Interiors of Enceladus and Rhea

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RST science objectives (tour)

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

Proposed measurements for the extended tour:

- Quadrupole field of Enceladus and Iapetus
- Verification/disproof of “Pioneer anomaly”

Measurement method and data set

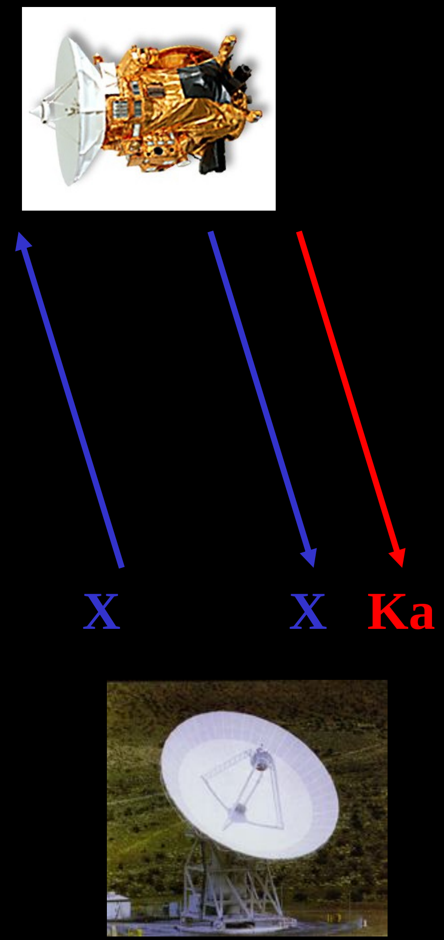
Gravity field parameters determined by means of range rate measurements over multiple arcs across flyby.

Optical imaging not required when reliable a priori estimates of spacecraft state vector are available.

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)



DSN antennas

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

Input to ODP:

- Planetary Ephemerides
- Planetary Partials
- Satellite Ephemerides
- Satellite Partials

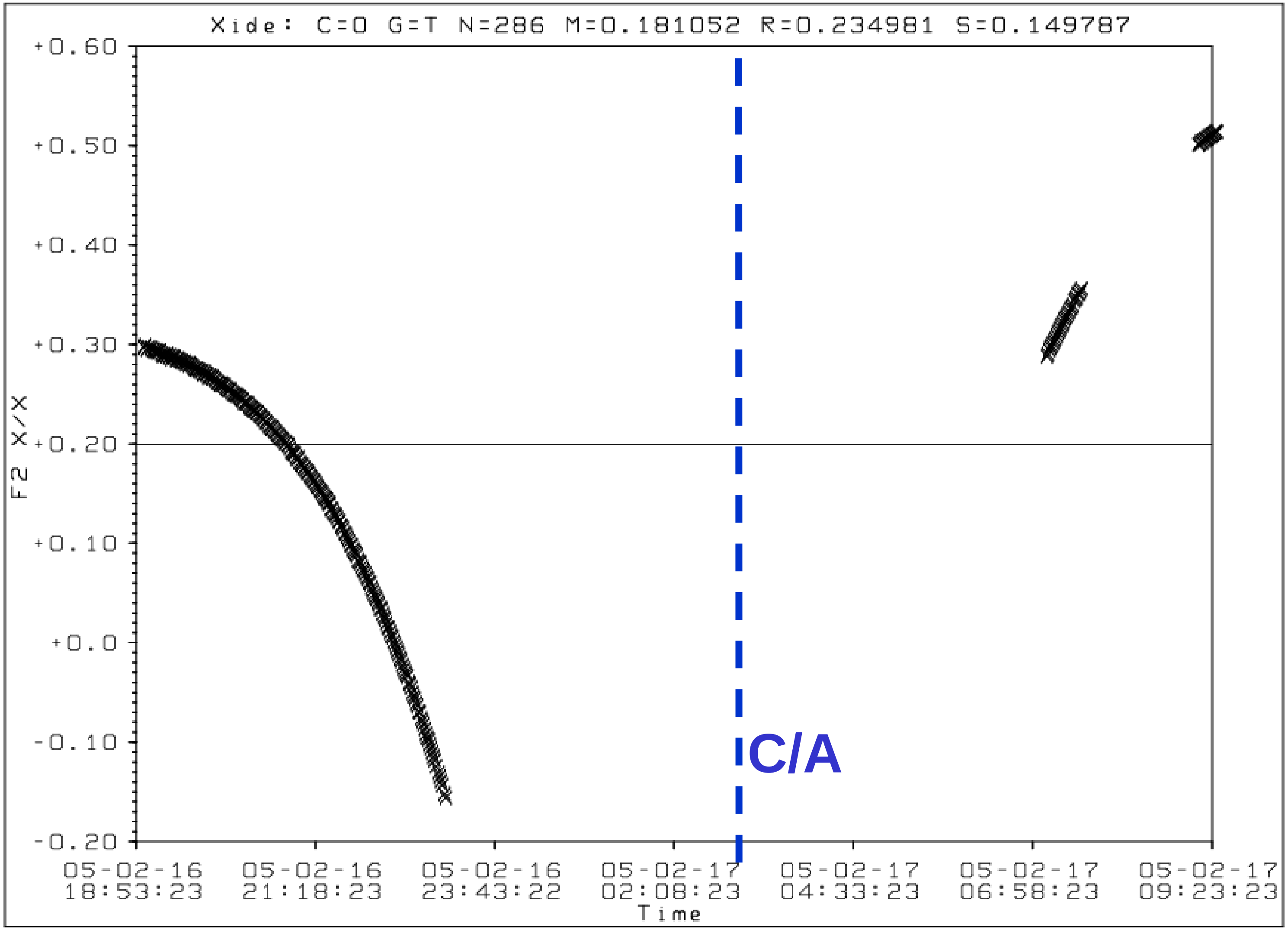
Non-gravitational accelerations:

- RTG (fixed in the SC frame – mostly radial 5 10^{-12} km/s^2)
- Solar pressure (included, but very small)
- No maneuvers in orbital arc

Solve-for parameters:

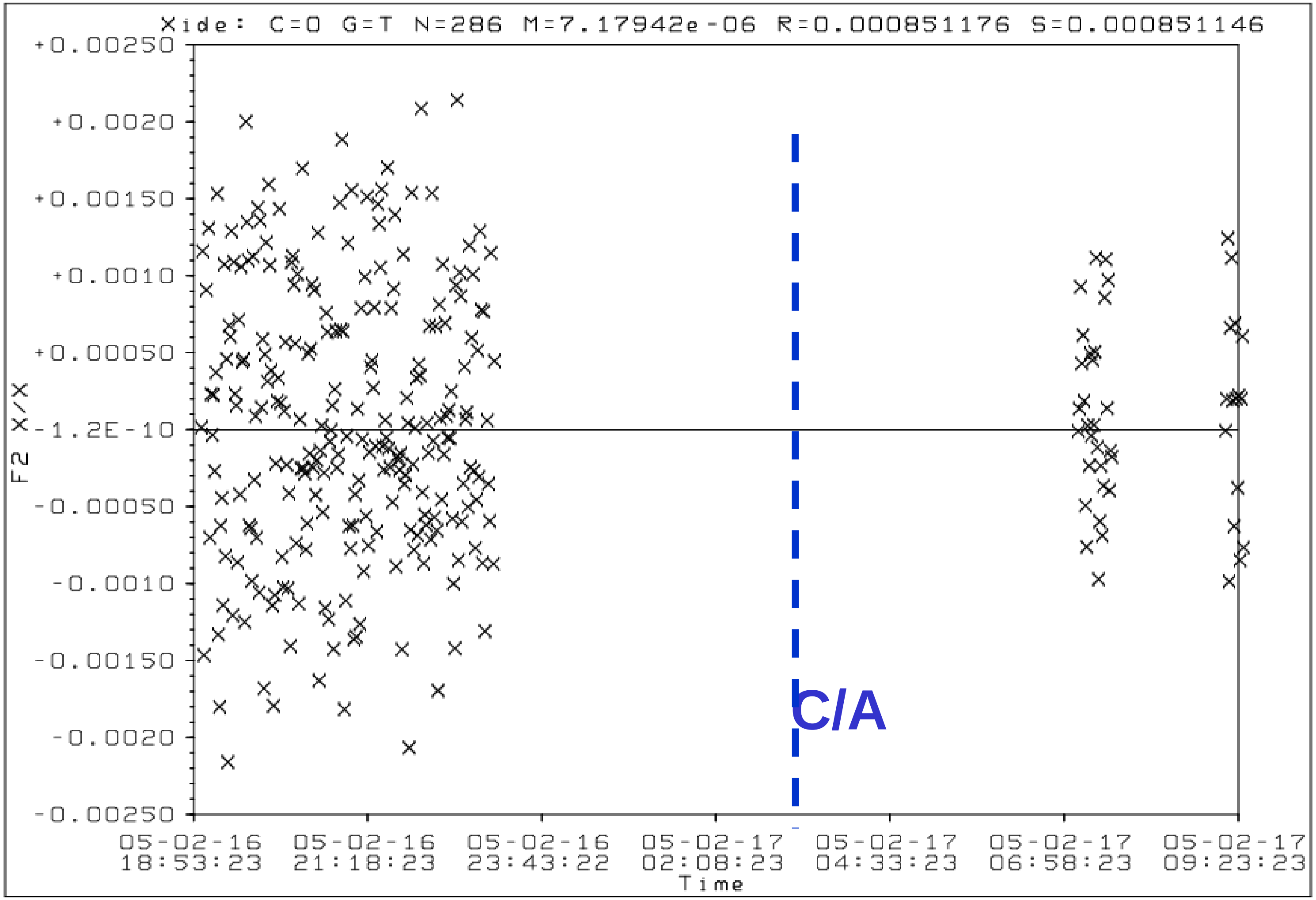
- Cassini state vector at epoch
- Satellite GM, J2 and C22 (Rhea)
- Satellite state vector at epoch

Enceladus Doppler Residuals (pre fit)



Enceladus Doppler Residuals(post fit)

331 data points rms range rate error: 0.03 mm/s @60s



Mass Estimation

Enceladus:

GM = 7.207 ± 1.1×10^{-2} km^3/s^2

ρ = 1605 ± 14 kg/m^3

INTERIOR OF ENCELADUS

- Density of 1605 +/- 14 kg/m^3, higher than pre-Cassini estimates, requires a substantial amount of rock $\Rightarrow$ warmer interior $\Rightarrow$ enhance likelihood of differentiation of water from rock-metal. Assume no porosity.
- Assuming Io's mean density for the rock-metal component, one finds its fractional mass to be 0.52 +/- 0.06.
- There is evidence that Enceladus may be differentiated:
  - Areas devoid of craters must be geologically young.
  - Systems of ridges, fractures, and groove indicate that the surface has been tectonically altered.
  - Viscous relaxation of craters has occurred.
  - The plumes near the South pole indicate venting of subsurface volatiles.

Fig. 1

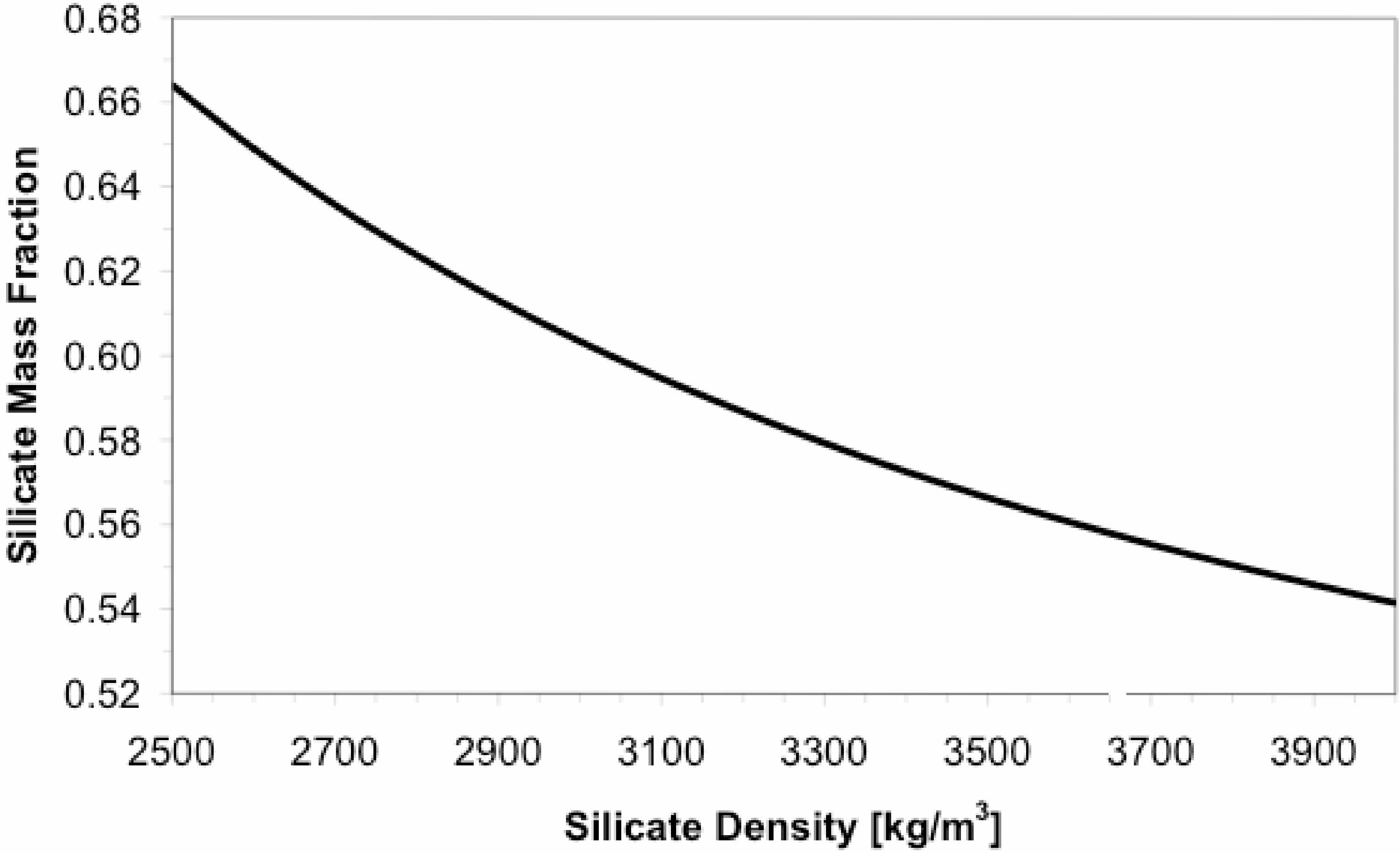
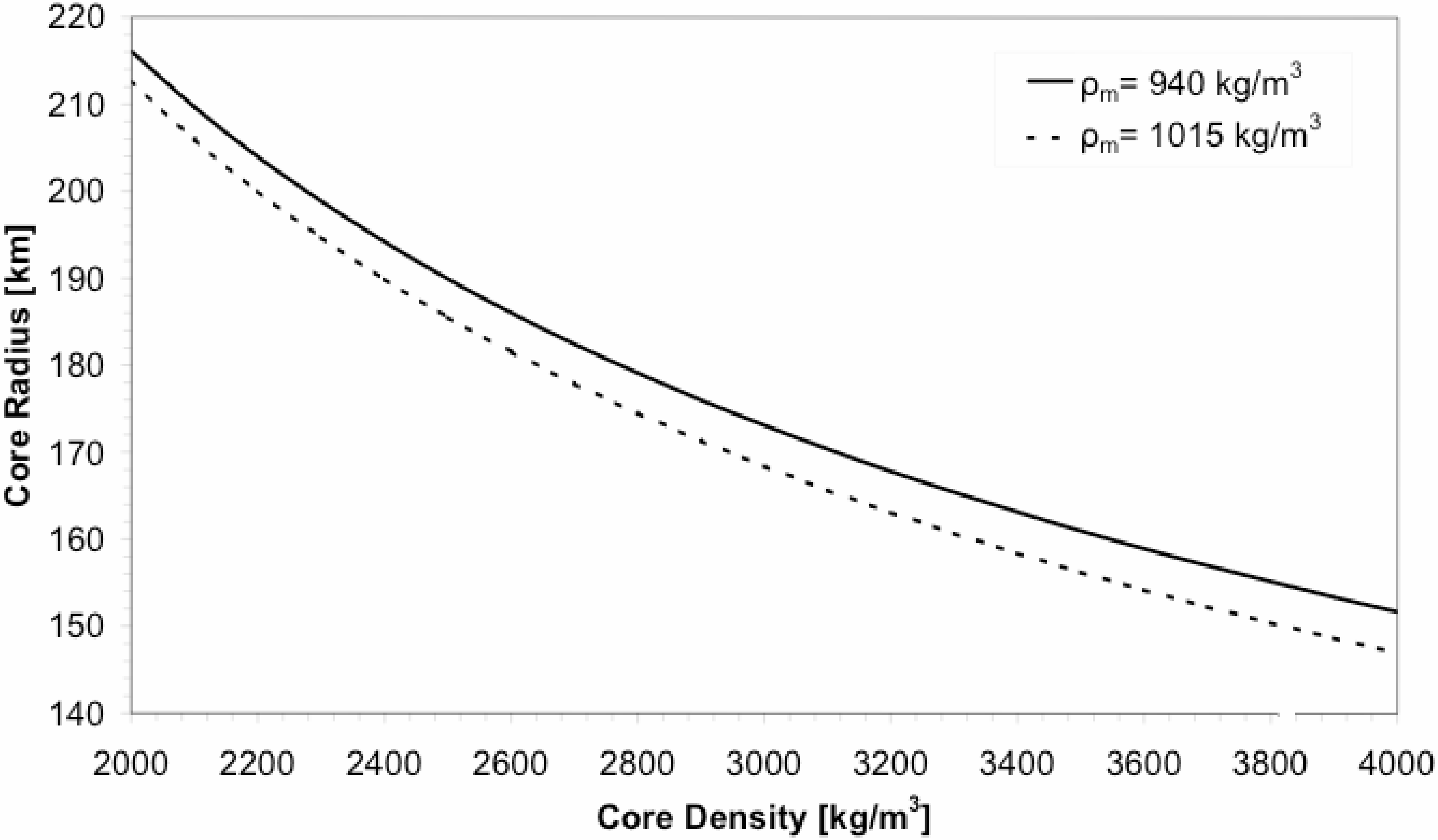
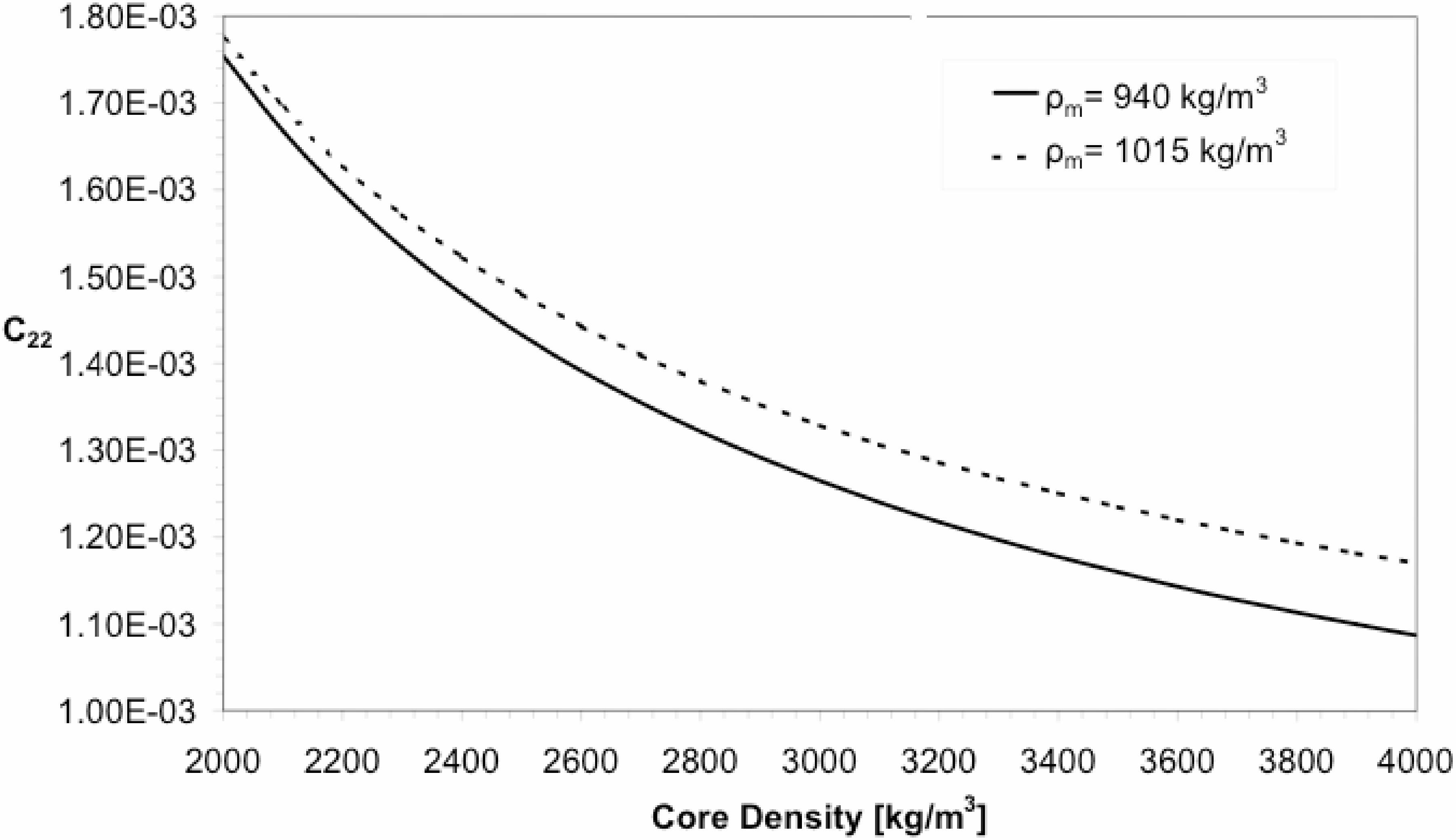

0.68
0.66
0.64
0.62
0.60
0.58
0.56
0.54
0.52
Silicate Mass Fraction
2500
2700
2900
3100
3300
3500
3700
3900
Silicate Density [kg/m3]

Fig. 2



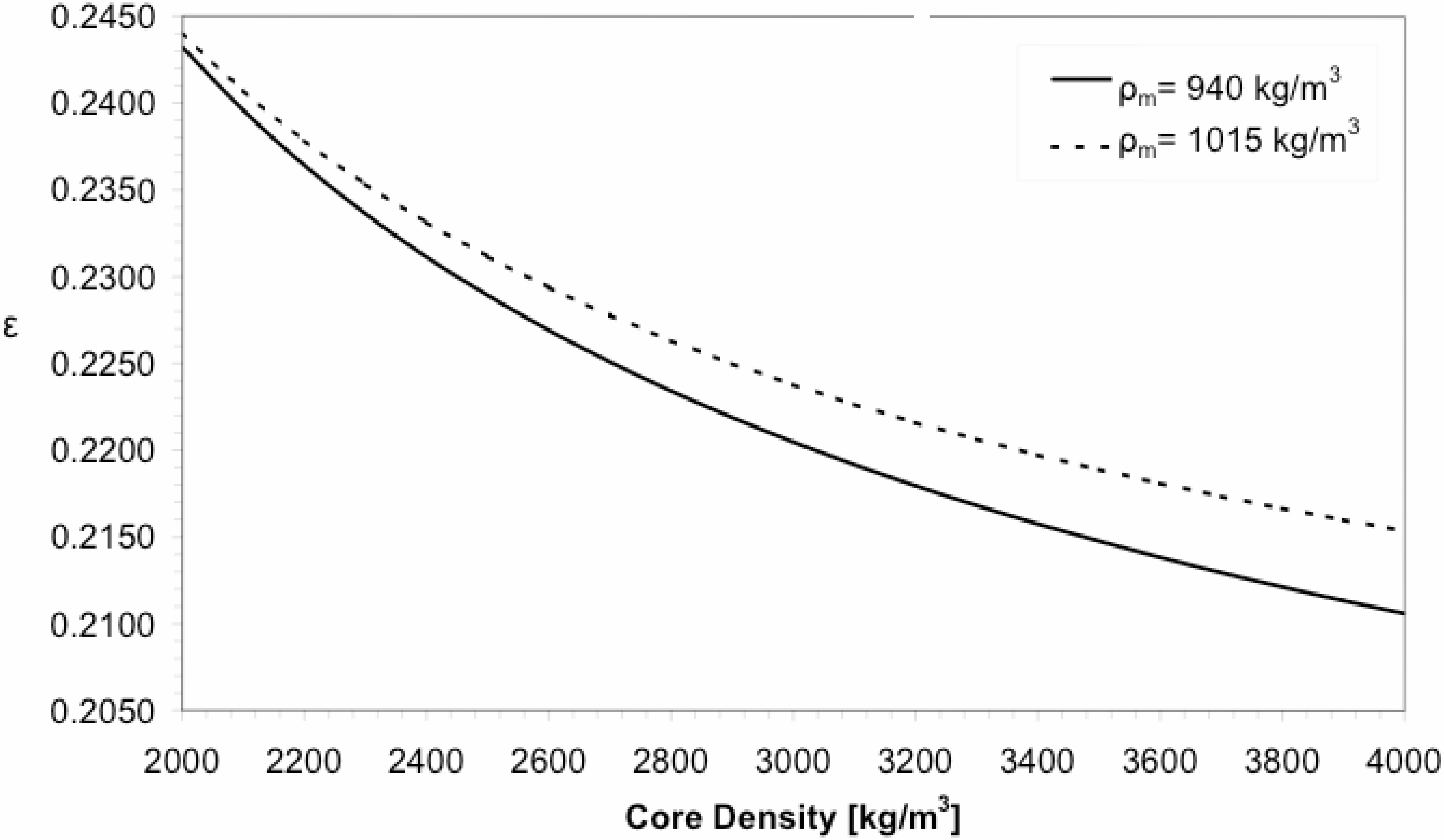
ρ_m= 940 kg/m^3
ρ_m= 1015 kg/m^3
220
210
200
190
180
170
160
150
140
Core Radius [km]
2000
2200
2400
2600
2800
3000
3200
3400
3600
3800
4000
Core Density [kg/m^3]

Fig. 3



ρm= 940 kg/m3
ρm= 1015 kg/m3
C22
1.80E-03
1.70E-03
1.60E-03
1.50E-03
1.40E-03
1.30E-03
1.20E-03
1.10E-03
1.00E-03
2000
2200
2400
2600
2800
3000
3200
3400
3600
3800
4000
Core Density [kg/m3]

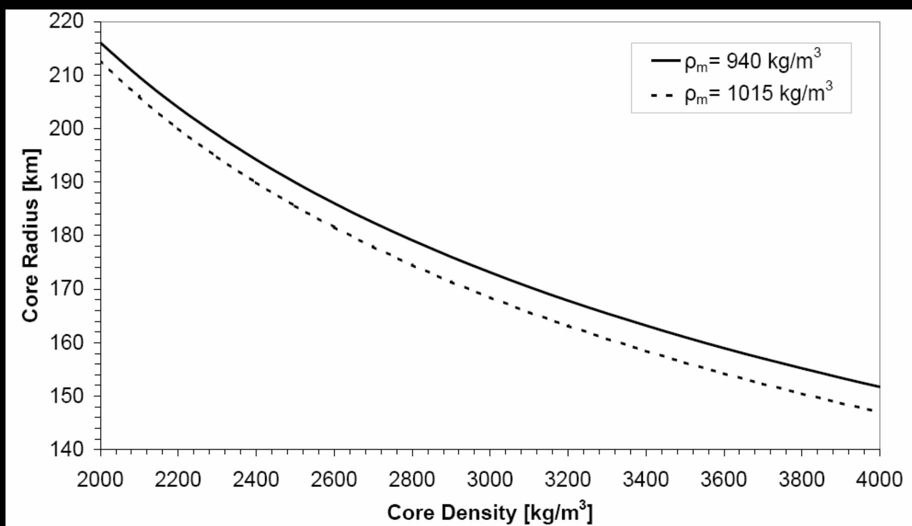
Fig. 4

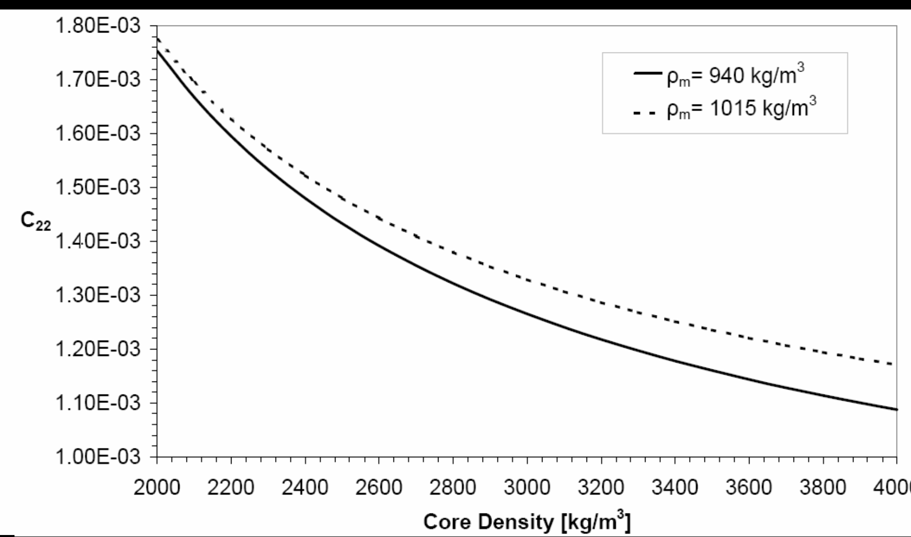


0.2450
0.2400
0.2350
0.2300
0.2250
0.2200
0.2150
0.2100
0.2050
ε
2000
2200
2400
2600
2800
3000
3200
3400
3600
3800
4000
Core Density [kg/m3]
ρm= 940 kg/m3
ρm= 1015 kg/m3

INTERIOR OF ENCELADUS

- A two layer model leads to a radius of the core equal to 0.62 the total radius = 160 km. The overlying ice shell extends to the surface (R=252 km).



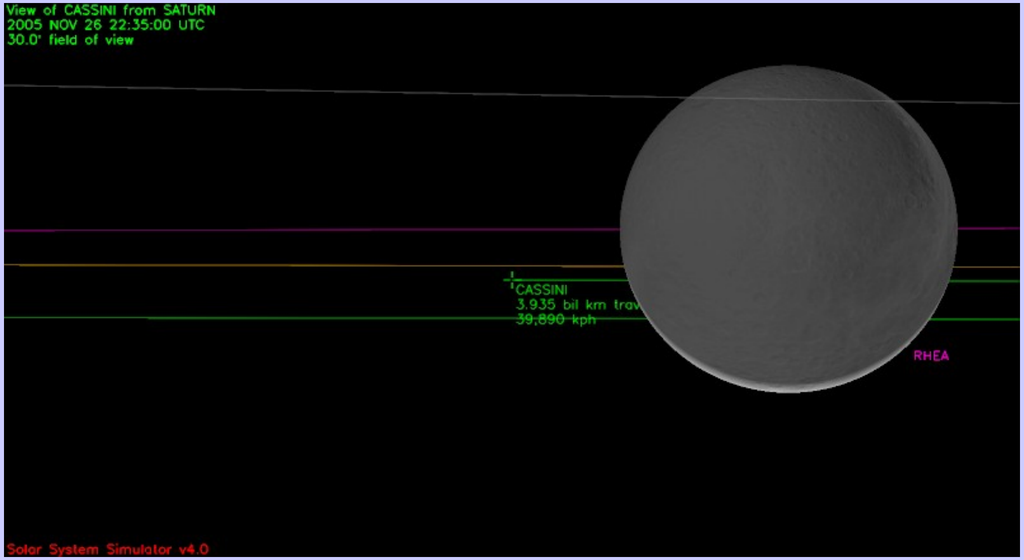


- Normalized moment of inertia is small (0.24-0.26)
- Secondary resonance unlikely

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 $k_f = 1.5$:

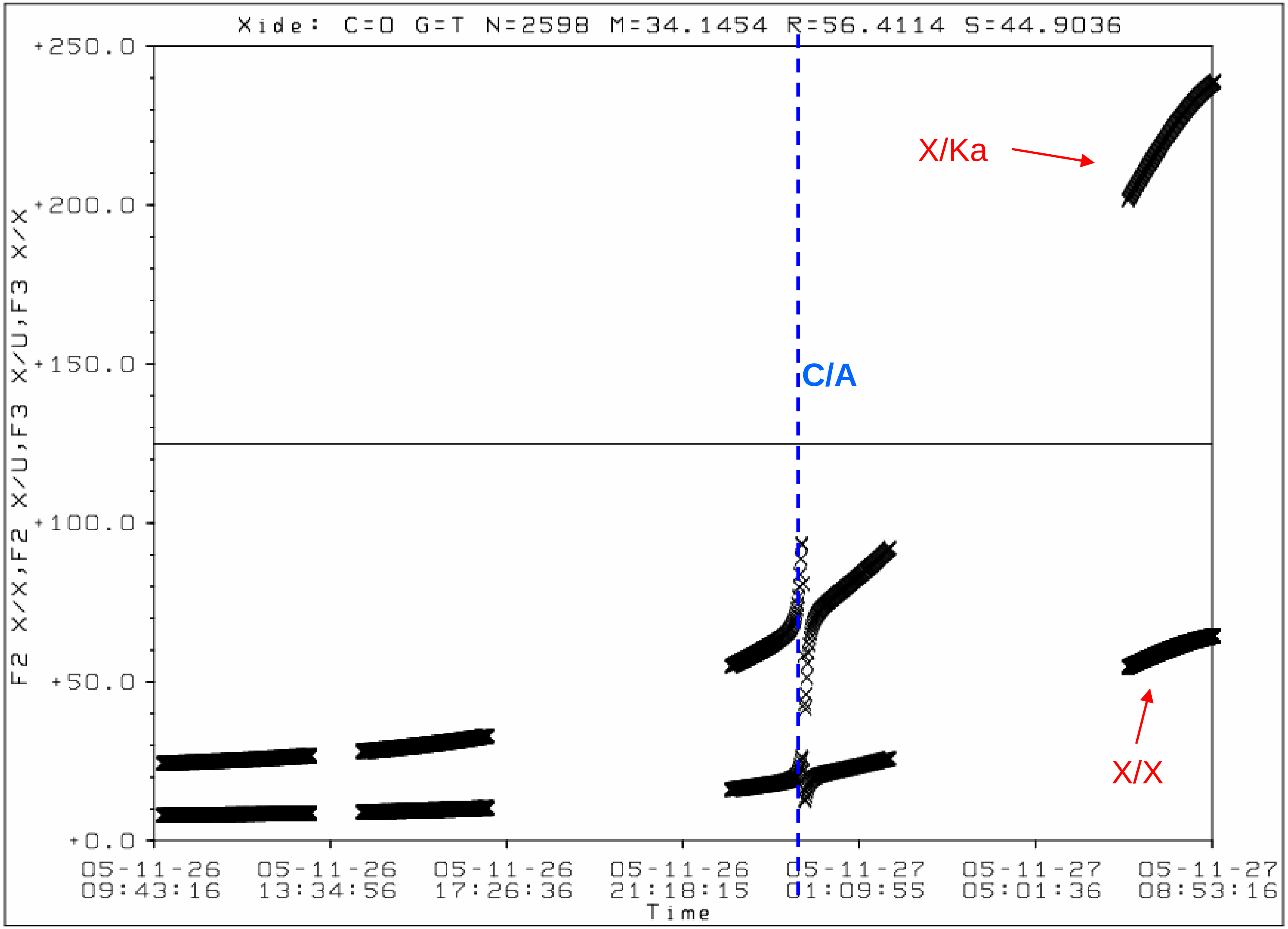
$$C_{20} \cong -9.3 \cdot 10^{-4}$$

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

with ratio:

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

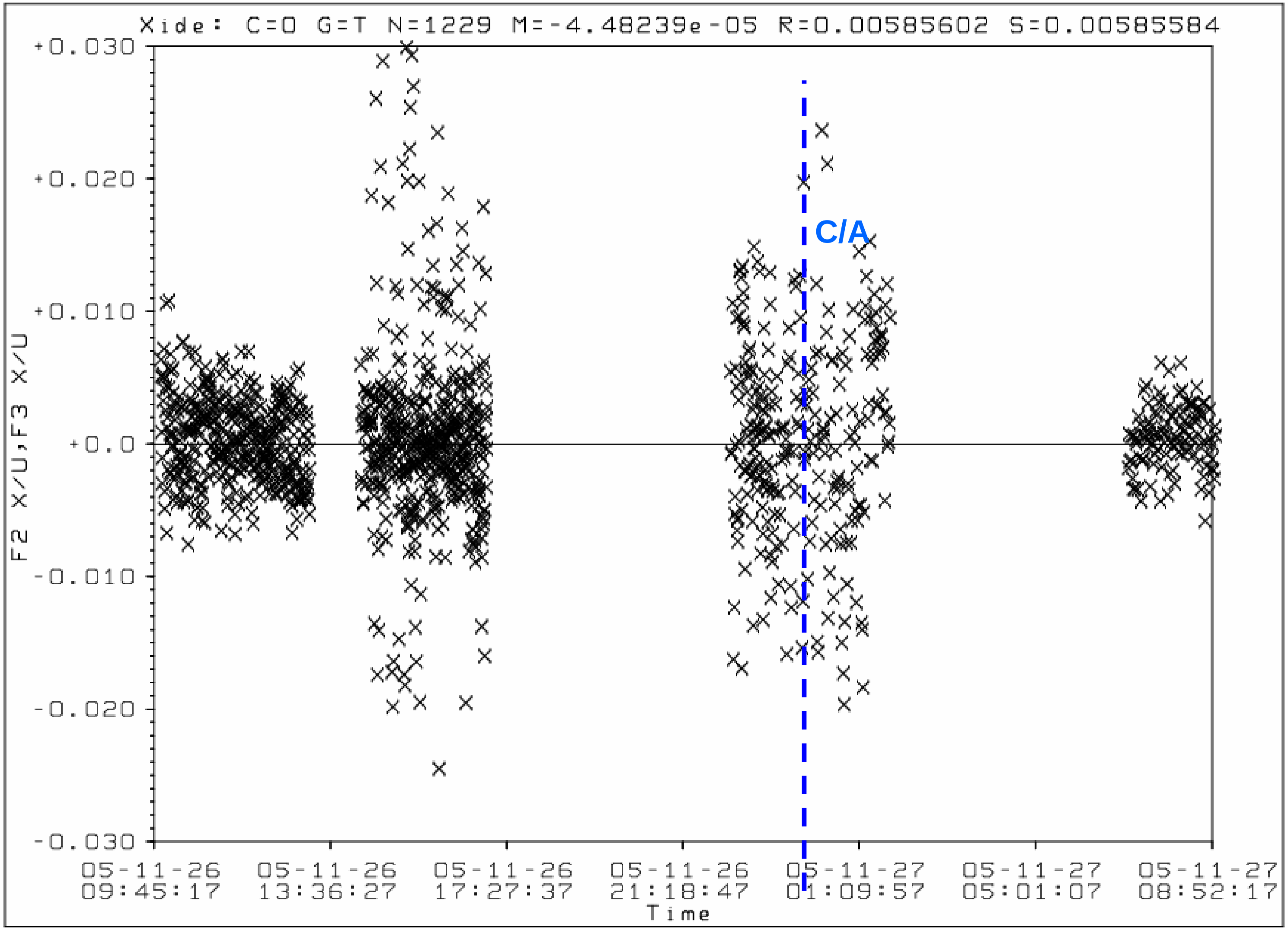
Rhea Doppler Residuals (pre fit)



Rhea Doppler Residuals X/Ka (postfit)

1471 F3 data points

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



Rhea Measured quantities

- GM = 153.9528 ± 0.0162 km^3/s^2
- ρ = **1233 ± 10 kg/m^3**
- C_{20} = $7.10 \cdot 10^{-4} \pm 1.59 \cdot 10^{-4}$
- C_{22} = $2.34 \cdot 10^{-4} \pm 3.61 \cdot 10^{-6}$
- Hydrostatic values
- All models indicate a low degree of differentiation

$$\sigma_{rel}(C_{20}) = 22\%$$

$$\sigma_{rel}(C_{22}) = 1.5\%$$

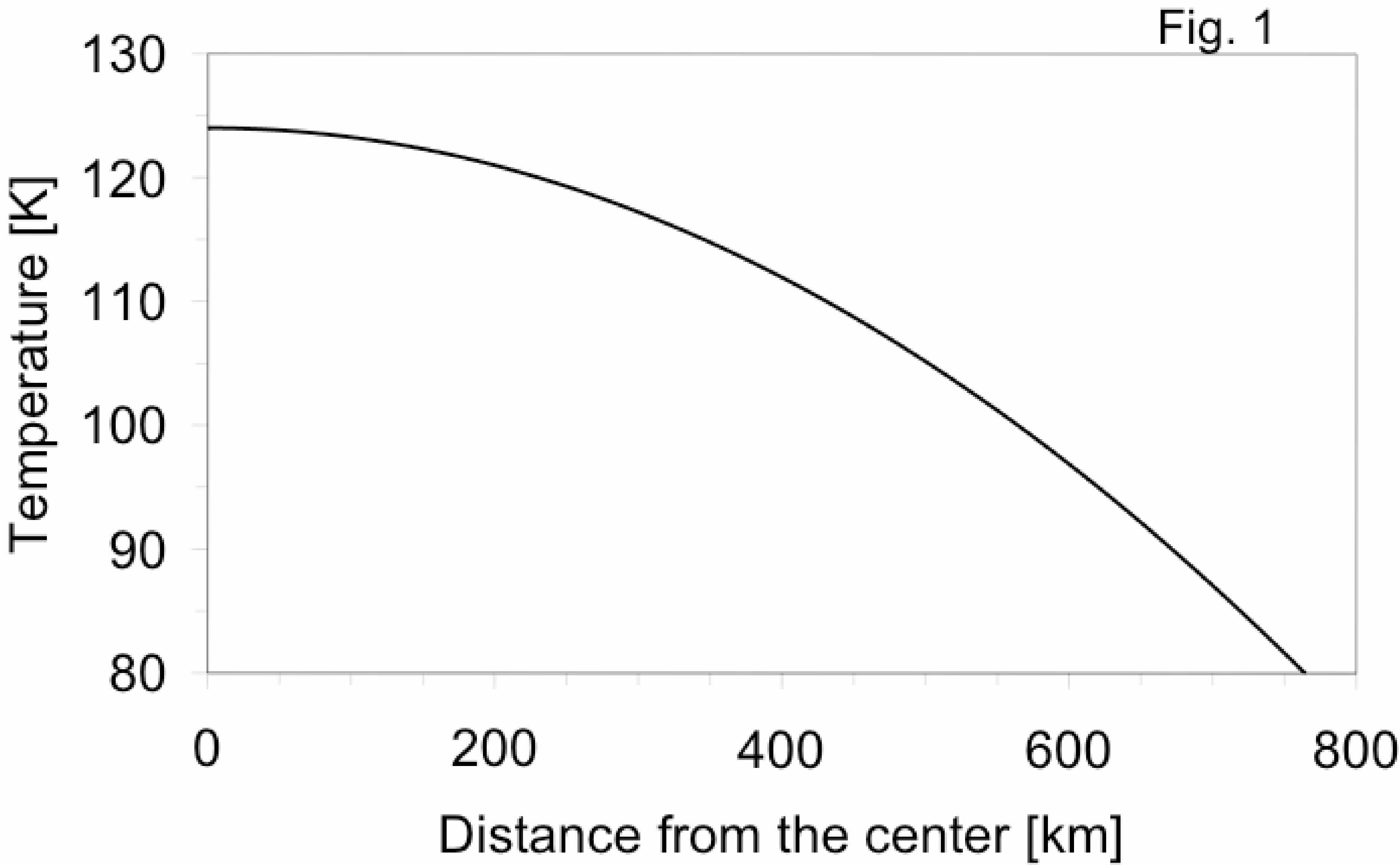
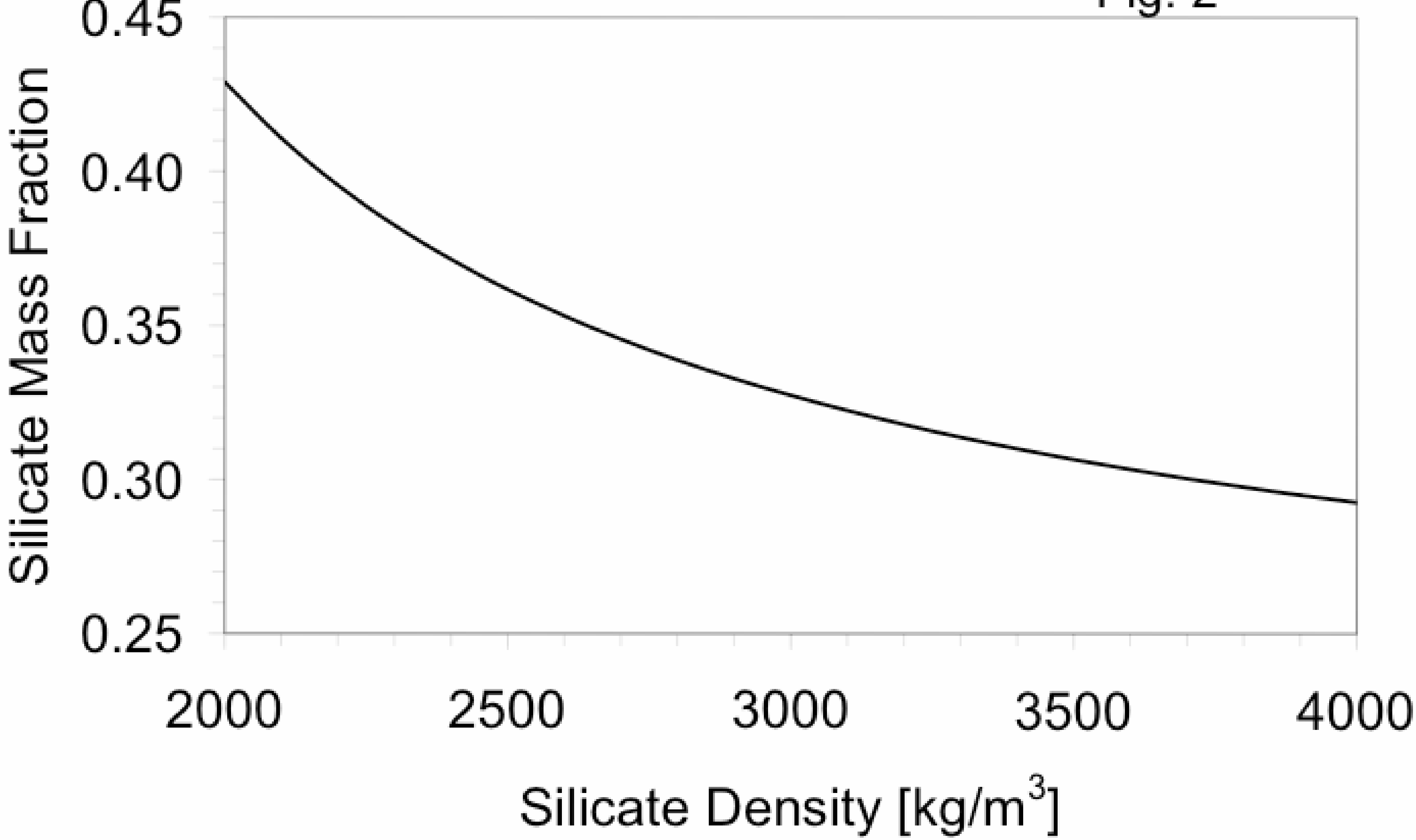


Fig. 1
130
120
110
100
90
80
0
200
400
600
800
Temperature [K]
Distance from the center [km]


0.45
0.40
0.35
0.30
0.25
Silicate Mass Fraction
2000
2500
3000
3500
4000
Silicate Density [kg/m3]

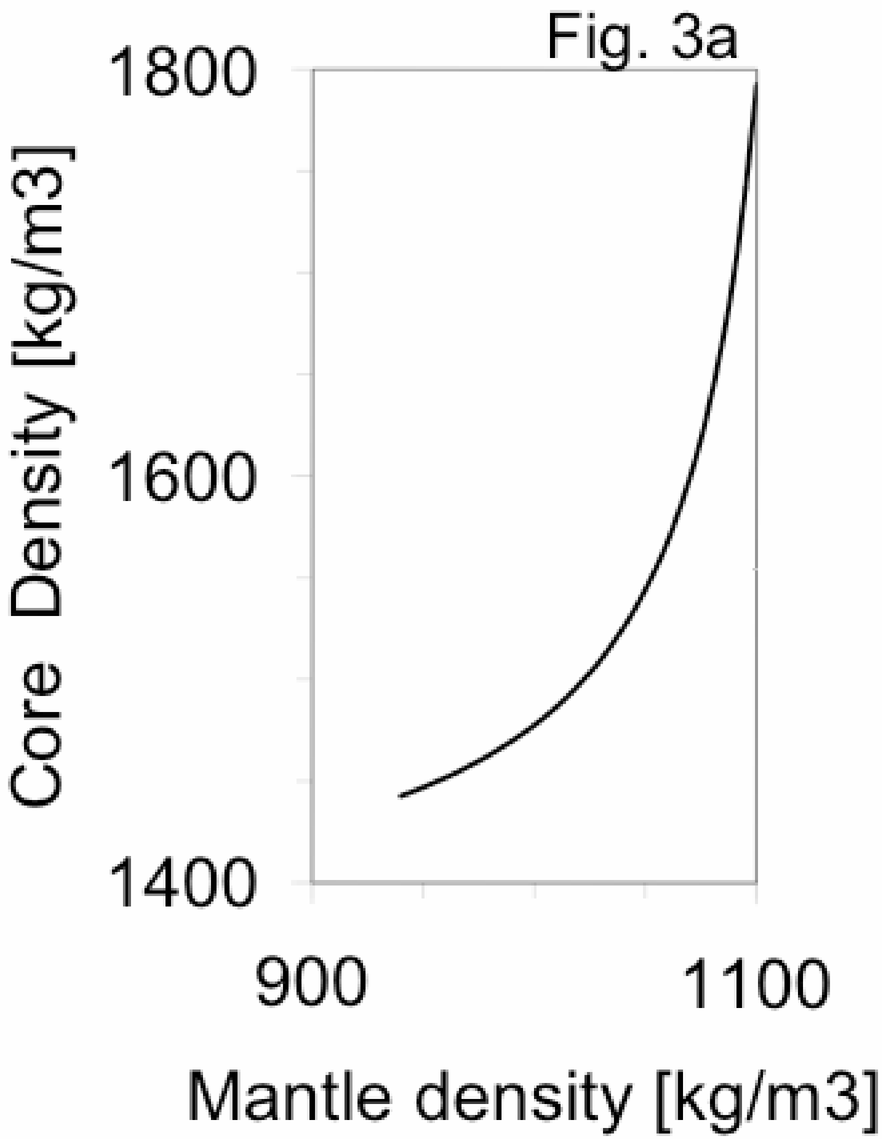


Fig. 3a
1800
1600
1400
Core Density [kg/m3]
900
1100
Mantle density [kg/m3]

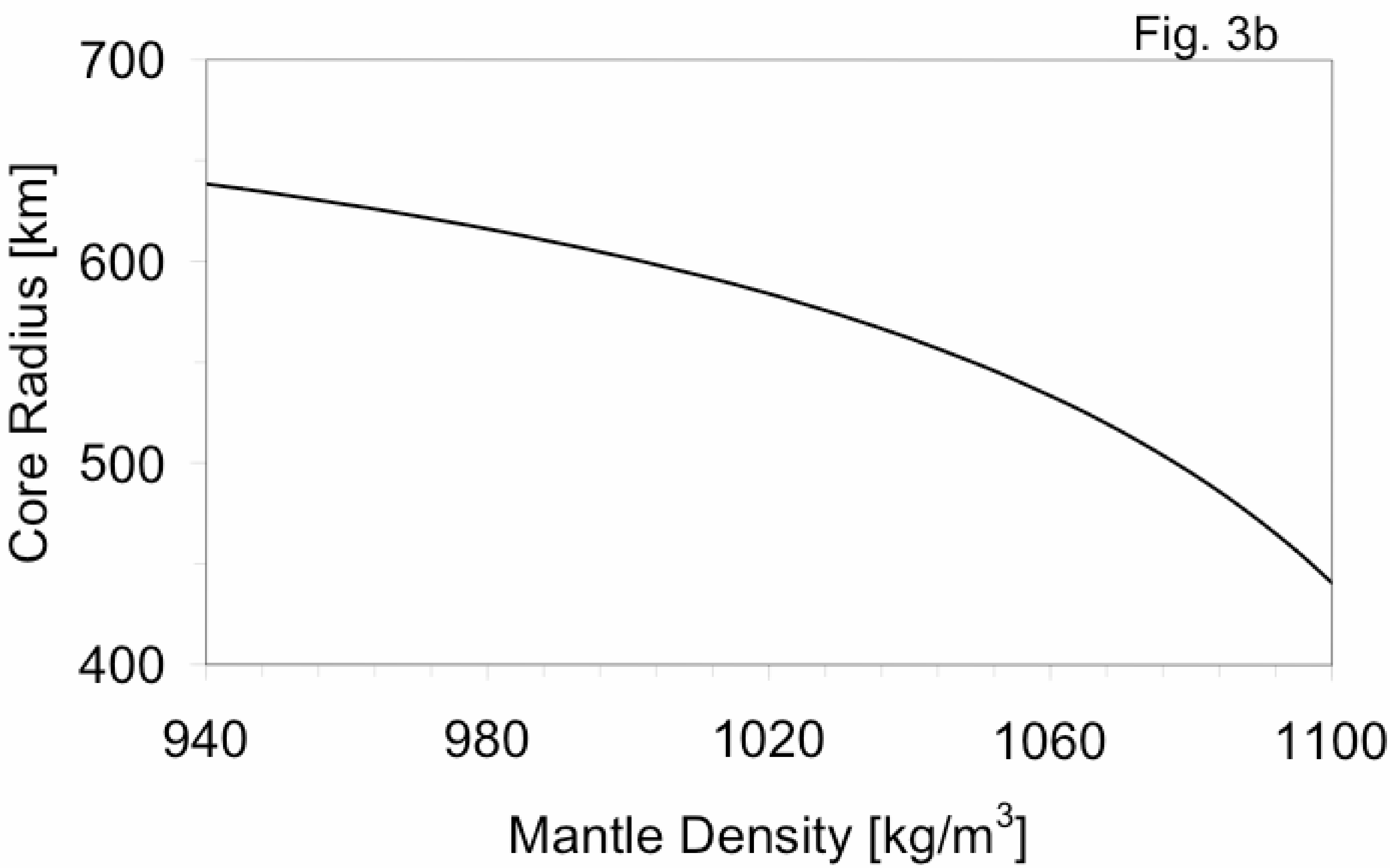


Fig. 3b
700
600
500
400
Core Radius [km]
940
980
1020
1060
1100
Mantle Density [kg/m3]

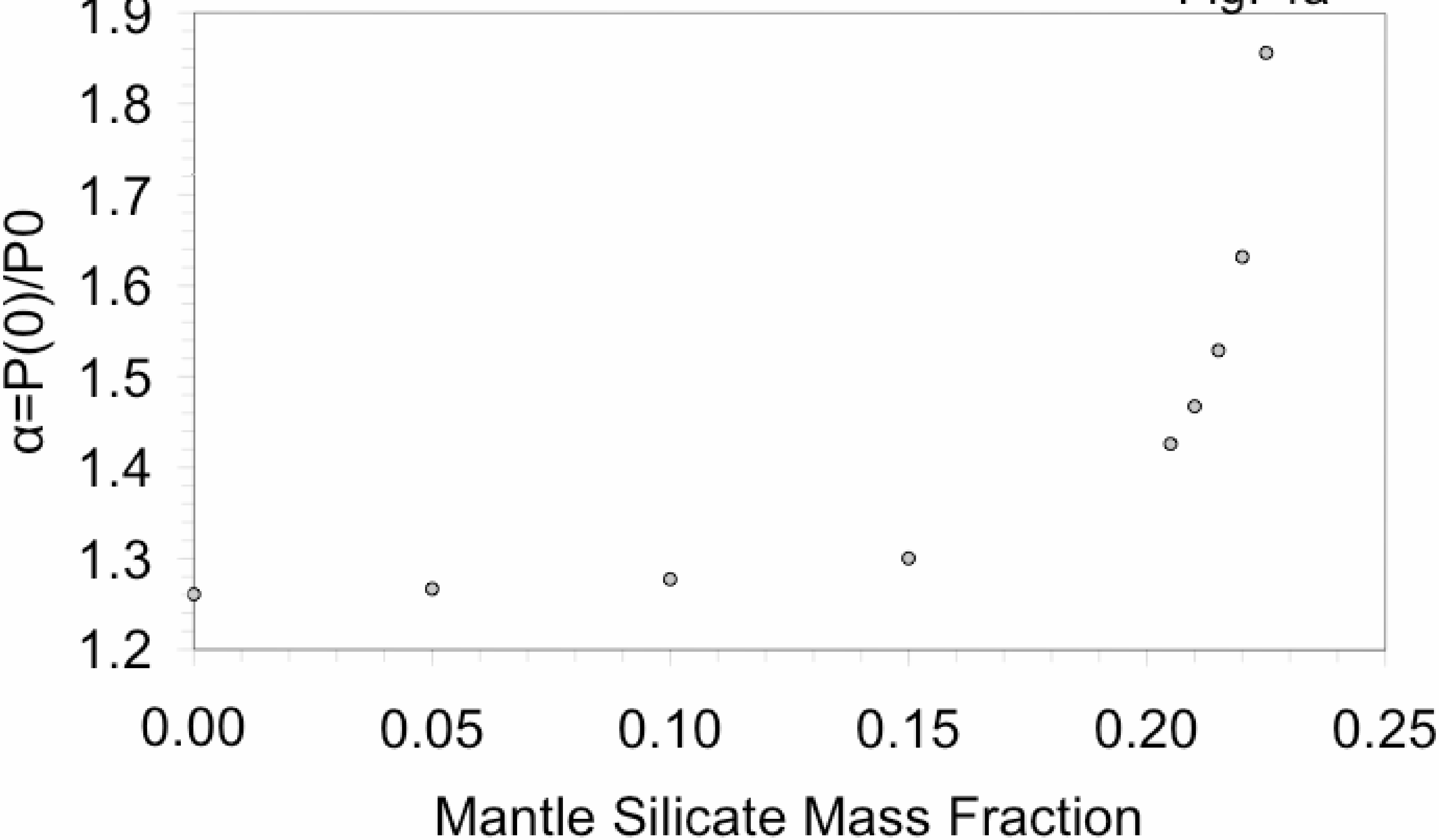

1.9
1.8
1.7
1.6
1.5
1.4
1.3
1.2
α=P(0)/P0
0.00
0.05
0.10
0.15
0.20
0.25
Mantle Silicate Mass Fraction

Fig. 4a

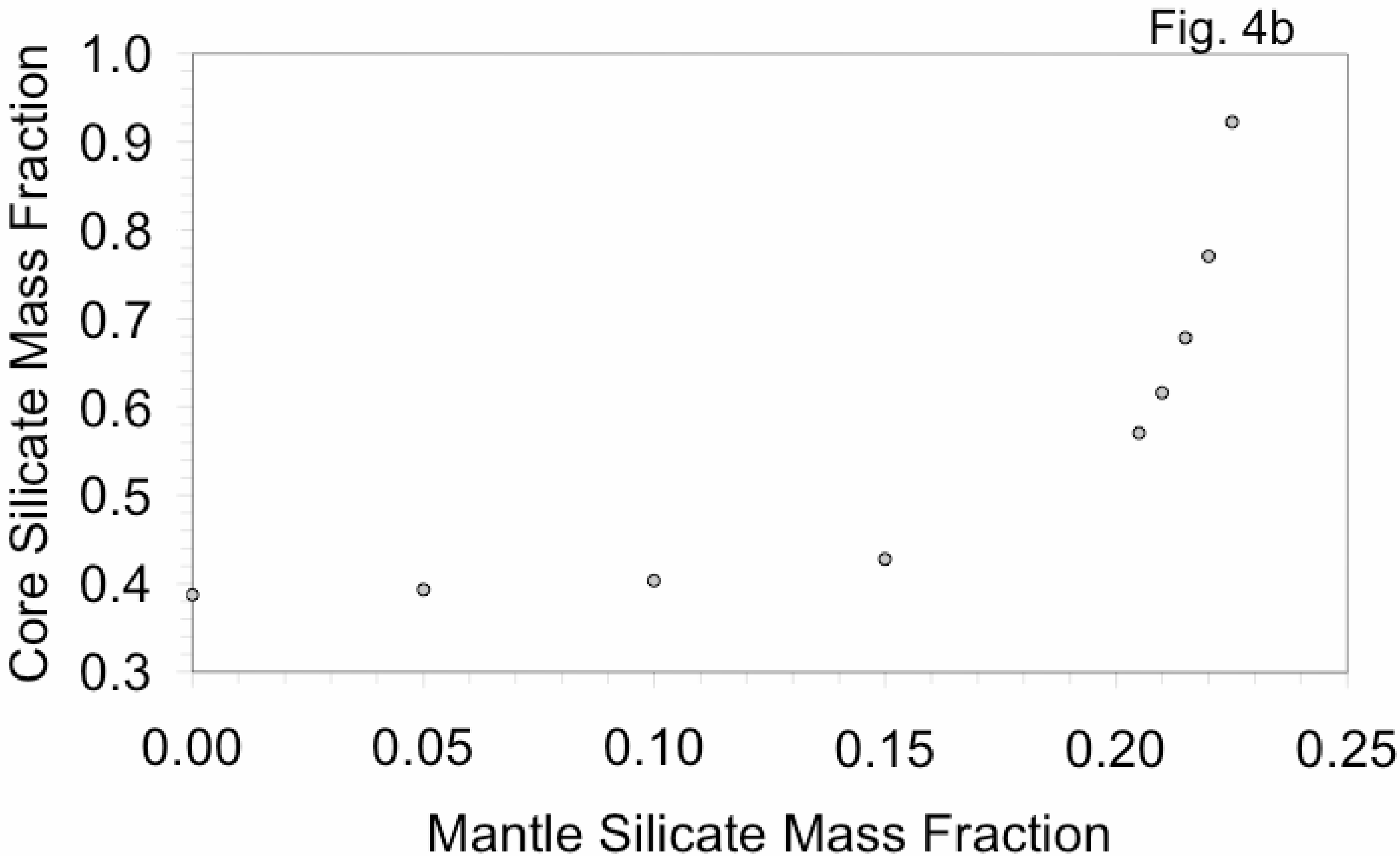


Fig. 4b
Core Silicate Mass Fraction
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.00
0.05
0.10
0.15
0.20
0.25
Mantle Silicate Mass Fraction

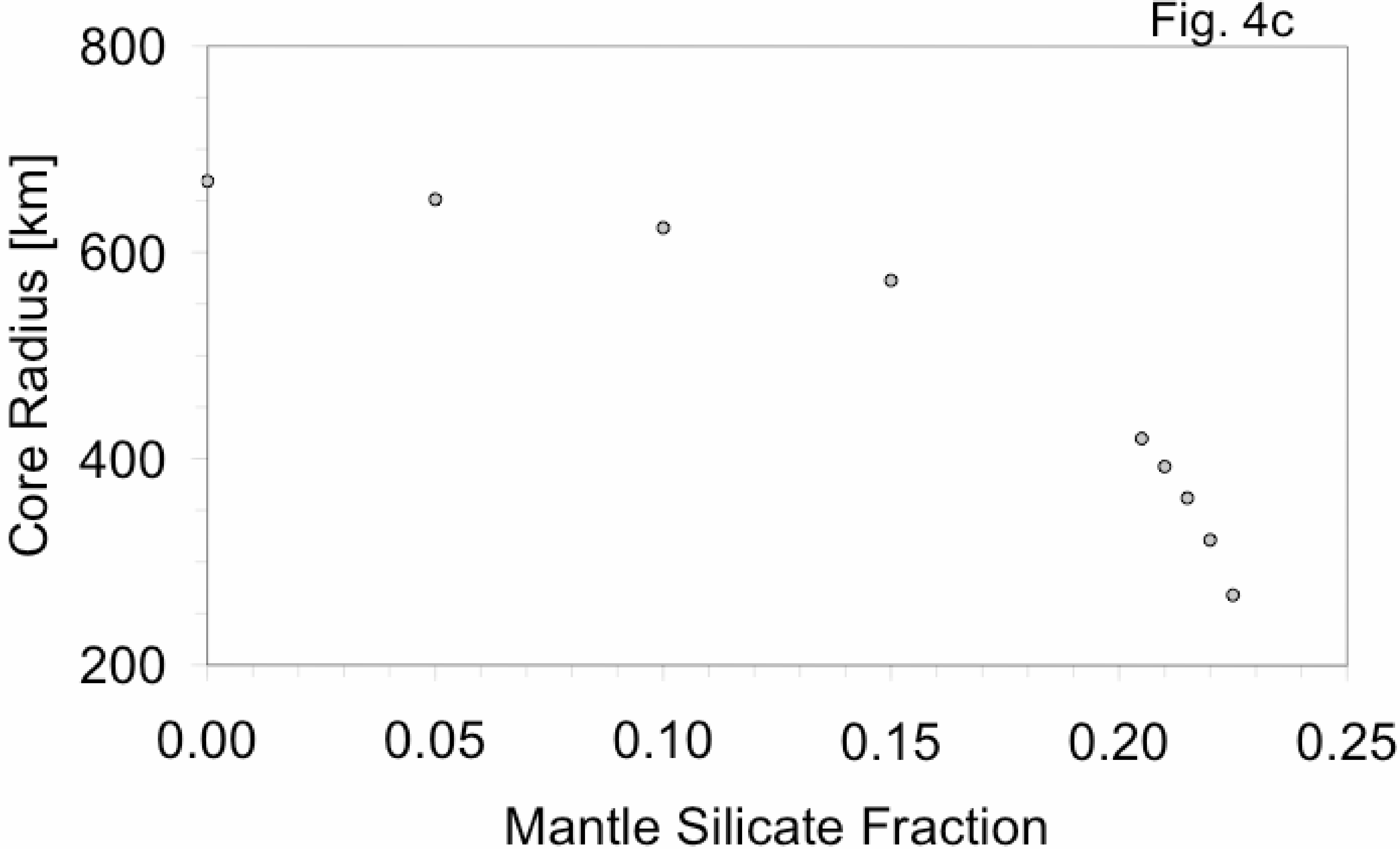


Fig. 4c
800
600
400
200
Core Radius [km]
0.00
0.05
0.10
0.15
0.20
0.25
Mantle Silicate Fraction

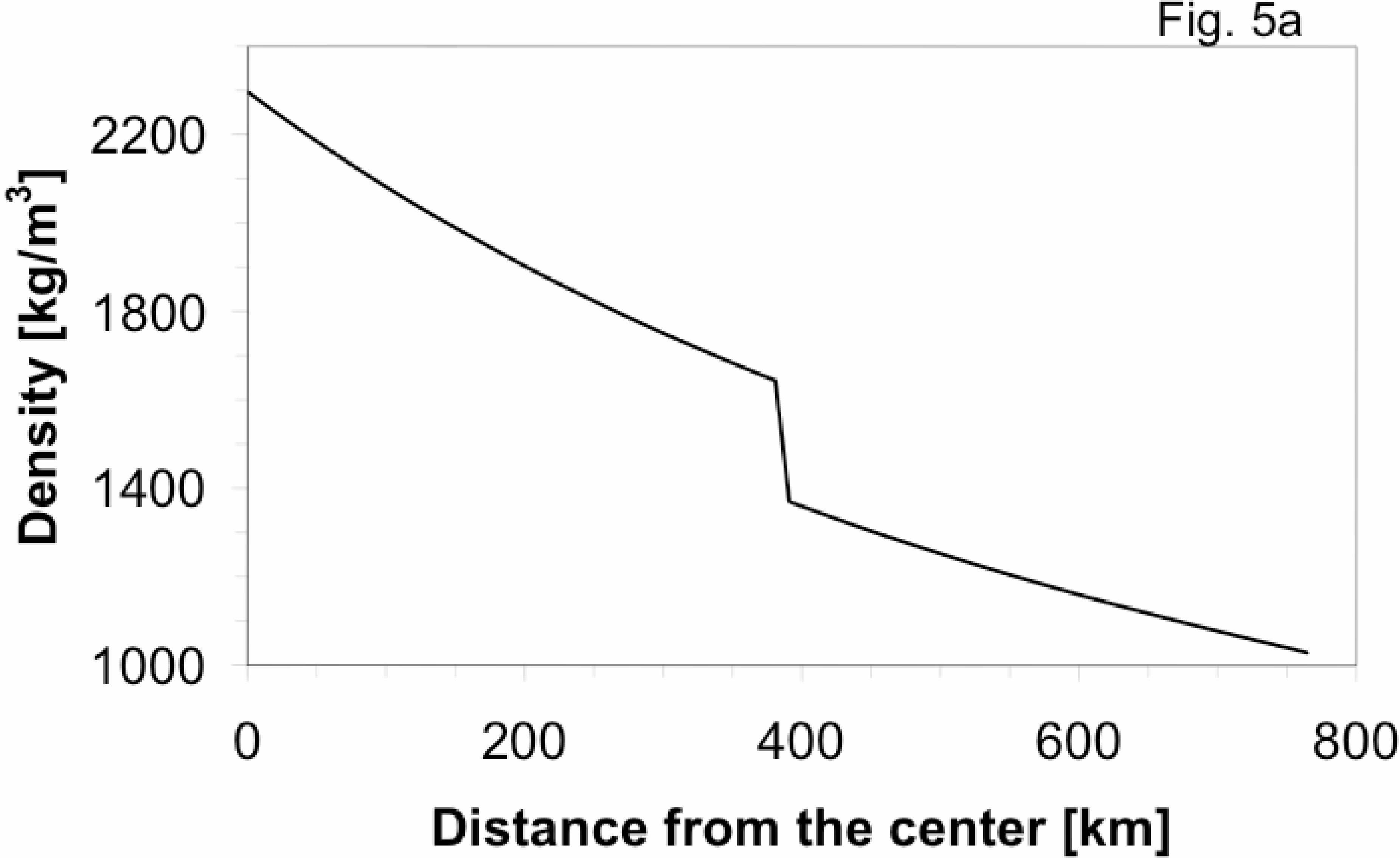


Fig. 5a
Density [kg/m3]
2200
1800
1400
1000
0
200
400
600
800
Distance from the center [km]

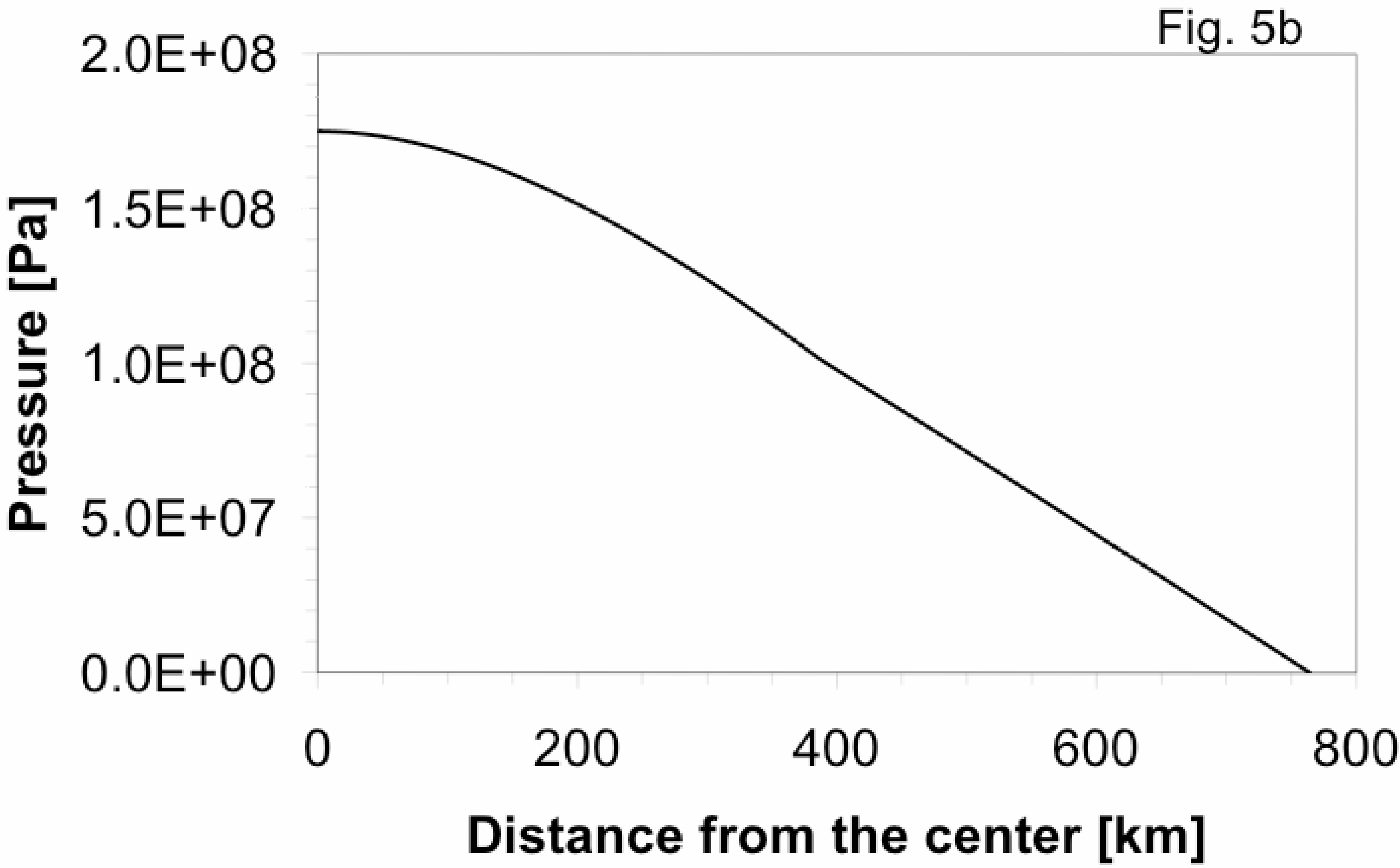


Fig. 5b
2.0E+08
1.5E+08
1.0E+08
5.0E+07
0.0E+00
Pressure [Pa]
0
200
400
600
800
Distance from the center [km]

Next measurements

- Titan quadrupole field (first gravity flyby completed on 28 Feb. 2006)
- Titan dynamic Love number
- Titan obliquity and moment of inertia (in collaboration with the Radar Team)
- Theoretical models of Titan interior make accurate predictions on k_2 and C/MR^2 (Tobie, Lunine and Sotin, 2006)