SOLAR SYSTEM SCIENCE – RECENT HIGHLIGHTS FROM SOFIA AND ALMA

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OUTLINE

The New York Times

There's Water and Ice on the Moon, and in **More Places Than NASA Thought**

Future astronauts seeking water on the moon may not need to go into the most treacherous craters in its polar regions to find it.

Demonstrate current observational capabilities Selected recent results:

- Lunar water
- Winds on Jupiter
- Phosphine on Venus
- Comets
- Occultations

Hyperactive Comets Hint at Origins of Earth's Oceans A new study suggests primordial seawater may lurk hidden at the hearts of many comets SCIENTIFIC
AMERICAN

SPACE

"By flying in Pluto's shadow we can observe the light passing through Pluto's atmosphere to analyze its characteristics."

LUNAR HYDRATION

Boogert et al. 2015, ARAA Figure 1: Overview of the strongest ice and dust features in the MYSO AFGL 7009S

Most ice features are detected as pure absorption bands against infrared continuum point sources. Studies of the spatial variations of the spatial variations of the ice properties are the ice p

shown (dashed line) to indicate the multiple H2O bands.

Apollo samples: Initial analysis showed no minerals containing water Advances in instrumentation $4 - 46$ ppm H_2O

2009: Independent detections of the 3 µm hydration band
by Chandrayaan-1, Deep Impact, and Cassini – by Chandrayaan-1, Deep Impact, and Cassini – widespread, shows variations with latitude, temperature, and lunar time

The 3 µm band (symmetric and asymmetric stretch of the OH bond) cannot distinguish between water and hydroxyl

Differences in the center wavelength and band shape, dependence on the mineral composition, surface properties, etc.

The H₂O bending vibration at 6.1 μ m is unique to water molecules

CHANDRAYAAN-1 -- MOON MINERALOGY MAPPER (M³)

and OH applicable for lunar comparisons. These spectra are highly dependent

 $r \sim$ Orange and pink: iron-bearing minerals. sion component becomes Green: 2.4 µm surface brightness. Blue: OH and H_2O .

Visible and NIR imaging spectrometer (JPL), 0.43–3 µm, 260 channels; 70 m resolution

Absorption features at 2.8 – 3 µm, near the poles, attributed to hydroxyl or water-bearing materials

beyond the spectral range of M3

. Calculations are based on optical constants are based on optical constants are based on \mathcal{C}

SOFIA OBSERVATIONS

Extending Data Pierre Air Secteurs: Image of Claudius maps. Left: Image of Claudius crater from quickmap that show that show that show the visible image with the SOFIA slit areas show by the SOFIA slit areas show by the S the same image of Clavius crater but with the SOT ratio overlaid to highlight compositions. The SOFIAN overlaid to highlight compositions. The SOFIAN overlaint color ratio overlain variations. The SOFIAN overlaint composit

NATURE ASTRONOMY LETTERS

- A high southern latitude region near Clavius crater (high total water abundance in the M3 data)
- A low-latitude portion of Mare Serenitalis (control region with little or no water)

5

Strong 6 µm emission at Clavius crater reflections of the luncar and surrounding terrain relative to the control location near lunar equator ı ı MORB tion in laboratory samples, but they are not exactly correlated. More l^{c} example, the depth of the $\frac{1}{2}$ data are required to a the real to the possible reasons $\frac{1}{2}$

Normalized frequency

Mapper (M3

the Clavius region section).

much is due to hydroxyl. At present, the 3µm band cannot be used to distinguish between molecular water and hydroxyl. To begin to understand the relative abundances of water and hydroxyl, we directly compare our molecular water abundances with total water abundances (OH+H2O) derived from the Moon Mineralogy

Methods (see the Extended discussion on estimated abundances in

There are several mechanisms for the origin of water in lunar soil that are relevant to our data. Water present in the lunar exosphere

the differences between SOFIA and M3

Fig. 3. We note that there has been disagreement regarding the distri-

Fig. 2 $\frac{1}{\epsilon}$ $\frac{1}{\epsilon}$ $\frac{1}{\epsilon}$ $\frac{1}{\epsilon}$ observed the contractions. Mean water abundance in the Clavius regio Mean water abundance in the Clavius region 200 μ g g⁻¹

 \blacksquare of the distribution different from that implied by abundances is not clear. The two wavelength regions are not probing precisely the same portions of register α data – local geology rather than a global phenomenon grains and within void spaces. (We note that the lunar band centres Latitude distribution different from that implied by M³

> datasets are discussed in the wavelenaths do not probe the same de The two wavelengths do not probe the same depths, local variations in the location of hydroxyl and water in t the regolith grains. We instead the physical models that \sim

ORIGIN OF LUNAR WATER

Water detected by SOFIA resides within the interior of lunar grains (more likely) or is trapped between grains shielded from the harsh lunar environment

The measured water abundance implies 300 to 1300 μ g g⁻¹ H₂O in impact glasses – within the range of laboratory measurements

Water entrained in impact glass explains the observations, but the data do not exclude in situ conversion of hydroxyl to water

Observations are more consistent with a mechanism that produces water by impact from pre-existing lunar material than impact delivered water

A follow-up SOFIA Legacy Program currently under way

AURORAL AND EQUATORIAL JETS IN JUPITER'S STRATOSPHERE

Tropospheric wind pattern: alternating prograde and retrograde zonal jets (up to 100 m s^{-1}

Above the tropopause, no tracers to infer the wind pattern from visible

HCN and CO, two species delivered by the SL9 impact, can be studied using ALMA at exquisite spatial and spectral resolution (100 m s⁻¹ winds superposed on 12.5 km s-1 Jovian rotation at the equator)

AURORAL AND EQUATORIAL JETS IN JUPITER'S STRATOSPHERE

Zonal winds at low-to-mid latitudes

Strong and broad prograde jet at 9 – 11o N at 1 mbar (E limb +215 m s^{-1} , W limb -115 m s^{-1})

Nonzonal winds in the N and S polar regions at 0.1 mbar (300 – 400 m s-1)

Counter-rotating velocities, 100s of km below the ionospheric auroral winds (lower tails)

May help increase the efficiency of chemical complexification

PHOSPHINE ON VENUS

Submm detection of PH_3 at ~20 ppb in the atmosphere of Venus (ALMA+JCMT).

Could originate from unknown photochemistry of geochemistry, or by analogy with biological production of PH₃ on Earth, from the presence of life.

Inconsistent with a stringent IR upper limit of 5 ppb (3σ).

Also, availability of water in the Venus cloud deck, as quantified by the "water activity" parameter, is 2 orders of magnitude below the limit for known extremophiles. $\mathbf{u} = \mathbf{c}$ abundance at the cloud top is presented in the cloud to ty of water in the Venu $\overline{\text{S}}$ in the NASA in the NASA International Telescope Facility at the $\overline{\text{S}}$ high spectral capabilities (*R* = 80 000 at 7 µm) and spatial capa-

THE ORIGIN OF EARTH'S WATER

Snow Line

• Water mass fraction increases with distance from the Sun

• "Textbook model": temperature in the terrestrial planet zone too high for water ice to exist

• Water and organics were most likely delivered later by comet or asteroid-like bodies

• Alternative: water could have survived, incorporated into olivine grains or through oxidation of an early H atmosphere by FeO in the magma ocean

ISOTOPIC MEASUREMENTS

Deep Impact/EPOXI

Remote sensing — statistical studies of objects that have atmospheres

- Comets: variations between one and three times terrestrial value
- No trends with physical or dynamical parameters

 0.0 ky

- Grand Tack Model: inward then outward migration of Jupiter and Saturn (~5 Myr)
- Nice Model: Saturn migration into 1:2 orbital resonance with Jupiter — Late Heavy Bombardment (~500 Myr)

D/H DISTRIBUTION: INNER VS. OUTER SOLAR SYSTEM

D/H in the inner Solar System relatively well constrained by measurements in meteorites (100+ measurements)

D/H in the outer Solar System poorly constrained – a few measurements in comets with large uncertainties

SOFIA Comet Wirtanen D/H= $(1.61\pm0.65) \times 10^{-4}$

Comets with high active fractions typically have terrestrial D/H ratios

Water release from sublimating icy grains in the coma

COMETS WITH ALMA

Fig. 3. Map of the integrated intensity in Jy.km.s[−]¹ of the CH3OH line Comet Wirtanen – HDO 464 GHz 452.4 GHz obtained with the ACA interferometer. \mathcal{F} $I \text{C} \cap -1$ $I \cup J$ 404

Preliminary D/H = 1.5 × VSMOW

Consistent with the SOFIA measurement within the error bars

May indicate variations in the D/H within the FoV (direct release vs. icy grains)

ALMA and SOFIA observations are very complementary!

ALMA imaging observations allow discerning parent(HCN) from daughter/distributed source species (e.g., CS, H_2CO , HNC, possibly CH_3OH) ACA and ALMA autocorrelation spectroscopy

PLUTO OCCULTATIONS

Seconds from midtime

Early KAO highlights — detection of the Uranian ring system and the atmosphere of Pluto "Central flash" provides constraints on *haze densities* and thermal gradients in lower atmosphere, bounds on hazeparticle sizes

Multi-wavelength observations allow analysis of atmospheric profiles and aerosol or haze content

Multi-epoch observations allow studies of a possible *temporal variability*

Stability of Pluto's atmosphere over 25 years

LOOKING INTO THE FUTURE

Astro2020 Report Published and Planetary Decadal Report expected in April

FIR Flagship – *Origins* – would provide measurements of the D/H ratio in 100s comets – 2040

FIR Probe would allow first statistical studied – 2030

It is critically important to take full advantage of the complementarity of the existing FIR/submm facilities

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