Investigating the Formation, Evolution, and Habitability of the Galilean Satellites with High Performance Mass Spectrometry

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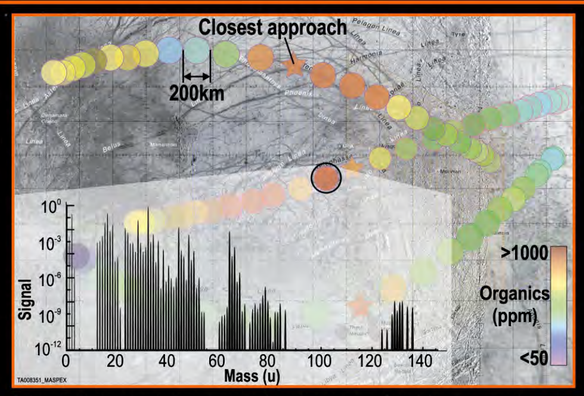
How High Resolution / High Sensitivity Mass Spectrometry Can Help Us Understand the Origin, Evolution and Habitability of Europa

Objective 1: Measuring surface composition through direct sampling



Surface sampling simulation showing the spatial resolution of our instrument. Each circle represents a high resolution spectrum from which we derive abundances for organic content, H_2, CH_4, SO_2, CO_2, H_2O, etc. The spatial resolution shown is derived from simulations of a 100 km altitude flyby assuming compositions from Cassidy[27].

Chemical and isotopic composition of the sputtered or outgassed material is analyzed using advanced mass spectrometry

Cryosampling mode allows for detection at parts per trillion

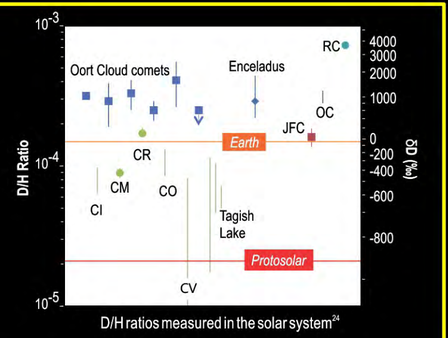
Key Measurement Species

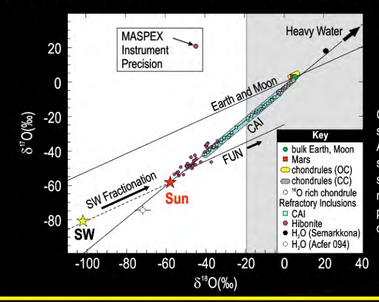
- **H_2O-ice abundances**
- **NH_3, N_2, CH_4, HCN**
- **CO_2**
  - -In free ice, as trace component in water ice, as an adsorbate on other minerals, or as hydrated carbonate or bicarbonate
- **SO_2**
  - -S allotropes, H_2S (as a sputter product of surface H_2SO_4
  - -Noble gases
  - -K, Na, ^{40}Ar
- **Organics**
  - -Detection threshold set at 10 ppm based on Enceladus and Titan
  - -Needed to distinguish between classes of organic compounds
  - -Aliphatic and aromatic hydrocarbons
  - -Nitriles
  - -Oxygen-bearing hydrocarbons

Objective 2: Sources of Europa's Water

Critical measurements that bear on Europa's origin

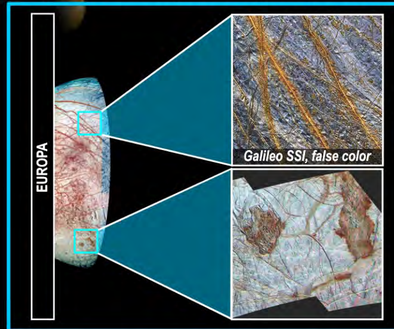
- **D/H ratio of water**
  - -Primary tracer of solar system formation and dynamical evolution
  - -Protosolar nebular formation vs. Jupiter subnebula formation
- **Oxygen isotope measurements**
  - -Oxygen in the Sun is dominated by ^{16}O relative to oxygen in the Earth-Moon system
  - -Oxygen isotope measurements have not been made to date
  - -Would provide evidence toward material origins for Europa
- **Noble gases**
  - -Important tracers of volatile evolution
  - -Trapping/condensation at low temperatures in the nebula/subnebula
  - -Non-reactive
  - -Measures of Xe/O, Kr/O, and Ar/O will enable estimates of the extent of devolatilzation





Oxygen three isotope plot showing representative compositions of solar system matter, the solar wind (SW), and the value for the Sun[19]. All data fall predominantly on the slope-one line. The shaded area shows the best in situ oxygen isotope knowledge of icy bodies in the solar system from Giotto ($\delta^{18}O$ range -51 to 128 per mil). No measurement of $\delta^{17}O$ was obtained. In contrast, our instrument will provide measurements of both $\delta^{18}O$ and $\delta^{17}O$ with error bars the size of the dot indicated in the upper left inset.

Objective 3: Linking surface geologic features with the interior



KNOWN COMPOUNDS
H_2O, SO_2, CO_2, H_2O_2, O_2, O_3, H_2SO_4 hydrate

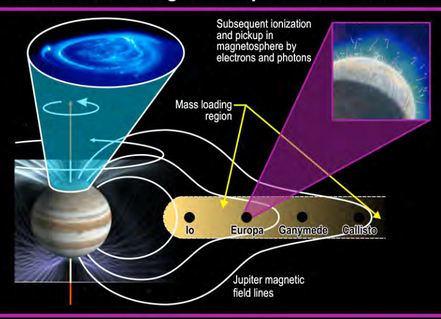
EXPECTED OR SUSPECTED COMPOUNDS
Hydrates of $MgSO_4$, Na_2SO_4 and Na_2CO_3, Na and K salts, S allotropes, organics

On earth, faults, fractures and folds are major controls on fluid and gas transport

Europa's large fault systems have likely served as pathways for volatile movement

- **Measurements of H_2 and CH_4 that may be outgassed from interior**
  - -Isotopic compositions may infer hydrothermal activity
- **Noble gases, especially ^{40}Ar**
  - -Provides constraints on geologic activity and rates of overturn

Objective 4: Characterizing the exosphere and neutral clouds



- The neutral density plays a strong role in determining the nature and degree of plasma interaction with the satellite
- A relatively dense atmosphere/ionsphere will act to divert plasma around a satellite, reducing radiation dose
- Allows for characterization of exosphere/magnetosphere interactions, thus characterizing the radiation environment at Europa
- 3D neutral density distributions
- Spatial and temporal observations
- Determine sources and sinks of plasma in the magnetosphere

Organic compounds as indicators of evolution and habitability on Europa

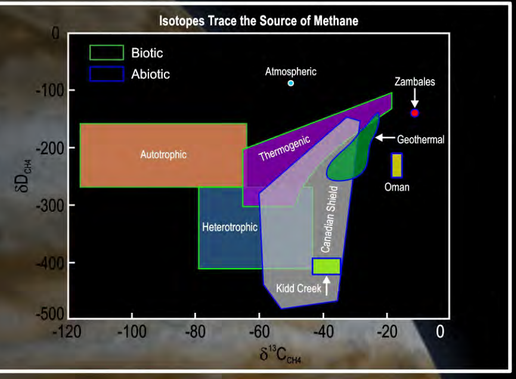
What are the origins of organics on Europa?[1]
- External: from cometary and micrometeorite bombardment.
- Internal: from hydrothermal processing or biogenic sources.

What can the mass spectrometer detect?
- Heavy ion sputtering launches surface molecules to spacecraft altitude.
- Radiolysis rapidly breaks surface organic molecules apart so large organic molecules are likely from newly exposed material.
- Plumes provide a direct source of interior sampling unaffected by radiolysis.

C and H isotopic ratios indicate habitability and evolution
- H_2O and CO_2 isotopic ratios define the feedstock composition for organic synthesis.
- Measurement of the C and H isotopic ratios of the organics provides insight into the creation processes e.g.
  - ♦Fischer-Tropsch (abiotic)[2]
  - ♦Cometary (primordial)[3]
  - ♦Biological[4,5]

Methane isotopic ratios are a key indicator for the source of organics[6]
- Studies of terrestrial hydrothermal vents enables the differentiation of abiotic and biotic sources.

Sci Obj 1 | Sci Obj 2 | Sci Obj 3

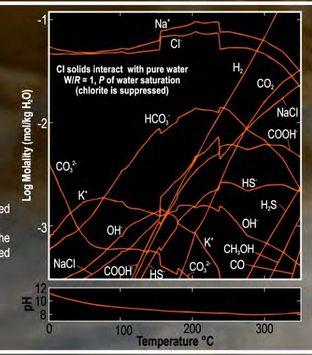


Outgassing volatiles indicate the evolutionary state of an internal ocean

Evolved - volatile ratios in equilibrium indicate hydrothermal processing
- Equilibrium values indicate the oxidation state and fugacity of the mineral / solvent system[7,8].
  - ♦Oxidation states more reducing than the fayalite-magnetite-quartz fugacity buffer (FMQ) can preserve and promote abiotic synthesis of complex organic compounds[9].
- How does hydrothermal activity affect habitability?
  - ♦Hydration of minerals produces hydrogen[10,11], which can fuel microbial systems[12].
  - ♦Hydrothermal activity implies a primary source of energy and cycles biogenic elements in and out of the ocean.

Unevolved – volatile ratios in disequilibrium indicate a comet like body[22]
- Reactive primitive species e.g. CO and HCN indicate an unprocessed environment.

Models can predict the equilibrium ratios of dissolved volatiles in hydrothermal systems[25]
The figure shows the effect of temperature on the composition and pH of aqueous solutions equilibrated with CI-type solids.



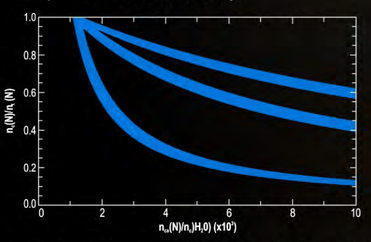
Sci Obj 1 | Sci Obj 2 | Sci Obj 3 | Sci Obj 4

Isotopic ratios of NH_3 and N_2 show origin and evolution

Origin
- The Galileo probe N_2 measurement[20] gives the origin N_2 isotopic ratio for the Jovian subnebula (primordial).

Evolution
- The Titan N_2 isotopic ratio is very different[21] due to its creation from NH_3 delivered in ices similar to comets[22].

Europa's N_2 isotope ratio
- Comparison of Europa's N_2 isotope ratio with the Galileo value will indicate if the origin is purely primordial or contains a contribution from NH_3 hydrothermal processing (origin and evolution).
- N is more available for biogenic incorporation as NH_3 than as N_2 so the incorporation of cometary ices to Europa increases its habitability.



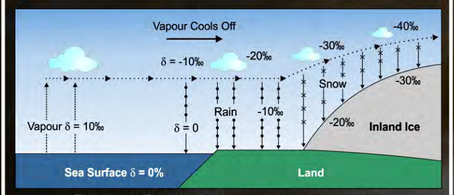
[21]The proportion of terrestrial nitrogen due to comets $n_c(N)/n_c(N)$ as a function of the abundance of isotopically anomalous nitrogen in comets $n_{co}(N)/n_c(H_2O)$. Each curve corresponds to a different value of the primitive Earth nitrogen isotopic ratio: $(^{15}N/^{14}N)_e$ = 2.3×10^{-3}, 3.0×10^{-3} and 3.55×10^{-3} from top to bottom. The width of the curves accounts for the uncertainty on the measured cometary $(^{15}N/^{14}N)_{co}$.

Sci Obj 1 | Sci Obj 2

Isotopes of water trace origins

What are the origins of Europa's water?[16,17,18,19]
- Devolatilization of carbonaceous chondrites[14] indicated by protosolar nebular ratios.
- Icy planetesimals[15] indicated by cometary ices / Titan & Enceladus ratios.

Can the spatial distribution of O isotopes identify oceanic upwelling?
- Vaporization and condensation of water fractionates the oxygen isotopes[13,26].
- Water vapor migration and condensation away from the source vent creates an O isotopic fractionation pattern on the surface that can be measured.

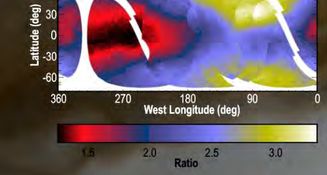


[26]Changes in $\delta^{18}O$ from the first evaporation to the final snow fall.

Sci Obj 2 | Sci Obj 3

Where does Europa's sulfur come from?

Is it native or transferred from Io?
- Compare isotopes from surface sputtering and SO_2 in the neutral cloud for similarities.
- Similar isotope ratios show that Europa's sulfur may be obtained from Io rather than from oceanic salts.

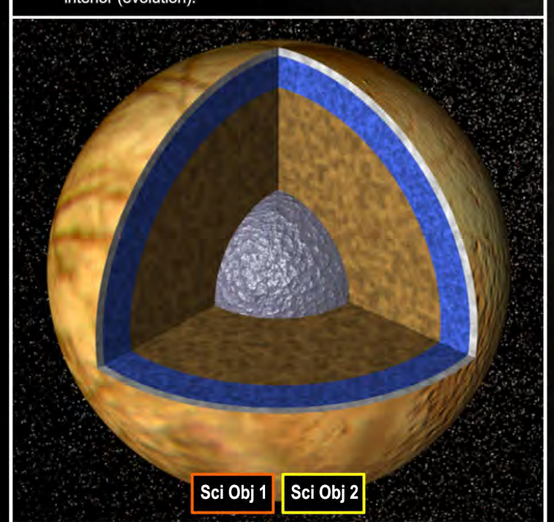


[23]The surface of Europa could contain the compositional imprint of an underlying interior ocean, but competing hypotheses differ over whether spectral observations from the Galileo spacecraft (top right) show the signature of ocean evaporates or simply surface radiation products unrelated to the interior. Recent Keck spectra (bottom right) show a previously undetected distinct signature of magnesium sulfate salts on Europa confined to the trailing hemisphere and spatially correlated with the presence of radiation products like sulfuric acid and SO_2. This suggests that $MgSO_4$ is also a radiation product, rather than a constituent of a Europa ocean brine.

Sci Obj 1 | Sci Obj 2 | Sci Obj 3

How active is Europa's interior?

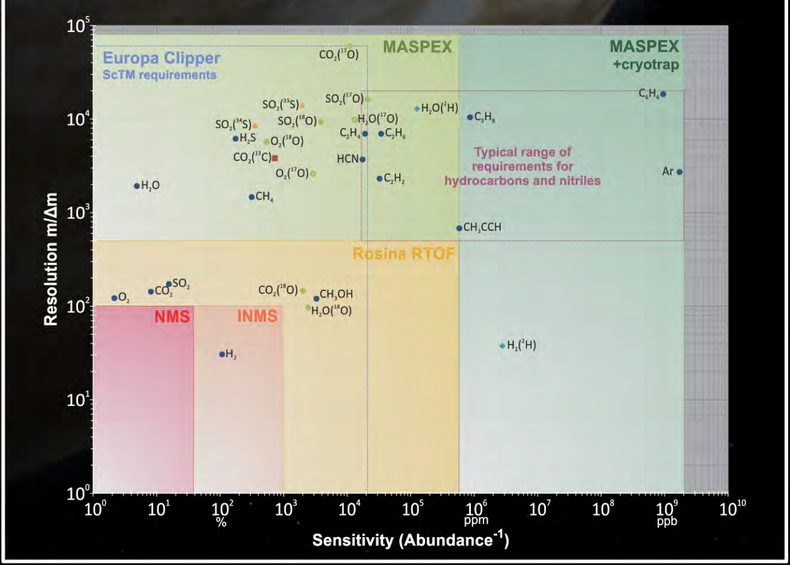
^{40}Ar release indicates overturn
- Decay of ^{40}K in rocks creates ^{40}Ar, which remains trapped until geologic activity releases it.
- Detection of ^{40}Ar is a measure of overturn and convection of the interior (evolution).



Sci Obj 1 | Sci Obj 2

Analysis requirements for Europa's atmosphere observed during a 100km altitude flyby

The Europa Clipper Science Traceability Matrix requirement is outlined along with performance envelopes for the strawman instrument - NMS (Nozomi), Cassini INMS, Rosina RTOF and MASPEX (with and without cryotrapping)



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