

The Galileo Mission to the Jupiter System

NIMS and Satellites' Surface Composition

*How it was in the old days
and how this scientist got to Galileo*

Tom McCord

Presented at:

The Galileo Mission 30th Celebration

December 8, 2025

My Instructions

- *Speak to the young scientists.*
- *Describe what it was like for me, then.*
- *Examples of some science*

My Interpretation:

- *Give background and context for me and the times.*
- *More anecdotal than a science talk.*
- *But some science too, especially the BIG stuff.*

So, where do old Galileo Scientists come from?

- *Well, from the past – in some cases way past!*
- *Nearly a century ago.*

My Boyhood Background

- Born during the Great Depression, the 1930s.
- Remember scenes during World War II.
- Grew up during the roaring 1950s
- Rural, farming, small town, southeastern Pennsylvania
- At the interface of Appalachia and Conestoga Valley--Amish country

My Background: Working Amish Farms



Rural farming community. Worked on Amish farms using horses and mules, making hay, cutting corn and tobacco. Fishing, trapping and hunting.



My Background: Into adulthood, before collage

- 1 ½ years out of high school, shoveling corn off the back of a truck in freezing rain.
- Had to be something better than this – had to promote a change.
- Volunteered for USAF and Merchant Marines. The USAF called first.
- USAF, 4 years , 1958-61
- Did isolated duty on the front-line of the Cold War.

My Background: USAF 4 years 1958-61



On the Greenland ice cap, east of Sonderstrom Fiord, 1960-61.

Including one year: Frontline and isolated duty during the Cold War.
DEW Line: Distant Early Warning site

My Journey to joining the Galileo team

USAF to Ph.D.

- I had an epiphany! Six months after joining the Air Force.
 - Decided I wanted to be a Ph.D. Physicist. An example of what happens when you do something very different to break up an experience that isn't going anywhere.
 - Where'd that come from???
- Did about 2 years of college piece-meal while in the Air Force
 - Marymount College, Salina KS: me and 498 girls.
 - U. Md professors in Greenland.
- Went to college full time after AF, studying physics and eventually its application to the Solar System.
- Real campuses:
 - BS: Physics Penn State,
 - MS: Geology and Ph.D.: Planetary Science and Astronomy, Caltech.

The early days of telescope observing

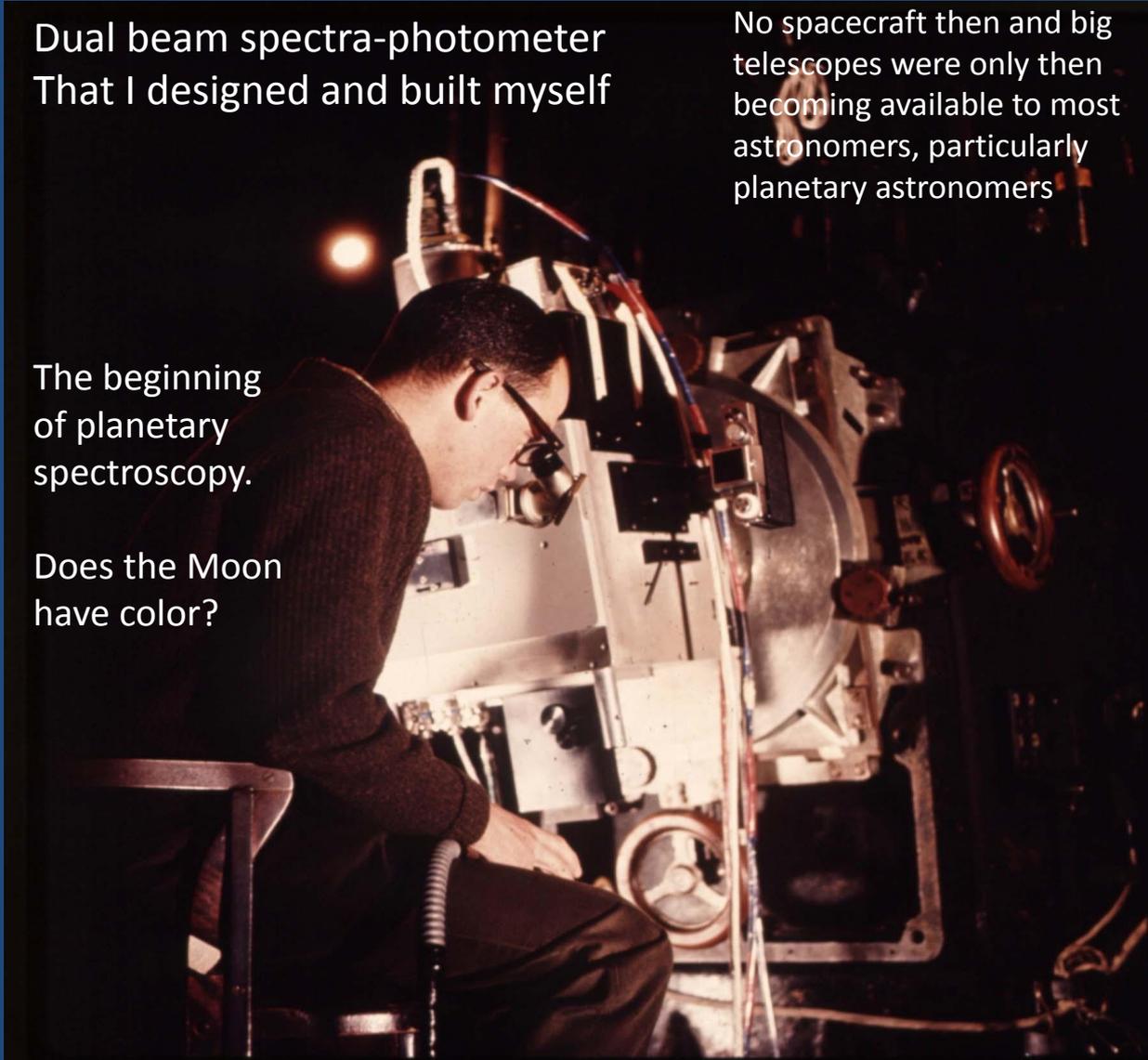
Tom at the Mt. Wilson 60 inch, ca. 1966

Dual beam spectra-photometer
That I designed and built myself

No spacecraft then and big
telescopes were only then
becoming available to most
astronomers, particularly
planetary astronomers

The beginning
of planetary
spectroscopy.

Does the Moon
have color?



The early days of telescope observing

Jeff Bosel
and myself.



We built our own electronics, carried them to the world's largest telescopes and set them up for multi-day over-night runs.

How I got selected by NASA to be on the Galileo team

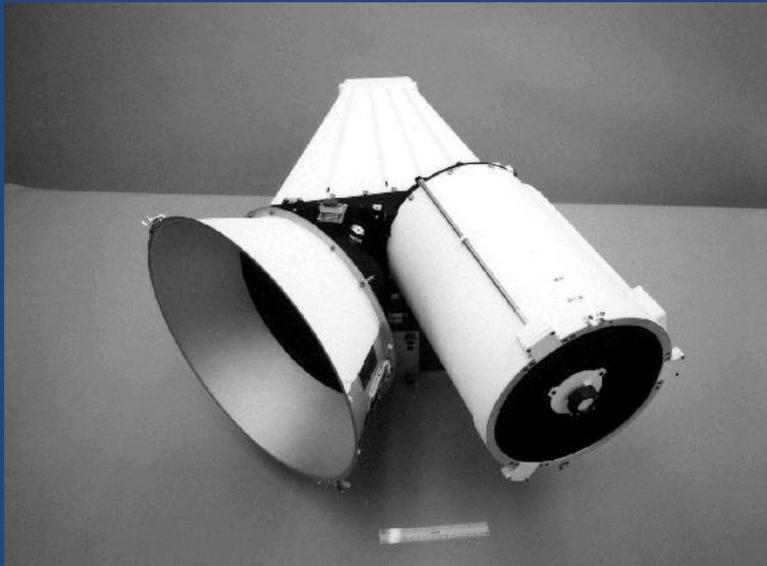
- Was a very early developer and user of reflectance and IR spectroscopy to determine SS object surface compositions.
 - Using ground-based large telescopes (no spacecraft available then)
 - IR detectors just becoming available for science in 1960s. (Technology out of WWII.)
- Proposed through MIT to provide the spectrometer for Galileo.
- JPL woke up and also proposed in the last few days of the open competition.
- NASA selected JPL but put me on their NIMS team.
- Torrence Johnson was the PI; had been my first Post-Doc at MIT the year before.
- Some interesting back-stories, best left to bar room discussions.

NIMS Instrument

on the Galileo team

- **N**ear **I**nfrared **M**apping **S**pectrometer

0.7 to 5.2 μm with up to 408 spectral channels
scan the spectrum in wavelength (17 steps) and in space
0.5 mrad IFOV



One of the first “modern” spectrometer in space. Used linear array of IR solid state detectors. It worked pretty well!

I went on to help over ~50 years design/build/provide other spectrometers for space with JPL.

Galileo was A Long Haul

1975 to 2003 – 28 years

- 1975 NASA approved the Galileo Mission.
- 1976 NASA AO for instrument selections.
- 1977 NASA announces instrument selections.
- 1986 Galileo first suppose to launch, but Challenger disaster cancelled it.
- 1989 Galileo finally launched.
- 1995 Jupiter orbit insertion.
- 1995 First satellite encounter, Ganymede.
- 2003 End of Mission - crash into Jupiter.

Early Science at the Jupiter System after orbit insertion, December 1995

June 27, 1996: First NIMS science measurements at Jupiter: At Ganymede.

First –ever spatially resolved IR spectra from the Jovian system.

April 1998: My first publication, Galileo at Jupiter.

Non-ice Constituents on Ganymede and Callisto -- JGR

Our first composition results: *Non-Ice Constituents on Ganymede and Callisto*

Demonstrated we could detect, identify and map surface materials using NIMS.

T. B. McCord, G. B. Hansen, R. N. Clark, P. D. Martin, C. A. Hibbitts, F.P. Fanale, J. C. Granahan, M. Segura, D. L. Matson, T. V. Johnson, R. W. Carlson, W. D. Smythe, G. E. Danielson, and The NIMS Team

*JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 103,
APRIL 25, 1998*

Materials suggested:
S-H, SO₂, CO₂, C—N and
organic material like tholins

Hydrated Salt Minerals on Europa's surface

Discovery paper:

Hydrated Salt minerals on the surface of Europa deposited from the ocean below.

SCIENCE, VOL. 280, 22 MAY 1998

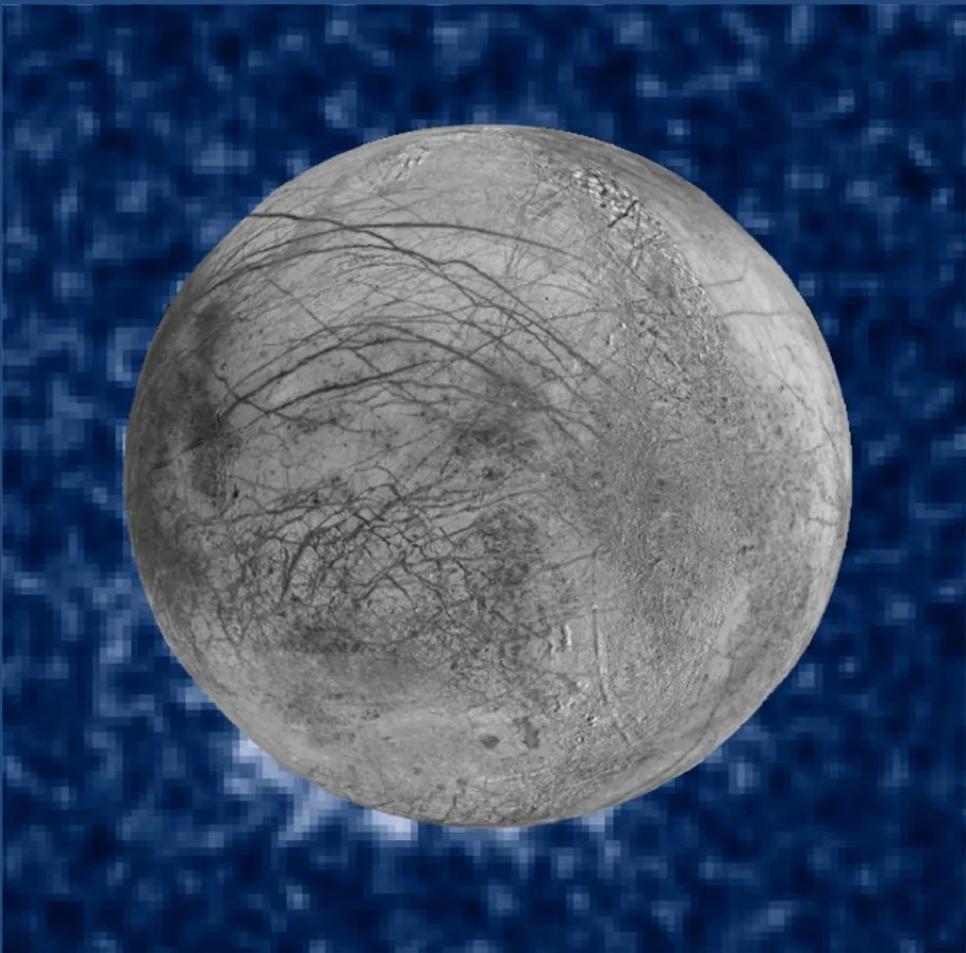
One of the three pieces of evidence that there is likely a liquid ocean beneath the icy crust.

Geologic features

Magnetic field

Salt minerals on surface from salty sea.

**Liquid water with hydrated salt minerals
erupting on Europa's surface**



Hydrated salt Minerals on Europa's surface

Expanded discovery paper:
*Hydrated Salt minerals on Europa's
surface.*

JGR, VOL. 104, MAY 1999

BUT! ANOTHER IDEA!!

Radiation Creates Sulfuric Acid

Bob Carlson, Bob Johnson, et al.

Jupiter ionosphere must damage surface materials.

Sulfur from Io must impact the surface.

Ice plus sulfur, irradiated, should create sulfur compounds.

Hydrated sulfuric acid spectra looks a lot like Europa dark material spectra. Not exactly, but close.

**Sulfuric Acid is the answer
Instead of hydrated salt minerals**

Sulfuric Acid on Europa and the Radiolytic Sulfur Cycle

SCIENCE, VOL. 286, 1999

R. W. Carlson, R. E. Johnson, M.S. Anderson

A comparison of laboratory spectra with Galileo data indicates that hydrated sulfuric acid is present and is a major component of Europa's surface. In addition, this moon's visually dark surface material, which spatially correlates with the sulfuric acid concentration, is identified as radiolytically altered sulfur polymers. Radiolysis of the surface by magnetospheric plasma bombardment continuously cycles sulfur between three forms: sulfuric acid, sulfur dioxide, and sulfur polymers, with sulfuric acid being about 50 times as abundant as the other forms. Enhanced sulfuric acid concentrations are found in Europa's geologically young terrains, suggesting that low-temperature, liquid sulfuric acid may influence geological processes

Sulfuric Acid is the answer

Sulfuric Acid Production on Europa: The Radiolysis of Sulfur in Water Ice

ICARUS, VOL. 157, 2002

R. W. Carlson, M.S. Anderson, R. E. Johnson, M. B. Schulman, A. H. Yavroulan

Europa's surface is chemically altered by radiolysis from energetic charged particle bombardment. It has been suggested that hydrated sulfuric acid ($\text{H}_2\text{SO}_4 \cdot n\text{H}_2\text{O}$) is a major surface species and is part of a radiolytic sulfur cycle, where a dynamic equilibrium exists between continuous production and destruction of sulfur polymers S_x , sulfur dioxide SO_2 , hydrogen sulfide H_2S , and $\text{H}_2\text{SO}_4 \cdot n\text{H}_2\text{O}$. We measured the rate of sulfate anion production for cyclo-octal sulfur grains in frozen water at temperatures, energies, and dose rates appropriate for Europa using energetic electrons. The measured rate is $G_{\text{Mixture}}(\text{SO}_4^{2-}) = f_{\text{Sulfur}} (r_0/r)^\beta G_1$ molecules $(100 \text{ eV})^{-1}$, where f_{Sulfur} is the sulfur weight fraction, r is the grain radius, $r_0 = 50 \text{ } \mu\text{m}$, $\beta \approx 1.9$, and $G_1 = 0.4 \pm 0.1$. Equilibrium column densities N are derived for Europa's surface and follow the ordering $N(\text{H}_2\text{SO}_4) \gg N(\text{S}) > N(\text{SO}_2) > N(\text{H}_2\text{S})$. The lifetime of a sulfur atom on Europa's surface for radiolysis to H_2SO_4 is $\tau(-\text{S}) = 120(r/r_0)^\beta$ years. Rapid radiolytic processing hides the identity of the original source of the sulfurous material, but logenic plasma ion implantation and an acidic or salty ocean are candidate sources. Sulfate salts, if present, would be decomposed in < 3800 years and be rapidly assimilated into the sulfur cycle.

How sulfuric acid could be made on Europa's surface

Stability of hydrated salt minerals to thermal and radiation conditions.

*Can hydrated salt minerals survive
under Europa surface conditions?*

JGR, VOL. 106, 2001

Yes!

Hydrated Mg⁺⁺ sulfates could survive for geologic time on the surface of Europa.

But: Na⁺ sulfates could be desorbed including to the atmosphere and leaving H⁺ and sulfates to form sulfuric acid.

Both salt minerals and sulfuric acid,
Hydrogen Sulfate, as a by product.

Brines exposed to Europa surface conditions

Hydrated Salt minerals under realistic Europa surface conditions.

JGR, VOL. 107, 2002

Flash freezing makes a difference.

Non-ice material on Europa can be disordered, heavily hydrated Mg and perhaps Na sulfates that are probably from an ocean below. Some Na⁺ may be removed by radiation and replaced with H⁺, producing some H₂SO₄ and providing a source for the neutral Na observed coming off Europa [Johnson, 2000b].

Brines exposed to Europa surface conditions

Thomas B. McCord,¹ Glenn Teeter,² Gary B. Hansen,¹ Mathew T. Sieger,^{2,3} and Thomas M. Orlando^{2,4}

Received 20 January 2001; revised 30 August 2001; accepted 2 October 2001; published 29 January 2002.

[1] Evidence for an ocean beneath the icy crust of Europa includes reflectance spectra of disrupted surface regions indicating hydrated materials such as salts. We simulated exposure of salty brine on the cold surface of Europa by flash-freezing sulfate and carbonate solutions. This produces materials that have near-infrared reflectance spectra distinct from those for crystalline minerals and more similar to those for Europa's non-ice regions. These new spectroscopic data, along with geophysical evidence, geochemical models, and meteorite studies, strongly suggest that the non-ice materials in the disrupted regions on Europa's surface contain large amounts of disordered and heavily hydrated MgSO₄ and perhaps Na₂SO₄ that are endogenic in origin. **INDEX TERMS:** 6218 Planetology: Solar system objects: Jovian satellites, 5470 Planetology: Solid Surface Planets: Surface materials and properties, 5460 Planetology: Solid Surface Planets: Physical properties of materials, 5410 Planetology: Solid Surface Planets: Composition; **KEYWORDS:** Europa, Galilean satellites, surface materials, material properties, salt minerals, hydrated minerals

[2] A growing body of evidence indicates that an ocean may be hidden beneath the icy crust of Jupiter's second moon, Europa [e.g., Stevenson, 2000]. Galileo mission data reveal a variety of surface features such as lineaments and chaos terrain that indicate surface fracturing, melting, and movement of blocks over a less viscous material [e.g., Pappalardo et al., 1999; Greeley et al., 1998; Greenberg et al., 1999]. Magnetic fields detected by Galileo indicate moving conducting fluids near the surface [Kivelson et al., 1999, 2000], and extensive cycloidal cracks over the surface are likely caused by ocean tides [Hoppa et al., 1999, 2000].

[3] There is also spectral evidence from the Galileo Near-Infrared Mapping Spectrometer (NIMS). This indicates heavily hydrated compounds on the surface that were interpreted to be endogenic salt minerals such as magnesium and sodium sulfate hydrates [McCord et al., 1998, 1999a]. McCord et al. [1998, 1999a] also showed these hydrate deposits to be associated closely with the fractures and disturbed terrain, as have subsequent studies [Fanale et al., 2000]. In addition, models of thermal evolution of Europa's interior and laboratory studies of meteorites [Fanale et al., 1977, 1998; Kargel, 1991, 1999; Kargel et al., 2000] predict production of magnesium sulfate hydrates and perhaps other salts in Europa.

[4] The surface environment of Europa is hostile with almost no atmosphere and midday temperatures between 80 K at the poles and 130 K at the equator [Spencer et al., 1999]. Radiation from Jupiter's magnetosphere constantly bombards the surface with 10⁸–10¹⁰ energetic particles cm⁻² s⁻¹ with the flux and energy deposition at the surface dominated by energetic (keV–MeV) electrons [Cooper et al., 2001]. In view of these unique surface conditions, processes might produce hydrated salt minerals that differ from terrestrial minerals [McCord et al., 2000]. Owing to rapid cooling during formation, forms such as glassy frozen brines and/or metastable crystalline hydrated salt minerals may result. These materials would tend to have different infrared (IR) reflectance spectra than the crystalline materials used in earlier Europa studies.

[5] These surface hydrates could originate from the subsurface ocean and thus be direct indicators of its chemistry. Direct exposure of briny ocean water, by cryovolcanism or open cracks (leads), is the most direct (but controversial) way of creating the surface deposits (cf. Kargel [1991] and Fagents et al. [2000] for a recent summary). Thus we attempted to simulate this process.

[6] We prepared frozen sulfate and carbonate brine samples by rapid thermal quenching and measured IR reflectance spectra of these flash-frozen brines as a function of hydration level under low temperatures (<130 K) and low pressures (<1 × 10⁻⁸ torr). We used the high-vacuum chamber and associated equipment described earlier [McCord et al., 2001]. It has a sample manipulator cooled by a helium cryostat capable of reaching ~50 K and a chromel-alumel thermocouple to monitor sample temperature. Sulfate and carbonate brines were prepared from 99.9999% purity Na₂SO₄ · 10H₂O and MgSO₄ · 7H₂O and from Na₂CO₃ obtained from a chemical supplier. Dilute aqueous solutions (1:1 mixtures by volume of saturated solution at 294 K) of Na₂SO₄, MgSO₄, and Na₂CO₃ were prepared. In addition to pure Na₂SO₄ and MgSO₄ dilute solutions, 2:1, 1:2, and 1:4 mixtures of the two were prepared. The brines were deposited in the chamber on the cold (~150–220 K) manipulator in situ in a dry nitrogen atmosphere, which prevented condensation of atmospheric water on the manipulator and sample. Vacuum was then rapidly restored, and the sample temperature dropped quickly to ~110 K.

[7] Each sample was thermally cycled several times to successively higher temperatures in vacuum in an attempt first to eliminate excess water (i.e., water molecules that are not within the salt ion solvation shells) and then to simulate any thermal or radiolytic loss of waters of hydration that might occur on Europa. The temperature cycles were achieved by gradual warming while monitoring evolved water vapor pressure. The heating rate was ~0.01 K s⁻¹. Pure water ice does not sublime significantly below ~155 K on laboratory timescales [Smith et al., 1996], and these hydrated salt minerals are stable at even higher temperatures [McCord et al., 2001; Zolotov and Shock, 2001]. Therefore, in order to remove significant water from a sample on laboratory timescales, the temperature had to reach ~200–235 K, below the temperature at which the hydrated salt is affected on laboratory timescales [McCord et al., 2001]. The maximum water vapor pressures observed during dehydration were typically in the range 10⁻⁴–10⁻⁵ torr. After each dehydration treatment the samples

¹Hawaii Institute of Geophysics and Planetology, University of Hawaii, Honolulu, Hawaii, USA.

²W. R. Wiley, Environmental Molecular Sciences Laboratory, Pacific Northwest National Laboratory, Richland, Washington, USA.

³Now at Intel Corporation, Portland, Oregon, USA.

⁴Now at School of Chemistry and Biochemistry and School of Physics, Georgia Institute of Technology, Atlanta, Georgia, USA.

The physics

The chemical nature of Europa surface material and the relation to a subsurface ocean.

Deep into the physics and chemistry

Icarus, VOL. 177, 2005

These laboratory data show best correlation with NIMS Europa spectra for multi-component mixtures of sodium and magnesium bearing sulfate salts mixed with sulfuric acid.

Sulfuric acid mostly from radiolysis of Na-sulfate.



Available online at www.sciencedirect.com

SCIENCE @ DIRECT®

Icarus 177 (2005) 528–533

ICARUS

www.elsevier.com/locate/icarus

The chemical nature of Europa surface material and the relation to a subsurface ocean

Thomas M. Orlando^{a,b,*}, Thomas B. McCord^c, Gregory A. Grieves^a

^a School of Chemistry and Biochemistry, Georgia Institute of Technology, 770 State St., Atlanta, GA 30332-0400, USA

^b School of Physics, Georgia Institute of Technology, Atlanta, GA 30332, USA

^c University of Hawaii, and Planetary Sciences Institute NW, P.O. Box 667, Winthrop, WA 98862, USA

Received 24 December 2004; revised 17 May 2005

Available online 6 July 2005

Abstract

The surface composition of Europa is of special interest due to the information it might provide regarding the presence of a subsurface ocean. One source of this information is the infrared reflectance spectrum. Certain surface regions of Europa exhibit distorted H₂O vibrational overtone bands in the 1.5 and 2.0 μm region, as measured by the Galileo mission Near Infrared Mapping Spectrometer (NIMS). These bands are clearly the result of highly concentrated solvated contaminants. However, two interpretations of their identity have been presented. One emphasizes hydrated salt minerals and the other sulfuric acid, although each does not specifically rule out some of the other. It has been pointed out that accurate chemical identification of the surface composition must depend on integrating spectral data with geochemical models, and information on the tenuous atmosphere sputtered from the surface. It is also extremely important to apply detailed chemistry when interpreting the spectral data, including knowledge of mineral dissolution chemistry and the subsequent optical signatures of ion solvation in low-temperature ice. We present studies of flash frozen acid and salt mixtures as Europa surface analogs and demonstrate that solvated protons, metal cations and inorganic anions all influence the spectra and must all, collectively, be considered when assigning Europa spectral features. These laboratory data show best correlation with NIMS Europa spectra for multi-component mixtures of sodium and magnesium bearing sulfate salts mixed with sulfuric acid. The data provide a concentration upper bound of 50-mol% for MgSO₄ and 40-mol% for Na₂SO₄. This newly reported higher sodium and proton content is consistent with low-temperature aqueous differentiation and hydrothermal processing of carbonaceous chondrite-forming materials during the formation and early evolution of Europa.
© 2005 Elsevier Inc. All rights reserved.

Keywords: Geochemistry; Ices; Satellites of Jupiter; Spectroscopy; Surfaces; Satellite

1. Introduction

Europa is the subject of intense scrutiny because of the possibility that its icy shell may conceal a liquid ocean capable of harboring life (Carr et al., 1998; Chyba, 2000; Chyba and Phillips, 2001). Evidence regarding crustal composition is limited, but includes sputtered atmospheric constituents (Brown, 2001; Brown and Hill, 1996; Hall et al., 1995) and near-infrared reflectance spectra of surface re-

gions from the Galileo NIMS investigation (Carlson et al., 1996). Reflectance spectra of certain Europa surface regions exhibit highly distorted H₂O vibrational overtone bands. One interpretation is that these suggest endogenic frozen salt mineral mixtures with some Na₂SO₄ converted to H₂SO₄ under irradiation at the surface (McCord, 1998a; McCord et al., 1999, 2002). The other proposes that H₂SO₄ in ice gives the best single-component match to the NIMS spectra (Carlson et al., 1999). In the former, the salts come from the ocean below. In the latter, H₂SO₄ is from radiation processing and sulfur ion implantation in water ice from the jovian plasma torus. Hopes of accurate chemical identification of the surface material, and extrapolation to a

* Corresponding author. Fax: +1 404 894 7452.
E-mail address: thomas.orlando@chemistry.gatech.edu (T.M. Orlando).

SO, What is the Answer? Both, and More.

BOTTOM LINE: A mixture of hydrated salt minerals and acids, as a byproduct.
And probably more.

Yes, sulfur and radiation must be there.

But heavily hydrated Magnesium Sulfate, being so soluble, is equally likely to be present,
and it is stable against irradiation.

Na⁺ salt compounds must also be there but are easily destroyed, as Na is in the atmosphere – but not Mg.

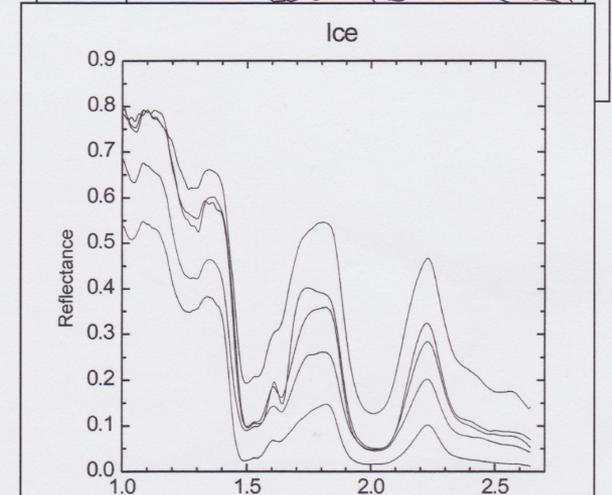
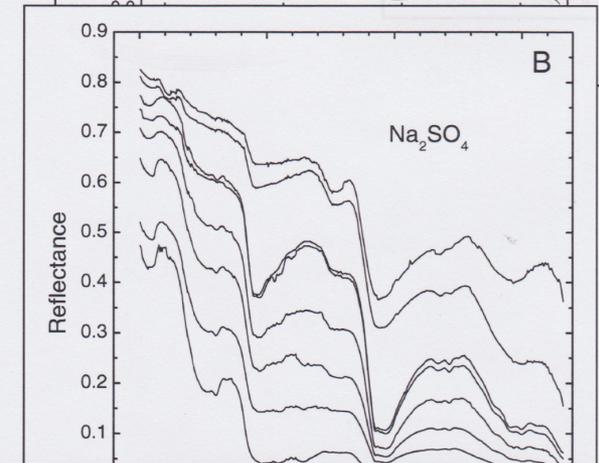
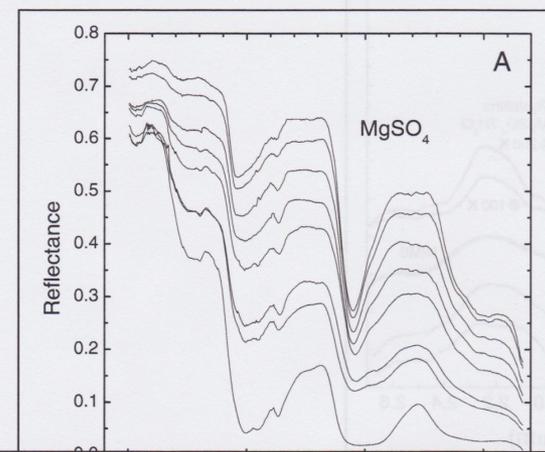
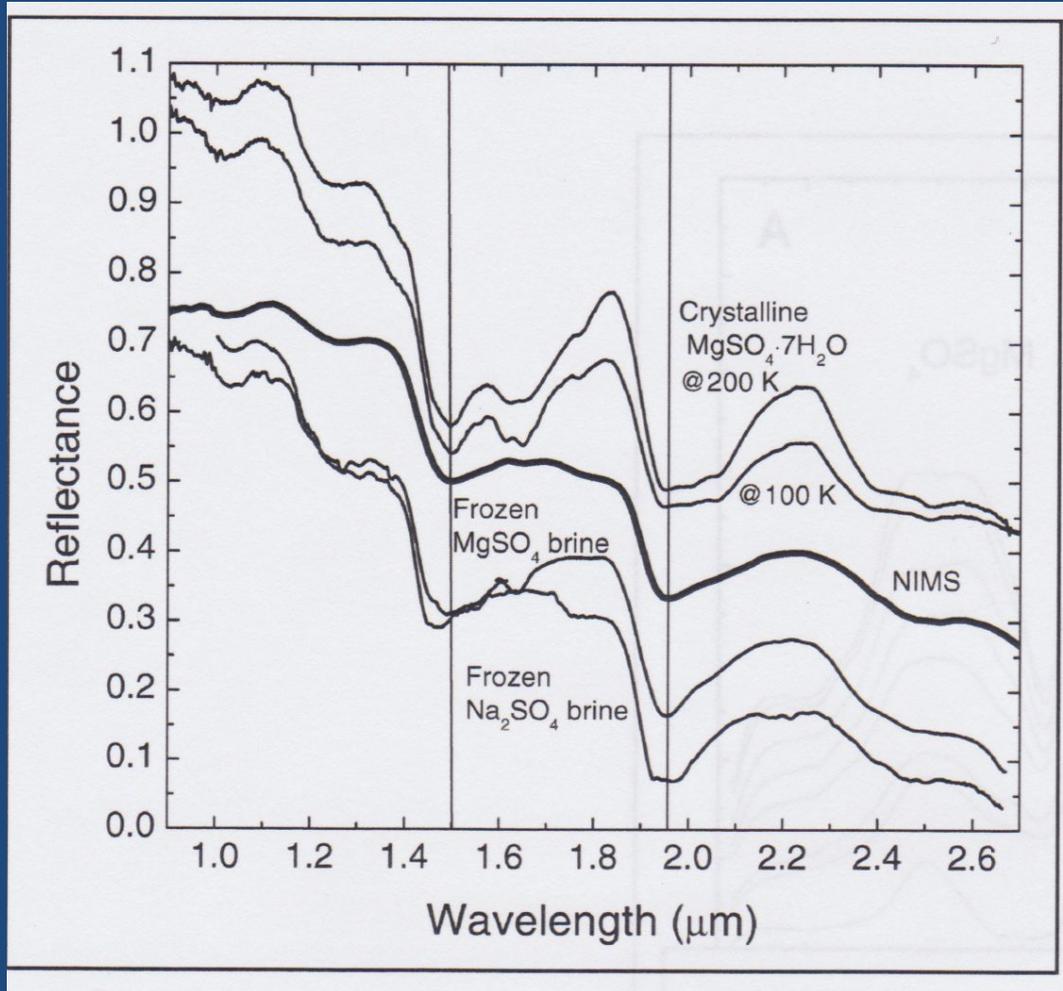
Mg⁺⁺ is doubly bonded and Na⁺ is singly bonded, so Na⁺ is weaker against irradiation.

A little S was also seen coming off in our lab tests of stability for MgSO₄*xH₂O.

So likely both are there, mixed together, and other soluble salt compounds as well.

We proposed this in our 2002 article, *Brines exposed on Europa's Surface*, JGR 2002 and in several later articles.

NIMS and Lab Spectra



We had fun, too!

Galileo Mission Science Team Meeting in Interesting places:
Including, in Hawaii

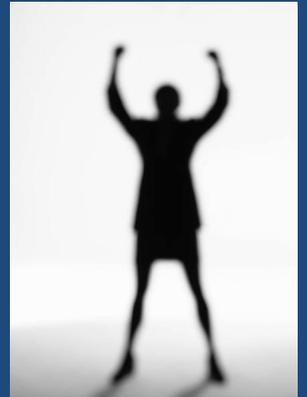
We had fun, too!

Team and PSG meetings at my home in Honolulu Hawaii.

Here: Torrence Johnson, Bonnie Burritti, Dennis Matson, et al.



The End



Brines Exposed to Europa Surface

Conditions

What does the spectrum of hydrated salts ejected onto the surface look like under Europa conditions

JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 107, NO. E1, 5004, 10.1029/2000JE001453, 2002

Thomas B. McCord, Glenn Teeter, Gary B. Hansen, Mathew T. Sieger, and Thomas M. Orlando

Evidence for an ocean beneath the icy crust of Europa includes reflectance spectra of disrupted surface regions indicating hydrated materials such as salts. **We simulated exposure of salty brine on the cold surface of Europa by flash-freezing sulfate and carbonate solutions.** This produces materials that have near-infrared reflectance spectra distinct from those for crystalline minerals and more similar to those for Europa's non-ice regions. These new spectroscopic data, along with geophysical evidence, geochemical models, and meteorite studies, strongly suggest that the non-ice materials in the disrupted regions on Europa's surface contain large amounts of disordered and heavily hydrated MgSO_4 and perhaps Na_2SO_4 that are endogenic in origin.

Finally, these materials are very closely associated with geological and morphologic features that are direct indicators of surface fracturing and melting. Thus, the spectroscopic and geologic evidence along with geochemical models and meteoritic studies all strongly suggest that at least a major portion of the non-ice material on Europa can be disordered, heavily hydrated Mg and perhaps Na sulfates that are closely associated with the surface disruption process and resulting features and thus are likely endogenic in origin, probably from an ocean below. Some Na^+ may be removed by radiation and replaced with H^+ , producing some H_2SO_4 and providing a source for the neutral Na observed coming off Europa [Johnson, 2000b].

Stability of Salt Minerals on the Surfaces

I teamed with the Environmental Molecular Sciences Laboratory at the Pacific Northwest National Laboratory, Richland Washington. Scientist Thom Orlando

JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 106, NO. E2, PAGES 3311-3319, FEBRUARY 25, 2001
Thermal and radiation stability of the hydrated salt
minerals epsomite, mirabilite, and natron
under Europa environmental conditions

Thomas B. McCord, Thomas M. Orlando, Glenn Teeter, Gary B. Hansen,
Matthew T. Sieger, Nikolay G. Petrik, and Lisa VanKeulen

Abstract. We report studies on the **thermal and radiolytic stability of the hydrated salt minerals** Epsomite ($\text{MgSO}_4 \cdot 7\text{H}_2\text{O}$), mirabilite ($\text{Na}_2\text{SO}_4 \cdot 10\text{H}_2\text{O}$), and natron ($\text{Na}_2\text{CO}_3 \cdot 10\text{H}_2\text{O}$) under the low-temperature and ultra high vacuum conditions characteristic of the surface of the Galilean Satellite Europa. We prepared samples, **ran temperature-programmed dehydration (TPD) profiles and irradiated the samples with electrons**. The TPD profiles are fit using Arrhenius-type first-order desorption kinetics. This analysis yields activation energies of 0.90 ± 0.10 , 0.70 ± 0.07 , and 0.45 ± 0.05 eV for removal of the hydration water for epsomite, natron, and mirabilite, respectively. A simple extrapolation indicates that at Europa surface temperatures (≤ 130 K), **Epsomite should remain hydrated over geologic timescales** ($\sim 10^{11}$ - 10^{10} TM years), whereas natron and mirabilite may dehydrate appreciably in approximately 10^8 and 10^3 years, respectively. A small amount of SO_2 was detected during and after 100 eV electron-beam irradiation of dehydrated epsomite and mirabilite samples, whereas products such as O_2 remained below detection limits. The upper limit for the 100 eV electron-induced damage cross section of mirabilite and Epsomite is ~ 10 - 19 cm^2 . The overall radiolytic stability of these minerals is partially due to (1) the multiply charged nature of the sulfate anion, (2) the low probability of reversing the attractive Madelung (mostly the attractive electrostatic) potential via Auger decay, and (3) solid-state caging effects. **Our laboratory results on the thermal and radiolytic stabilities of these salt minerals indicate that hydrated magnesium sulfate and perhaps other salts could exist for geologic time scales on the surface of Europa.**

The Process

1. DISCOVERY MODE:
Look at the first spectra to see what is there. Do a first Identification and publish.
2. MOST INTERESTING:
Materials most associated with apparent surface disruption. Hydrated non-ice material.
3. STABILITY CHECK:
Collaborate with a laboratory capable of doing the tests. PNNL/Thom Orlando.
Run the tests and publish results.
4. SIMULATE MATERIAL DEPOSITION ON EUROPA'S SURFACE:
Design the experiment, build the lab setup and run the simulations. Publish the results.
5. IDENTIFY THE DETAILED PHYSICS.
Allow the expert physical chemist to lead. Publish.

A mixture of hydrated salt minerals and acids

Chemical nature of Europa surface material

ICARUS, VOL. 177,, 10.1016/j.Icarus.2005

Thomas M. Orlando, Thomas B. McCord, Gregory A. Grievies

The surface composition of Europa is of special interest due to the information it might provide regarding the presence of a subsurface ocean. One source of this information is the infrared reflectance spectrum. Certain surface regions of Europa exhibit distorted H₂O vibrational overtone bands in the 1.5 and 2.0 μm region, as measured by the Galileo mission Near Infrared Mapping Spectrometer (NIMS). These bands are clearly the result of highly concentrated solvated contaminants. However, two interpretations of their identity have been presented. One emphasizes hydrated salt minerals and the other sulfuric acid, although each does not specifically rule out some of the other. It has been pointed out that accurate chemical identification of the surface composition must depend on integrating spectral data with geochemical models, and information on the tenuous atmosphere sputtered from the surface. It is also extremely important to apply detailed chemistry when interpreting the spectral data, including knowledge of mineral dissolution chemistry and the subsequent optical signatures of ion solvation in low-temperature ice. We present studies of flash frozen acid and salt mixtures as Europa surface analogs and demonstrate that solvated protons, metal cations and inorganic anions all influence the spectra and must all, collectively, be considered when assigning Europa spectral features. These laboratory data show best correlation with NIMS Europa spectra for multi-component mixtures of sodium and magnesium bearing sulfate salts mixed with sulfuric acid. The data provide a concentration upper bound of 50-mol% for MgSO₄ and 40-mol% for Na₂SO₄. This newly reported higher sodium and proton content is consistent with low-temperature aqueous differentiation and hydrothermal processing of carbonaceous chondrite-forming materials during the formation and early evolution of Europa.

A mixture of hydrated salt minerals and acids

The early days of telescope observing

Tom at the Mt. Wilson Snow telescope, 1965

Adjusting the mirrors
preparing for observations of
Comet Ikeya-Seki.

Tom as Caltech Grad student,
fall of 1965

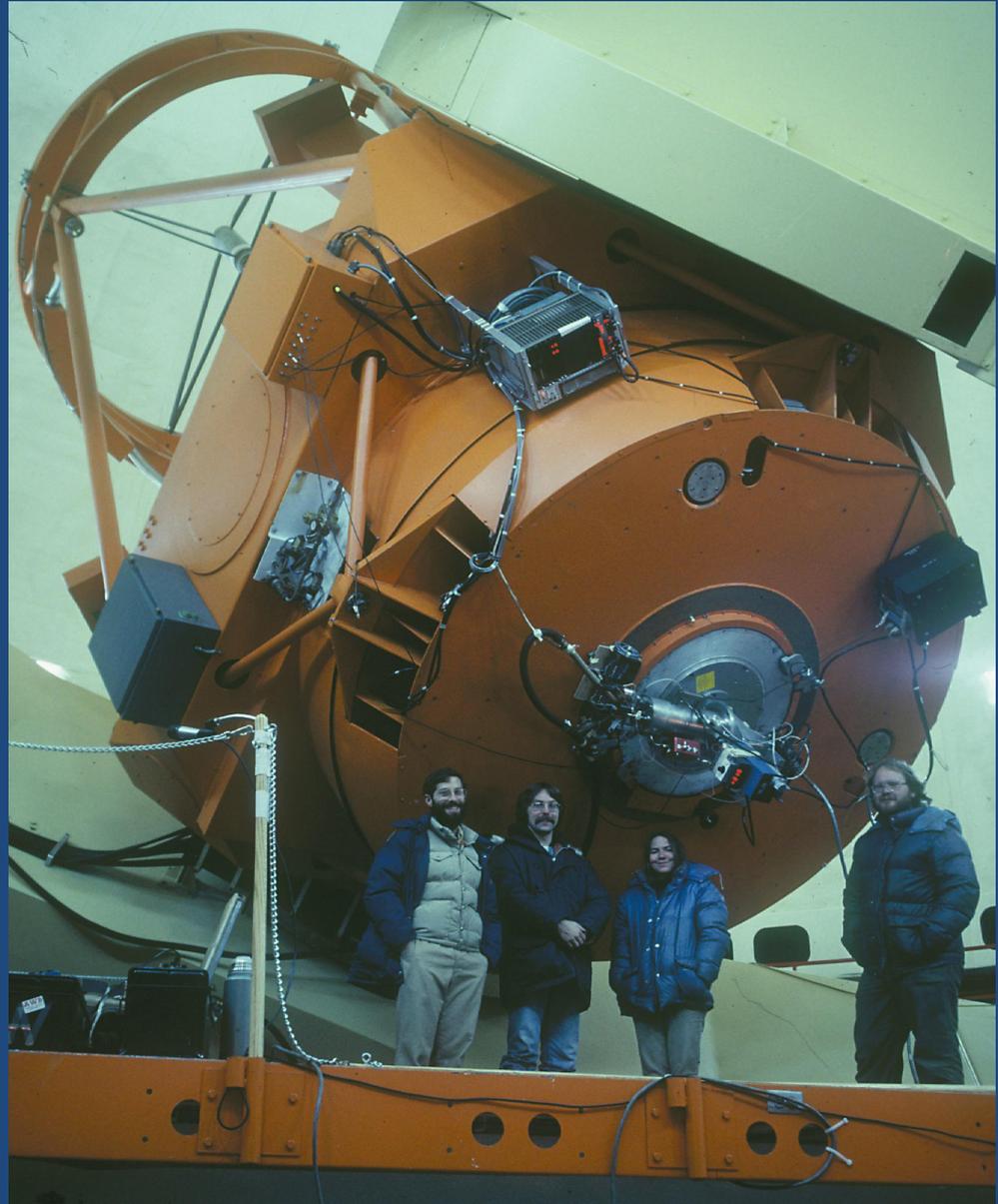


The early days of telescope observing

The IRTF telescope on Mauna Kea, Hawaii, ca. 1970s

My crew at the IRTF.
On the observing platform,
using one of our home-built
instruments

Left to right:
Jay Pasachoff,
Roger Clark,
Pam Owensby,
Mark Rognstad



Measurements

Galileo infrared imaging spectrometry measurements at the Moon

T. B. McCord, L. A. Soderblom, R. W. Carlson, F. P. Fanale, R. Lopes-Gautier, A. C. Ocampo, J. Forsythe, B. Campbell, J. C. Granahan, et al.

JOURNAL OF GEOPHYSICAL
RESEARCH,
VOL. 99, pp. 5587-5600, March 25,
1994

Also, first detection of H₂O/OH in the Moon surface material, but....

Galileo infrared imaging spectrometry measurements at the Moon

Thomas B. McCord,^{1,2} Larry A. Soderblom,³ Robert W. Carlson,⁴ Fraser P. Fanale,¹ Rosaly Lopes-Gautier,⁴ Adriana C. Ocampo,⁴ Jennifer Forsythe,² Bruce Campbell,⁵ James C. Granahan,¹ W. D. Smythe,⁴ P. R. Weissman,⁴ K. J. Becker,³ K. Edwards,³ Lucas Kamp,⁴ Juliana Lo,² R. Mehlman,⁶ J. Torson,³ G. E. Danielson,⁷ D. L. Matson,⁴ H. H. Kieffer,³ and T. V. Johnson⁴

Abstract. Imaging spectrometer observations were made of the surface of the Moon during the December 1990 flyby of the Earth-Moon system by the Galileo spacecraft. This article documents this data set and presents analyses of some of the data. The near infrared mapping spectrometer (NIMS) investigation obtained 17 separate mosaics of the Moon in 408 spectral channels between about 0.7 and 5.2 μm . The instrument was originally designed to operate in orbit about Jupiter and therefore saturates at many spectral channels for most measurement situations at 1 AU. However, sufficient measurements were made of the Moon to verify the proper operation of the instrument and to demonstrate its capabilities. Analysis of these data show that the NIMS worked as expected and produced measurements consistent with previous ground-based telescopic studies. These are the first imaging spectrometer measurements of this type from space for the Moon, and they illustrate several major points concerning this type of observation and about the NIMS capabilities specifically. Of major importance are the difference between framing and scanning instruments and the effects of the spacecraft and the scan platform on the performance of such an experiment. The science return of subsequent NIMS and other investigation measurements will be significantly enhanced by the experience and results gained.

Introduction

The Galileo spacecraft flew past the Earth-Moon system on December 8, 1990, in order to obtain a gravity assist and enable it to reach Jupiter orbit in 1995. This was not the initially planned trajectory, but the dramatic changes in the launch schedule, due to the Shuttle Challenger disaster, required that a new trajectory be adopted after most subsystems and instruments were built. The first scientifically interesting event along the new trajectory after launch was the encounter with Venus in February 1990. The near infrared mapping spectrometer (NIMS) results from the Venus encounter were presented previously [Carlson *et al.*, 1991]. The spacecraft flew past the asteroid Gaspra in August 1991 and again encountered the Earth-Moon system on December 7-8, 1992.

An important and unique data set was produced in the December 1990 Moon encounter, which is documented in this article. The results of the analysis of some of these first Earth-Moon encounter data are also presented.

Because the encounter was not part of the planned baseline mission, the capabilities of the spacecraft and instruments were not fully implemented, tested, and calibrated at the time of the encounter; but the performance of some subsystems will be improved for later encounters. For example, of specific interest is the pointing stability of the spacecraft scan platform, which was not yet fully up to the expected capability, and thus the pointing direction of the NIMS, located on the scan platform, jittered unexpectedly by several pixels while measurements were being made. Also of importance is the factor of 5 difference in distance from the Sun between the planned operating environment near Jupiter and at the Moon. Thus, the brightness of the Moon was about 25 times greater than that for which the instrument was designed. This led to saturation of some of the detectors during some of the Moon measurements, a condition which was anticipated when the measurements were planned after instrument delivery to the spacecraft, but about which nothing could be done.

The Instrument

The NIMS [Carlson *et al.*, 1992] is the first of several imaging spectrometers planned for NASA deep space and Earth-looking missions. It is basically a "whisk broom" imaging spectrometer (see Figure 1) covering the spectral range 0.7-5.2 μm with up to 408 adjacent and partially overlapping spectral channels. An internal mirror is used to

¹Planetary Geosciences Division, School of Ocean and Earth Science and Technology, University of Hawaii, Honolulu.

²SETS Technology, Incorporated, Mililani, Hawaii.

³U.S. Geological Survey, Flagstaff, Arizona.

⁴Jet Propulsion Laboratory, Pasadena, California.

⁵Center for Earth and Planetary Studies, National Air and Space Museum, Washington, D. C.

⁶Institute of Geophysics and Planetary Physics, University of California, Los Angeles.

⁷Division of Geology and Planetary Sciences, California Institute of Technology, Pasadena.

Copyright 1994 by the American Geophysical Union.

Paper number 93JE03434.
0148-0227/94/94JE-03434\$05.00

My Background Working Amish Farms

