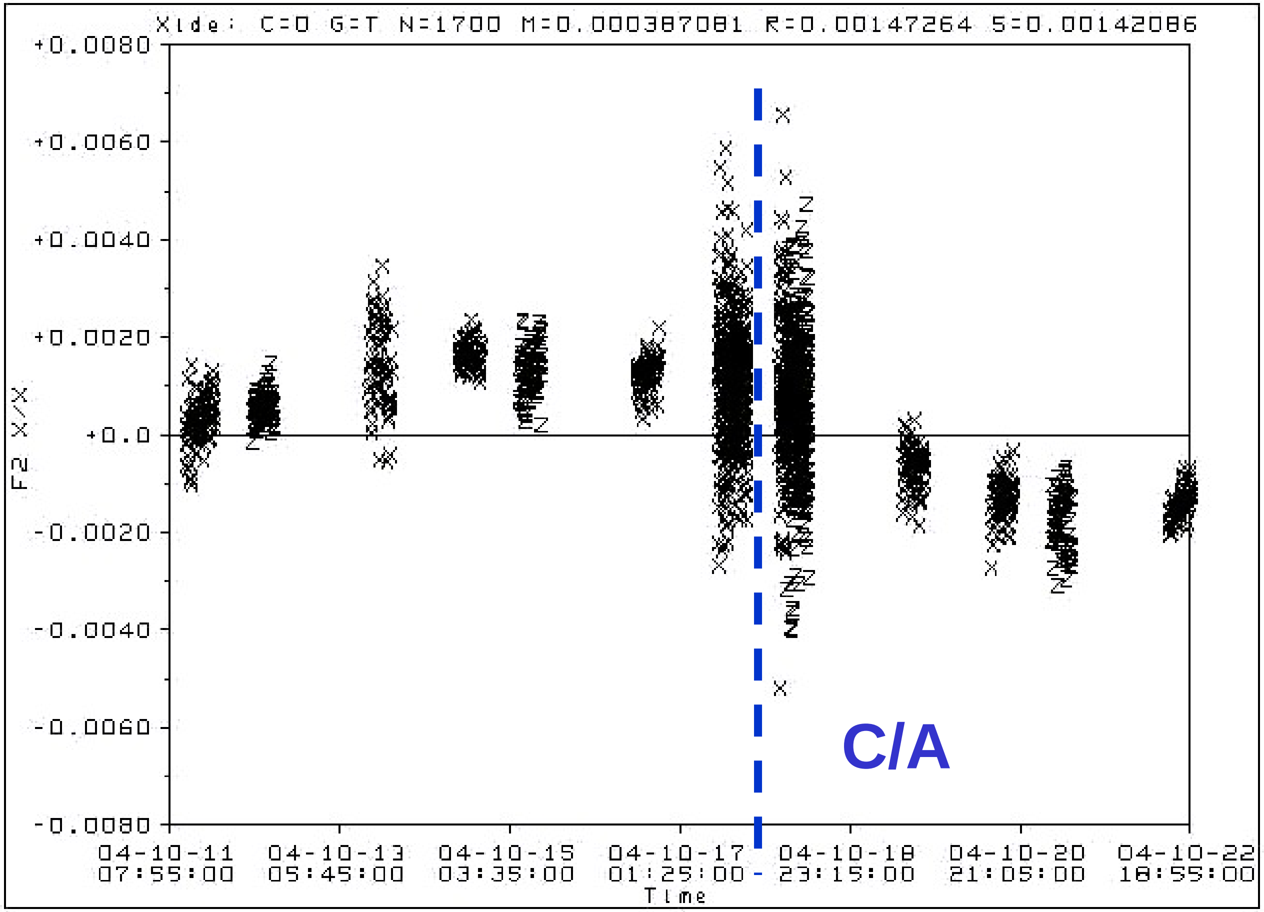
GEOMETRY OF IAPETUS FLYBY 1



Ecliptic plane projection

Marks every 12 h

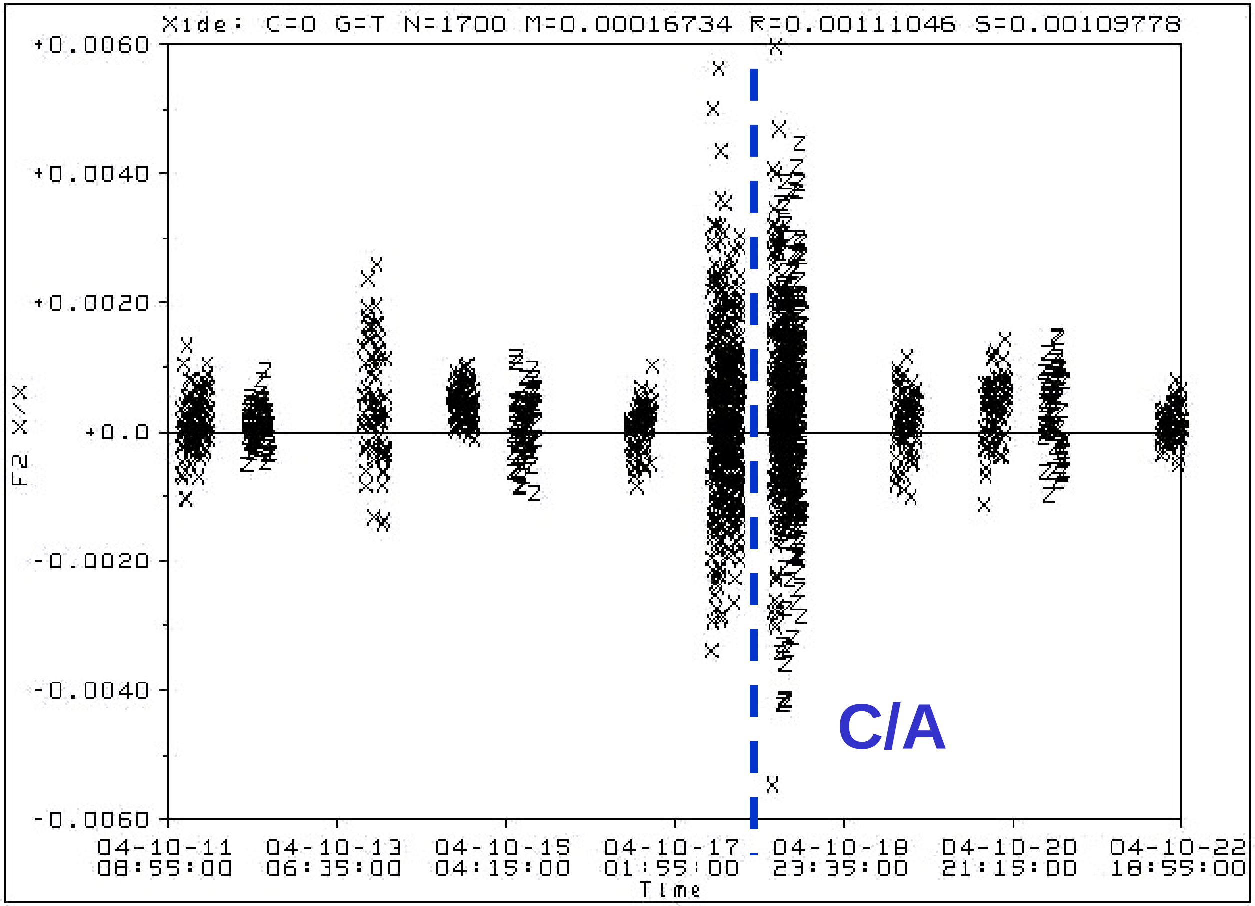
IAPETUS FLYBY-1
DOPPLER RESIDUALS (PRE-FIT)



IAPETUS FLYBY-1
DOPPLER RESIDUALS (POST-FIT)

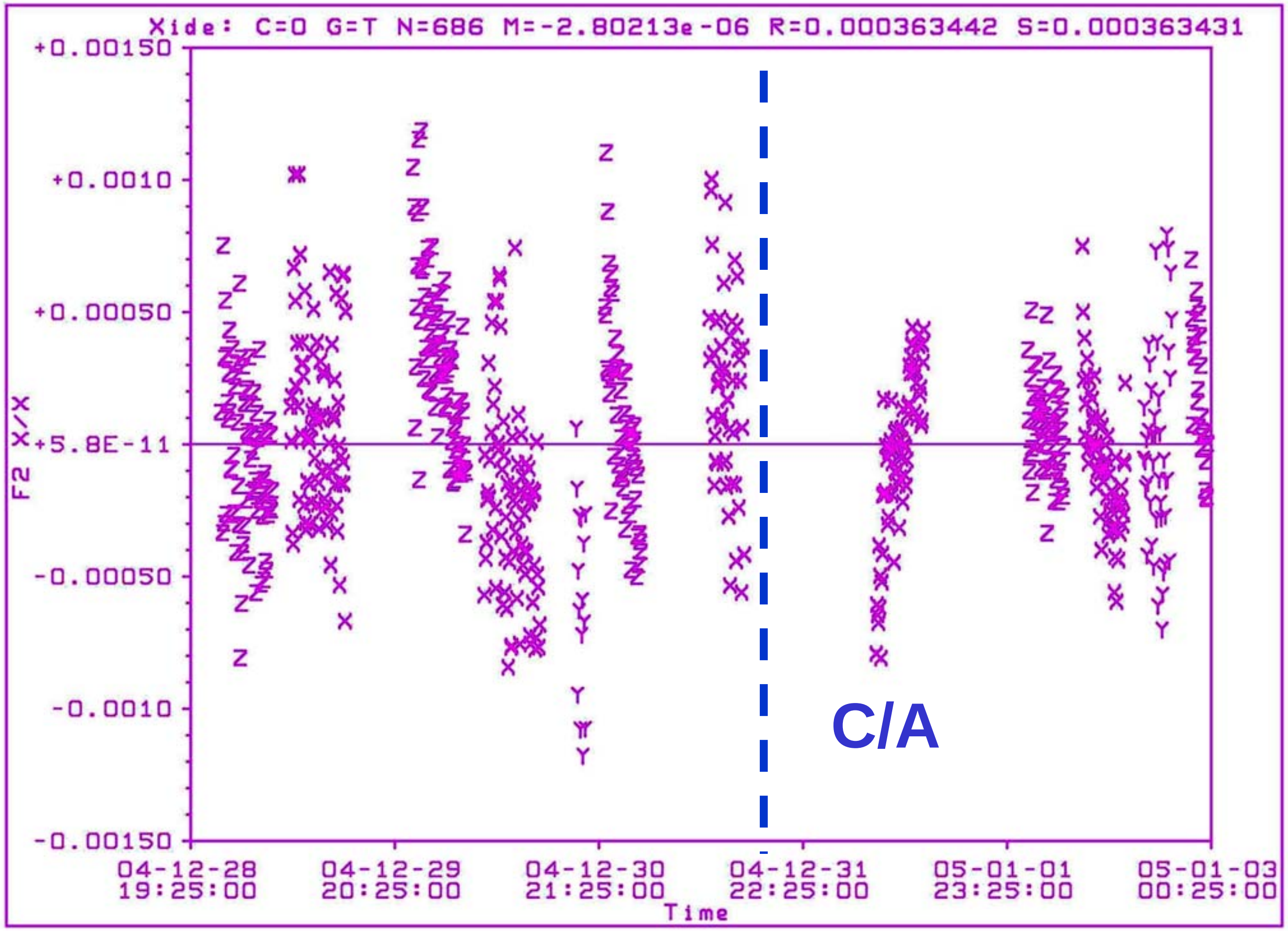
1700 data points @ 60 and 300 s rms range rate error: 3.0 10^{-3} cm/s^2

(@300s)



IAPETUS FLYBY-2
DOPPLER RESIDUALS (POST-FIT)

686 data points @ 300 s   rms range rate error: 1.3 10^{-3} cm/s^2



RESULTS FOR IAPETUS

- The first flyby gave:
  - GM = 120.20 +/- 0.063 km^3/s^2.
  - With a radius of 730 +/- 6 km this implies a density of 1.106 +/- 0.027 g/cm^3.
- The second flyby gave:
  - GM=120.51 +/- 0.003 km^3/s^2.
  - But the orbit of Iapetus was not updated and note that $\sigma(GM)/GM = |\sigma(v)/\Delta v| + |\sigma(b)/b|$
- The Cassini radio science estimation is that of the first flyby

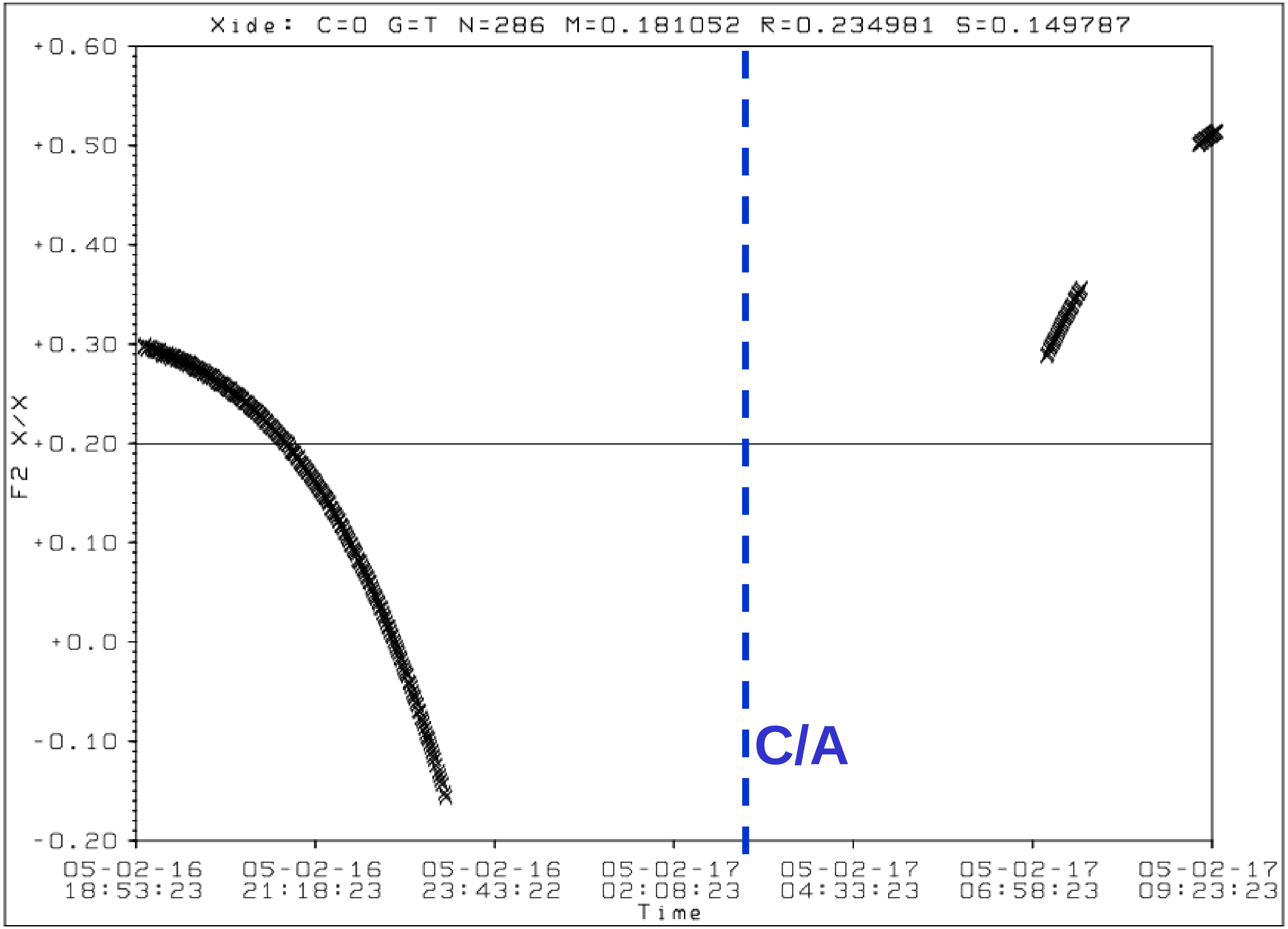
HYPERION MASS DETERMINATION

- The flyby of Hyperion was on September 26, 2005.
- The observation consisted of two segments, but the outbound one was lost due to a Madrid failure.
- Fortunately, the Cassini Radio Science Team had planned two Gravity Science Enhancement (GSE) passes before and after closest approach.
- GM = 0.375 +/- 0.017 km^3/s^2.

ENCELADUS MASS DETERMINATION

- The best Enceladus flyby occurred in February 2005.
- The data were acquired up to a distance of 1511 km.
- The flyby velocity was 6.7 km/s.
- The change in velocity of the spacecraft was 0.71 m/s, significantly larger than the measurement accuracy of 3×10^{-5} m/s at 60 seconds integration time.

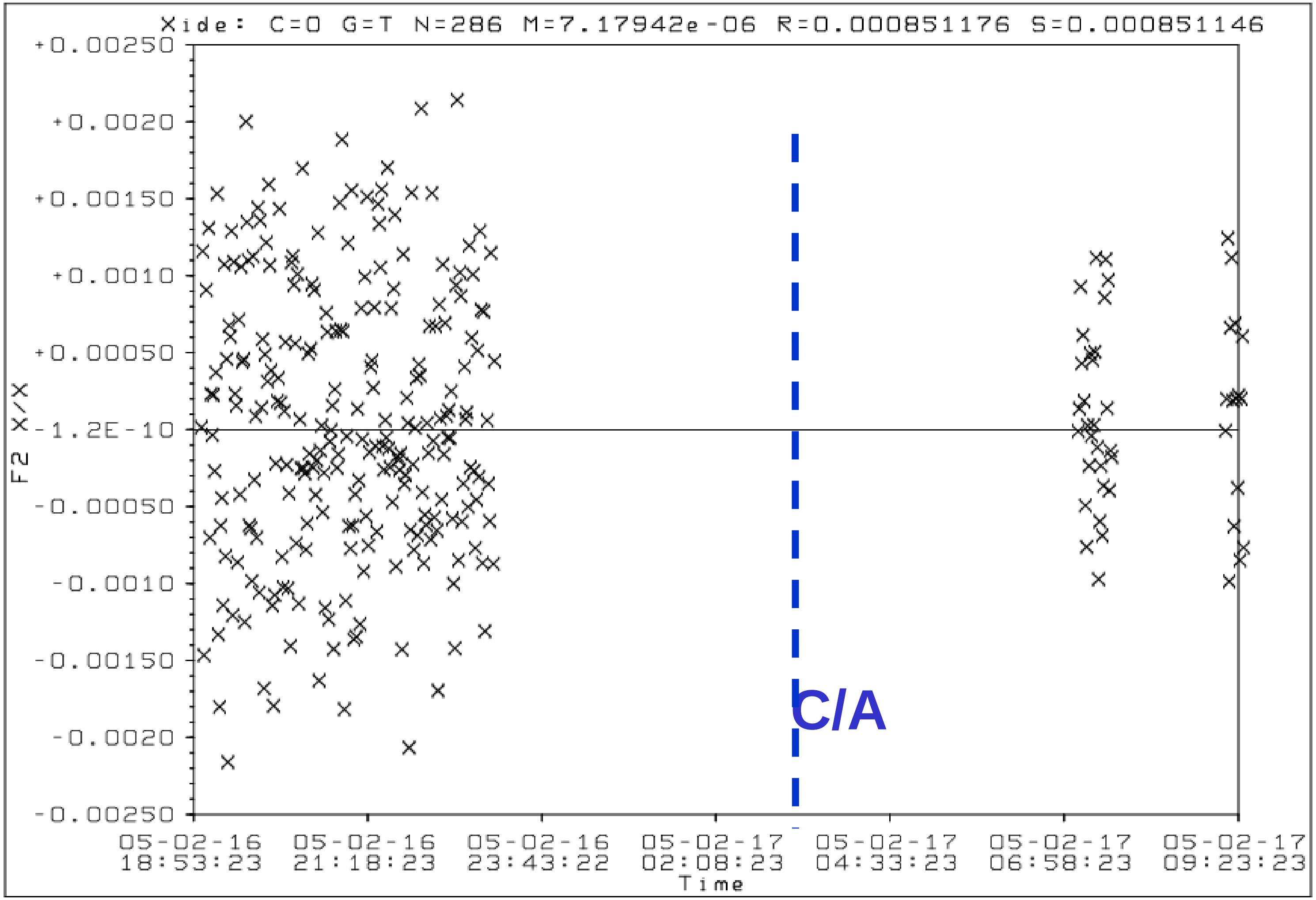
ENCELADUS DOPPLER RESIDUALS (PRE-FIT)



ENCELADUS DOPPLER RESIDUALS(POST-FIT)

331 data points

rms range rate error: 0.03 mm/s @60s



ENCELADUS MASS ESTIMATION

$GM = 7.207 \pm 1.1 \times 10^{-2}\ km^3/s^2$

$R = 252.3 \pm 0.6\ km$

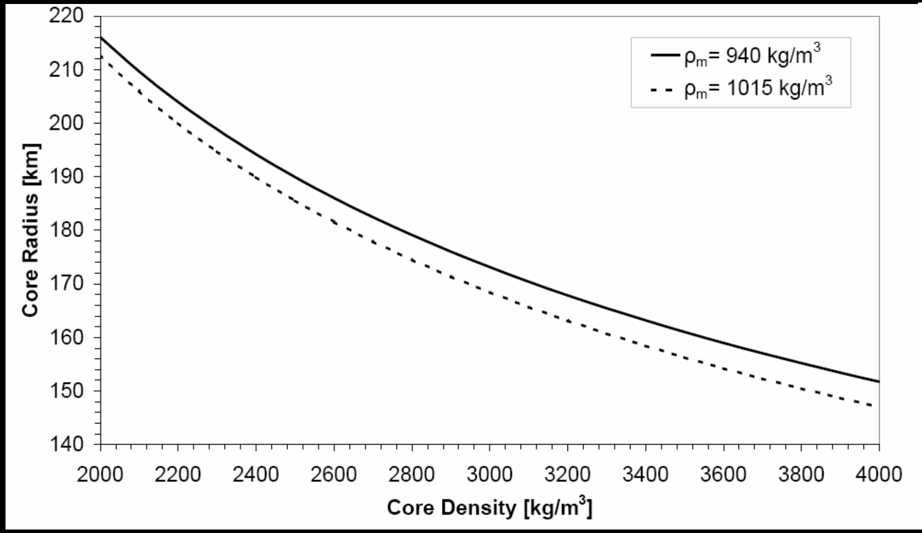
$\rho = 1605 \pm 14\ kg/m^3$

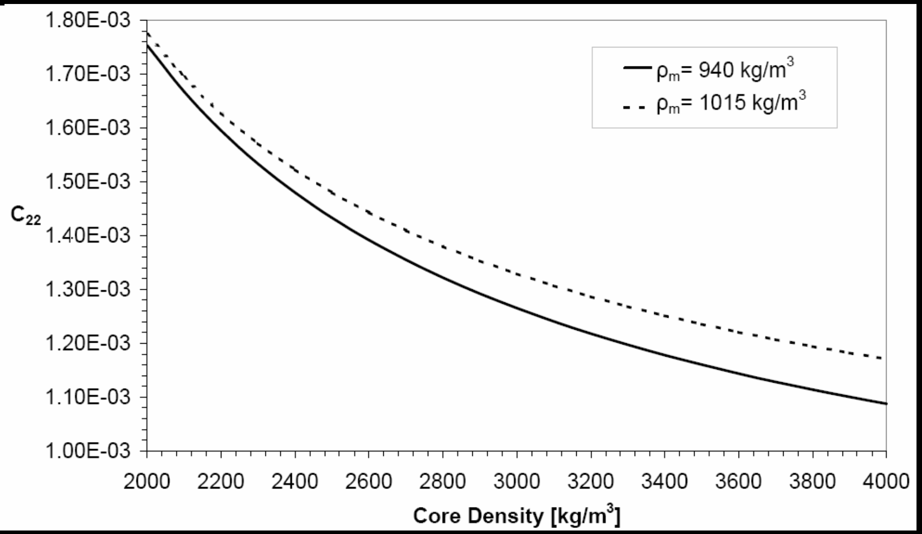
INTERIOR OF ENCELADUS

- Density of 1605 kg/m^3 requires a substantial amount of rock $\Rightarrow$ enhanced likelihood of differentiation.
- There is evidence that Enceladus may be differentiated:
- However it is difficult to understand why Enceladus would be differentiated.
- Assuming Io’s mean density for the silicate component, one finds its fractional mass to be 0.52 +/- 0.06.

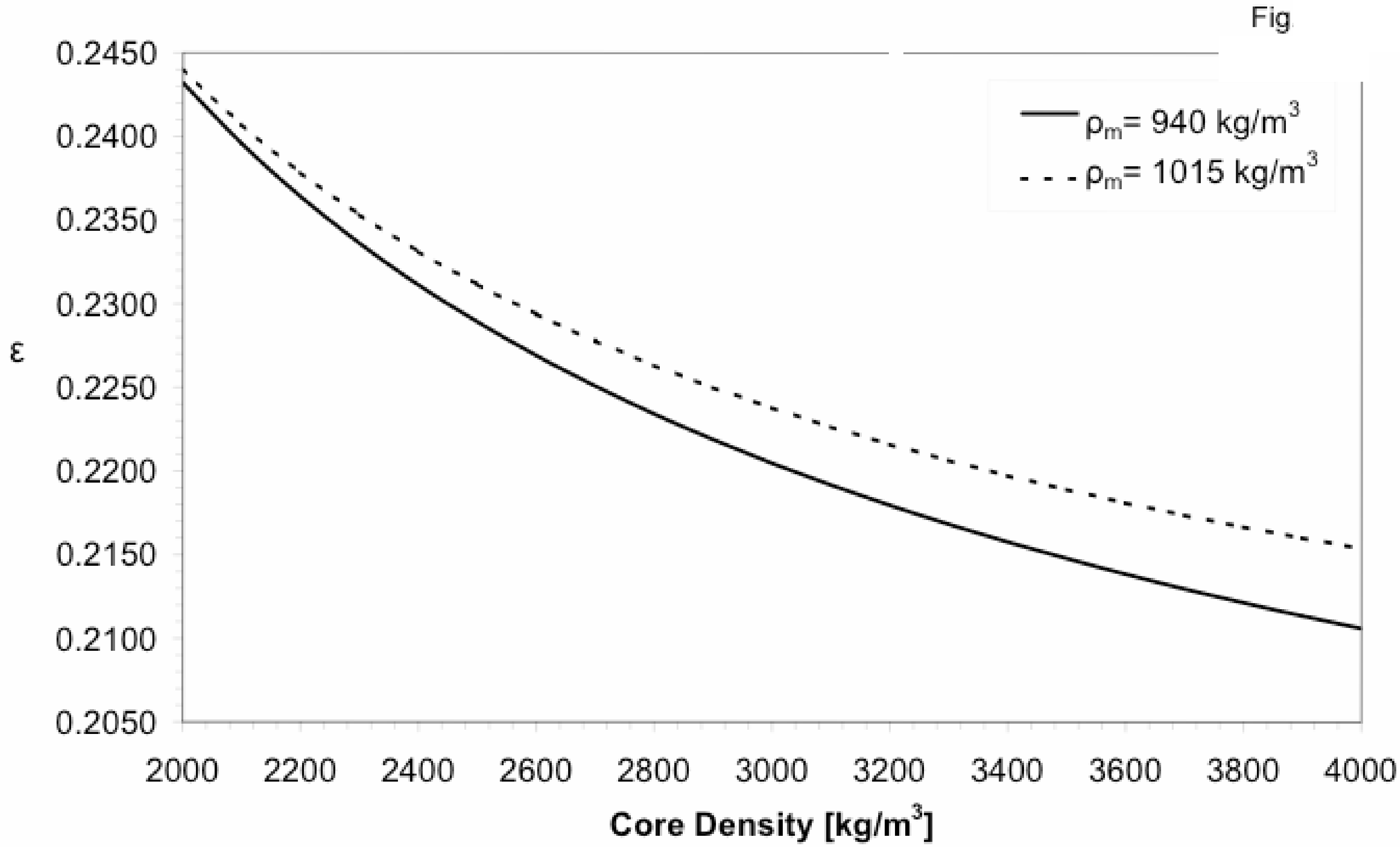
INTERIOR OF ENCELADUS

- A two layer model leads to the radius of the core as a function of the core density. If the density of the core is about 3500 kg/m^3, then the core radius would be 160 km. But if the core consist of hydrated silicate and has a density of 2500 kg/m^3, the radius of the core would be 190 km





POSTULATED SECONDARY RESONANCE



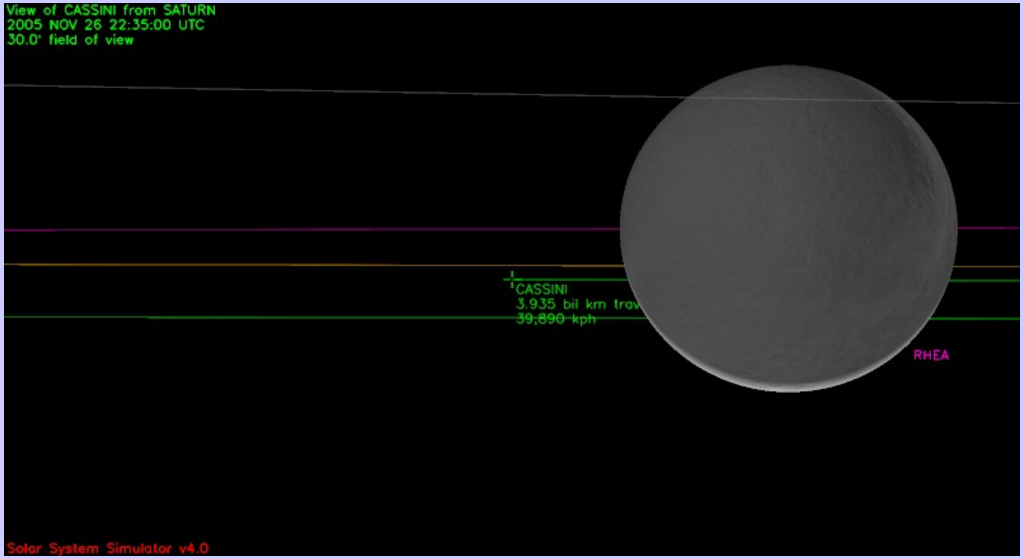
Ratio ε of the librational frequency to the orbital frequency < 0.33

⇒Secondary resonance postulated by Wisdom (2004) is impossible

RHEA FLYBY GEOMETRY

- Closest Approach = 1262 km
- TCA: 26-NOV-2005 22:37:42 UTC
- SEP angle = ~113°
- Relative velocity = ~7.3 km/s
- Orbit Inclination = ~10°

View from Saturn system north



View from Saturn

RHEA'S PUTATIVE QUADRUPOLE FIELD

Assuming:

- **Perturbing potential due to Saturn tidal and rotational potentials.**
- **Hydrostatic equilibrium.**
- **Principal axes reference frame coinciding with orbital reference frame at periapsis.**

Quadrupole coefficients:

$$C_{20} = -\frac{5}{6} k_f \frac{M_S}{M_R} \left(\frac{R_R}{a_R} \right)^3$$

$$C_{22} = \frac{1}{4} k_f \frac{M_S}{M_R} \left(\frac{R_R}{a_R} \right)^3$$

For a fluid body ***k_f=1.5*** :

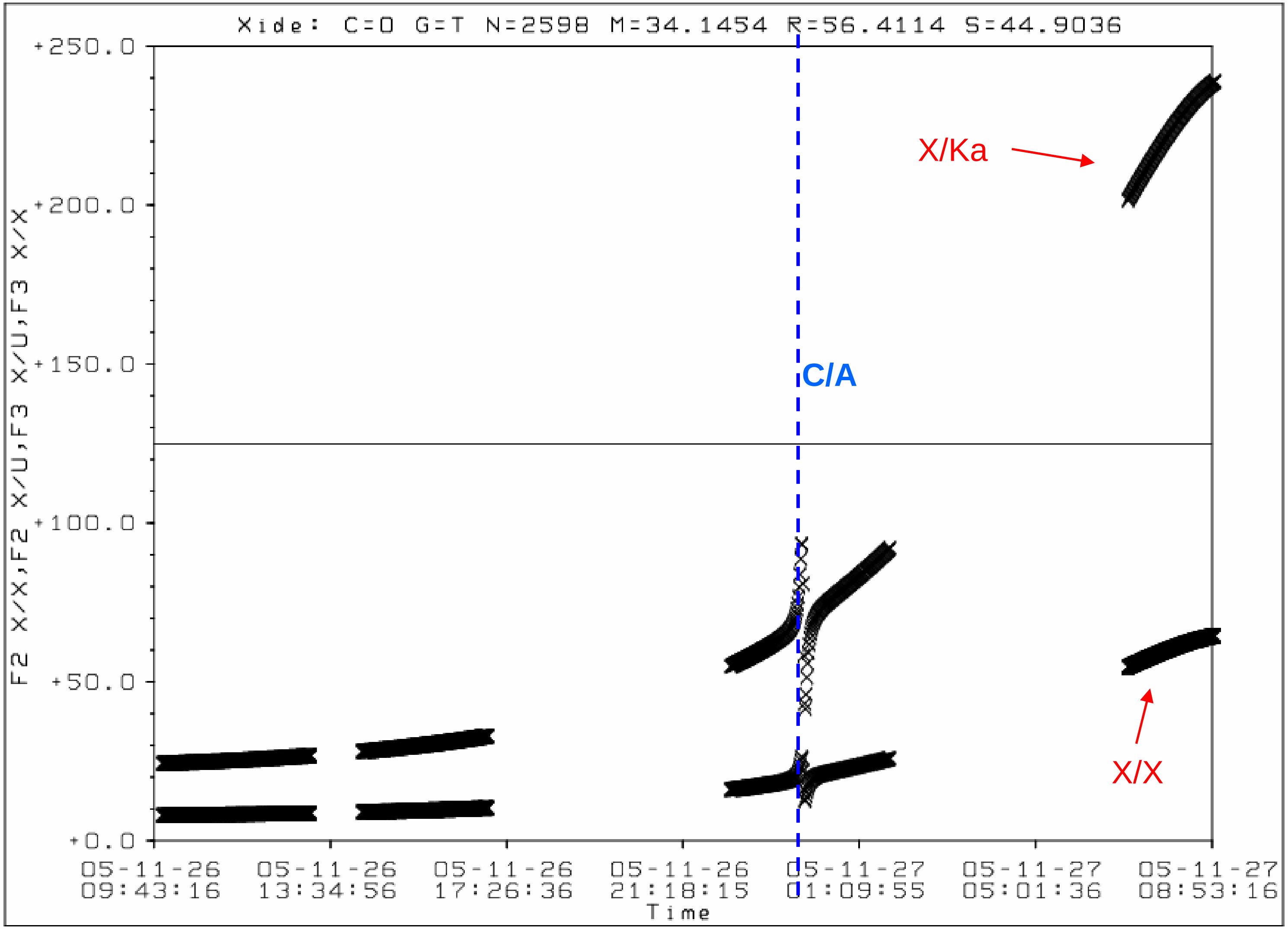
$$C_{20} \cong -9.3 \cdot 10^{-4}$$

$$C_{22} \cong 2.85 \cdot 10^{-4}$$

with ratio:

$$\frac{C_{20}}{C_{22}} = \frac{10}{3}$$

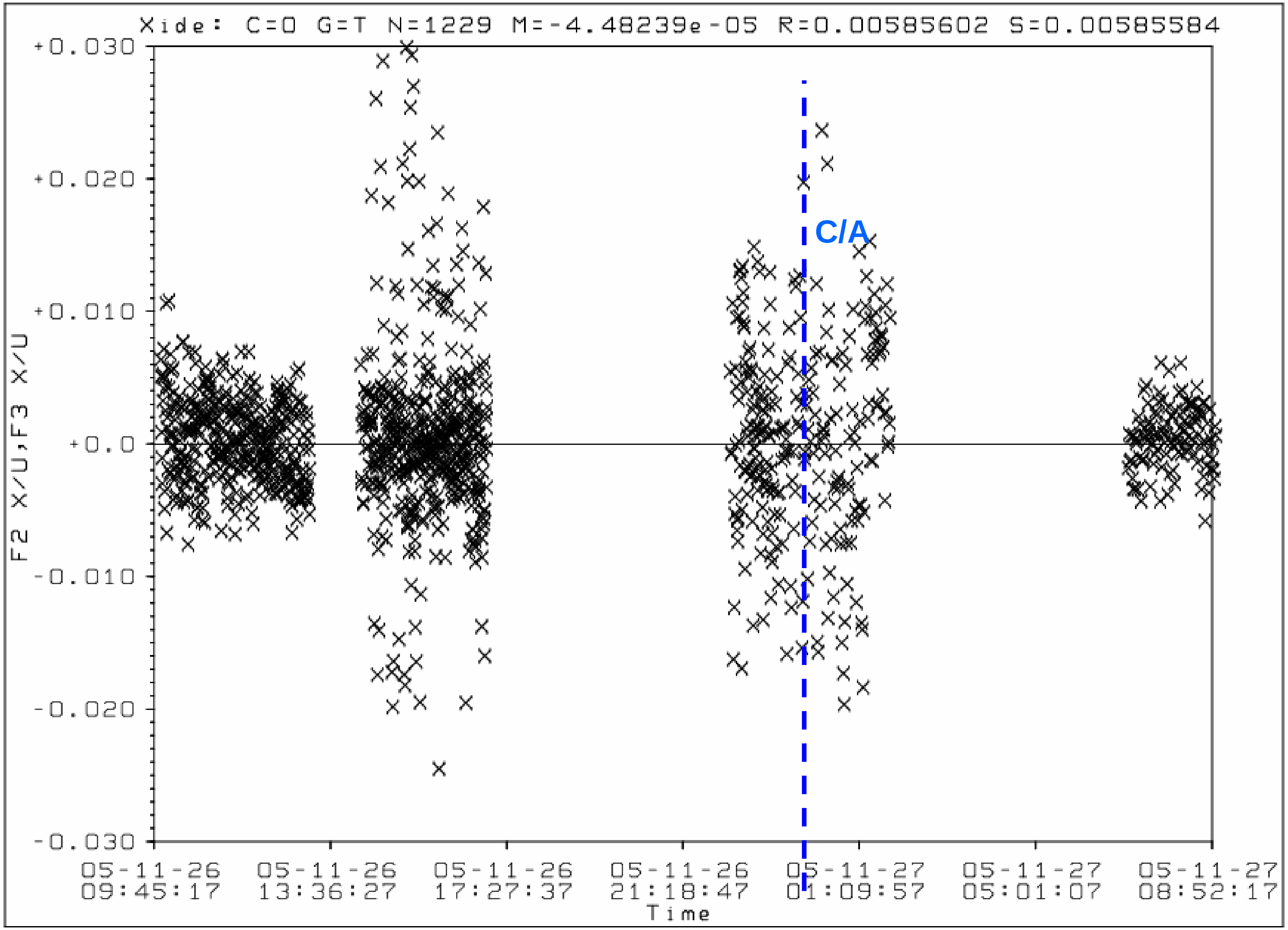
RHEA DOPPLER RESIDUALS (PRE-FIT)



RHEA DOPPLER RESIDUALS X/KA (POST-FIT)

1471 F3 data points

rms range rate error: 5.4 10^{-2} mm/s @ 60



RHEA MEASURED QUANTITIES

- GM = 153.939 ± 0.0018 km^3/s^2
- ρ = 1232.3 ± 9.7 kg/m^3
- C_{20} = - (7.947 ± 0.892)· × 10^{-4}
- C_{22} = (2.3526± 0.0476) ×·10^{-4}
- Hydrostatic values
- Close to values for an homogeneous fluid body

C_{20} measured to within 11%

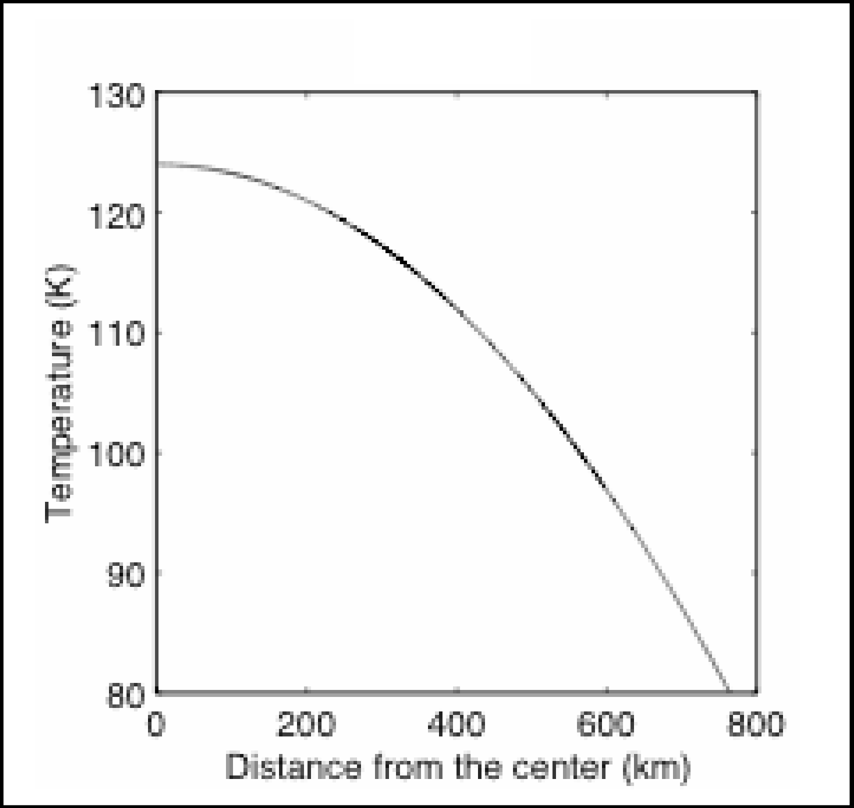
C_{22} measured to within 0.2%

MODELS OF RHEA INTERIOR STRUCTURE

- Numerical integration of the hydrostatic equation and mass equation.
- Equations of state for ice I, ice II, and the silicates (Lupo and Lewis, 1979)
- Temperature profile is given (Ellsworth and Schubert 1983).
- Computation of C_{22}:
  - Density profile $\rightarrow$ Normalized moment of inertia C/MR^2
  - C/MR^2 + Radau equation $\rightarrow$ Fluid Love number k_f
  - k_f + tidal parameter $\rightarrow$ C_{22} (Rappaport *et al.* 1997)
- Boundary conditions: Pressure at the surface, mass, C_{22} $\rightarrow$ Three algebraic equations.
- Several sets of variables possible among:
  - The pressure at the center
  - The radius of the core
  - The density of the core
  - The mass fraction of silicate in the core
  - The mass fraction of silicate in the mantle

TEMPERATURE PROFILE

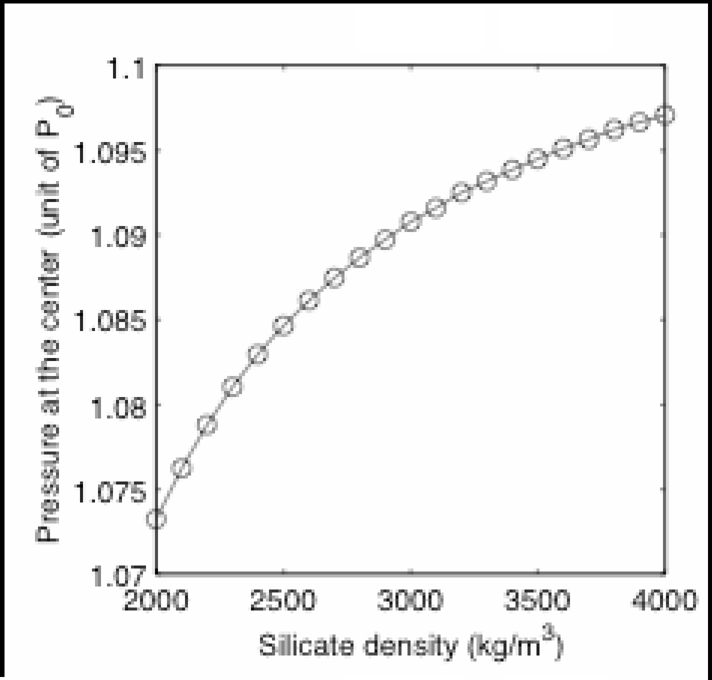
Fit to results of thermal evolution calculations by Ellsworth and Schubert (1983)

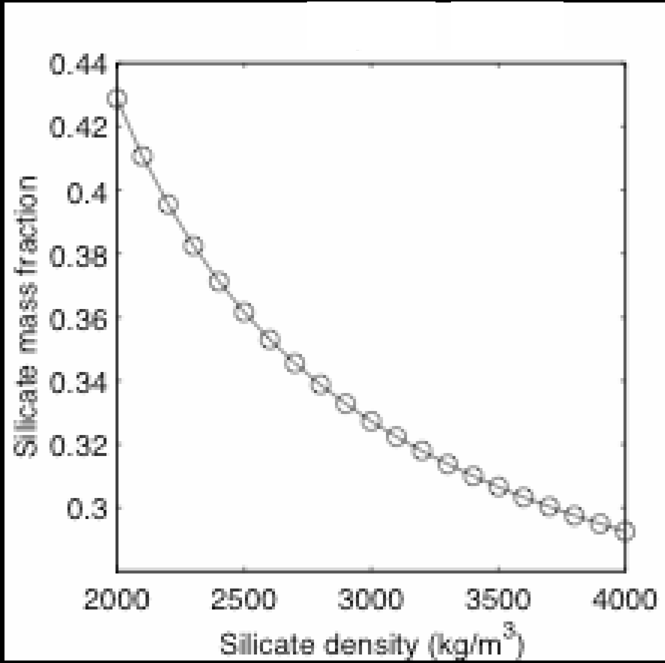


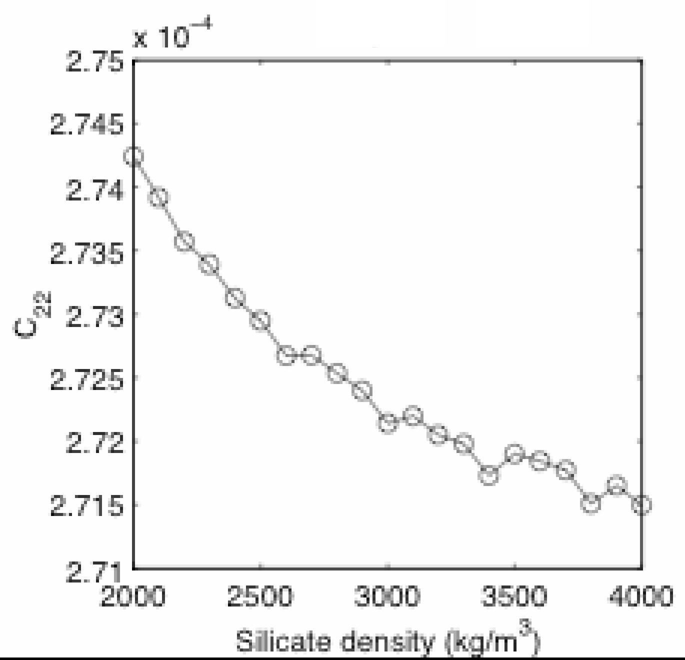
UNDIFFERENTIATED MODELS

- Two algebraic equations that we solve for the pressure at the center and the silicate mass fraction as a function of the silicate density.
- C22 > determined value

⇒ Rhea is differentiated

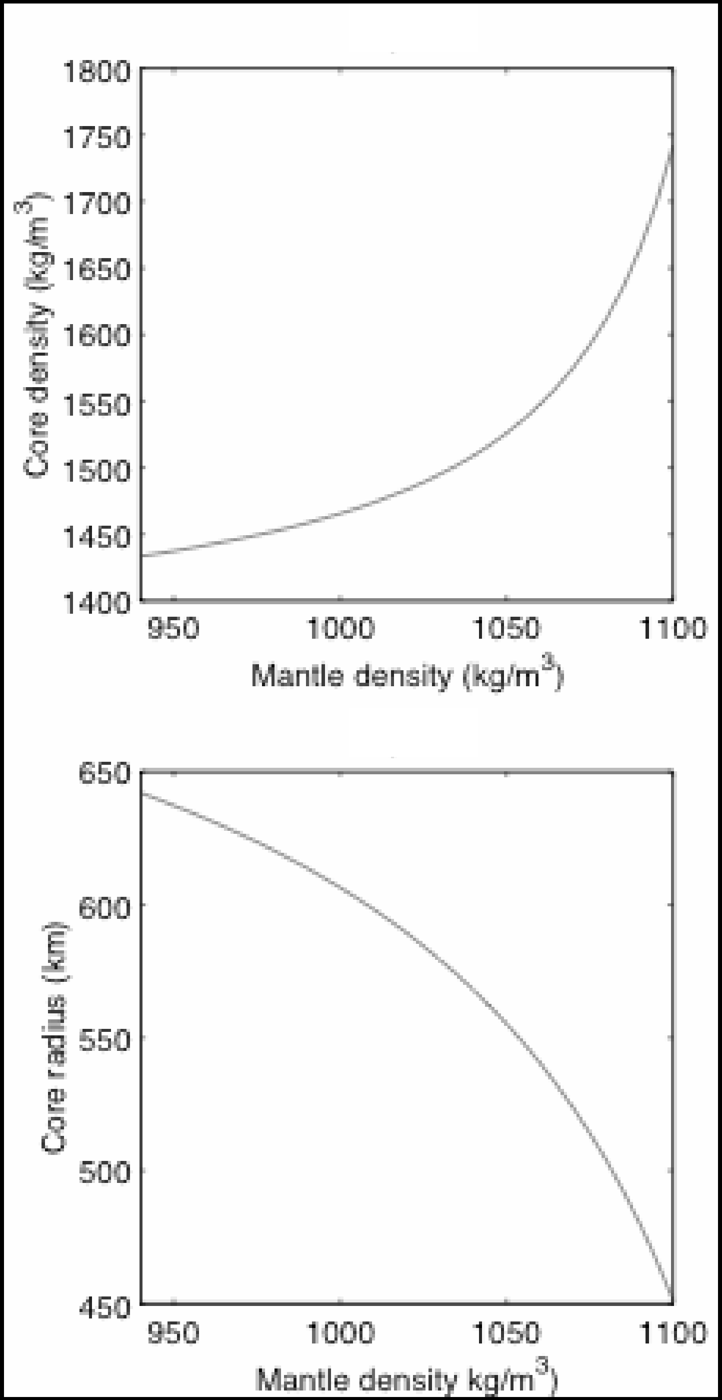






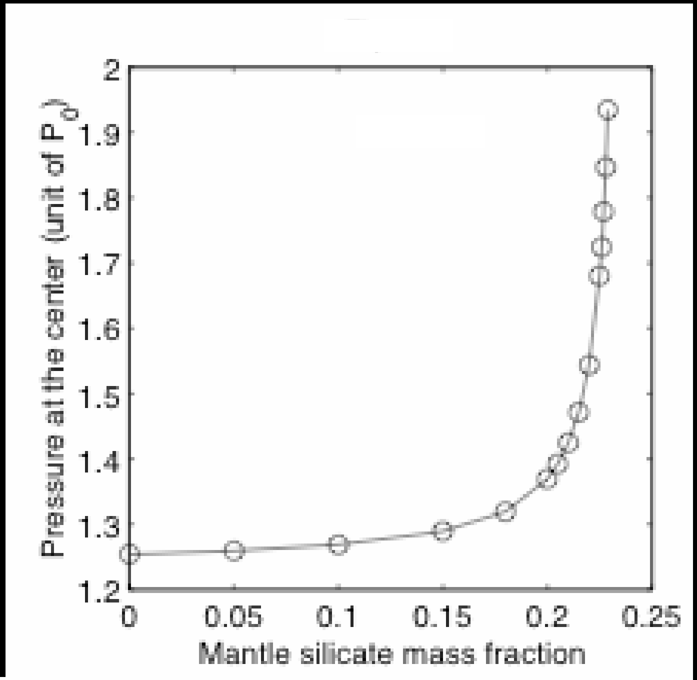
DIFFERENTIATED MODELS OF THE FIRST TYPE

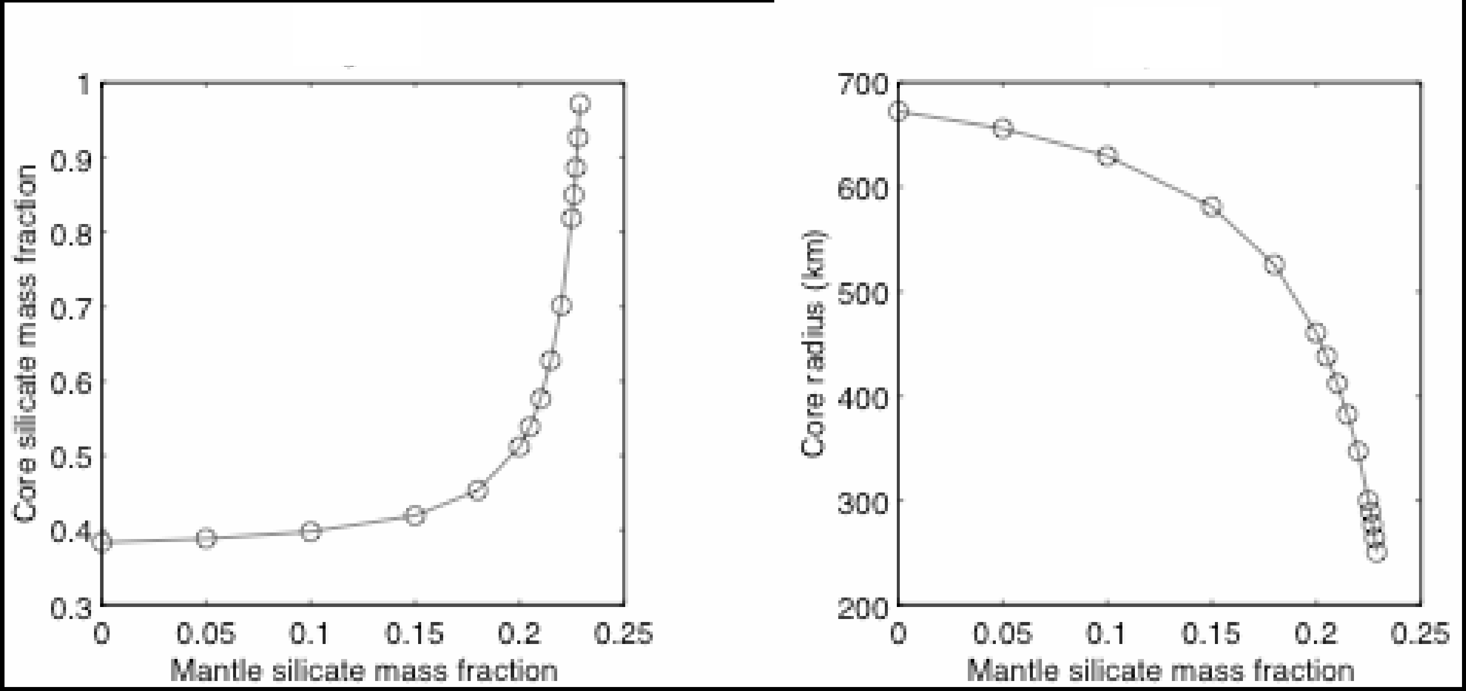
- Core of radius R_c and density ρ_c.
- Mantle of density ρ_m
- Pressure equation decouples from mass equation.
- Two algebraic equations that we solve for the core density and the core radius as a function of the mantle density.
- Large core radius + small core density ⇒ Rhea is weakly differentiated.



DIFFERENTIATED MODELS OF THE SECOND TYPE

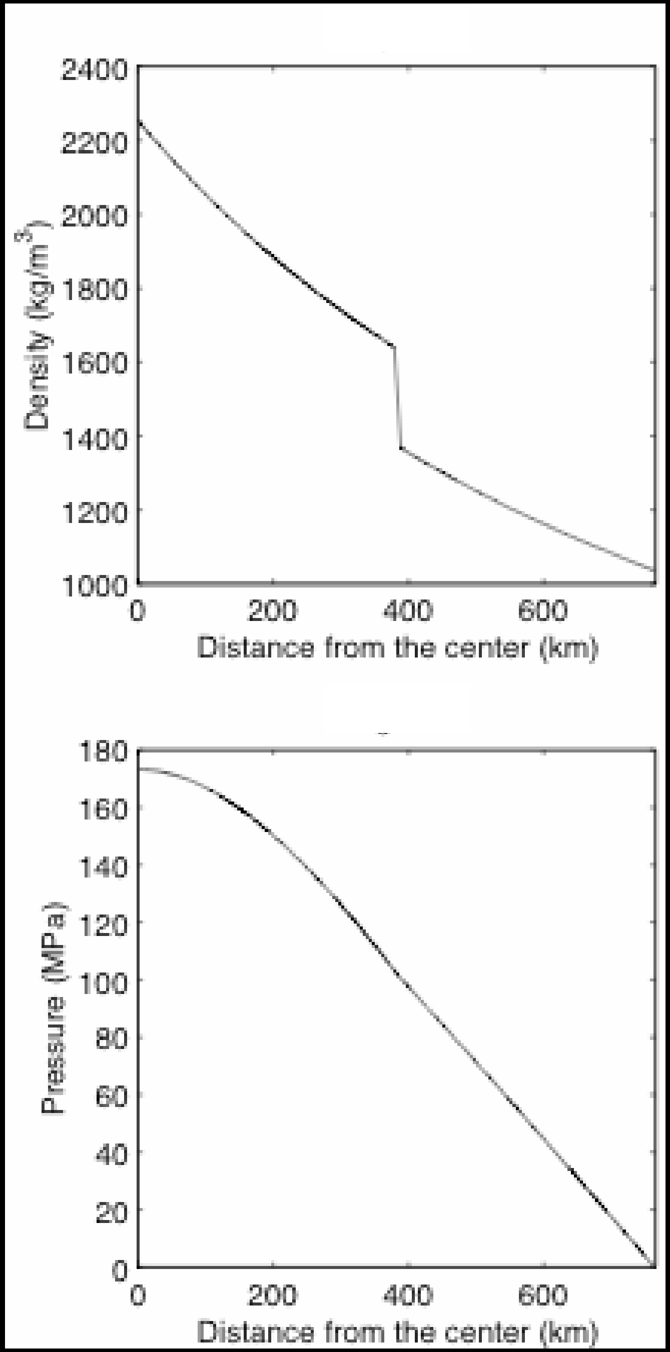
- Core and mantle consist of mixtures of ice and silicates in different ratios.
- Three algebraic equations that we solve for the pressure at the center, the core radius, and the core silicate mass fraction as a function of the mantle silicate mass fraction.
- A rocky core is excluded.





CONTINUOUS MODELS

- No clear discontinuity in composition between a core and a mantle. The silicate mass fraction varies linearly from the center to the surface.
- The silicate mass fraction decreases from 0.704 at the center to 0.132 near the surface.



SUMMARY

- Rhea is in a state of weak differentiation.
- Undifferentiated models cannot account for the gravity data.
- Models with a rocky core and an icy mantle are also excluded by the data.
- It is possible that Rhea consists of two layers, each being a mixture of ice and silicate.
- More simply, the mass fraction of silicates could smoothly decrease from the center to the surface.
- Transition from ice II to ice I occurs in all the models.