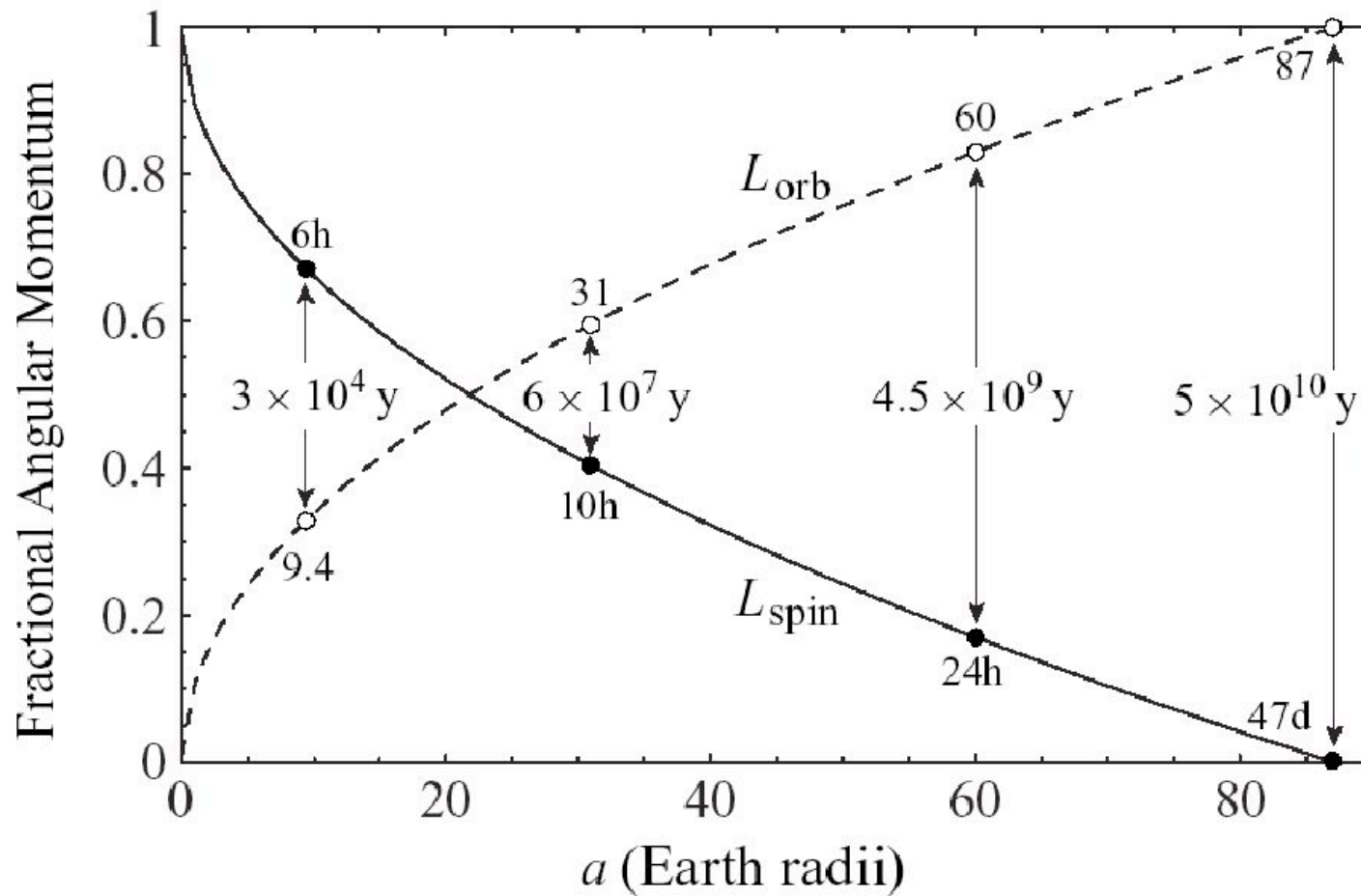
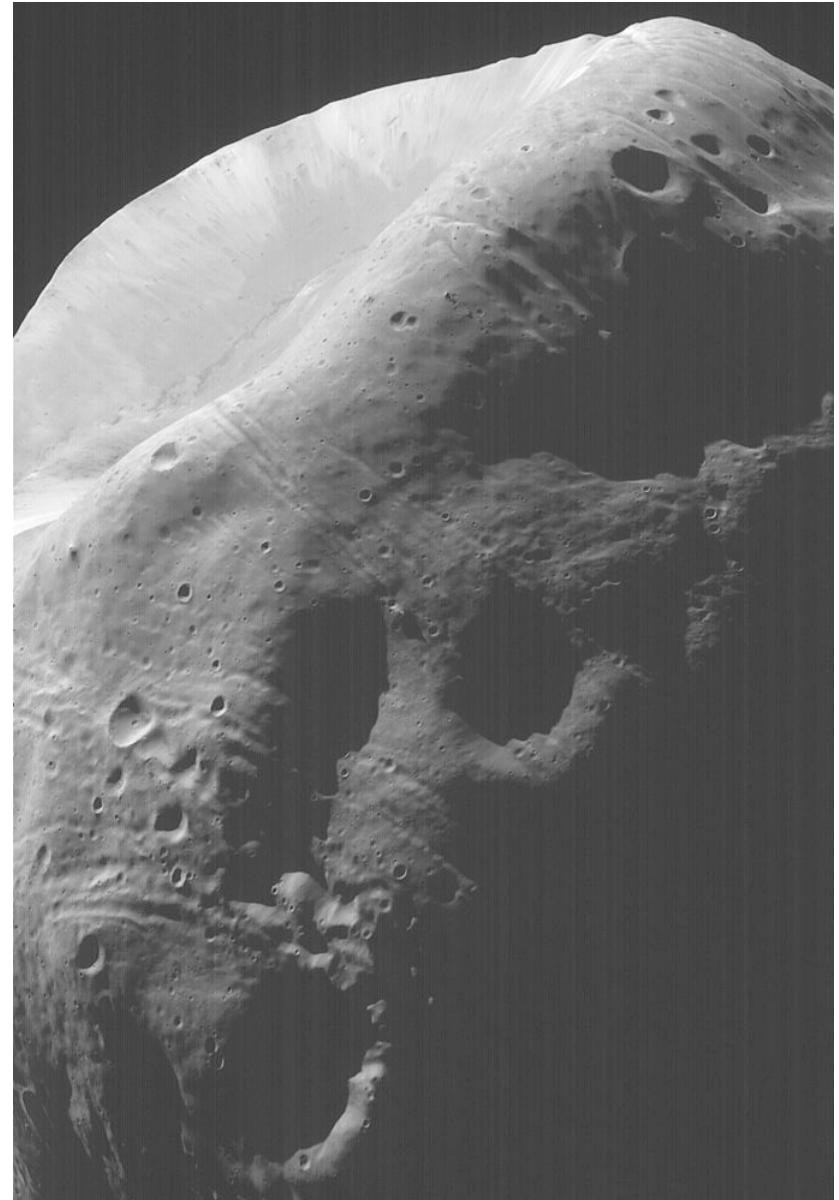
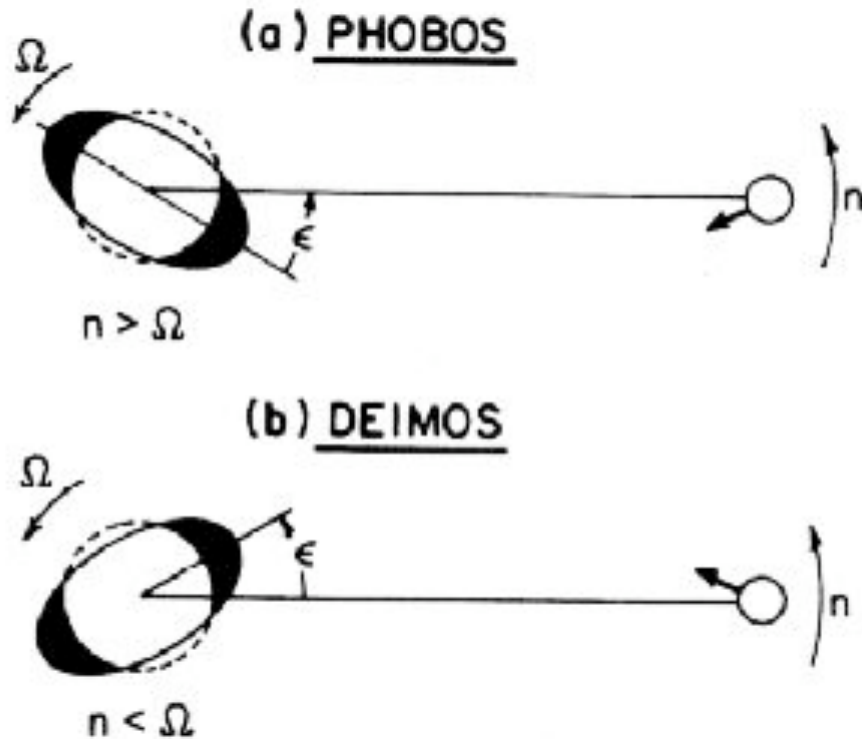


# Evolution lunaire



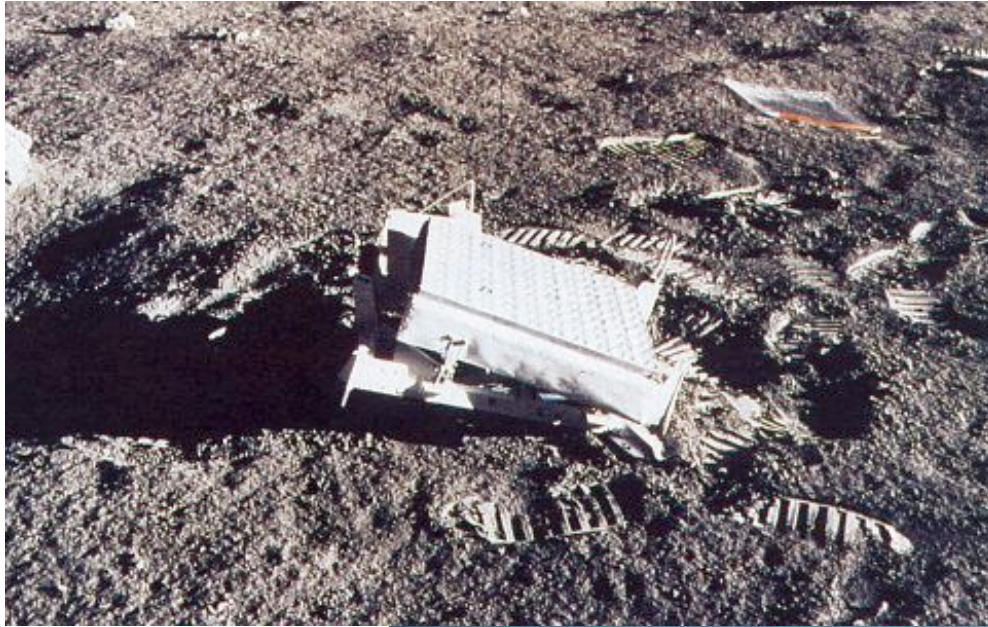
# Accélération séculaire de Phobos



- éloignement lent de Deimos
- chute de Phobos d'ici 20-30 millions d'années

# Mesure pour la Lune

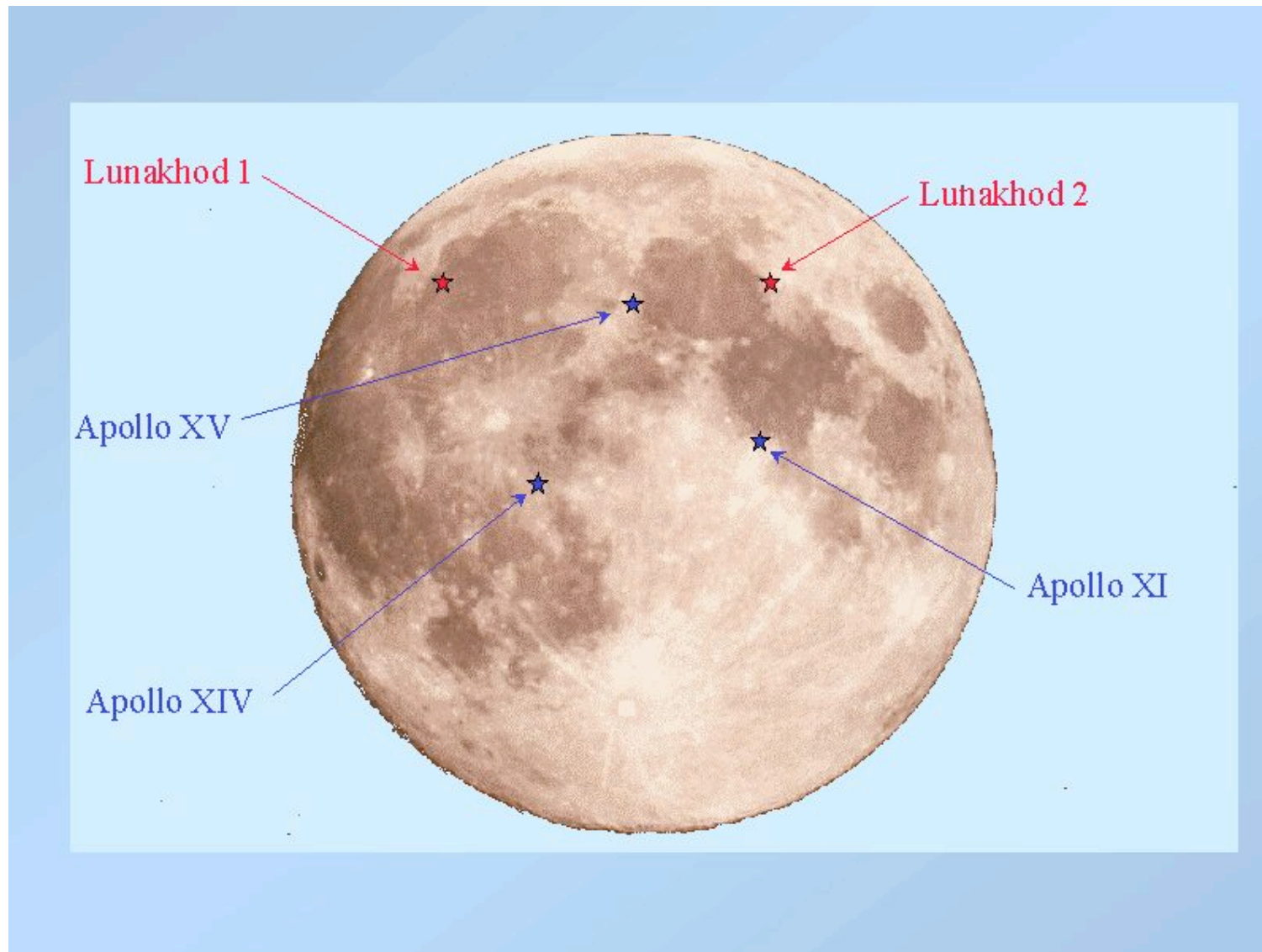
---



- $C/Ma2 = 0.3932 \pm 0.0002$



# Position des réflecteurs sur la Lune



# Interpretation

$$I = \int dV \rho d^2 \approx \frac{2}{3} \int dV \rho r^2$$

Cas homogène

$$\frac{I}{Ma^2} = 0.4$$

$$-\frac{dP}{dr} + \rho g = 0$$

$$M(r) = \frac{4\pi}{3} \rho r^3$$

$$g = -G \frac{M(r)}{r^2} = -\frac{4\pi G}{3} \rho r$$

d'où

$$P = P_s + \frac{2\pi G}{3} \rho^2 (a^2 - r^2)$$

Cas compressible

$$\rho \vec{g} - \nabla p = \vec{0}$$

$$\frac{1}{K} = \frac{1}{\rho} \frac{\partial \rho}{\partial P}$$

$$\nabla \cdot \vec{g} = -4\pi G \rho$$

d'où, si  $K=K_0+bp$  ( $K_0=1.5 \cdot 10^{11}$  Pa,  $b=8$ )

$$\rho = \rho_0 \left[ 1 + \frac{\xi}{a^2} (a^2 - r^2) - \frac{\eta}{a^4} (a^2 - r^2)^2 \right]$$

avec

$$\xi = \frac{2\pi}{3} \frac{G \rho_0^2 a^2}{K_0}, \eta = \frac{2\pi^2}{9} \frac{b G^2 \rho_0^4 a^4}{K_0^2} = \frac{1}{2} b \xi^2$$

et

$$M = \frac{4\pi}{3} a^3 \rho_0 \left( 1 + \frac{2}{5} \xi - \frac{8}{35} \eta \right), I = \frac{8\pi}{15} a^5 \rho_0 \left( 1 + \frac{2}{7} \xi - \frac{8}{63} \eta \right)$$

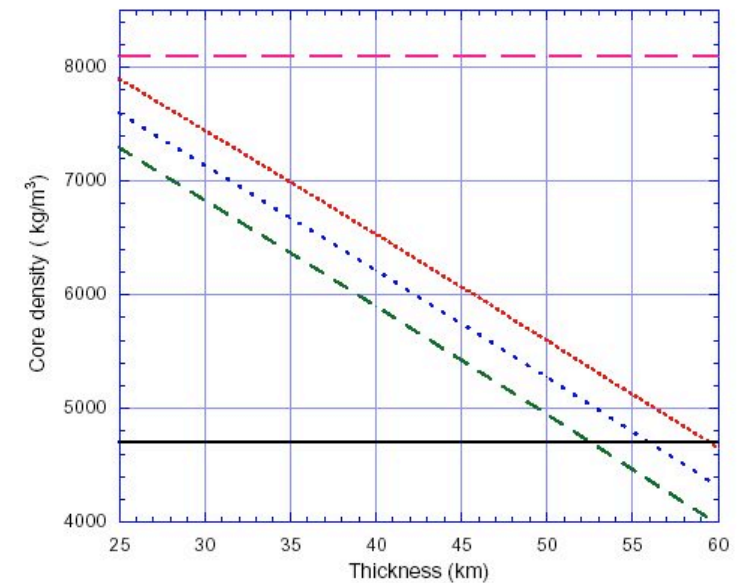
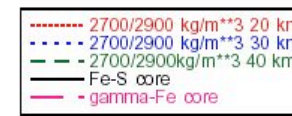
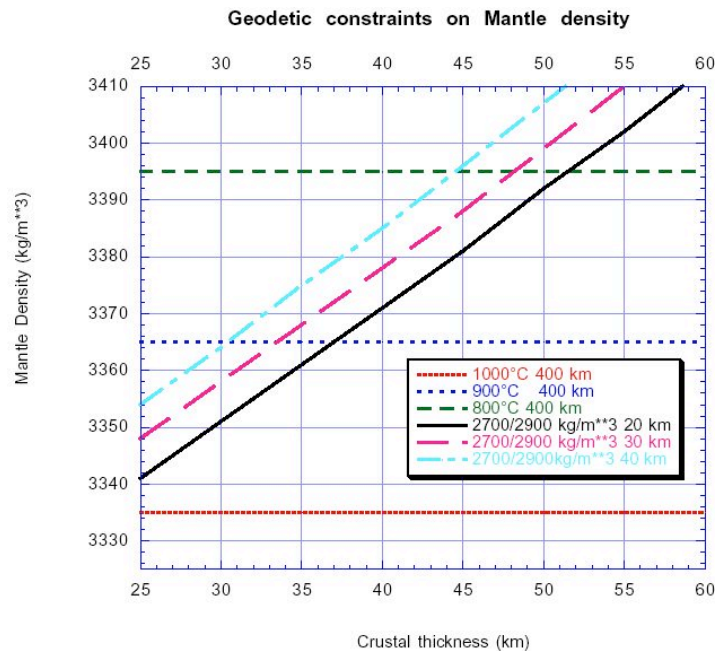
$$\frac{I}{Ma^2}$$

$$= 0.4 \left[ 1 - \frac{4}{35} \xi + \frac{8}{1575} (9 + 10b) \xi^2 \right]$$

$$= 0.3986$$

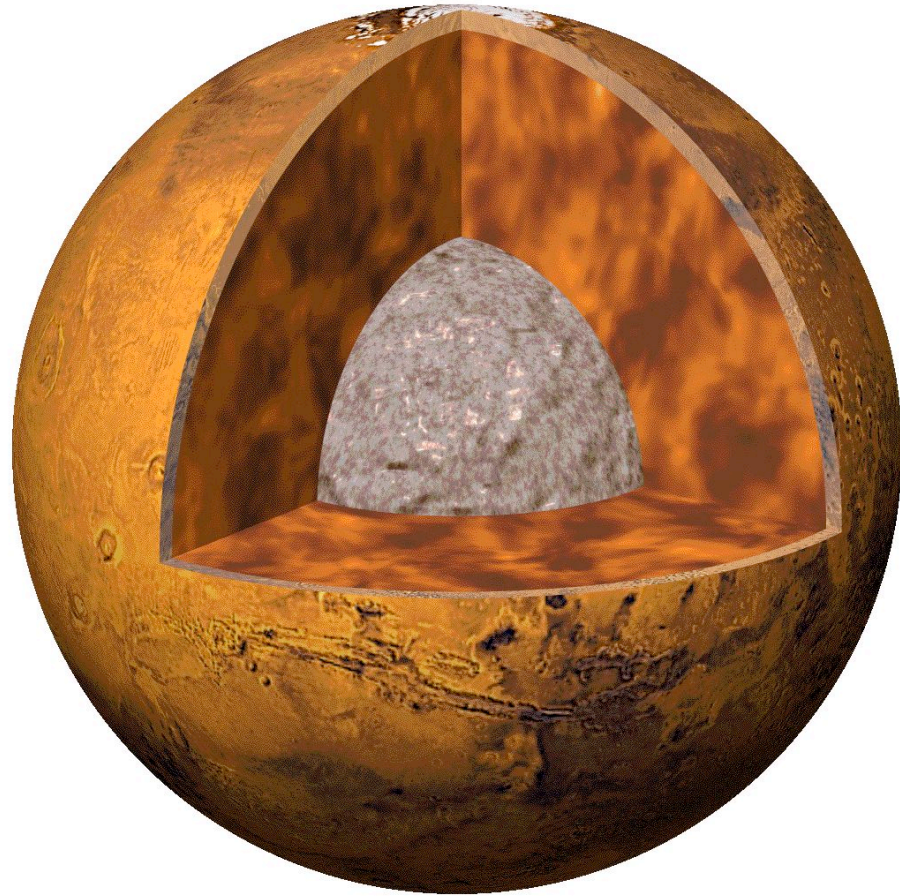
# Lune ....

- Nécessité de réduire encore le moment d'inertie par des gradients de densité avec la profondeur
  - Croûte ( $2900\text{-}3000\text{ kg/m}^3$ , 40-70 km)
  - Noyau ( $4000\text{-}8000\text{ kg/m}^3$ , 300-500 km)
- Mais indétermination forte ( 2 données, 5 paramètres pour un modèle à trois couches..)



# Mars

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# Mesure pour Mars

- Mesures de Doppler et de distance de Pathfinder, 20 ans après Viking
- Mesure directe de la vitesse de précession des équinoxes
- Le moment d'inertie est déduit à partir de l'équation de la rotation de la planète
  - Calcul des moments exercés par l'attraction des autres planètes

Constante de précession:

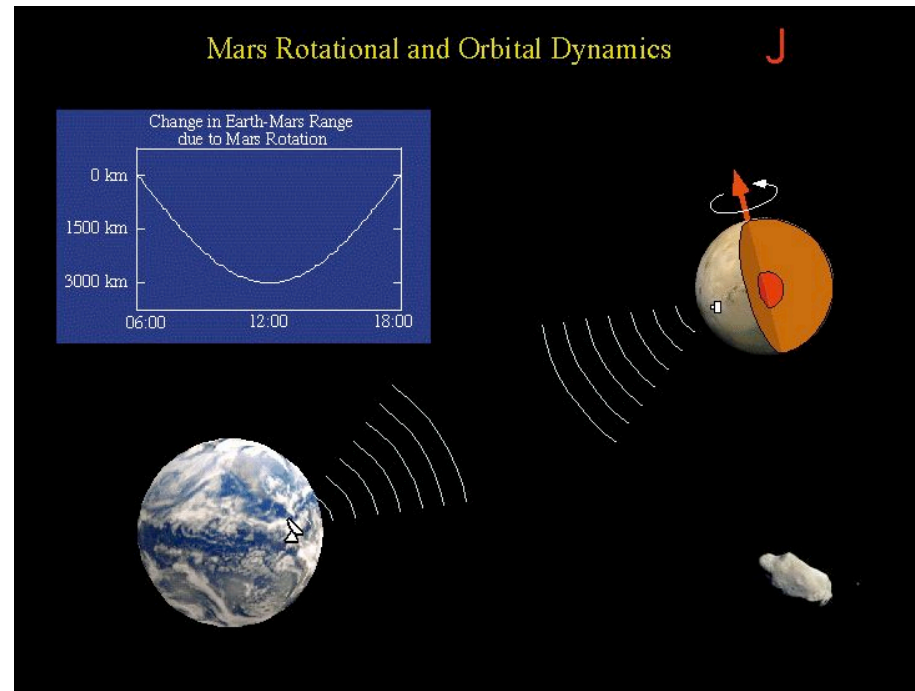
$-7576 \pm 35$  mas/an

Période de précession:

170 000 ans

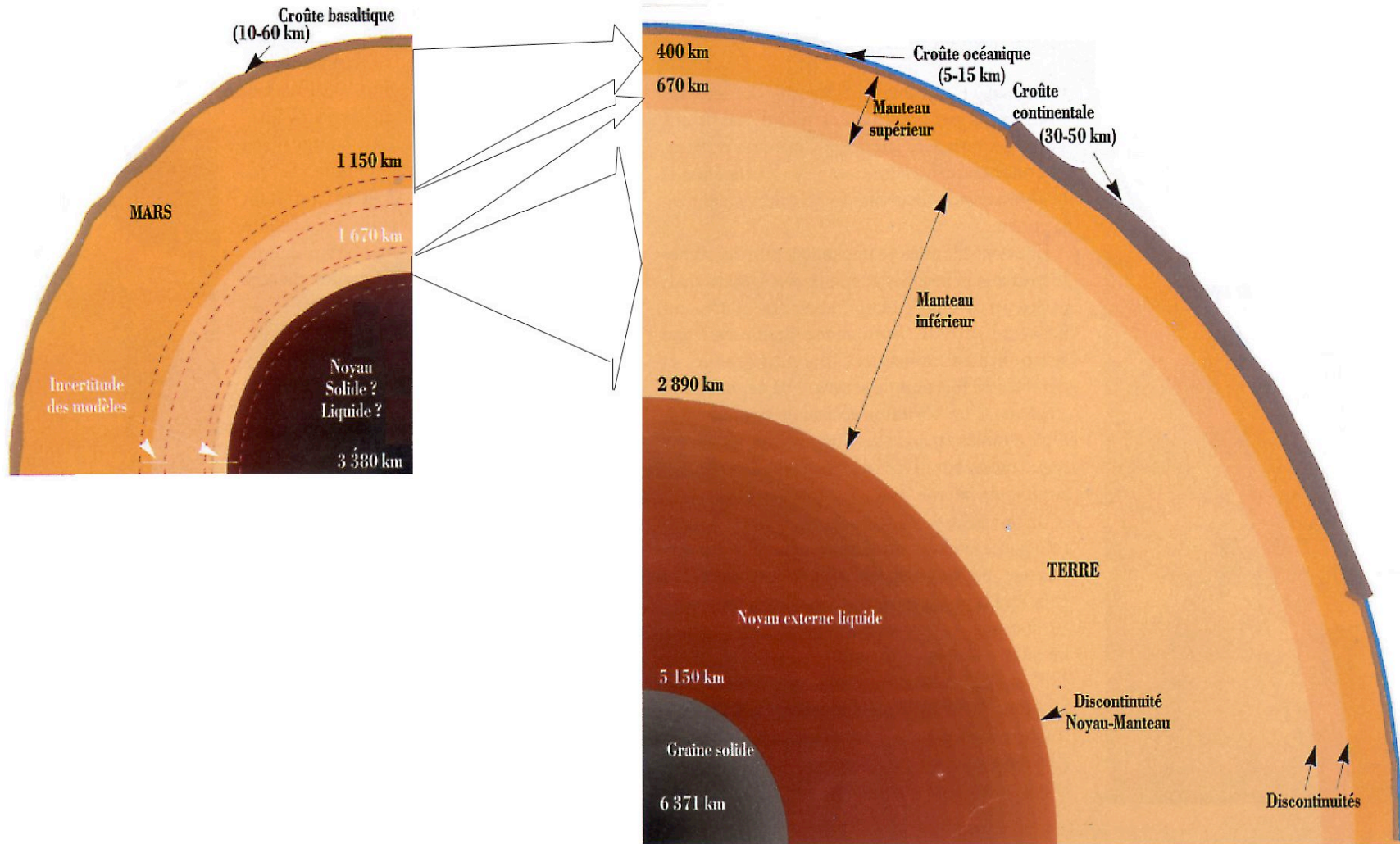
Moment d'inertie C

$C/Mr^2 = 0.3662 \pm 0.0017$



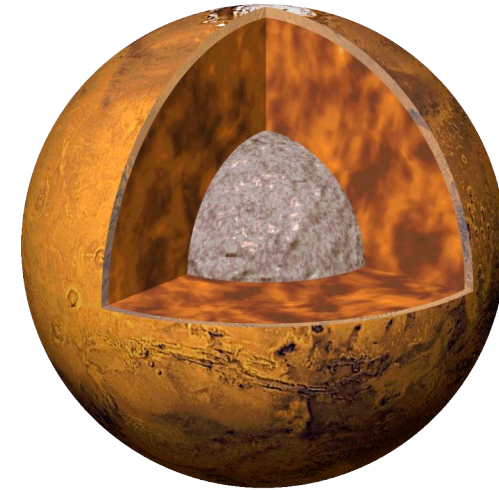
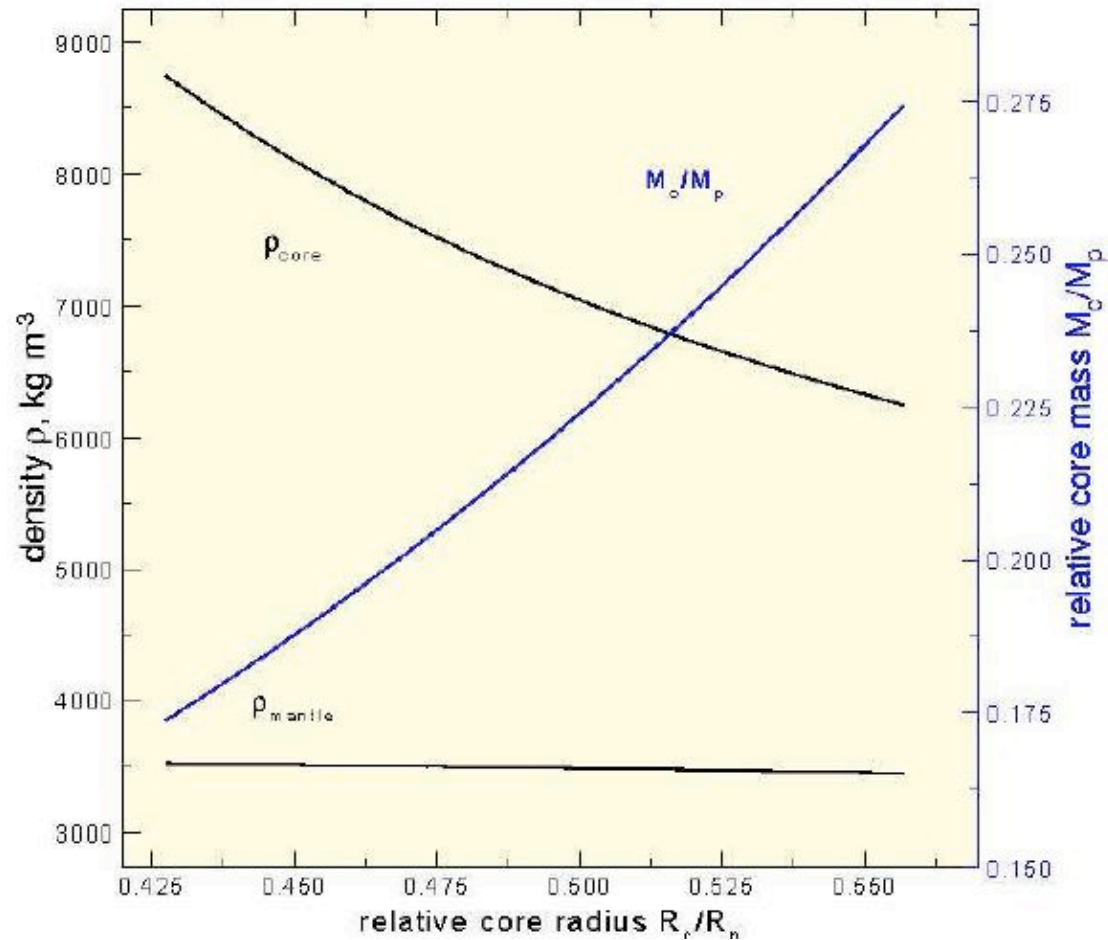


# Structure interne a priori



# Mars et son noyau

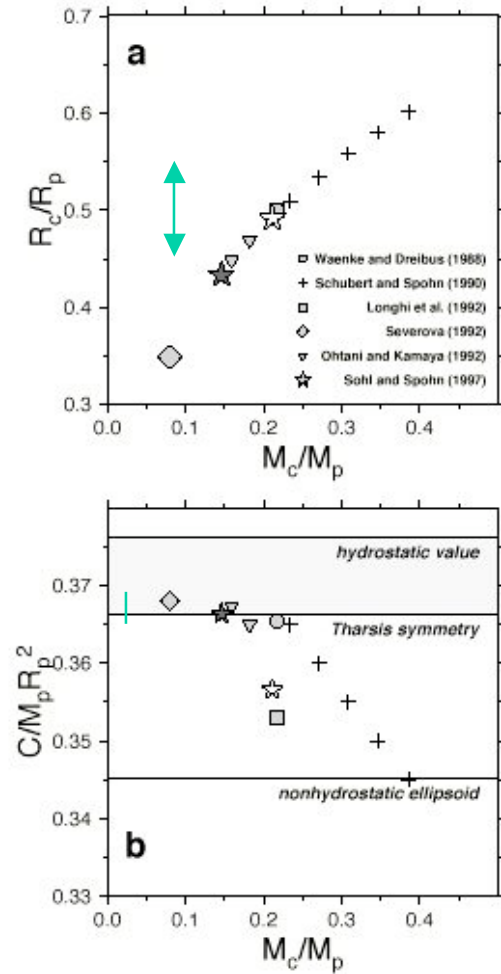
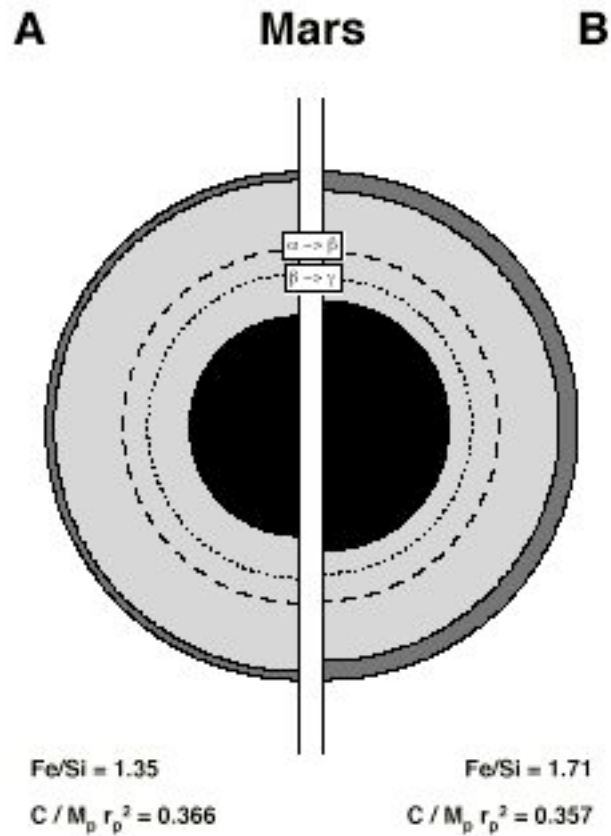
Mantle and Core Densities and Core Mass Fraction



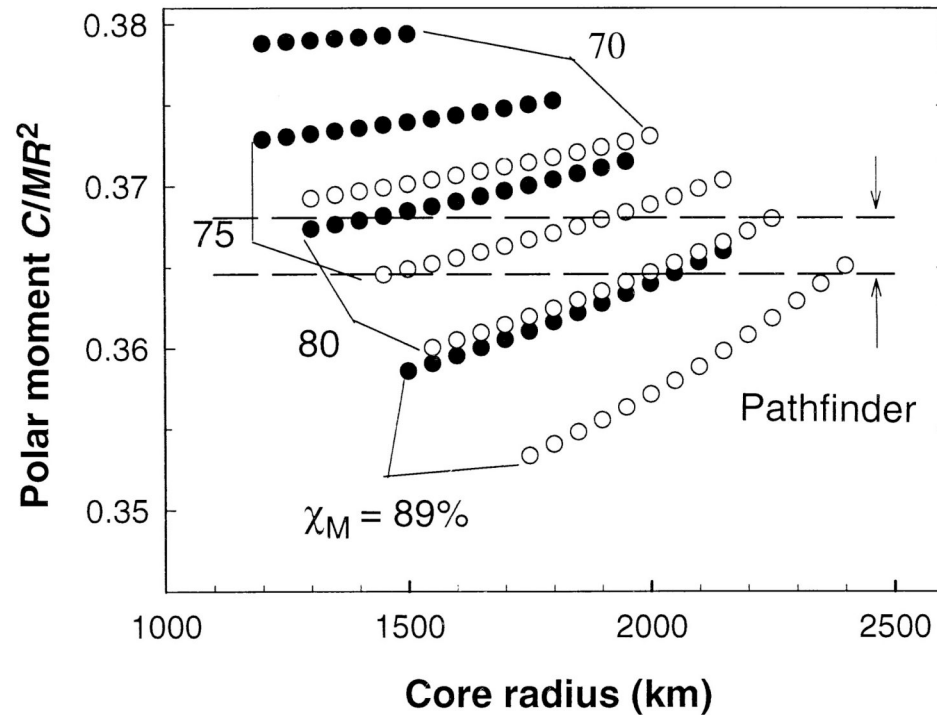
Mars

- **2 nombres sont disponibles**  
Si la densité du manteau est donnée, deux nombres peuvent être estimés ( taille et densité du noyau)

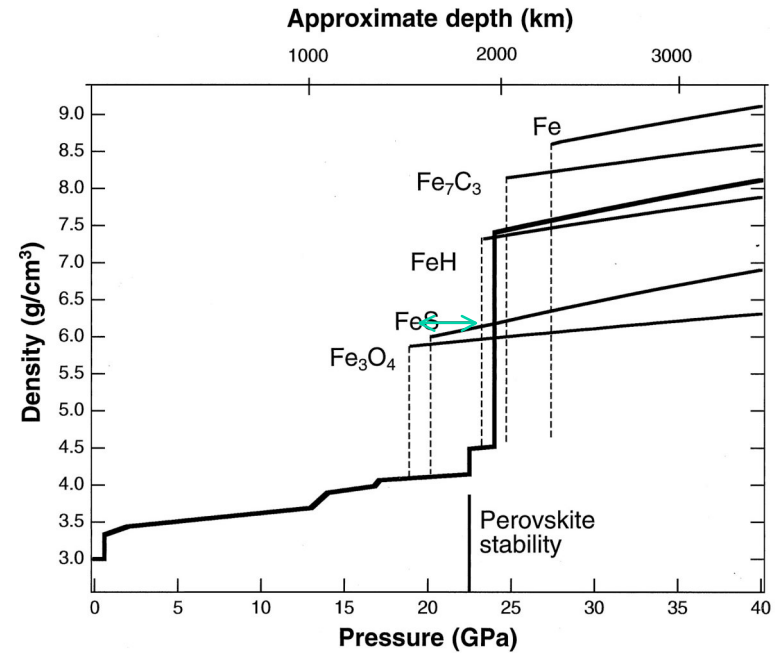
# Geophysical constraints...



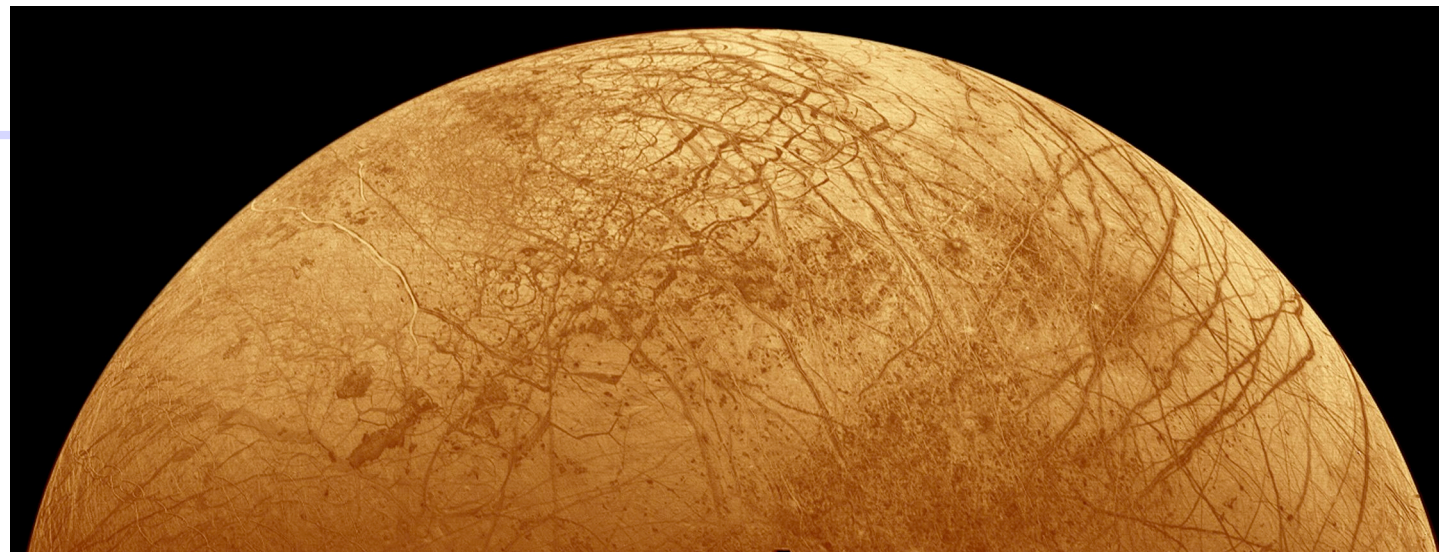
# Other constraints on the mantle and core ?



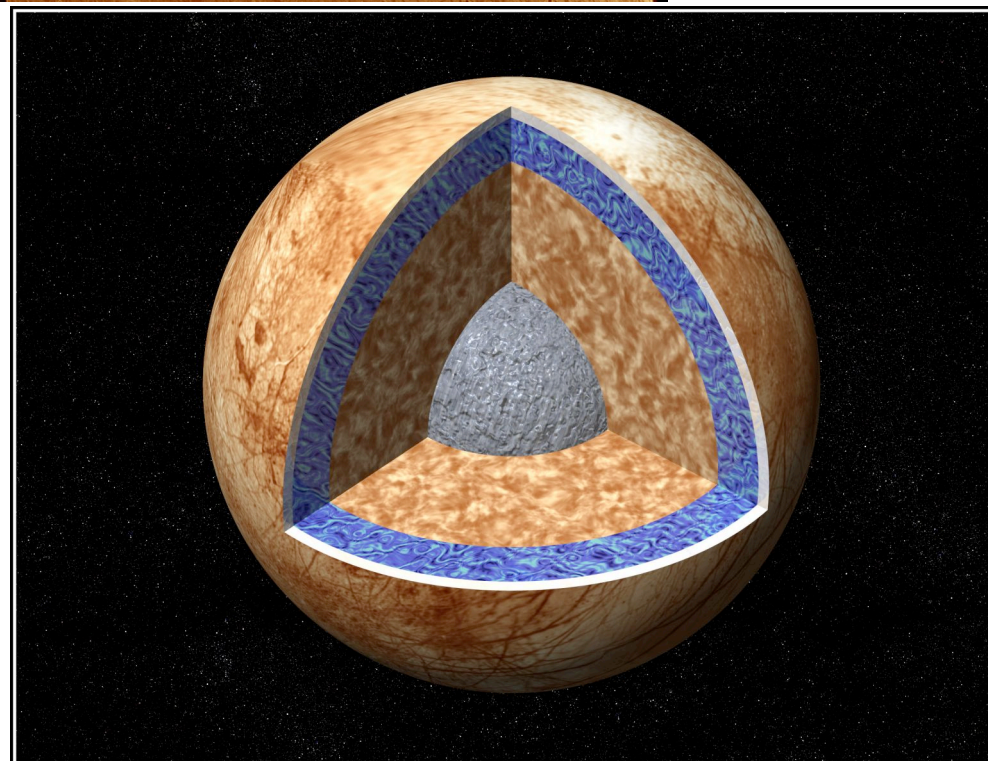
Constraints on the mantle temperature and Fe/Fe+Mg ratio:  
Folkner et Yoder, 1997



Constraints on the core size and composition: Bertka et Fei, 1998



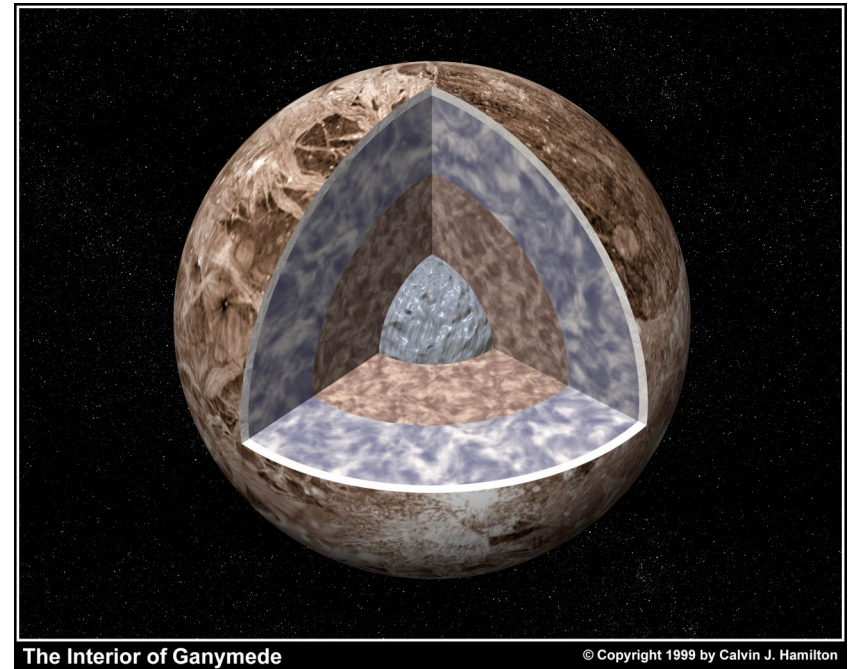
# Europa



The Interior of Europa

# Ganymede

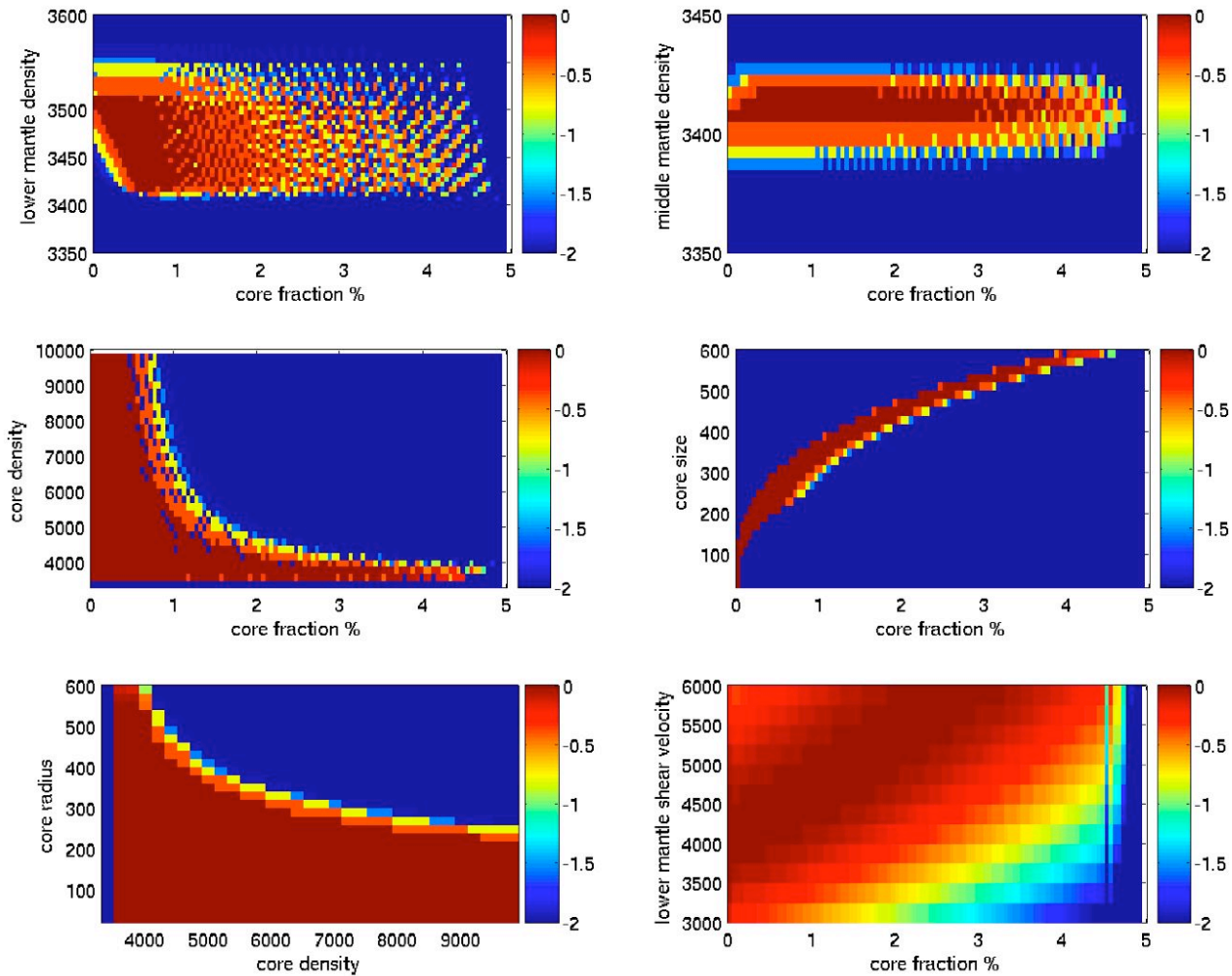
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Autre contrainte: marée

# Plus de contraintes avec la sismologie...( jusqu'à 1000km de profondeur)





# Nombre de Love et structure

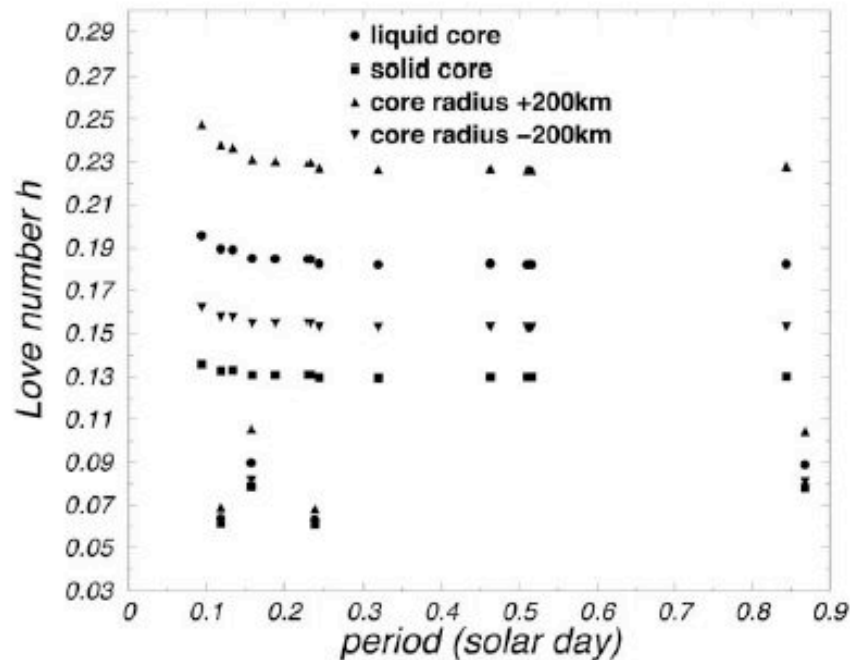


Fig. 5. Love number  $h^{(0)}$  for subdiurnal tides. Values of about 0.09 and about 0.06 are found for Love numbers of degree 3 and degree 4, respectively. All other values are for degree 2.

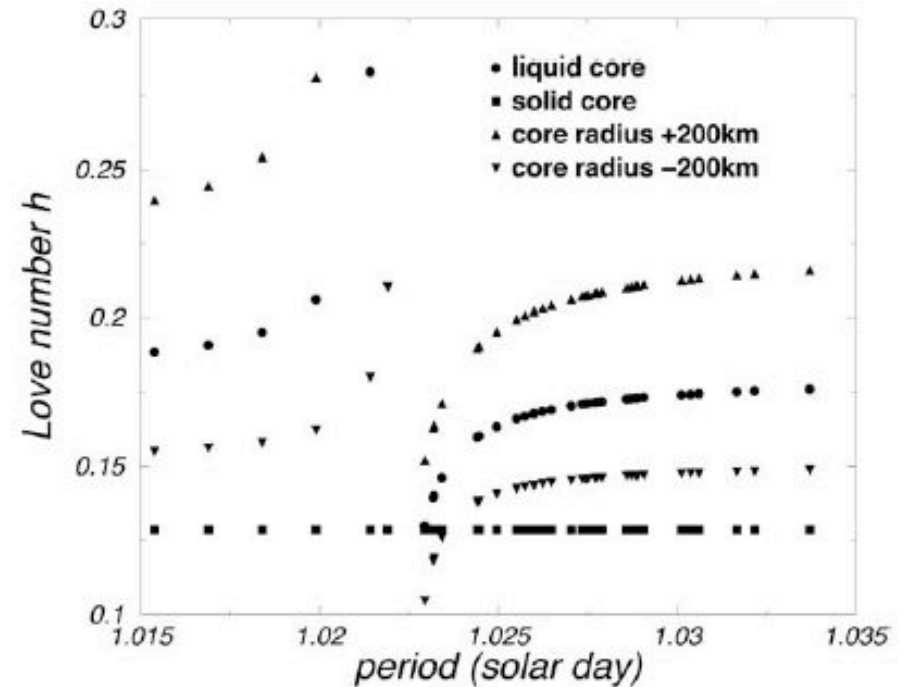


Fig. 6. Degree 2 Love number  $h^{(0)}$  for diurnal tides.

- Exemple de Mars ( cas avec ellipticit )

# Spectre d'excitation de marées (Mars)

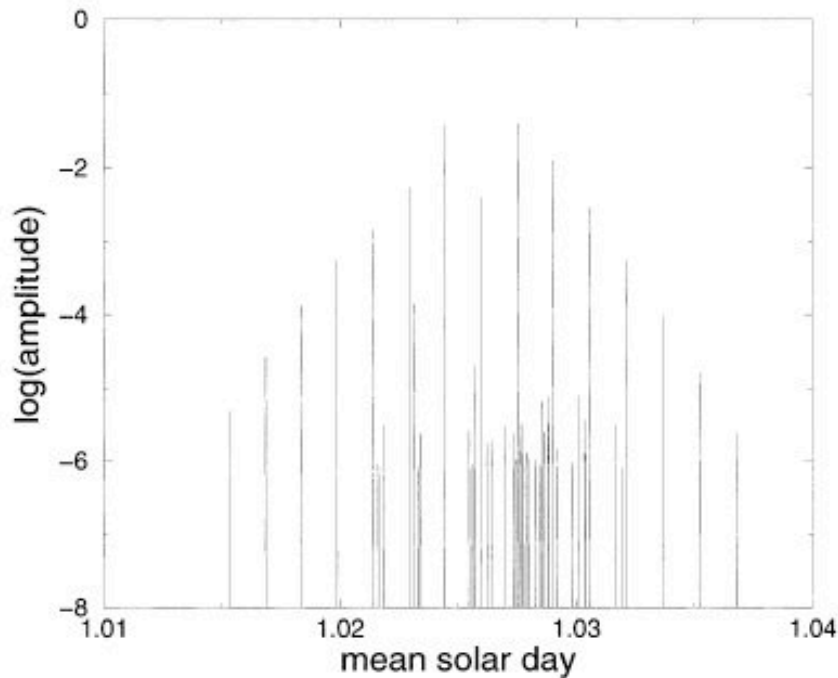


Fig. 2. Amplitudes of the diurnal tidal spectrum.

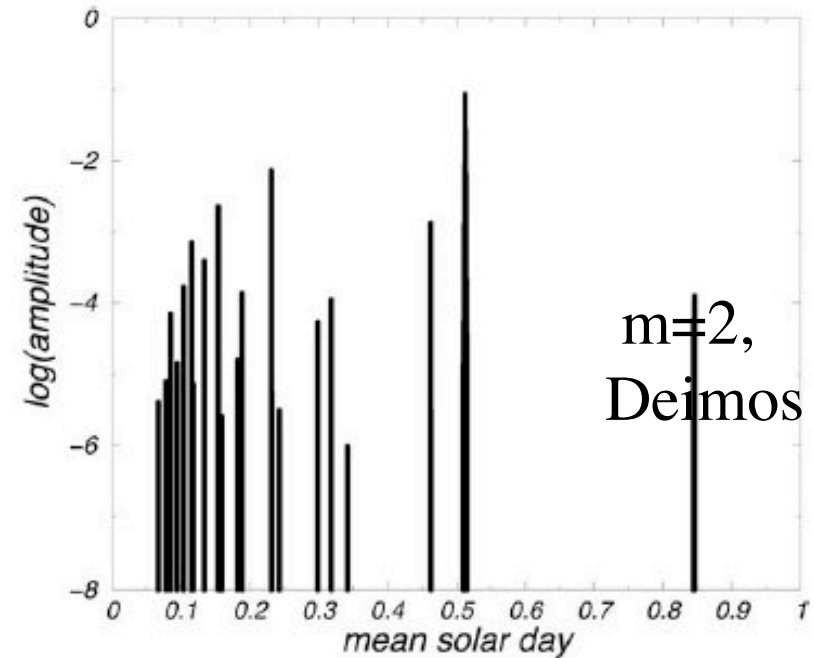


Fig. 4. Amplitudes of the subdiurnal tidal spectrum.

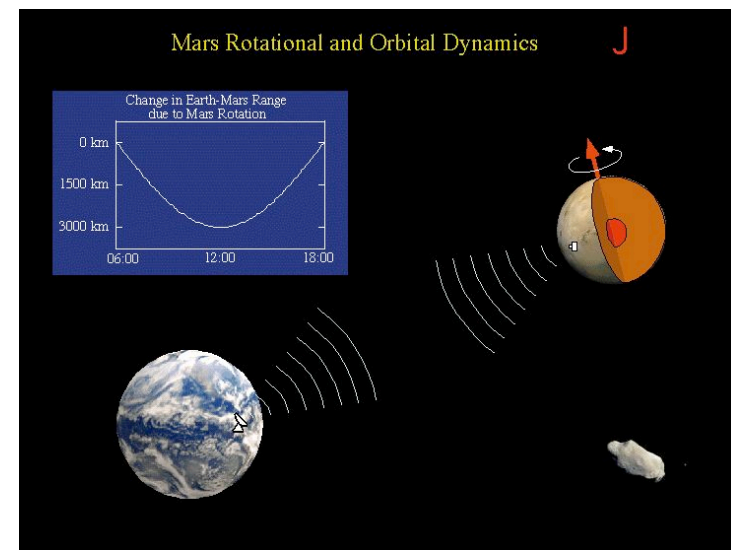
- spectre d'excitation ( compte tenue de l'excentricité et inclinaison des orbites)
- Période: Deimos ( 30h18), Phobos, (7h39), Mars 24h37
- ordre de grandeur  $\sim 1\text{cm}$  et  $10^{-8}$  de variation du potentiel

## Geophysical existing constraints (JPL radio-science team)

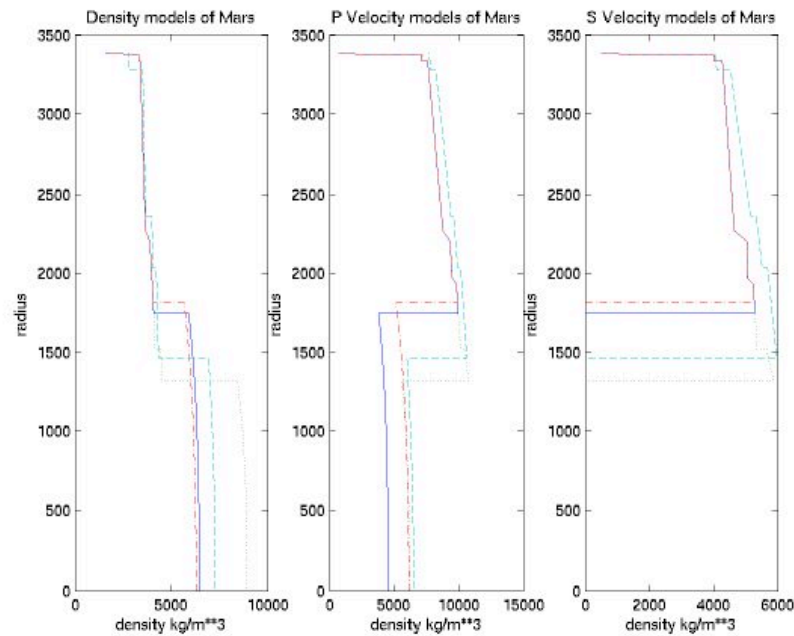
- **Moment of Inertia from Pathfinder**
  - Doppler and Range measurements from Pathfinder, 20 years after Viking
  - Direct measurement of the solar precession
  - Moment of inertia is then computed from the solid body equation of the planet
- **Solid tide Love Number from MGS gravity data**
  - The observed  $k_2$  is large enough to rule out a solid iron core and also indicates that at least the outer part of the core is liquid.

Love Number  
 $k_2 = 0.153 \pm 0.017$   
( $\pm 11\%$ )

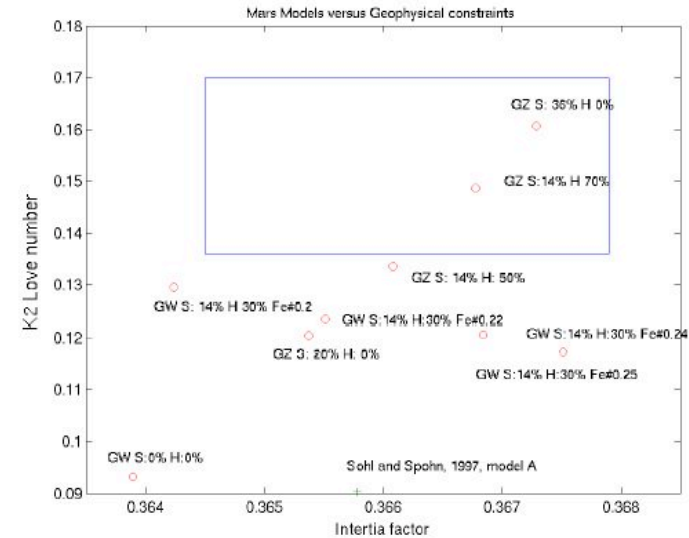
Inertia factor C  
 $C/Mr^2 = 0.3662 \pm 0.0017$   
( $\pm 0.46\%$ )



# Impact du nombre de Love



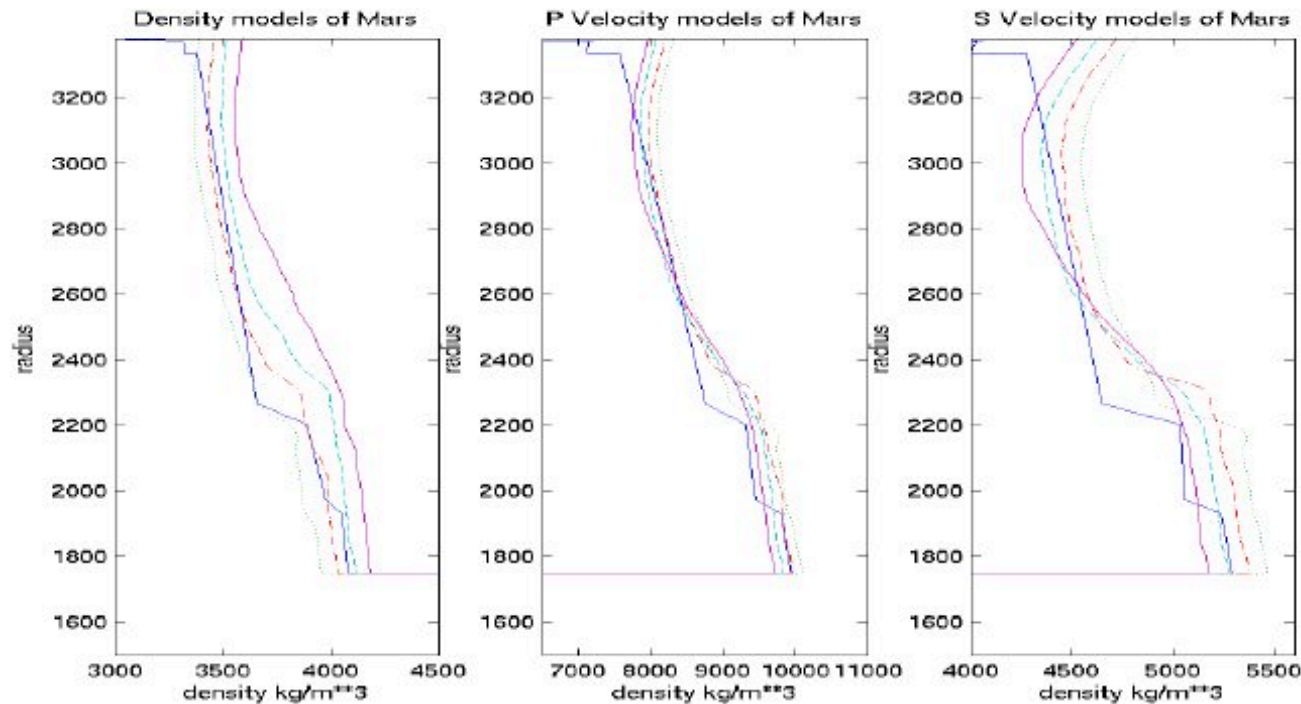
**Figure 8:** Models of Sohl and Spohn [1997], dashed line, and 3 models of *Gudkova & Zharkov* [2004]. The solid line and dotted line are for an hydrogen content in the core of 50% and 70%, with 14% of Sulfur in both cases, while the dashdotted line is for a sulfur content of 35% without hydrogen. *Sohl and Spohn* model has no hydrogen and 14% in sulfur.



**Figure 9:** Fit of the observed and computer K2 and inertia factors for several models of *Sohl and Spohn* [1997] and *Gudkova and Zharkov* [2004]. The observed limits are enclosed in the box.

- a priori, noyau relativement riche en éléments légers ( S, H, Si, ?) et liquide

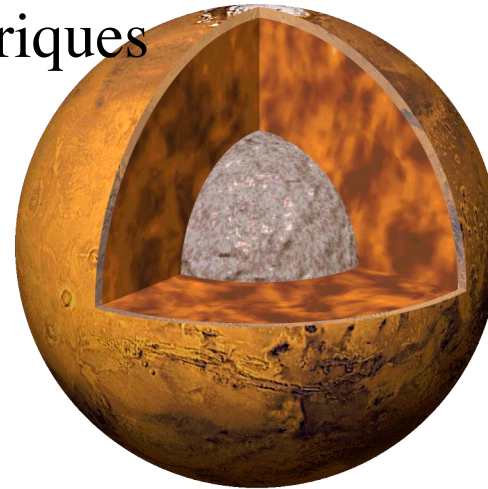
# Incertitudes actuelles



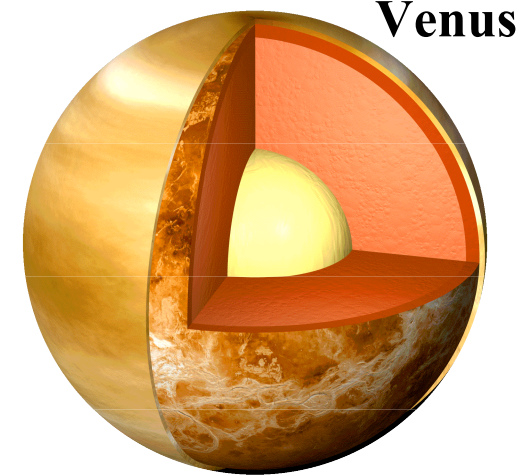
**Figure 10:** Mantle models of Mars, in term of density and seismic velocities for the model M7 of *Gudkova and Zharkov* [2004], continuous line, and the 4 models of *Mocquet et al.* [1996]. Models of *Mocquet et al.* [1996] have an increasing content of iron of 10,20,30 and 40 %, associated to dotted, dashdot, dashed and solid line. The main effect of an increase in Iron is to smooth the seismic discontinuities associated to  $\alpha$ -olivine to  $\beta$ -spinel and  $\beta$ -spinel to  $\gamma$ -spinel. *Gudkova and Zharkov* model has a 22% iron content in the mantle. The difference in depth of the discontinuities is mainly related to change in the core mantle boundary temperature. A temperature of about 2100K is taken at the CMB for the model of *Gudkova and Zharkov* [2004], while a more complex model, with temperature inversion in the mantle and mantle temperature about 500K colder at the depth of the discontinuities is take for *Mocquet et al.* [1996]. These colder temperatures shift the discontinuity to shallower depth.

# Noyaux planétaires

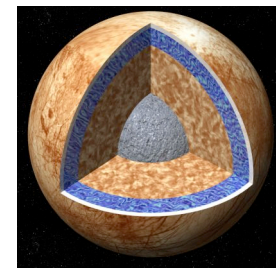
- Généralité des planètes telluriques
- Typiquement 0,5 en rayon
- Deux exceptions:
  - La Lune : petit noyau
  - Mercure Gros Noyau
- Une explication:
  - les impacts catastrophiques ?
  - La proximité du soleil pour Mercure?



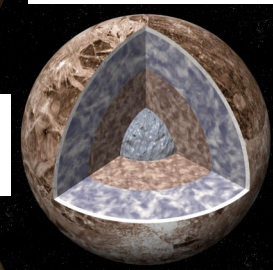
**Mars**



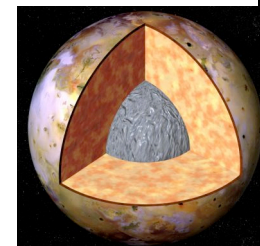
**Venus**



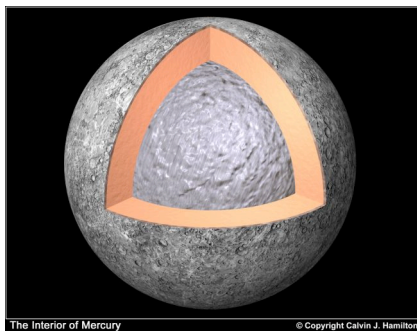
*Europa*



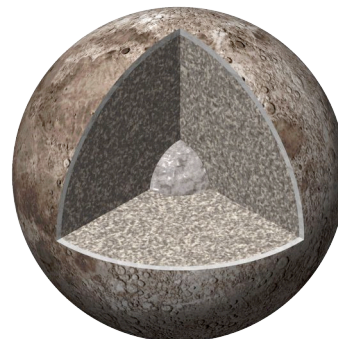
*Ganymede*



*Io*



**Mercure**



**Lune**

# Les impacts catastrophiques

- Les paramètres

- Vitesse d'impact: 20-30 km/s
- Vitesse de libération
- Où  $g$  est la gravité,  $a$  le rayon

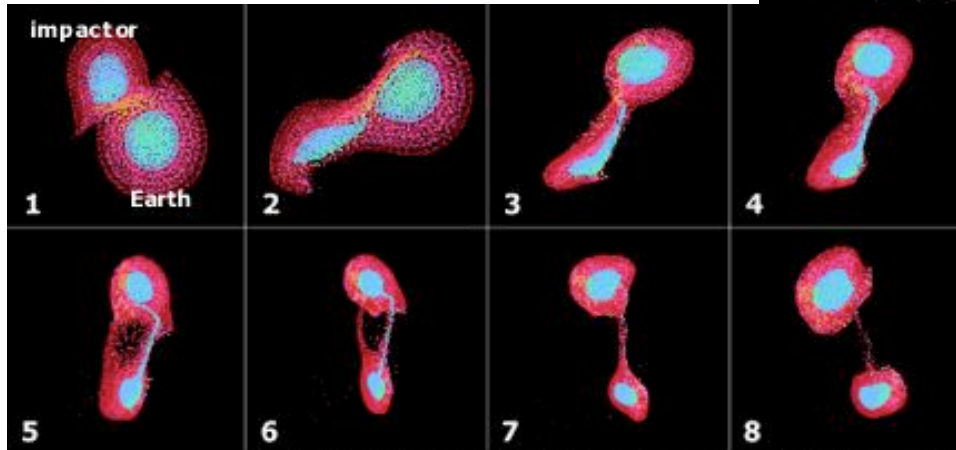
$$\frac{1}{2}v_{lib}^2 = G \frac{M}{a} = ga$$

d'où

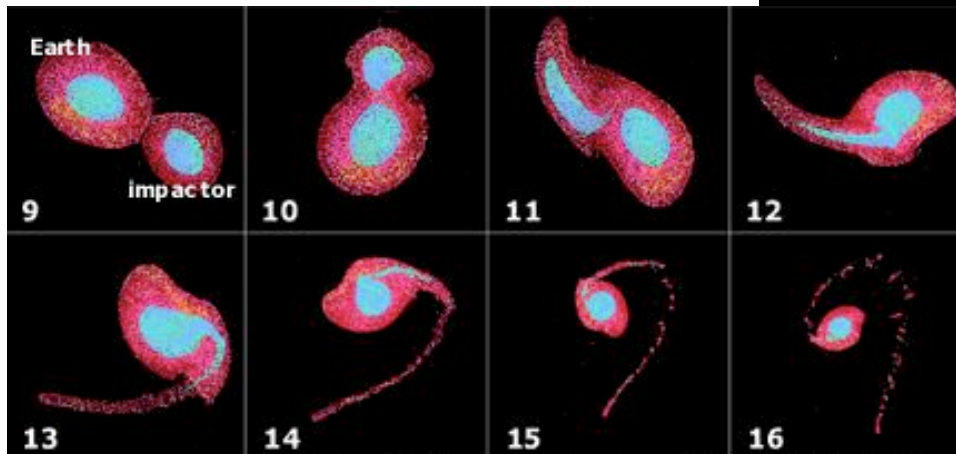
$$v_{lib} = \sqrt{2ga}$$

	Masse	Gravité	Vitesse libération (km/s)
Terre	1	9,78	11,18
Venus	0,815	8,60	10,36
Mercure	0,055	3,71	4,25
Mars	0,107	3,72	5,02

# Formation de la Lune: Impact

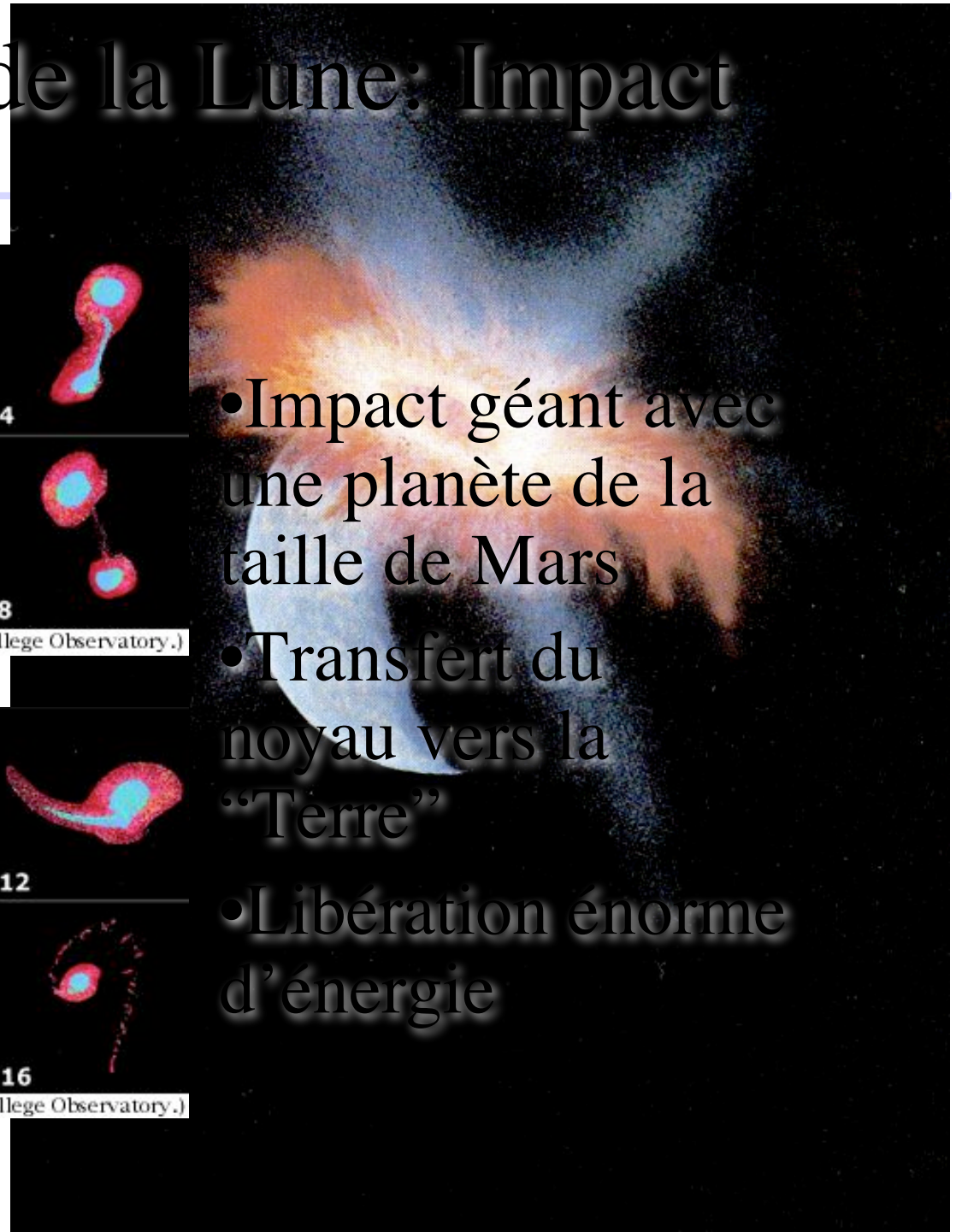


(Courtesy of A. G. W. Cameron, Harvard College Observatory.)



(Courtesy of A. G. W. Cameron, Harvard College Observatory.)

- Impact géant avec une planète de la taille de Mars
- Transfert du noyau vers la "Terre"
- Libération énorme d'énergie





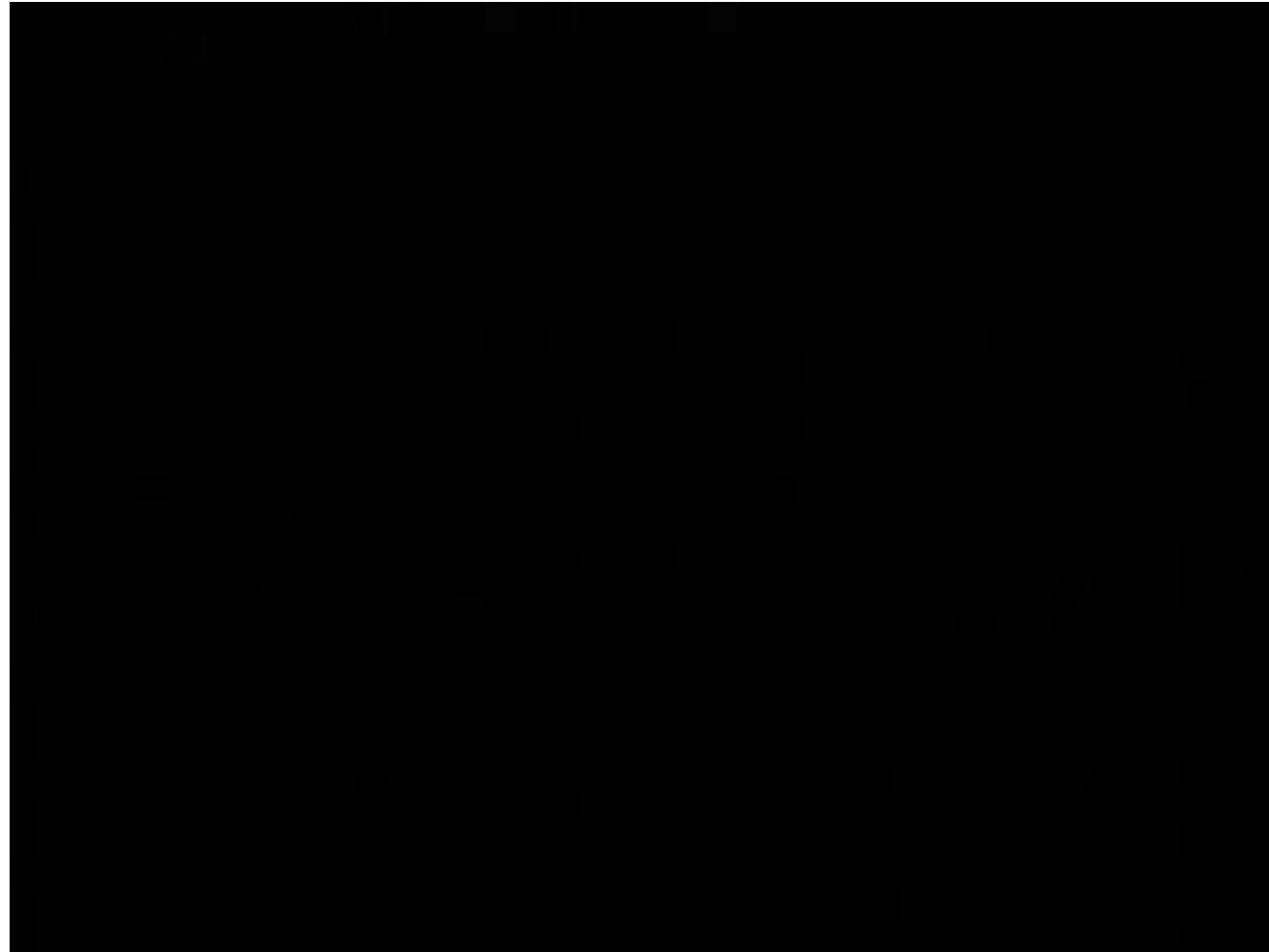
# Quelques arguments

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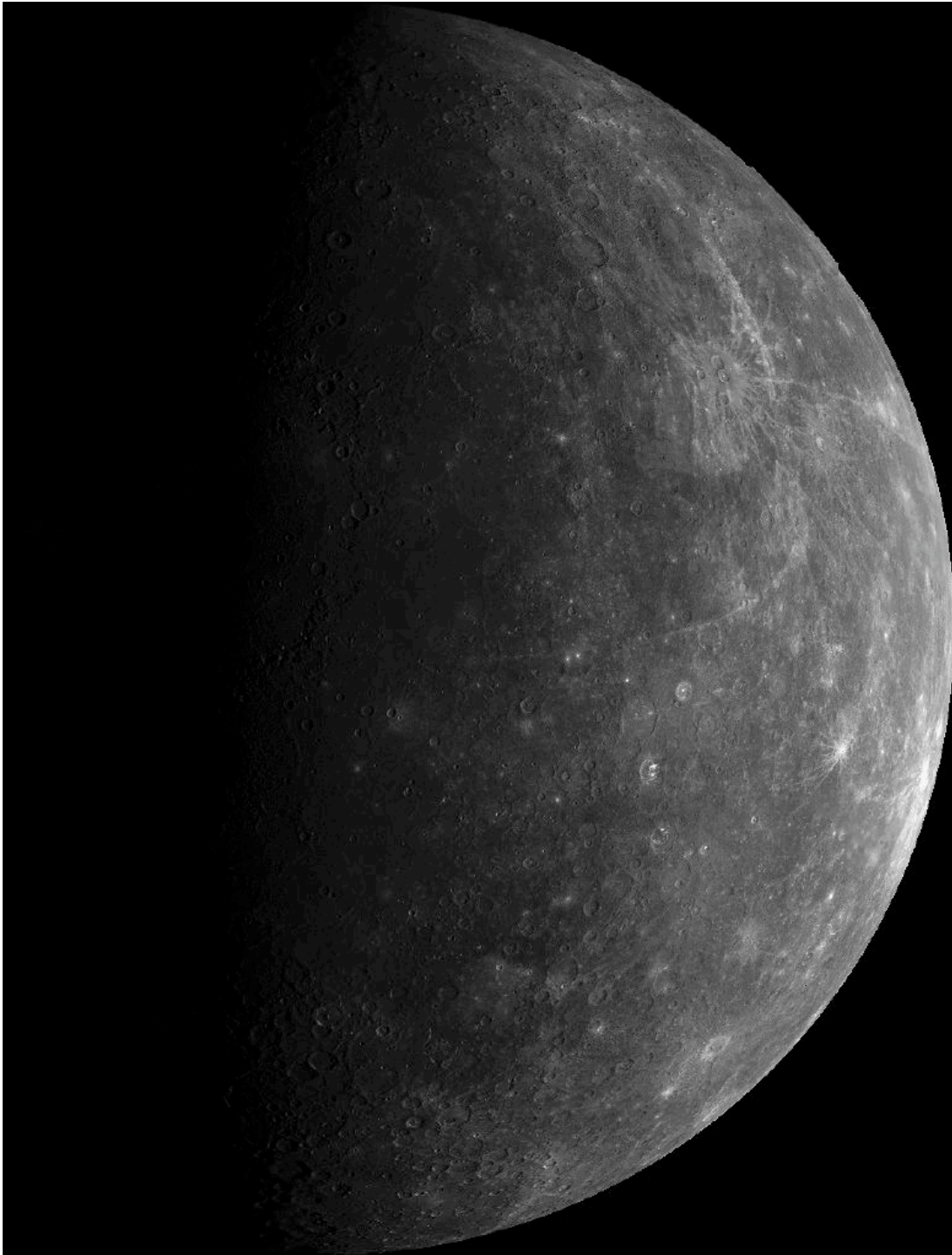
- Densité moyenne du système Terre-Lune = 4.09 ( Vénus = 4., léger enrichissement en éléments lourds)
- Signature isotopique du manteau et de la Lune très proche: les deux réservoirs ont été mélangés

# Les impacts catastrophiques: la Lune

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**Kokubo et al., 2000**



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Et Mercure ?

**Premières idées et théorie:**

- appauvrissement en volatiles en raison de la proximité du soleil dans la nébuleuse primitive
- accréation à partir de planétésimaux déjà appauvris en volatils

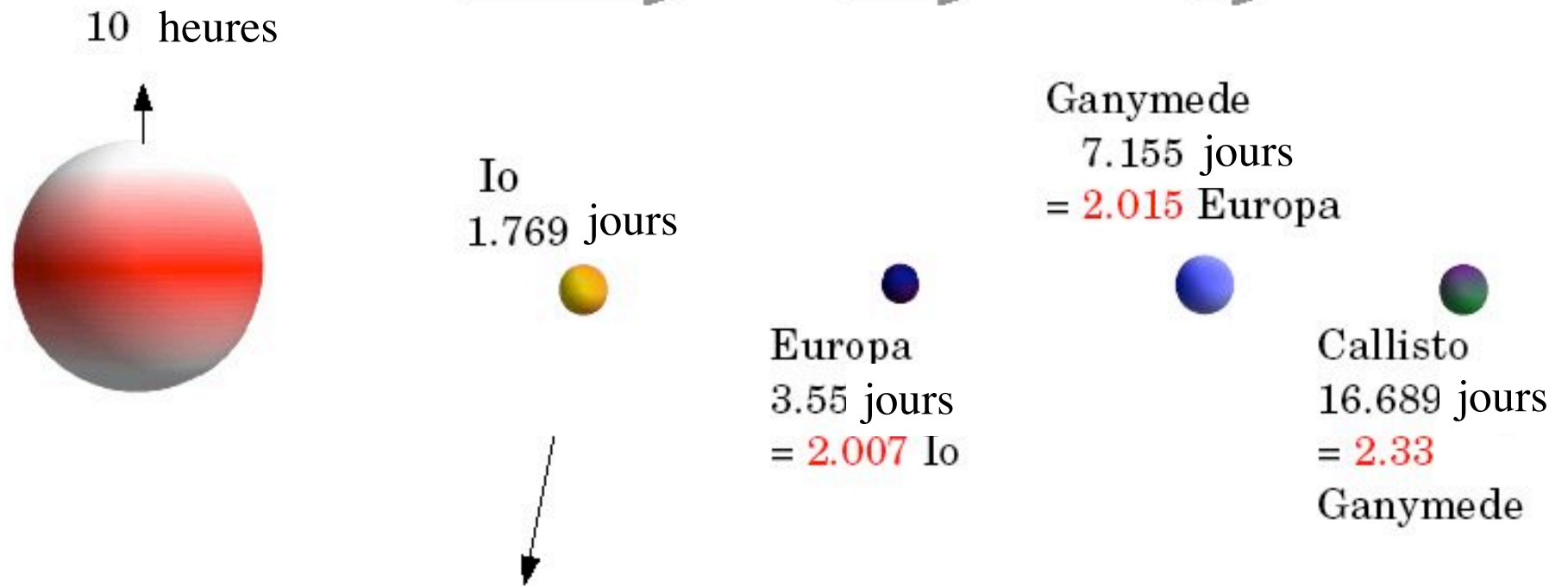


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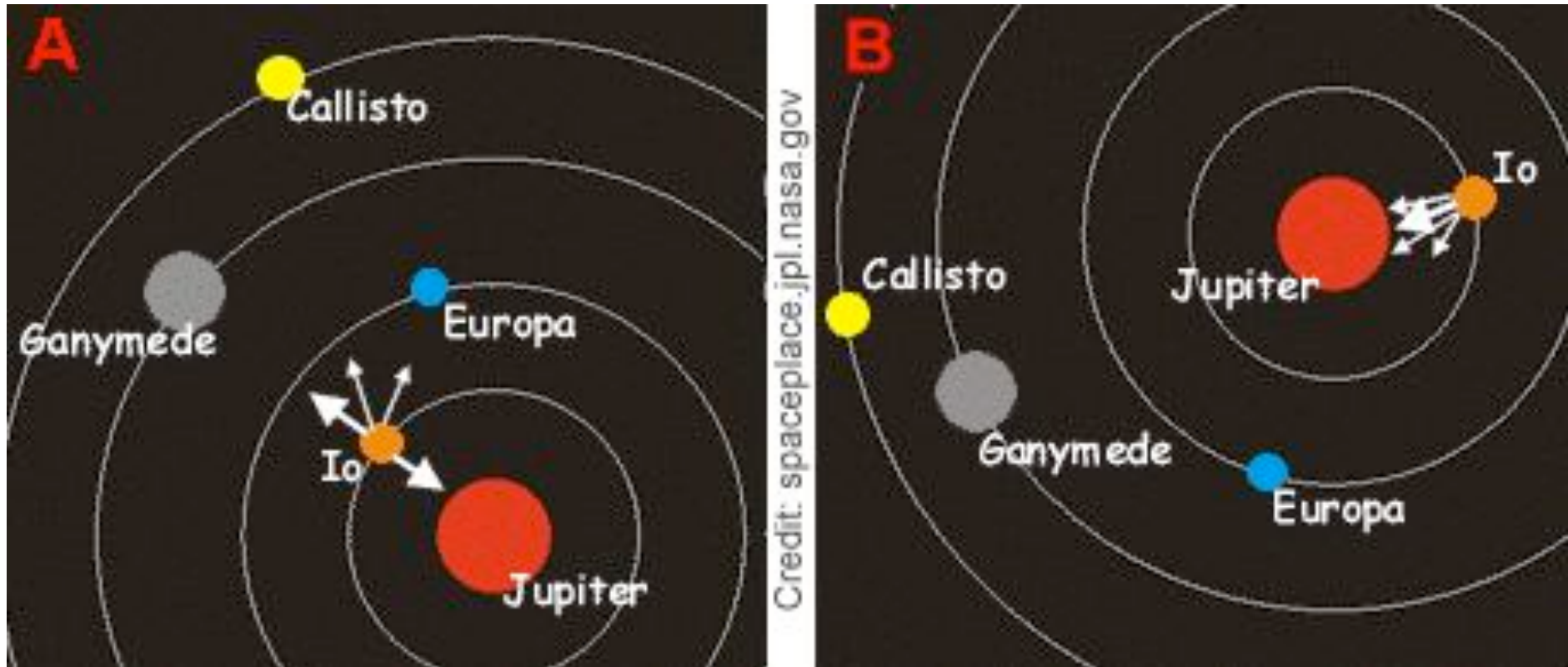
# Autre effet des marées

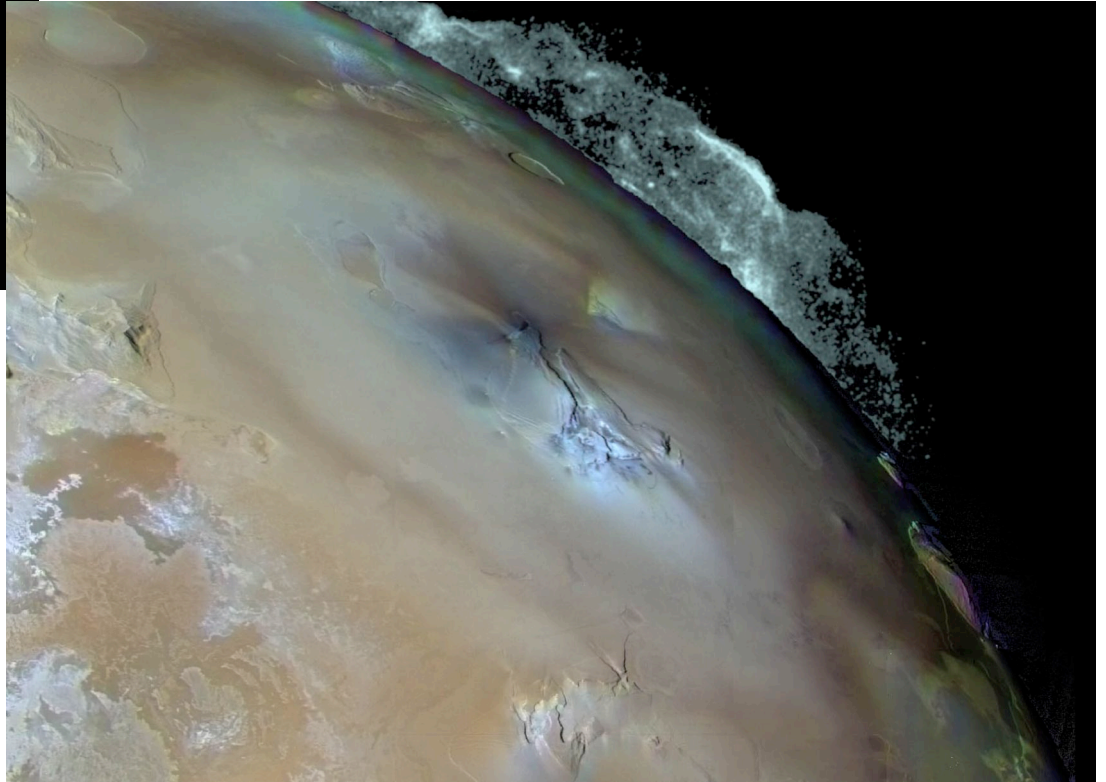
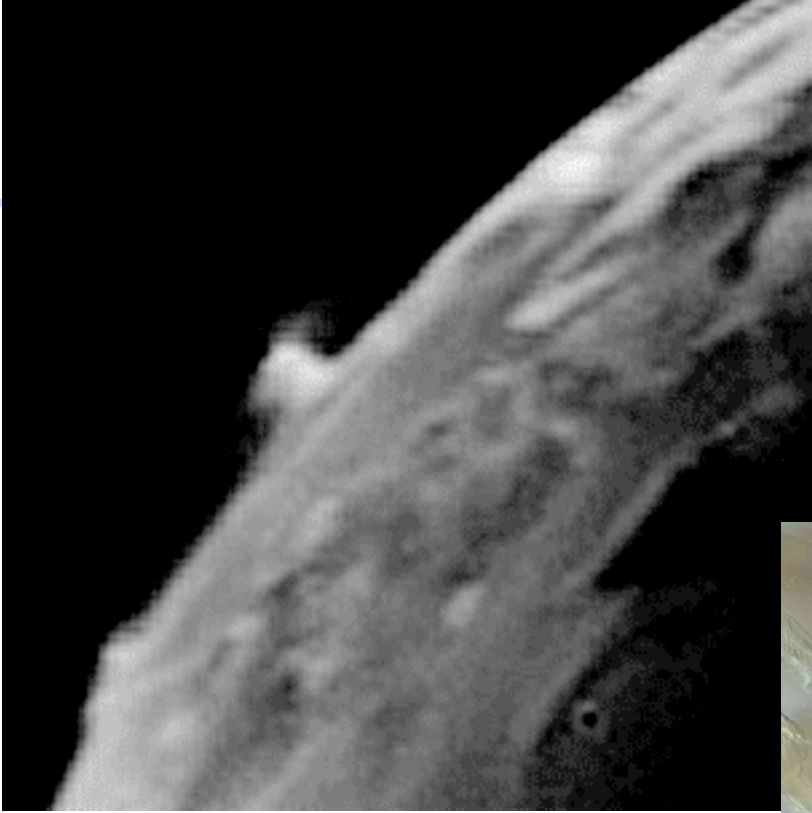
# Io et Jupiter

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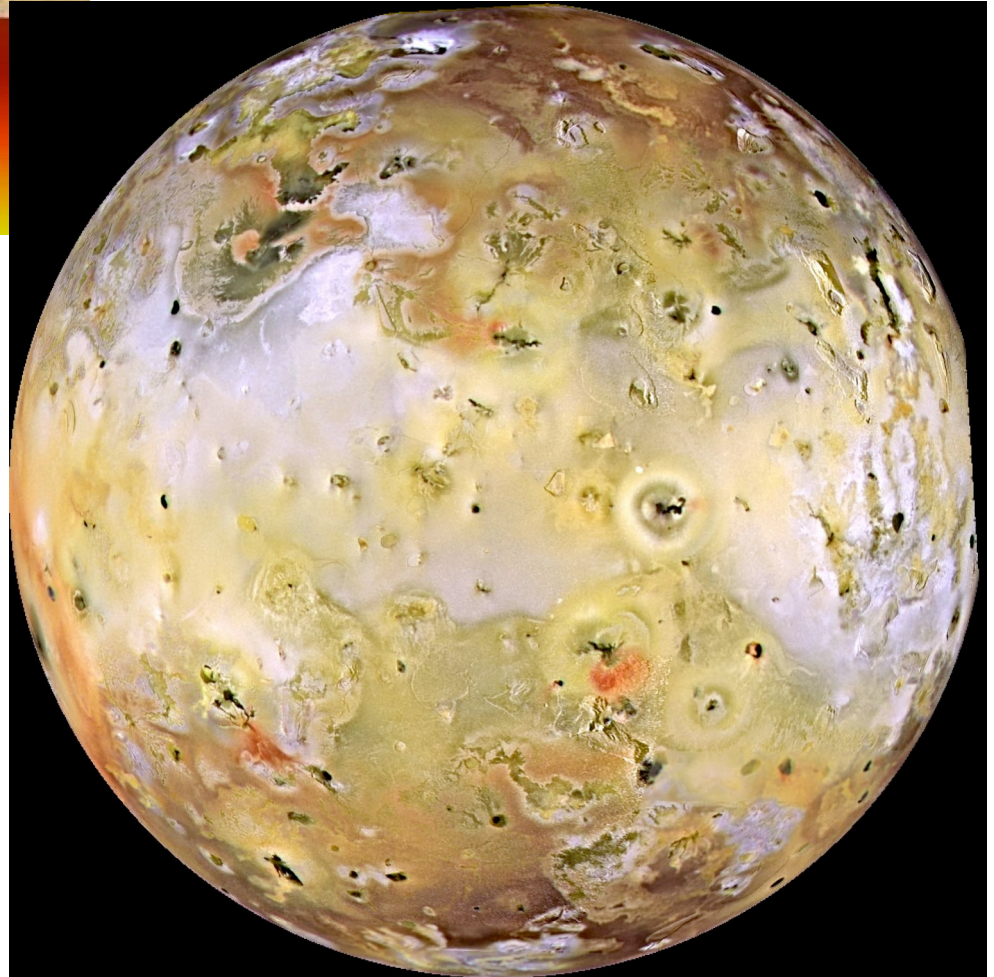
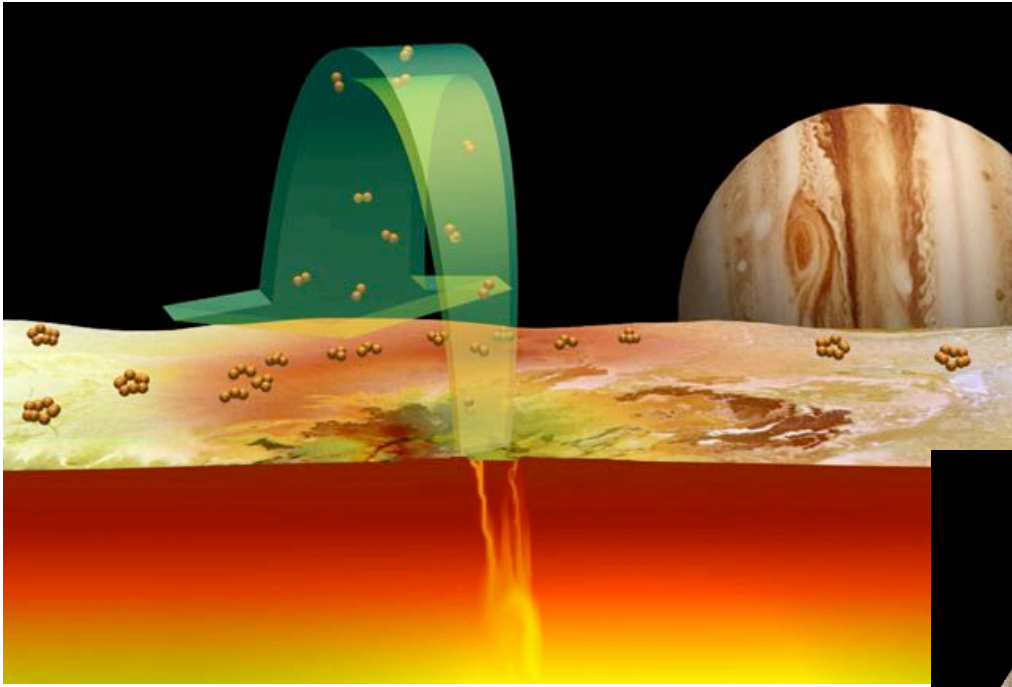


# Résonnance d'Io



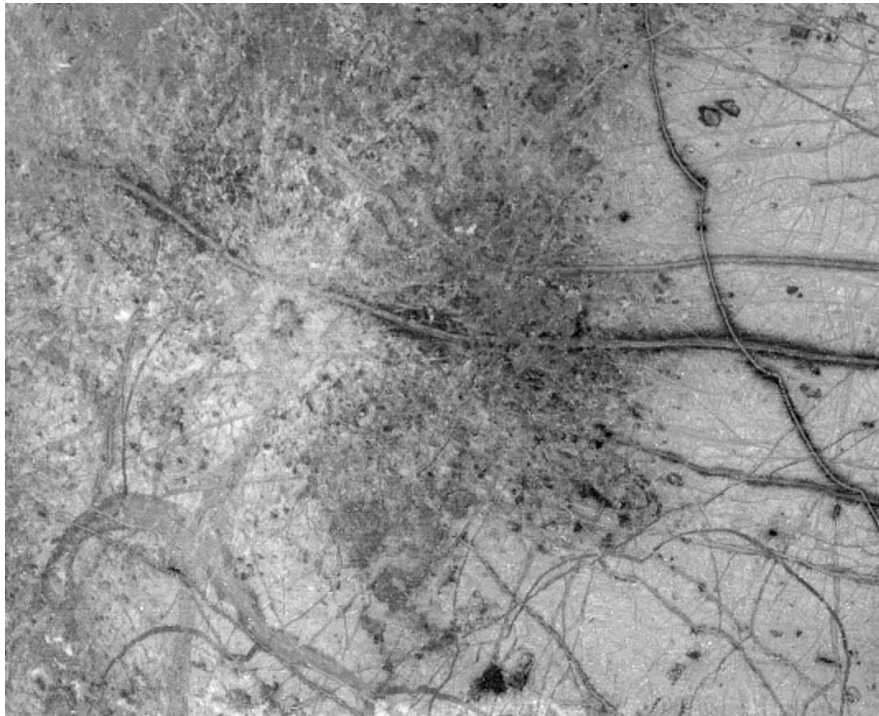




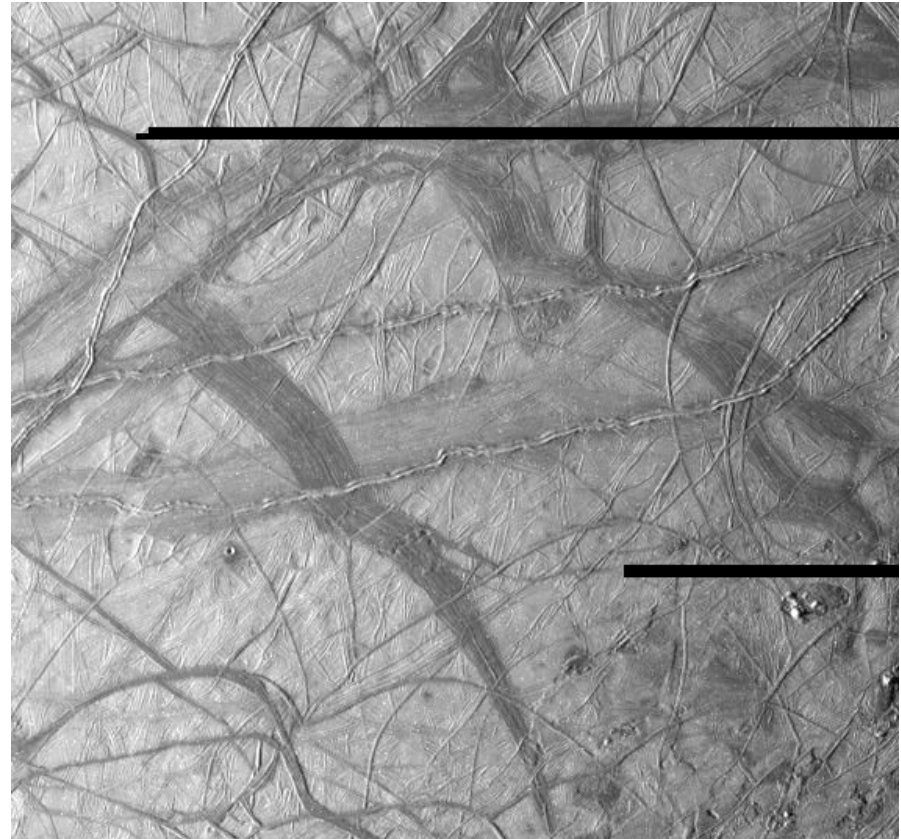


# Europe

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238 km x 225 km

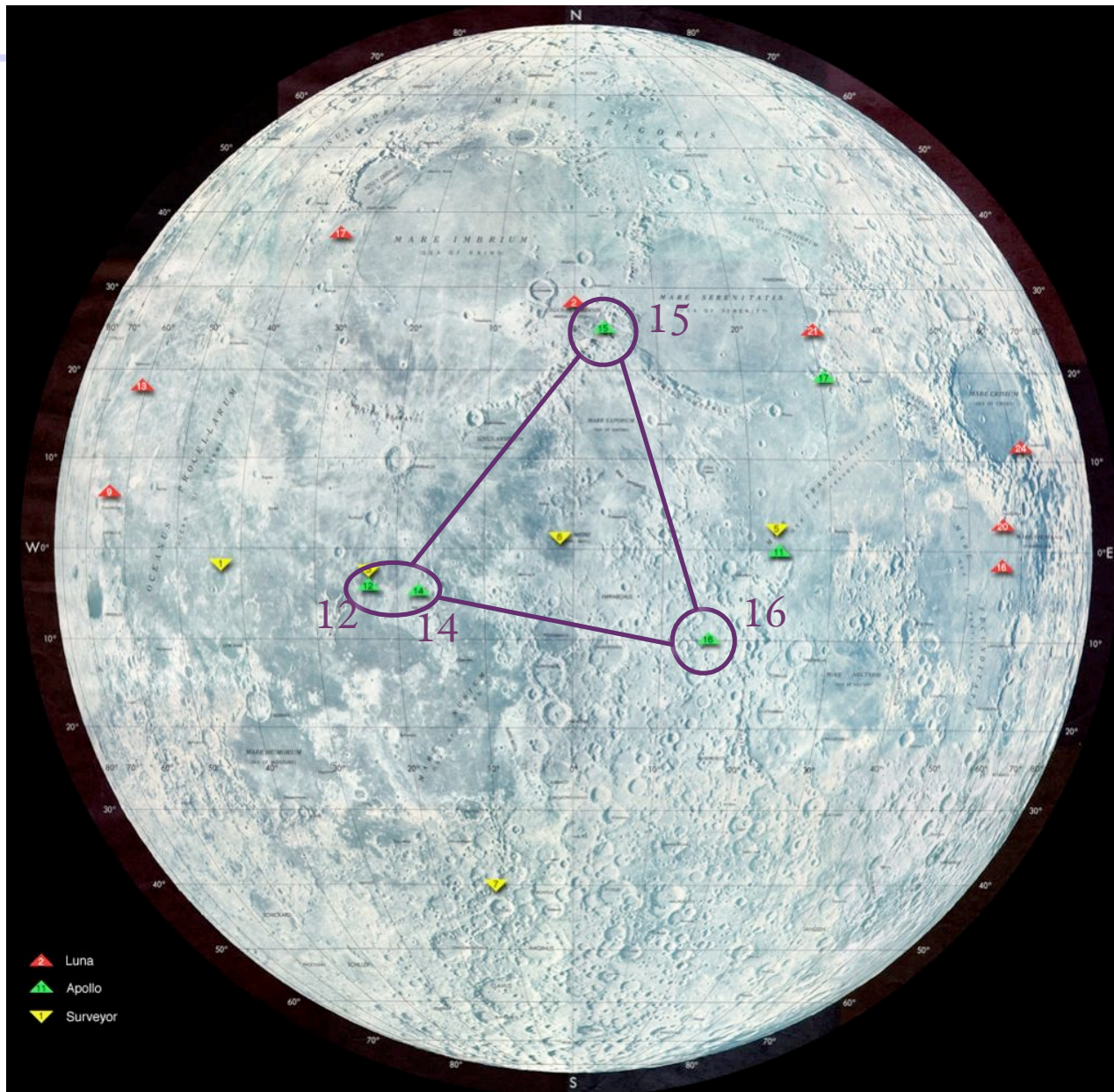


860 x 700 km

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# Séismes lunaires

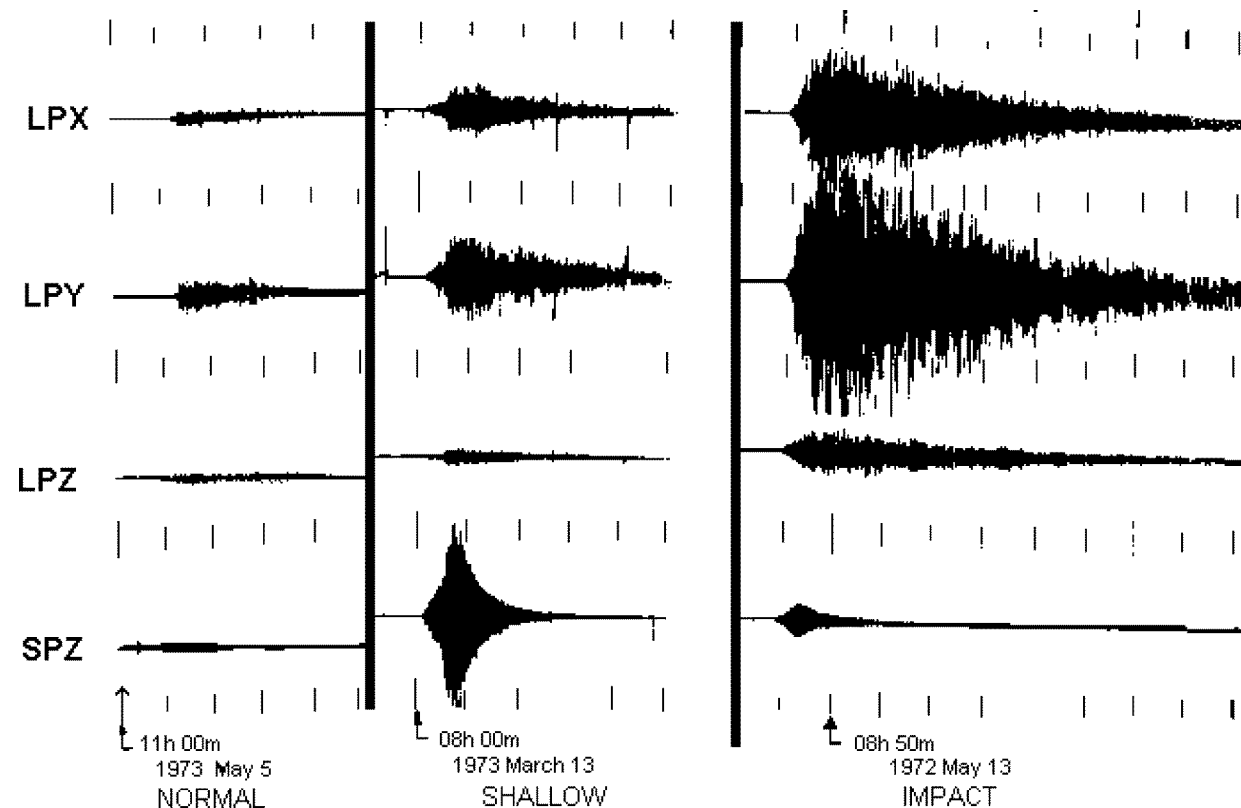
# Apollo Seismic Network



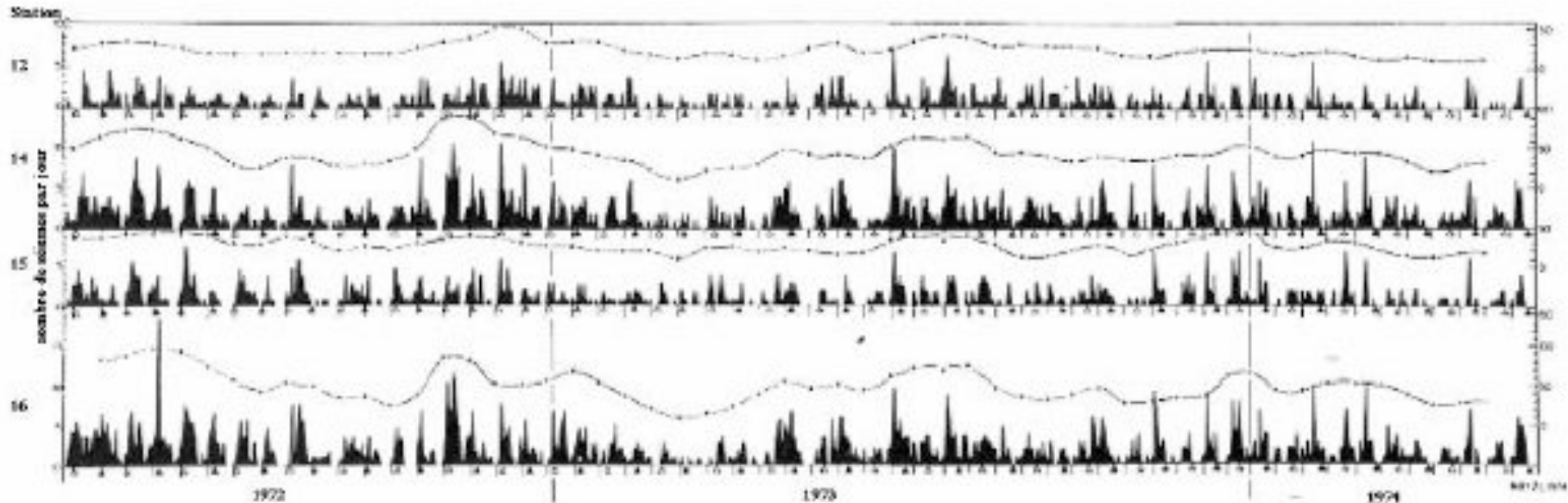
- 4 stations:  
Apollo sites 12,  
14, 15 and 16
- installed  
between 1969  
and 1972
- turned off in  
1977

# Moonquakes

- deep moonquakes
  - 700-1000 km depth, near just at the bottom of the elastic lithosphere of the Moon
  - Very small magnitudes quakes
  - Origin: accumulation of stress related to the thermoelastic cooling of the planet triggered by the Earth tide
  - Several faults identified where quakes occur repeatedly
- superficial moonquakes
- meteoroid & artificial impacts

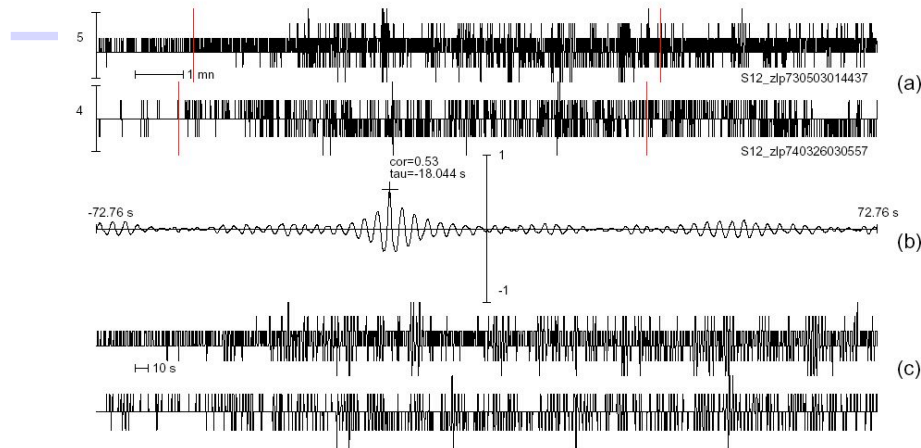


# Deep moonquakes

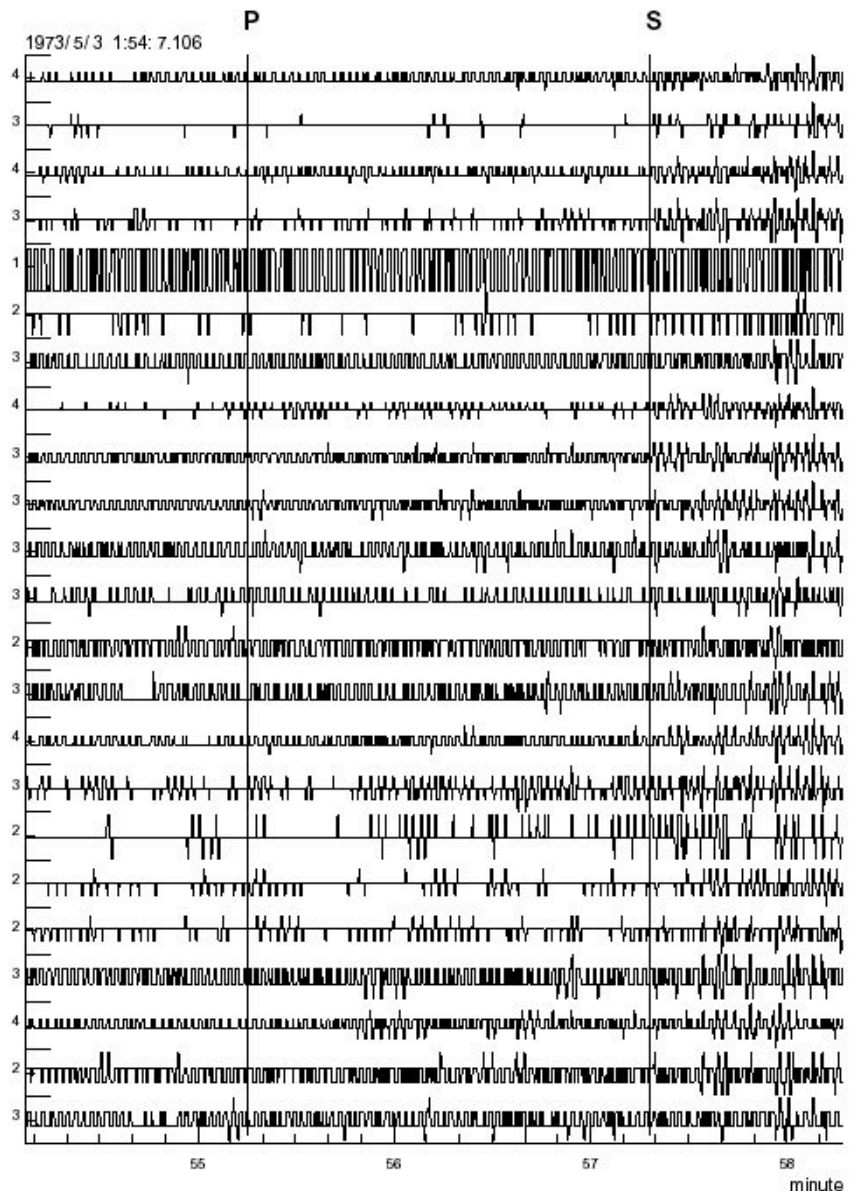


- Number and amplitude of quakes is related to the amplitude of tide
- About 50 active faults detected
- Quakes occur at the same fault regularly but with very low amplitudes, with ground displacement of a few Angströms at 2 sec ( $0.5 \cdot 10^{-9} \text{ ms}^{-2}$  of ground acceleration)

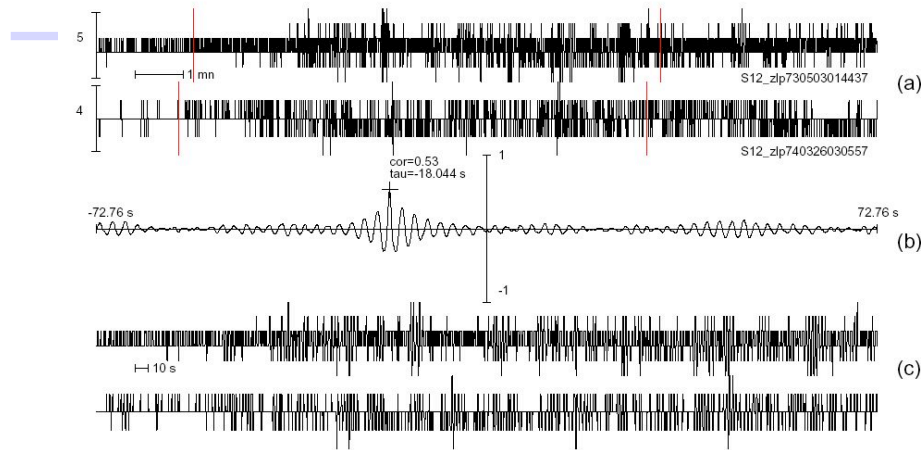
# Deep Moonquake



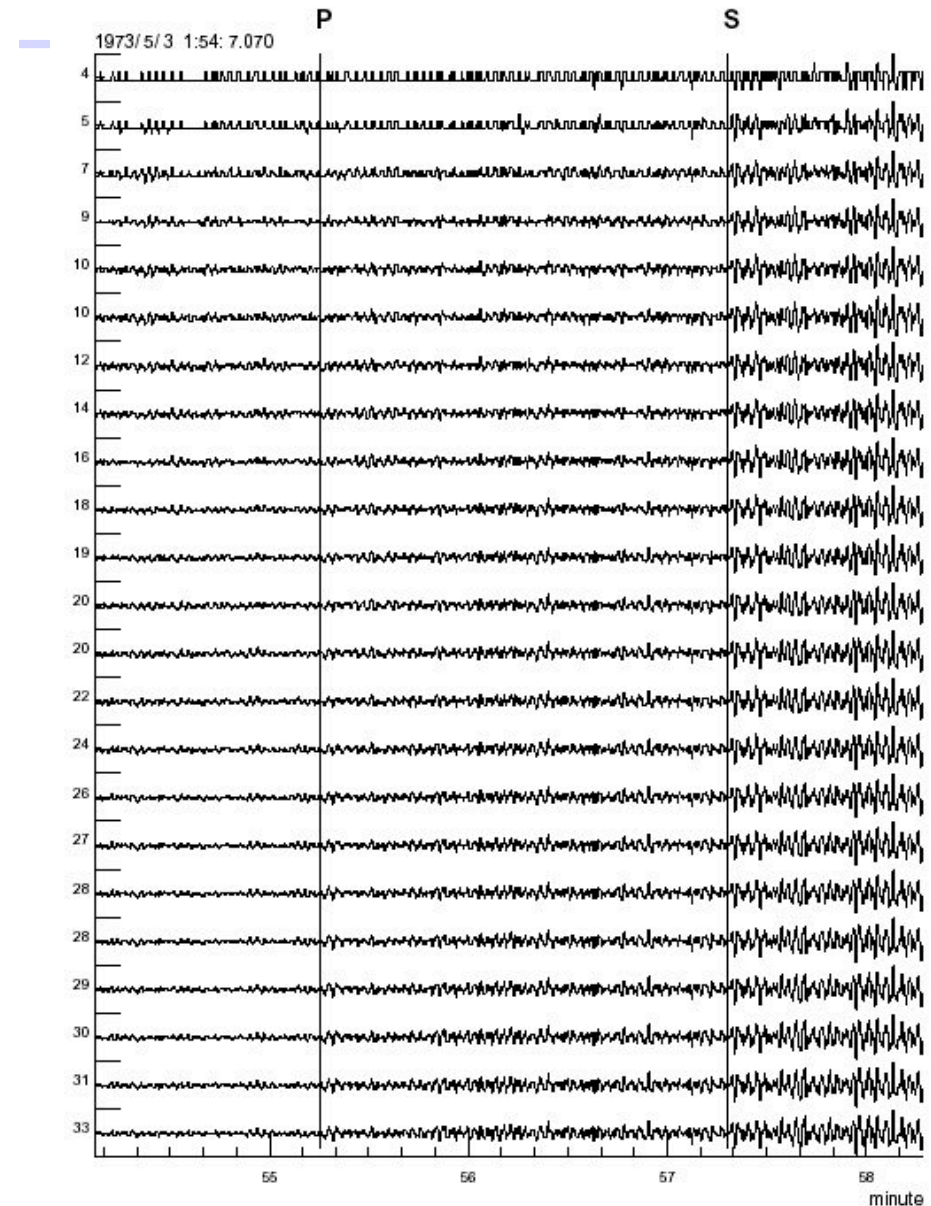
- example of two quakes from the same deep focus and their cross-correlation
- cross-correlation provides the time shift necessary to align the arrival times
- stacking can then be done



# Deep Moonquake

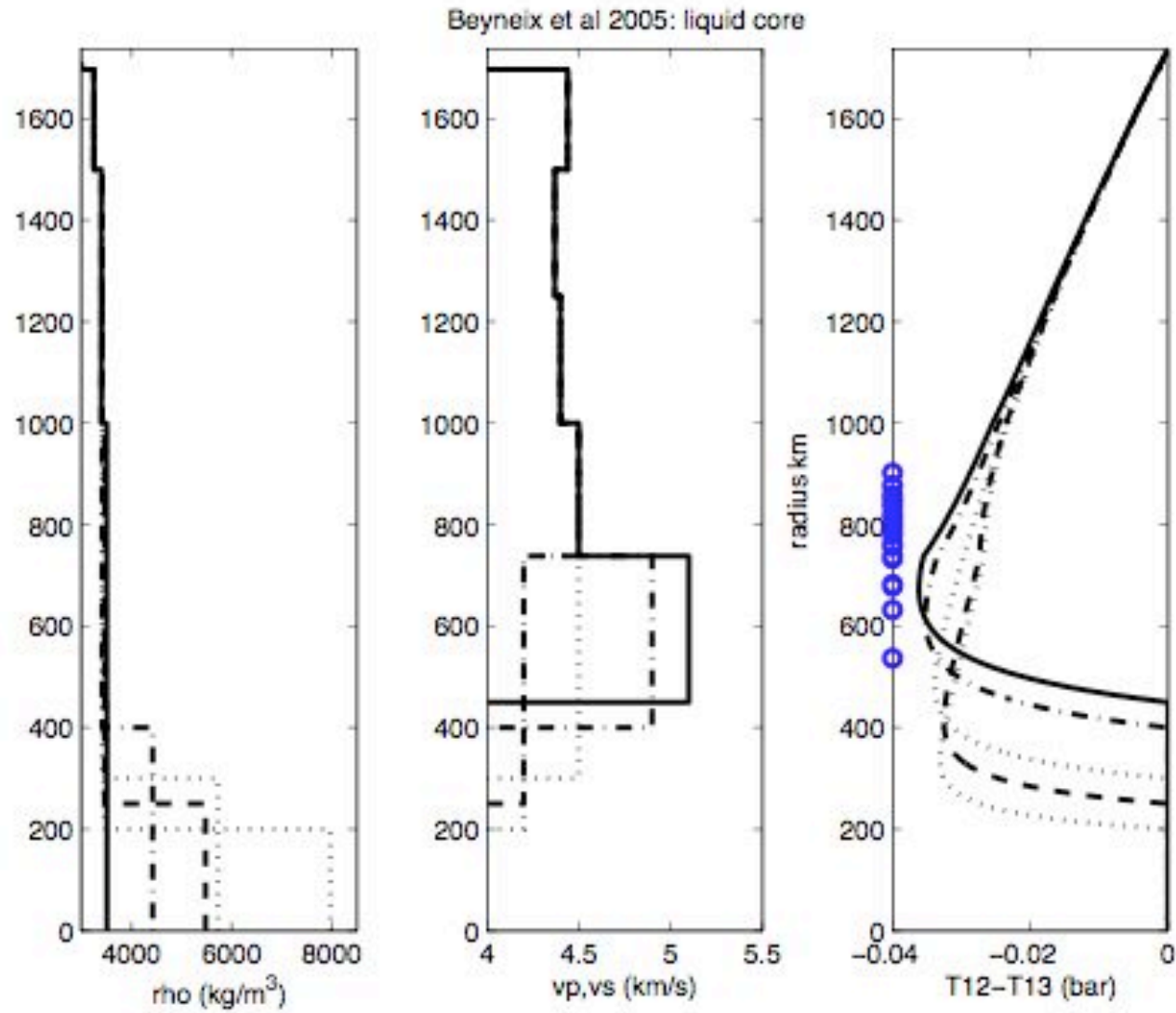


- example of two quakes from the same deep focus and their cross-correlation
- cross-correlation provides the time shift necessary to align the arrival times
- stacking can then be done





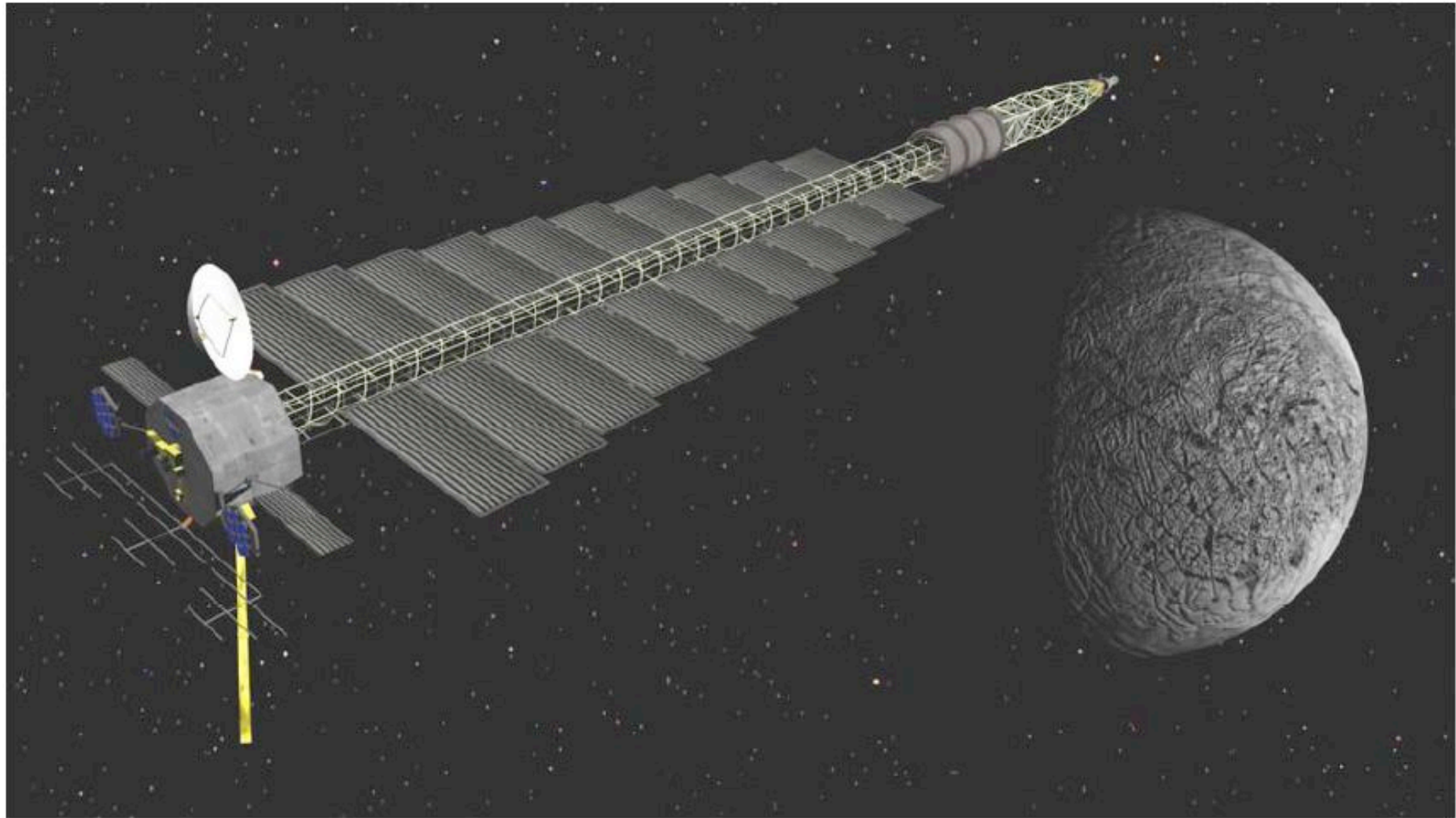
- Deep moonquakes and maximum of stress

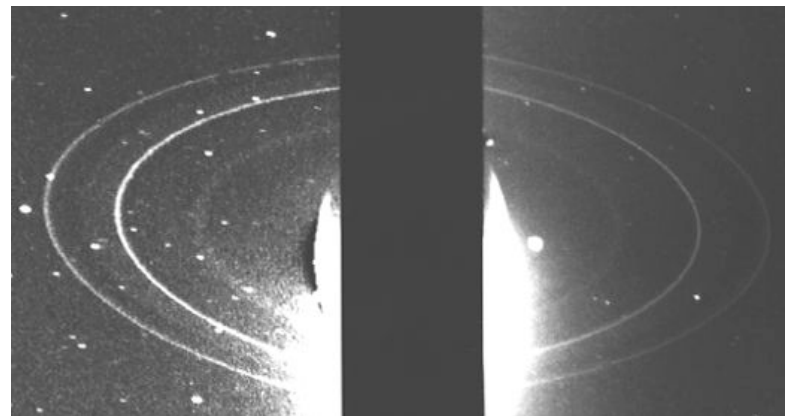
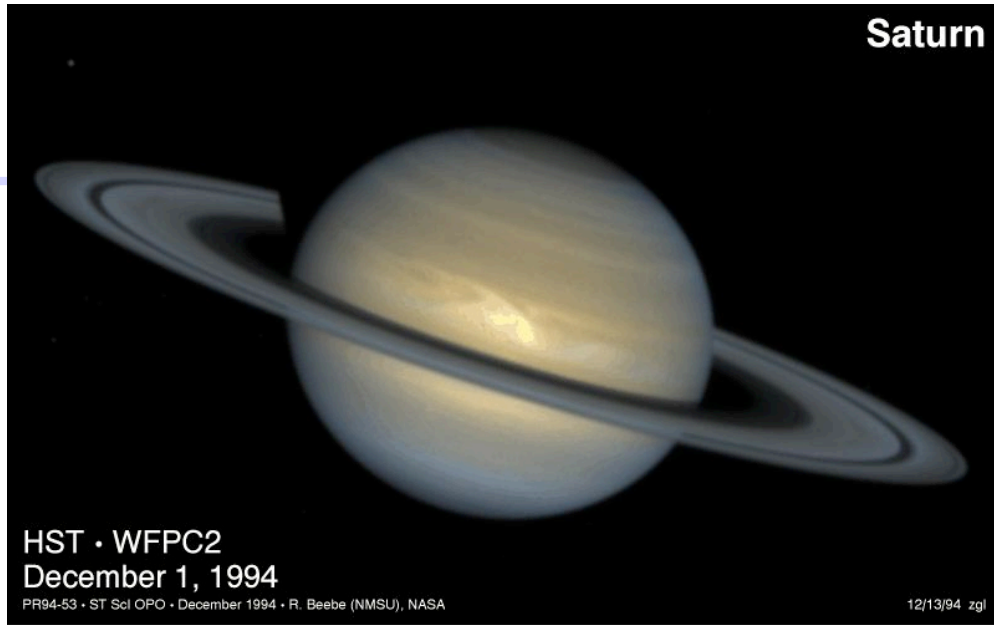


# Futur proche et lointain

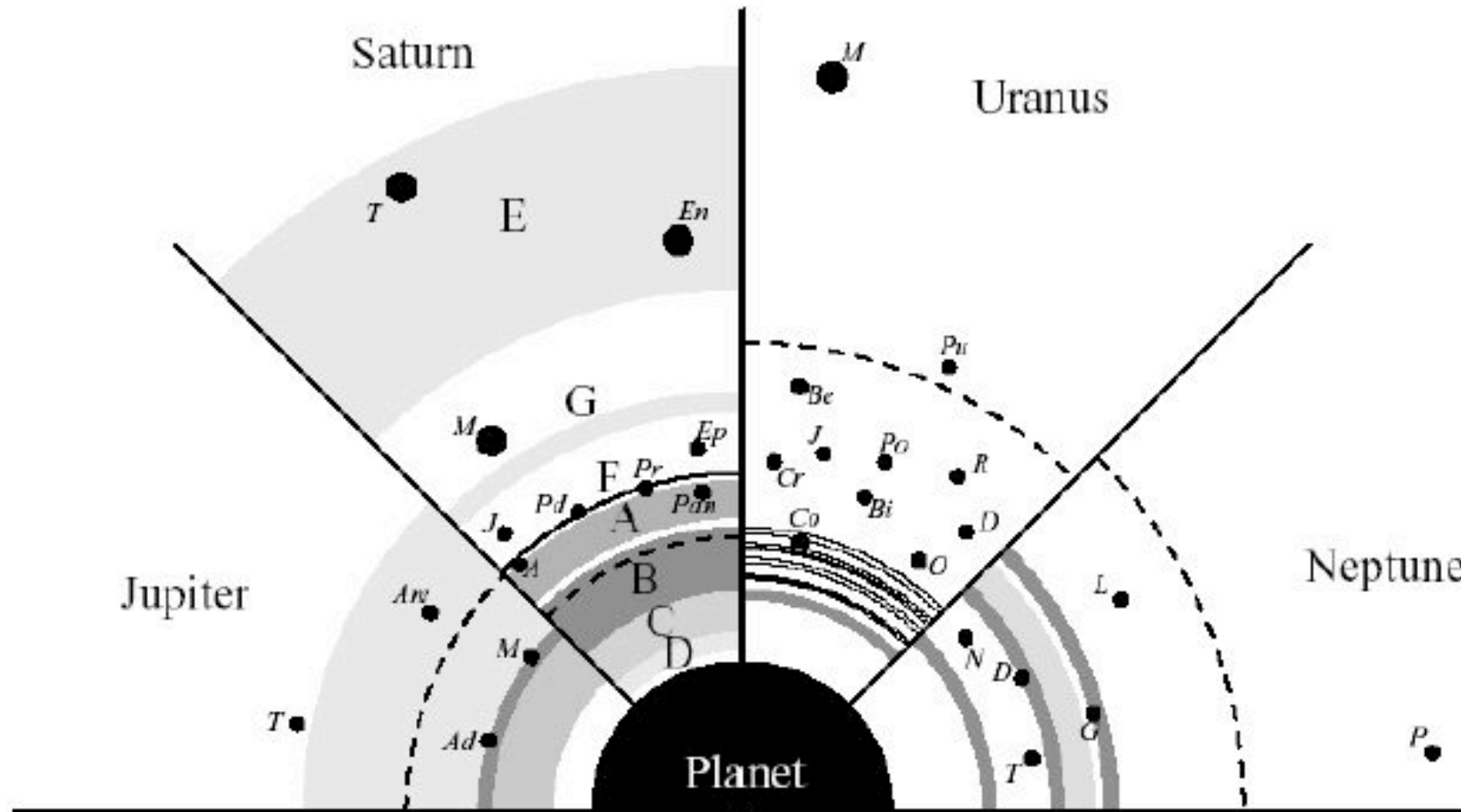
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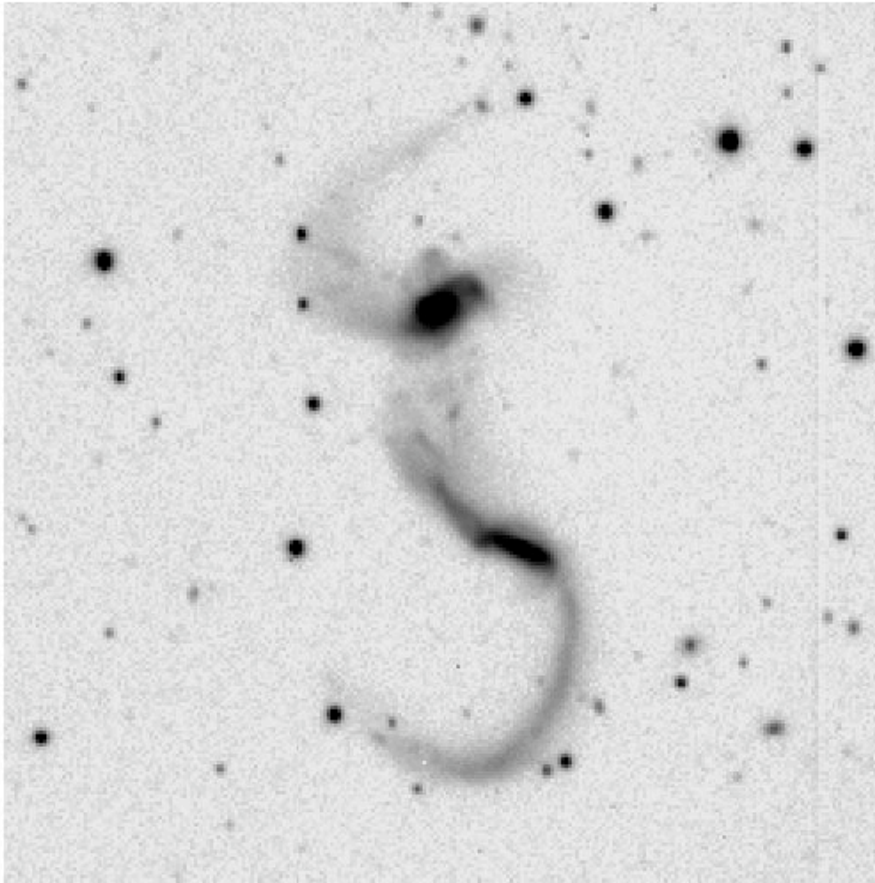


# Anneaux et limite de Roche



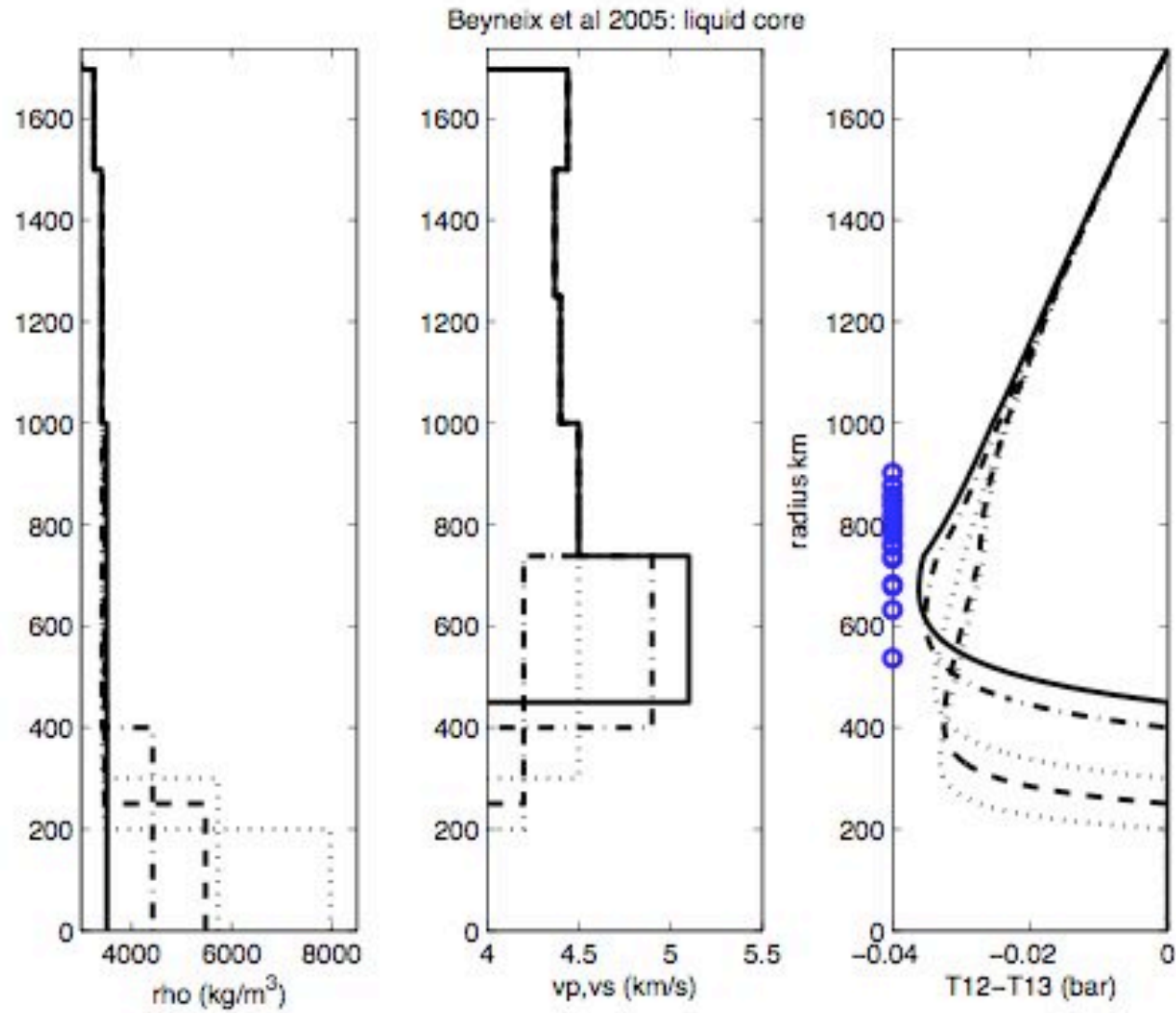
# Limite de Roche

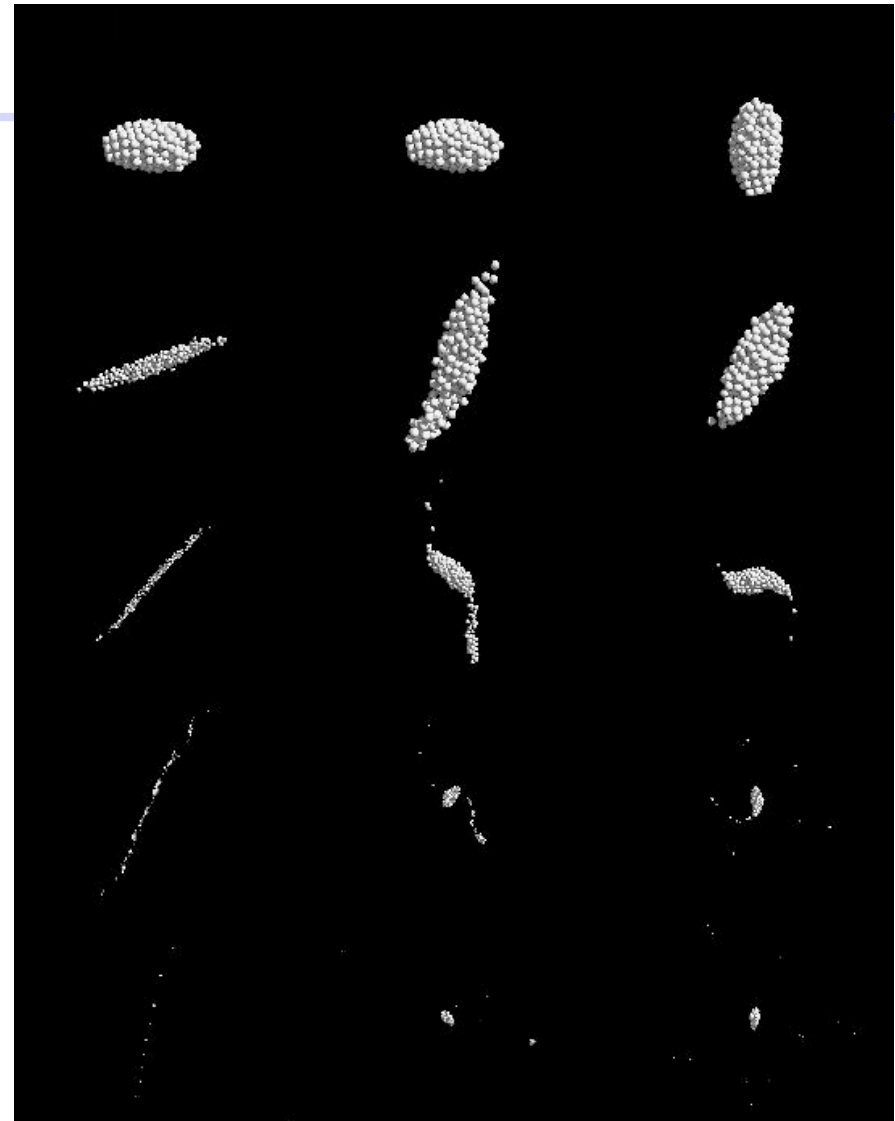
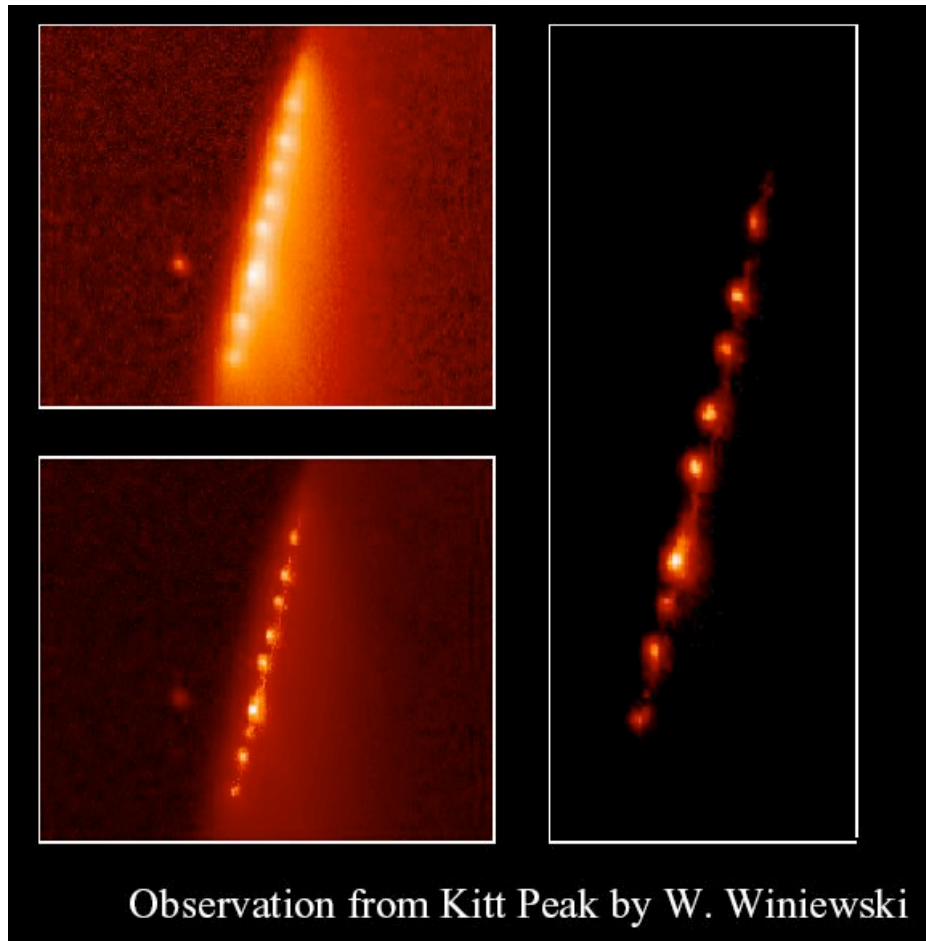
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Exemples de Galaxies  
brisées par des effets de  
Marées

- Deep moonquakes and maximum of stress





Brisure par effet de Marée de la  
comète  
Shoemaker-Levy 9 après un  
premier passage près de Jupiter