Carbon-rich composition of the icy moons of Jupiter and Saturn, and asteroid 1-Ceres

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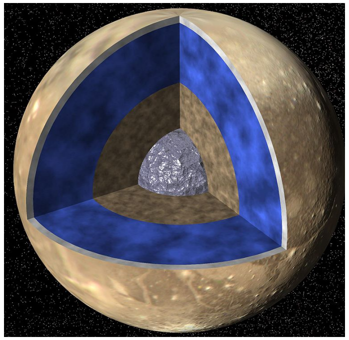
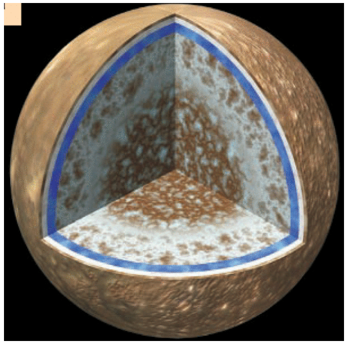
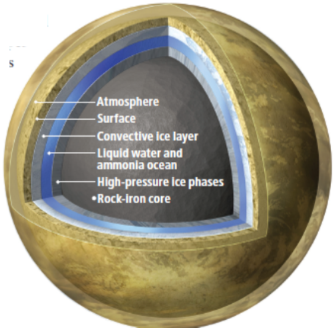
Internal structure and composition of icy moons of Jupiter and Saturn



Ganymede 1940 0.311



Callisto 1834 0.3549



Titan 1881 0.3414

Large icy moons (R ≈ 2500km)

Input data are size and mass (density)

MoI (reduced moment of inertia)

2/5 for a homogeneous sphere

less when mass is concentrated near the center

± tidal and magnetic observation

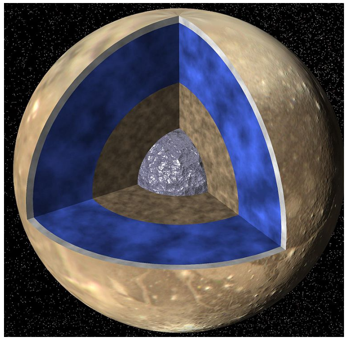
Ganymede

Fairly hot and differentiated body (~1000-1500K)
inner metallic core surrounded by silicate mantle

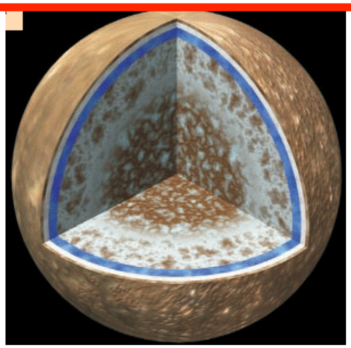
Titan, Callisto

Cold (~500-1000 K)
undifferentiated rocky core

Internal structure and « terrestrial » models



Ganymede 1940 0.311



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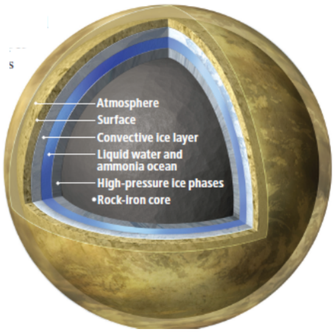


Titan 1881 0.3414

Ganymede

inner metallic core surrounded by silicate mantle in variable proportions

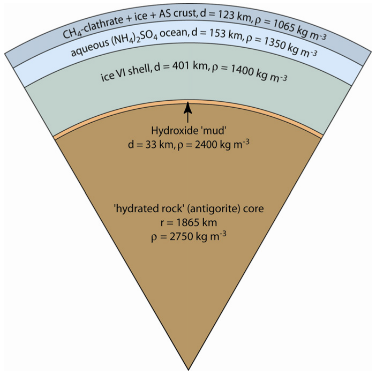
Fe/Si~4±1 (Sohl et al. Icarus 2002) largely above CI or solar

surrounded by ice and water layers

Titan (Callisto) low density cores 2300-2700 kg/m^3

ice-rock mixtures (Iess et al. Science 2010) but dynamically unstable

hydrous minerals (Fortes et al Icarus 2007)



core has the density of terrestrial serpentine

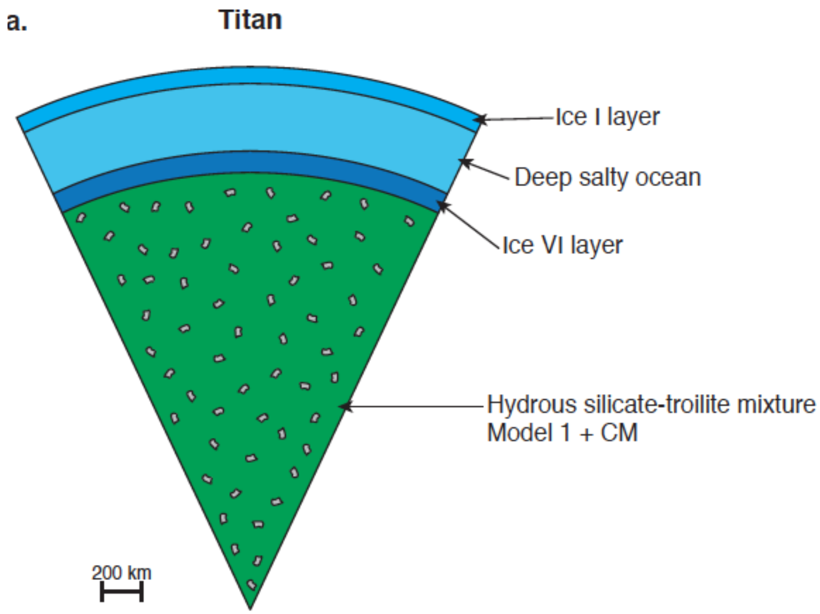
$$(Mg_{2.4}Fe_{0.4})Al_{0.3}Si_{1.9}O_5(OH)_4$$

but much higher Fe content is expected in extraterrestrial material

« Terrestrial models » = silicates/sulfide cores : exotic and non-chondritic compositions that are difficult to justify

A low density phase is needed: we propose this is carbonaceous matter (CM) derived from insoluble organic matter (IOM)

Density-moment of inertia modeling



Several compounds for which we need the density as a function of P and T
- H_2O (water and ices): equation of state data
- Silicates and iron sulfide: model proportions fixed by the CI chondrite composition
- IOM (large amounts in CI and comets) that evolves to carbonaceous matter (CM) with increasing T

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A carbonaceous chondrite and cometary origin for icy moons of Jupiter and Saturn

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Internal structure and composition models

Compositional model of the rocky core

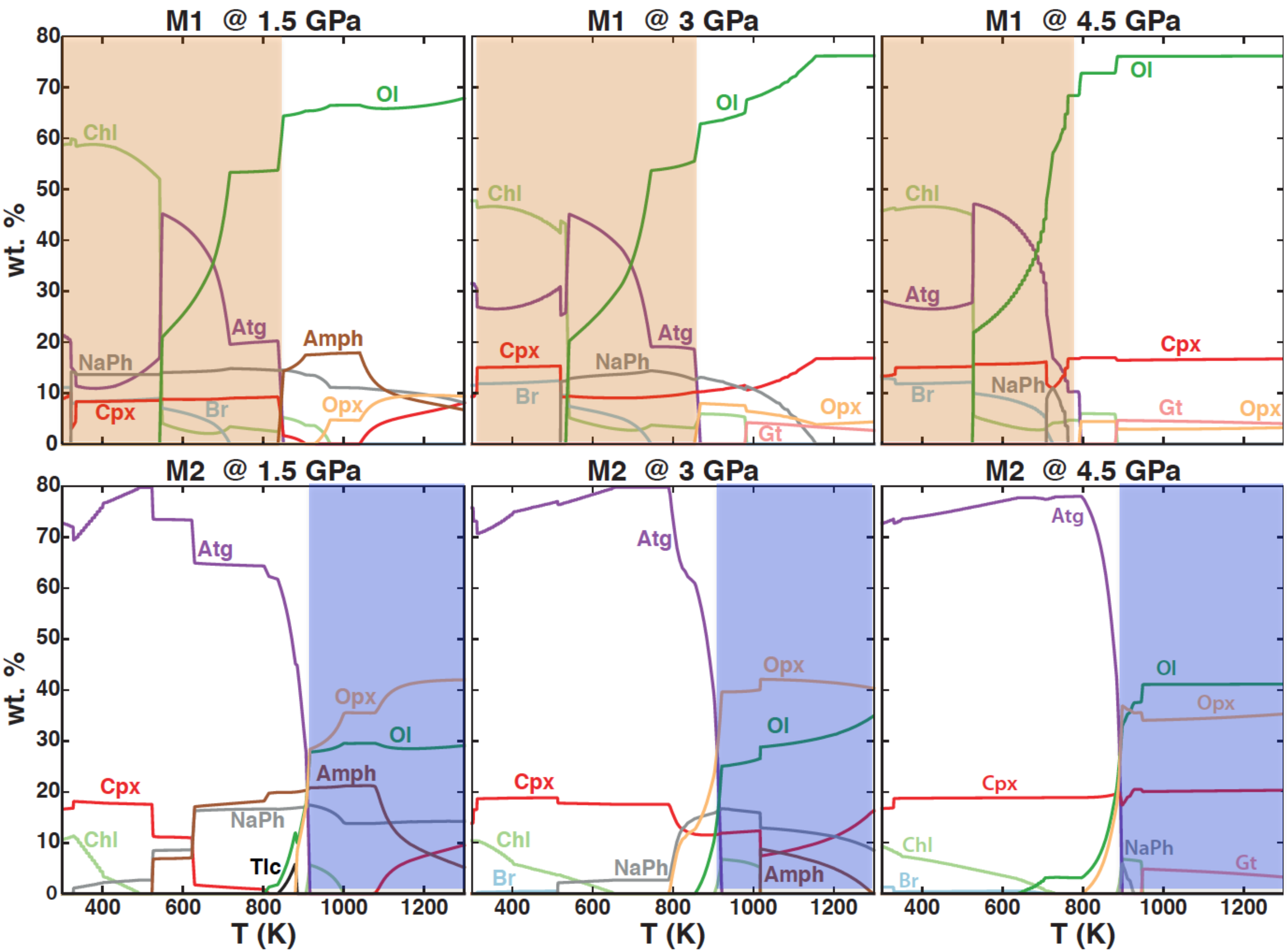
Silicates and metal phase with CI chondrite (=solar photosphere) composition

Oxide/sulfide (wt.%)	Undifferentiated	Silicate fraction Model 1	Silicate fraction Model 2
MgO	22.85	29.67	36.03
SiO_2	31.91	41.43	50.31
CaO	1.83	2.37	2.88
Na_2O	0.92	1.19	1.45
Al_2O_3	2.31	3.00	3.64
FeO	17.21	22.35	5.69
FeS	22.98	-	-

FeS: troilite in cold cores, assumed unreacted with silicates, simple mechanical mixture, Titan, Ceres
Fe-S(25wt%): eutectic liquid segregated from silicate outer core in inner metallic core, Ganymede

Use of Perple_X code for thermodynamic calculation of silicate fraction mineralogy as a function of P and T for a given composition
Perple_X succesfully used for predicting metamorphic mineralogy in varied rocks on Earth
assumes equilibrium, verified even for low T (500-1000K) rocks for metamorphic duration of 1-10 My

Predicted mineralogical silicate/oxide assemblages



M1

Hydrous silicates
@low T<800K

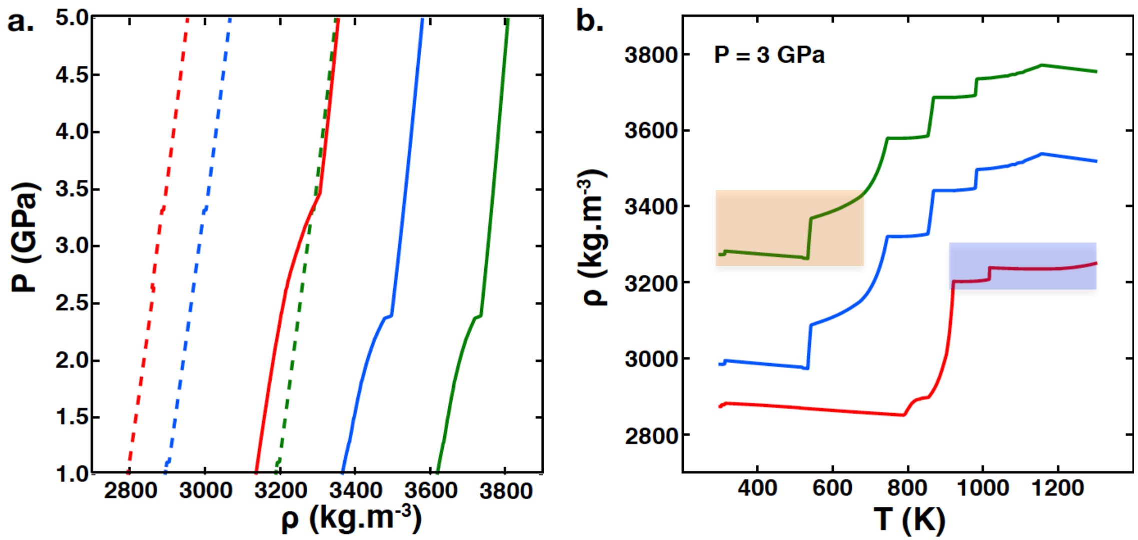
Titan, Ceres

M2

Dry silicates
@high T>900K

Ganymede

Silicate-sulfide-liquid metal densities



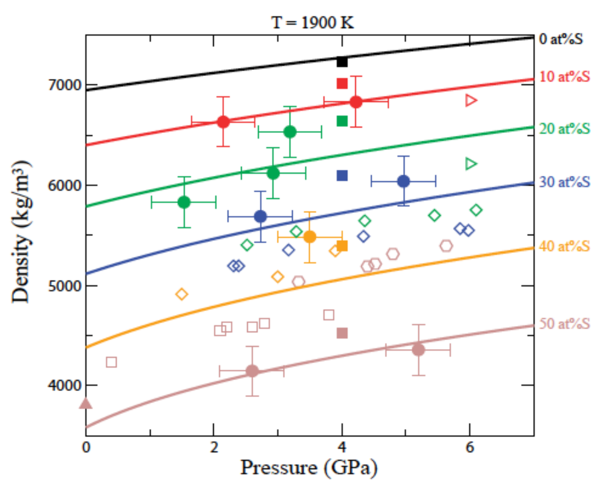
Silicates

Perple_X results

Néri et al. EPSL 2020

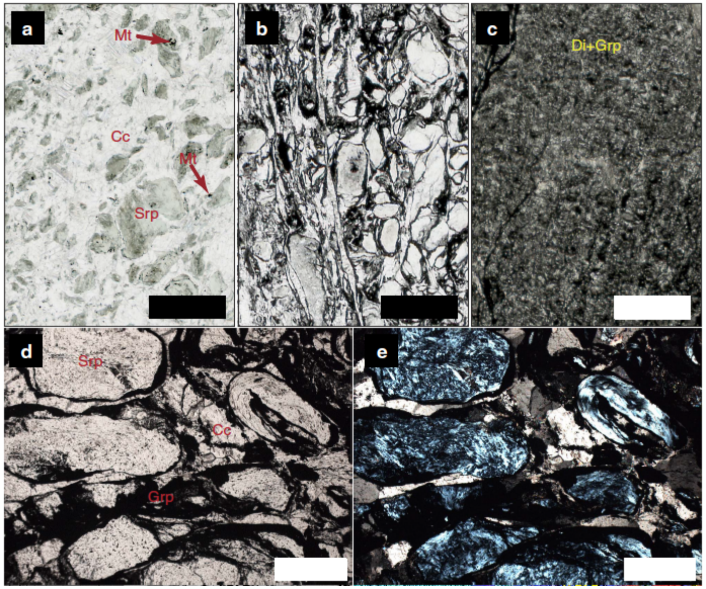
Solid and liquid iron sulfide density

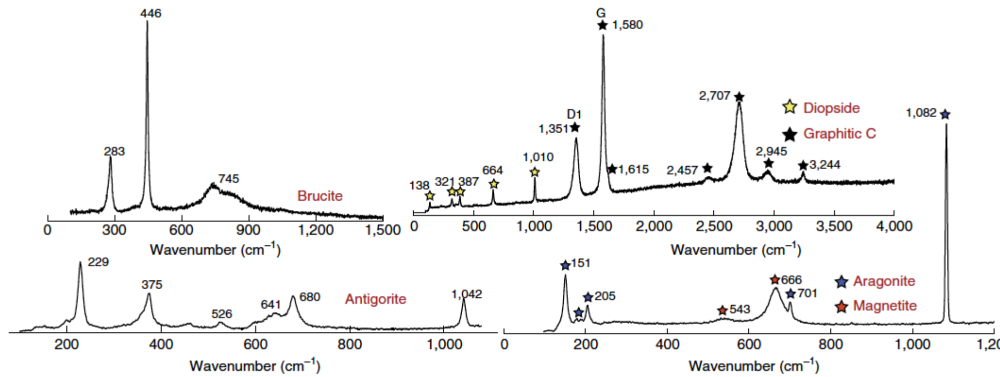
Murnaghan equation of state fitted to experimental data



Morard et al. Am Min (2018)

Carbonaceous matter in terrestrial metamorphic rocks





Vitale-Brovarone et al.NGeo 2017

CM can form and coexist with hydrous silicates in serpentinites

Little reaction at low T : mechanical mixture

High T : reactivity should be enhanced but little data of any, mechanical mixture assumed

Density estimated from measurements on carbonized coals at various T

Carbonaceous matter density

A STUDY OF THE FINE STRUCTURE OF CARBONACEOUS SOLIDS BY MEASUREMENTS OF TRUE AND APPARENT DENSITIES

PART II.—CARBONIZED COALS

By Rosalind E. Franklin

Received 15th February, 1949

Density estimated from measurements on carbonized coals at various T

1400±200 kg/m^3 at T<800K with hydrous silicates

1800±200 kg/m^3 at T>900K with dry silicates

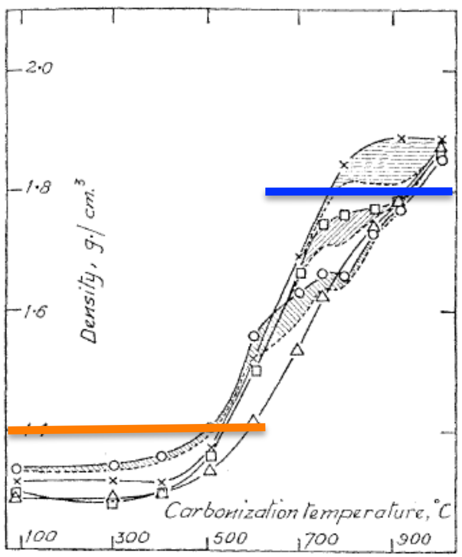


Fig. 2.—Coal F.

Helium. ○ Methanol. □ Water. △ n-Hexane.

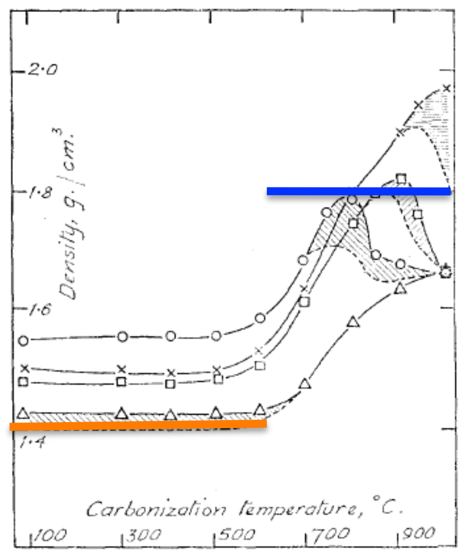


Fig. 1.—Anthracite C.

Helium. ○ Methanol. □ Water. △ n-Hexar

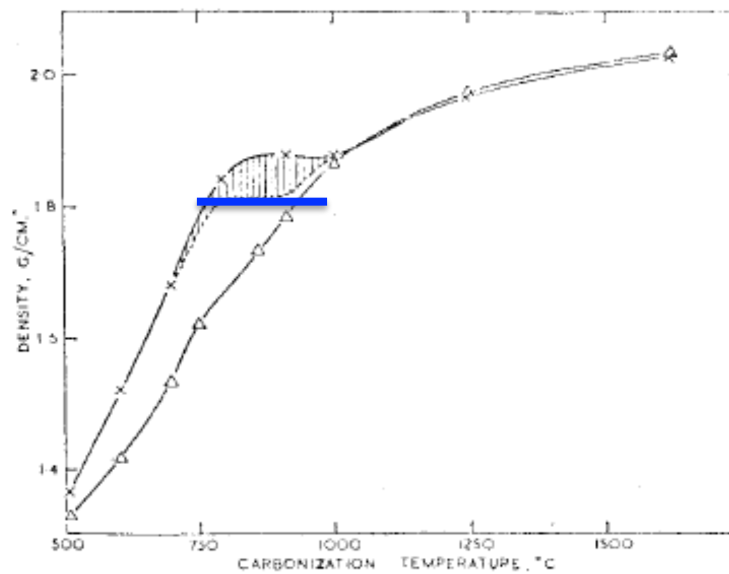
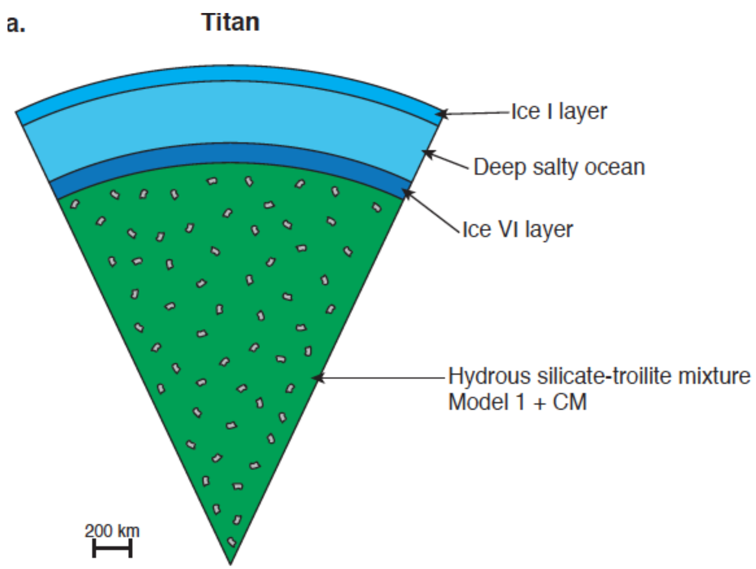
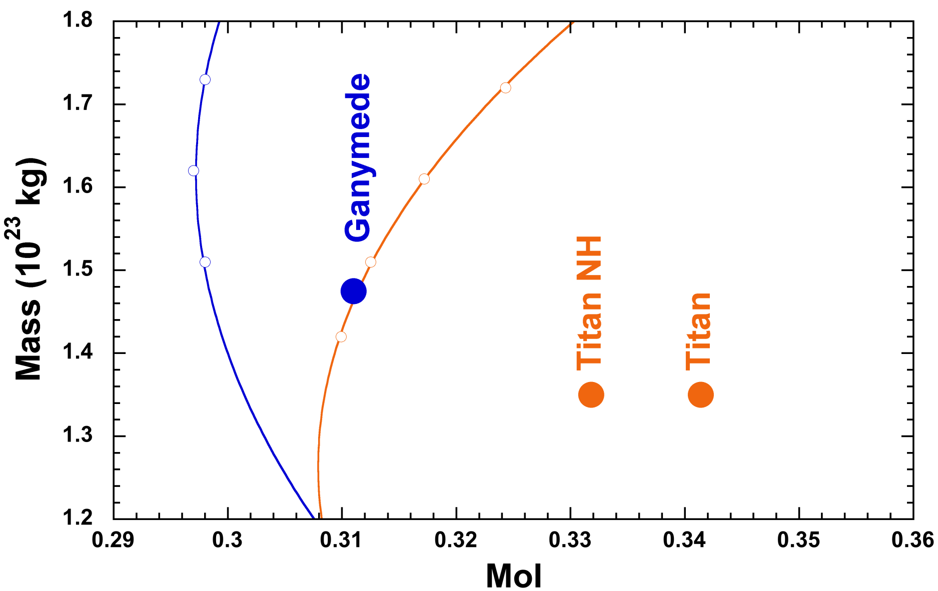


Fig. 5.—Coal F.

× Helium

Density-moment of inertia modeling



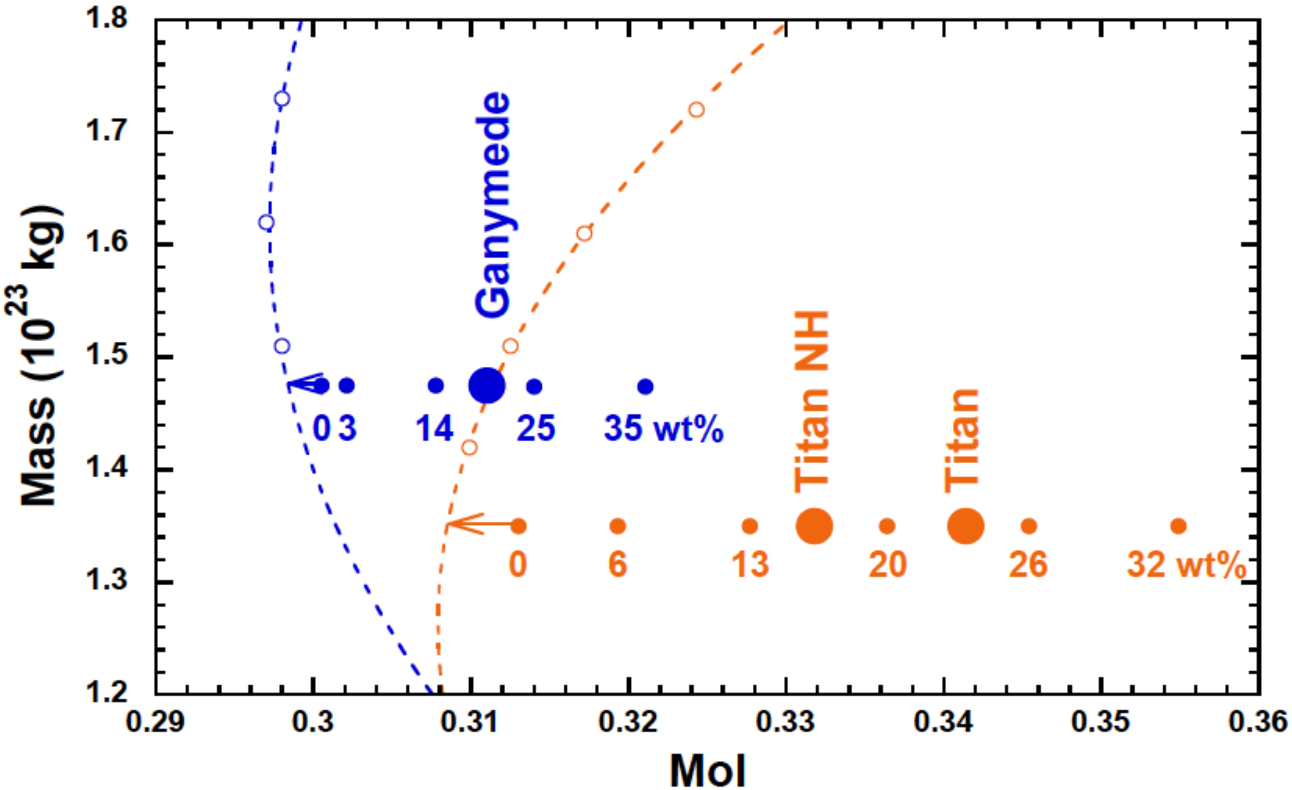


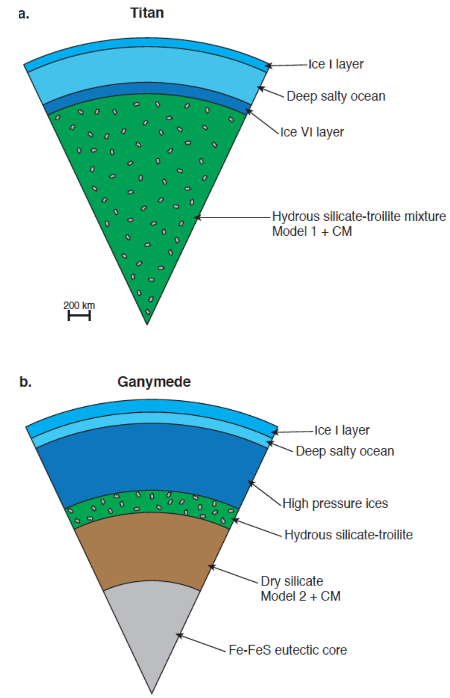
Vary ice/CI rock ratio:

Model do not match observation

Add CM to core composition until there is a match

Density-moment of inertia modeling





15-25 wt% of carbonaceous matter is needed to match observations

C/Si of 3-6 higher than CI (≈1) : addition from CM-rich comets

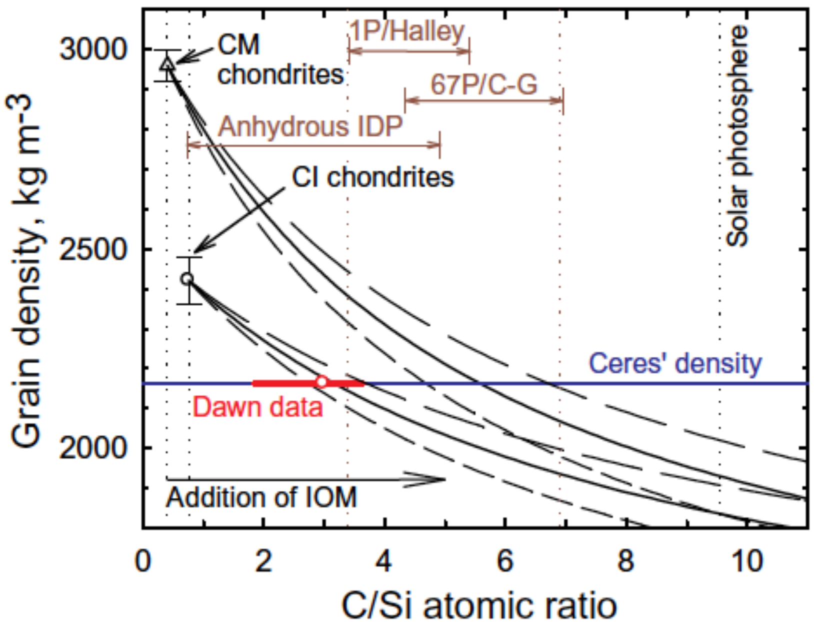
Source of hydrocarbons for life and Titan atmosphere from cracking of IOM

Reactivity at high T and over Gy?

1-Ceres

Applying the same model (Neri et al. 2020): ~25 wt% CM required to explain low MoI and core density of ~2400 km/m^3 (Ermakov et al. GRL 2017) equivalent to C/Si of ~6

Results consistent with recent estimates (Zolotov Icarus 2019)



Ceres and icy satellites include large amounts of CM-rich material