Origin
of water ice
on the Moon

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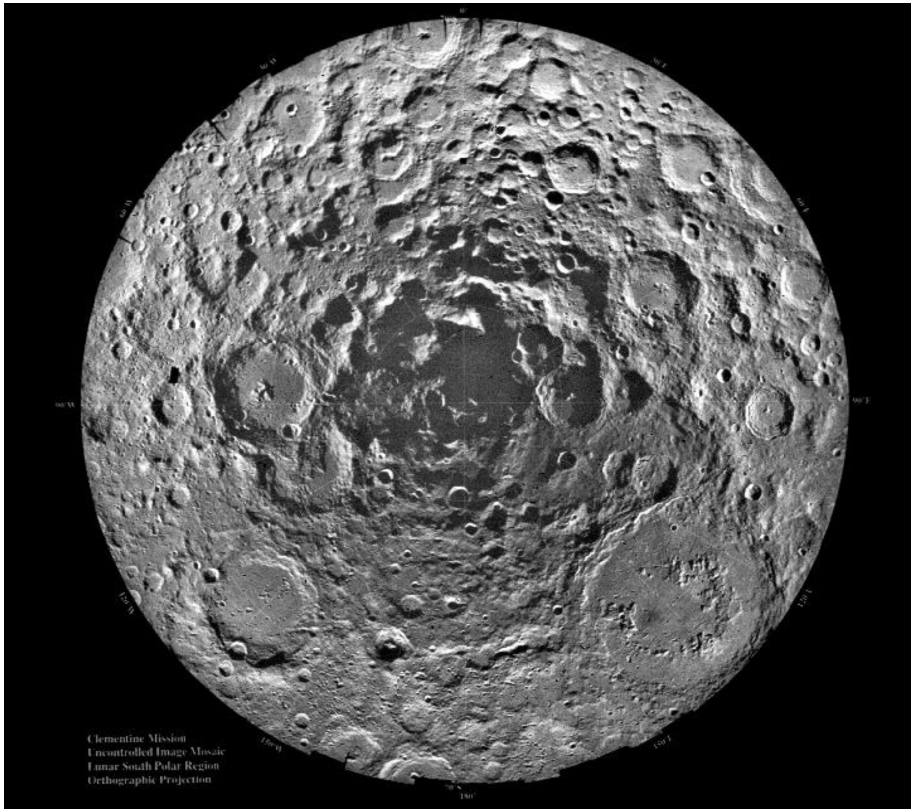
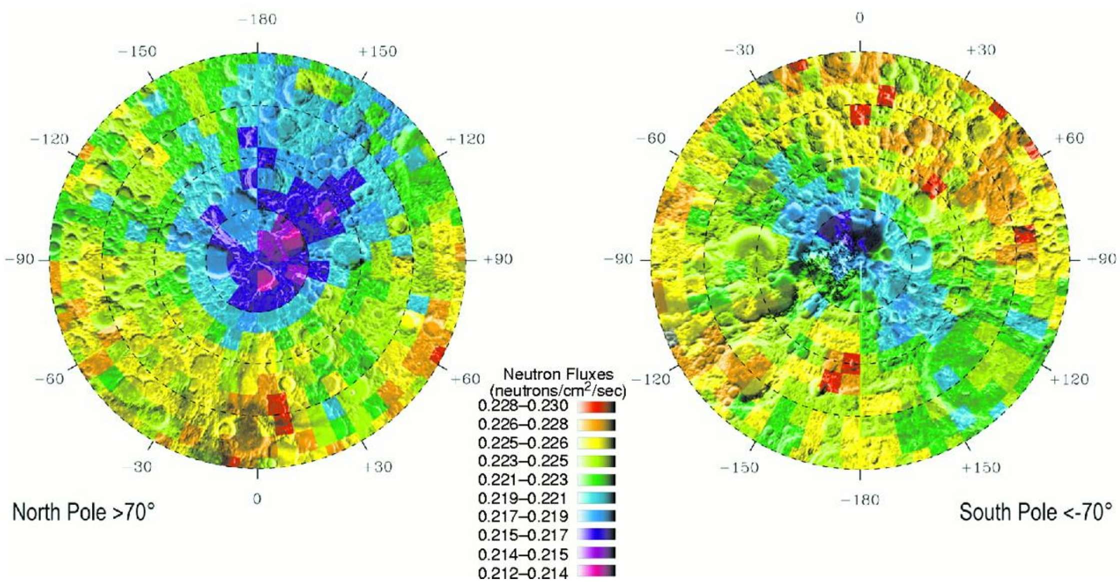
Clementine image
of the south pole of the Moon

- The temperature of permanently shaded regions at the lunar poles is low enough for survival of water ice and solar wind implanted hydrogen atoms during billions years.



Detection of hydrogen at the poles of the Moon by Lunar Prospector

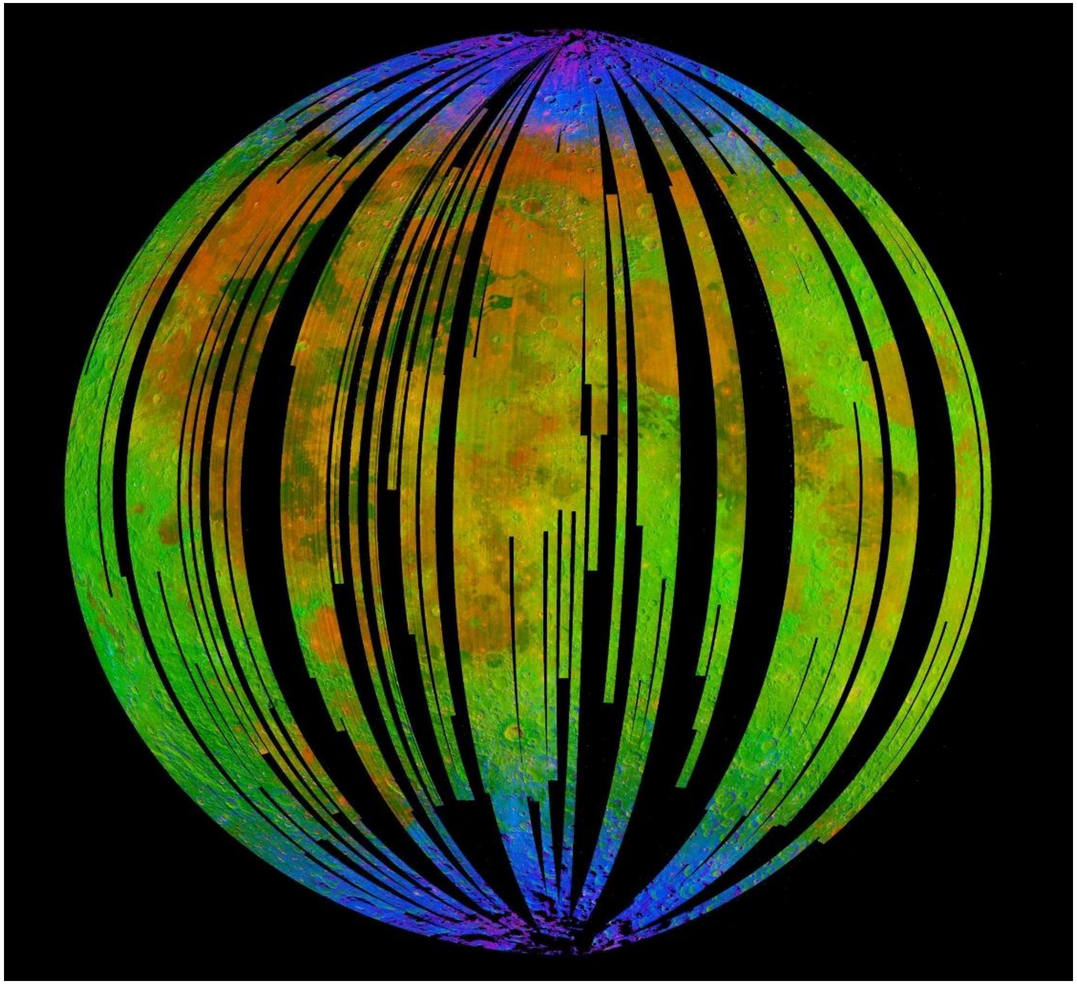


Lunar Prospector epithermal neutron counting rates map with surface relief maps of the lunar poles (Feldman et al., 1998).

Mass of water ice in south polar regions of the Moon is estimated as $2*10^{14}$ g (Feldman et al., 2000).

- Lunar Prospector detected significant decrease of epithermal neutron counting rate over lunar poles (Feldman et al., 1998).
- These results are interpreted as existence of hydrogen at the poles of the Moon, probably, in the form of water ice (Feldman et al., 2001).
- Water ice mass fraction is estimated as 3-5 wt% in permanently shadowed polar regions.

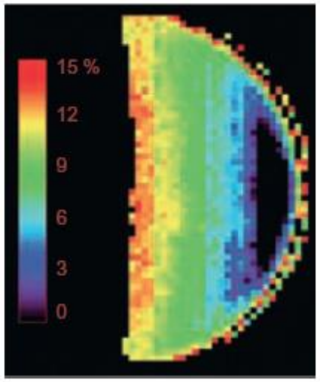
Image of the Moon
taken by the Moon Mineralogy Mapper
(Pieters et al., 2009)



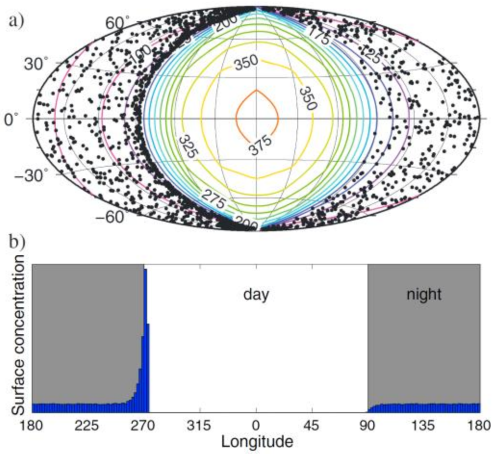
Blue shows the spectral signature of OH, green shows the brightness of the surface as measured by reflected infrared radiation from the Sun and red shows pyroxene.

The upper limit for OH zenith column density in the lunar exosphere is estimated as 10^{11} cm^{-2} (Wang et al., 2015).

Diurnal variations of the OH content on the Moon



Map of lunar hydration band depth in June 2009 (Sunshine et al., 2009)



Theoretical content of water on the Moon (Schorghofer, 2014)

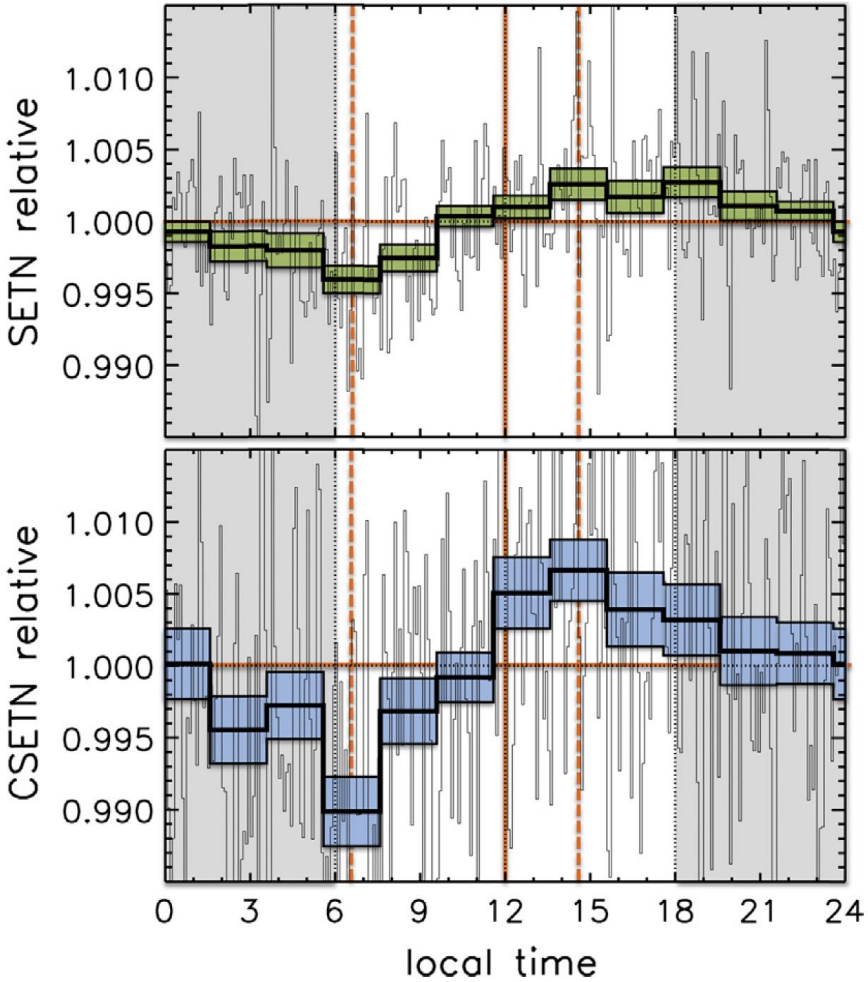
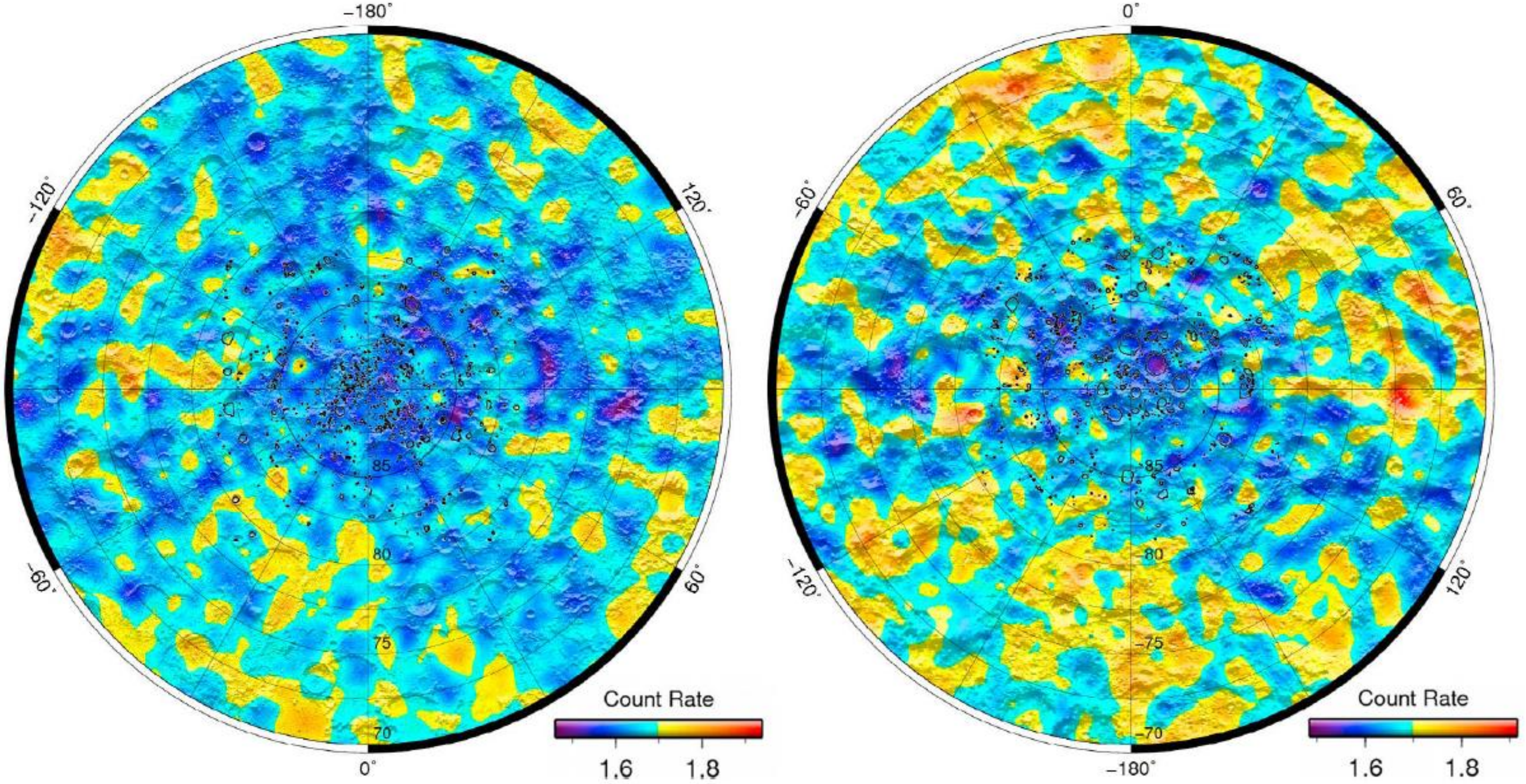


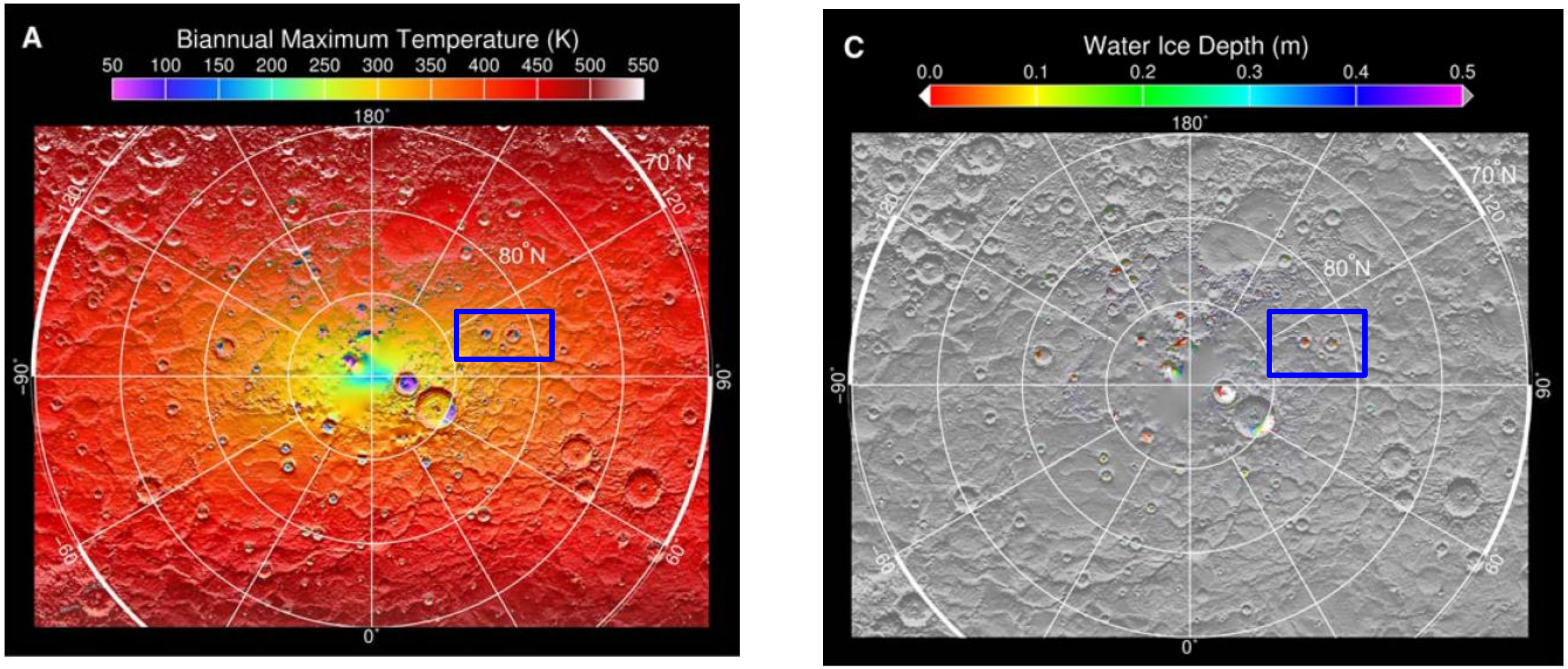
Fig. 3. Equatorial neutron detection rate varies as a function of local time for SETN (upper) and CSETN (lower) epithermal neutron detectors, relative to the median. Gray regions at left and right indicate measurements during lunar night. The light-toned rapidly-varying histogram shows flux measured in intervals of 5 min of lunar local time. The bold histogram and shaded envelope show mean and standard error of the mean in two-hour intervals of lunar local time. Greatest flux suppression is near the dawn terminator, slightly biased toward the day side.

Taken from Livengood et al. (2015)



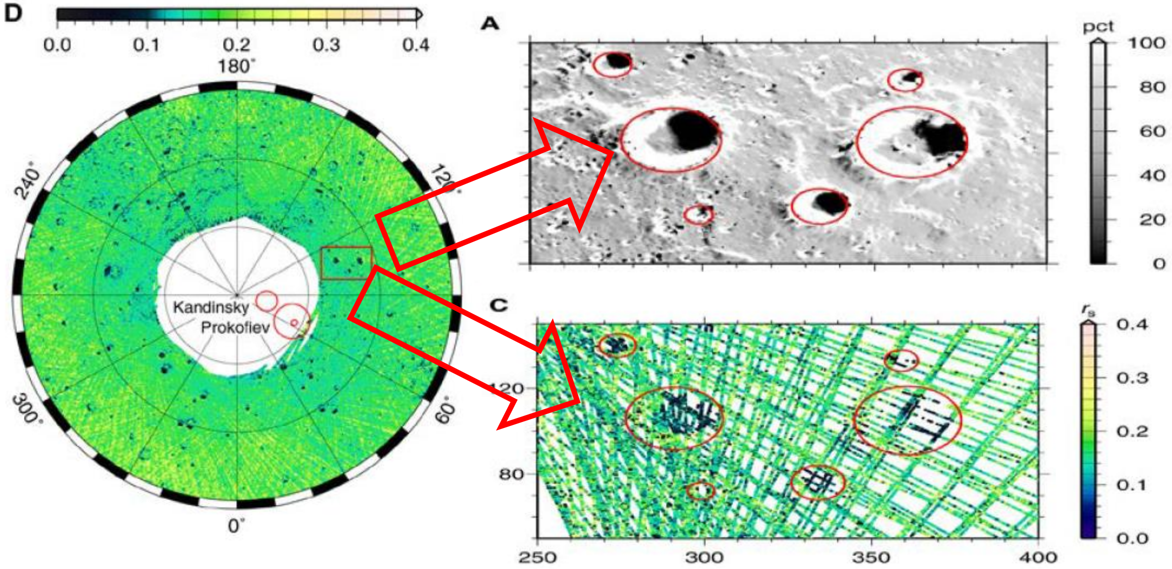
Flux of epithermal neutrons
at north (left) and south (right) poles of the Moon (Mitrofanov et al., 2012).

Decrease of epithermal neutron flux is explained
by presence of hydrogen-containing species.
Regions of water ice thermal stability are also shown.



Temperature regime and water ice at the north pole of Mercury

(Paige et al., 2012)



A – solar photon flux

C, D – albedo at 1064 nm.

Existence of dark cold traps can be explained by presence of organic compounds

(Neumann et al., 2012)

LCROSS impact on the Moon

(http://lcross.arc.nasa.gov)

Stability of different species at the poles of the Moon

(http://science.nasa.gov/science-news)

After LCROSS impact

H_2O, CO, H_2, Ca, Hg, Mg

(Gladstone et al., 2010),

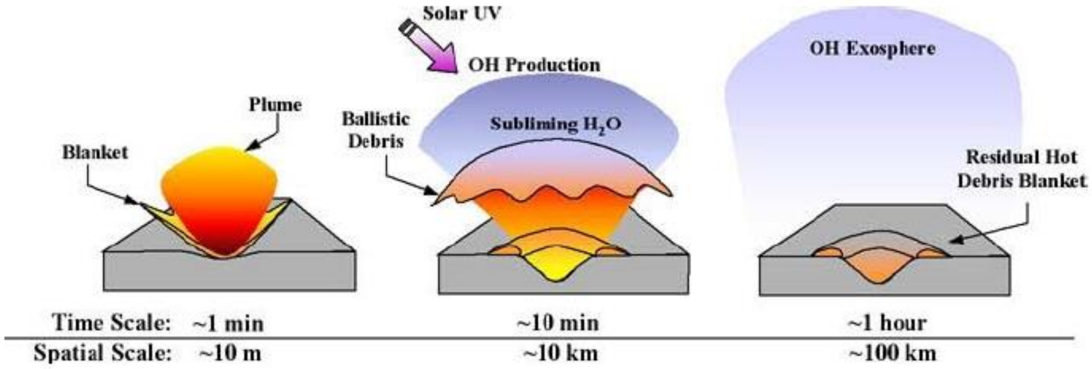
H_2O, H_2S, NH_3, SO_2, C_2H_4, CH_3OH, CH_4, OH

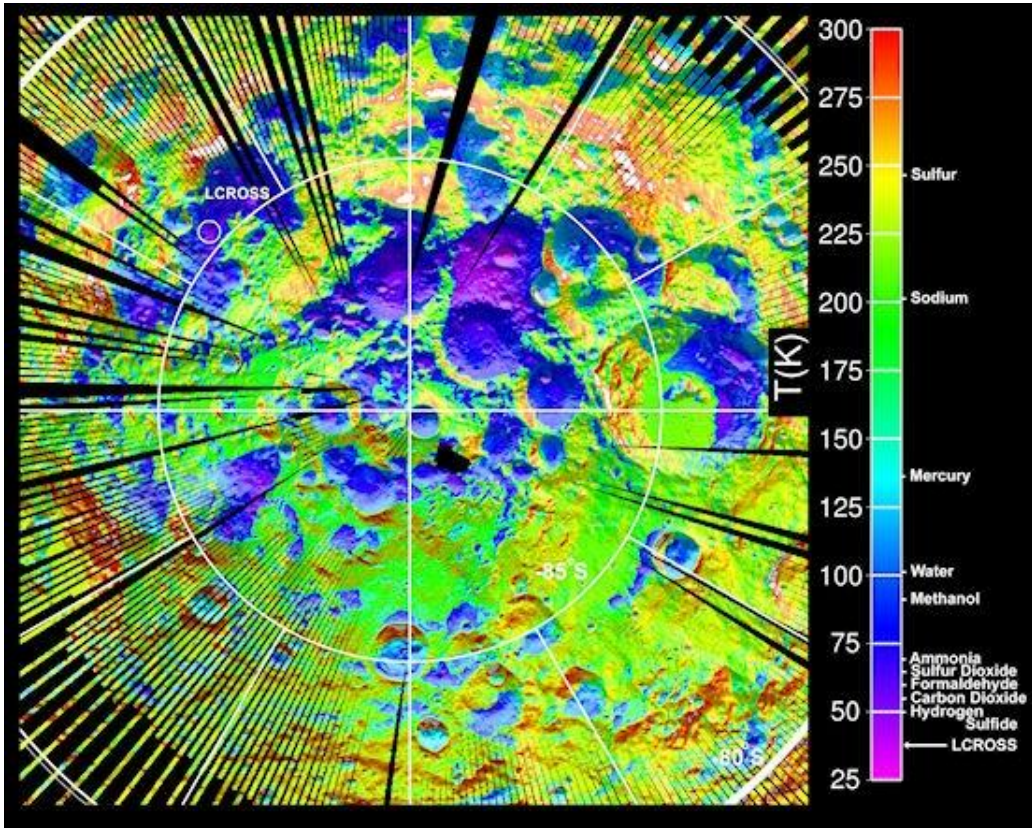
(Colaprete et al., 2010),

Na (Killen et al., 2010)

were detected in the LCROSS impact plume.

These species may be delivered to the poles of the Moon by impacts of comets, asteroids, and meteoroids.





Sources of volatiles on the Moon:

solar wind
impacts of comets, asteroids, and meteoroids
degassing from the lunar interiors

Possible forms of presence of hydrogen at the lunar poles:

water ice,
solar wind implanted hydrogen atoms,
adsorbed water molecules,
OH-containing minerals

Frequency of collisions of comets with the Moon (Jeffers et al., 2001)

Type of comets	Total impact probability, year^{-1}	Mean speed of collisions, km/s
Short-period	$2*10^{-8}$	18
Halley-type	$9*10^{-9}$	58
Long-period	$2*10^{-8}$	52

- These values are calculated for comets with $D > 400$ m
- Assuming $N_{(>D)} \sim D^{-2.07}$ (Donnison, 1986) there were just unique 3 km comet collision and about ten 1 km comet collisions with the Moon over last three billion years.

Capture of cometary matter by the Moon

- Velocity distribution in the fireball is close to linear

$V(r) \sim V_{max}\, r/R_{max}$, where V_{max} is the velocity of the outer cloud edge and R_{max} is the radius of edge (Zel'dovich, Raizer, 1967),

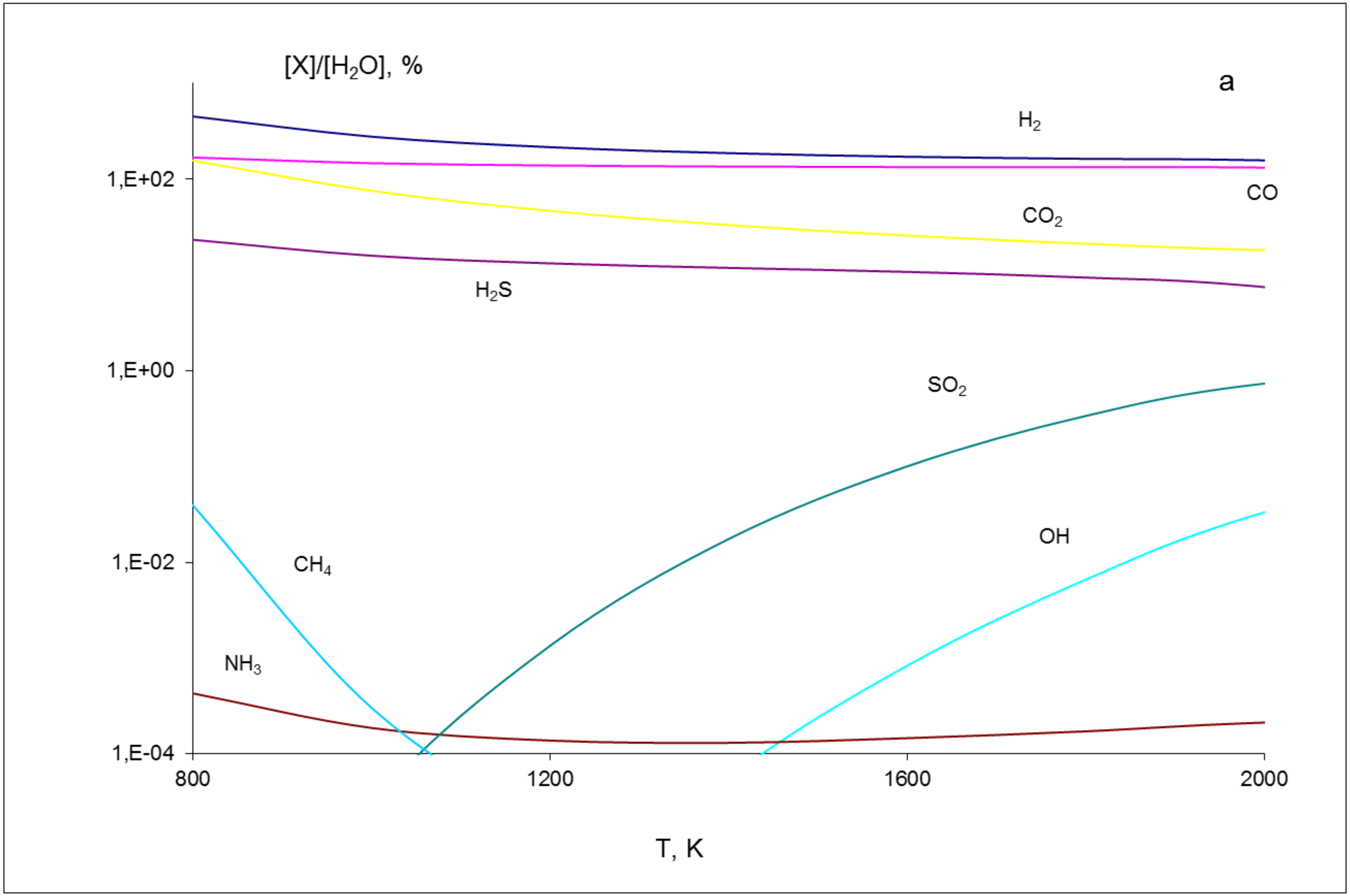
$V_{max} = c(V)*V_i$, where c = 0.3-0.5 at 10-20 km/s,

V_i is the comet impact velocity.

- Then the part of cometary matter captured by the Moon can be estimated as $(V_{esc}/V_i)^3$, where V_{esc}= 2.4 km/s.
- Let us assume that $c(V) \sim V_i^{-2}$ at V_i > 30 km/s.
- Then the mass fraction of the impact-induced vapor cloud retained by the Moon is equal to 0.06, 0.01, and 0.01 at impact velocities equal to 20, 30, and 60 km/s, respectively.

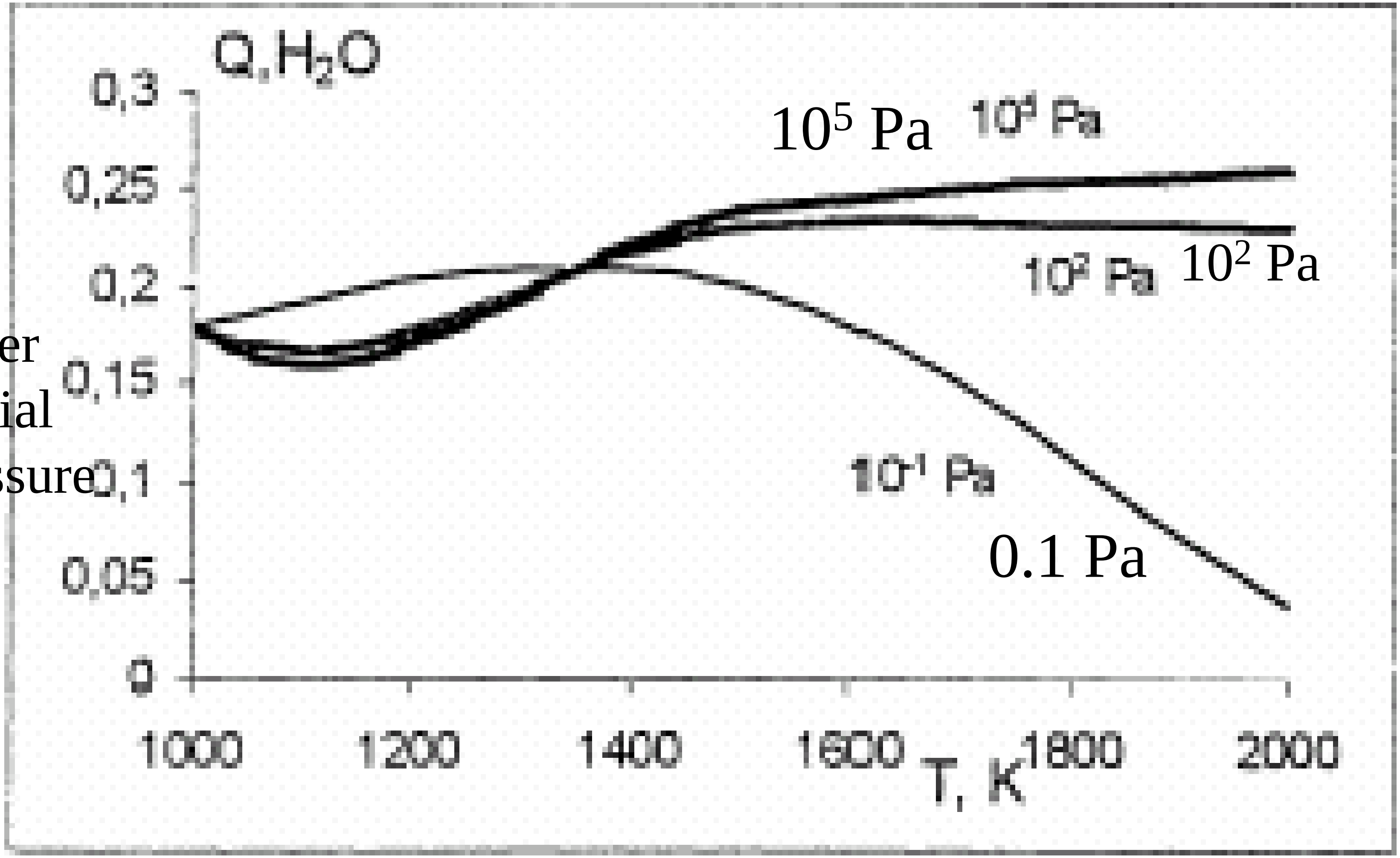
Chemical composition of the fireball

- Quenching of the chemical composition of the fireball occurs when hydrodynamic and chemical time scales become comparable.
- Hydrodynamic time scale is equal to R/c_s, where R is the comet radius, $c_s \sim 1$ km/s is the sound speed at 2000 K.
- Chemical time scale is equal to $([X]k)^{-1}$, where k is the rate constant, $[X]$ is the abundance of reactive molecule.
- Main reactions in the fireball are $H+H_2O=H_2+OH$, $H+CO_2=OH+CO$, $H_2+CO_2= H_2O+CO$.
- For 1 km comet impact quenching of gas-phase reactions occurs at 1000 - 2000 K and 0.01 – 1 bar. However, catalysis of the chemical reactions on dust grains can significantly decrease quenching temperature and pressure.

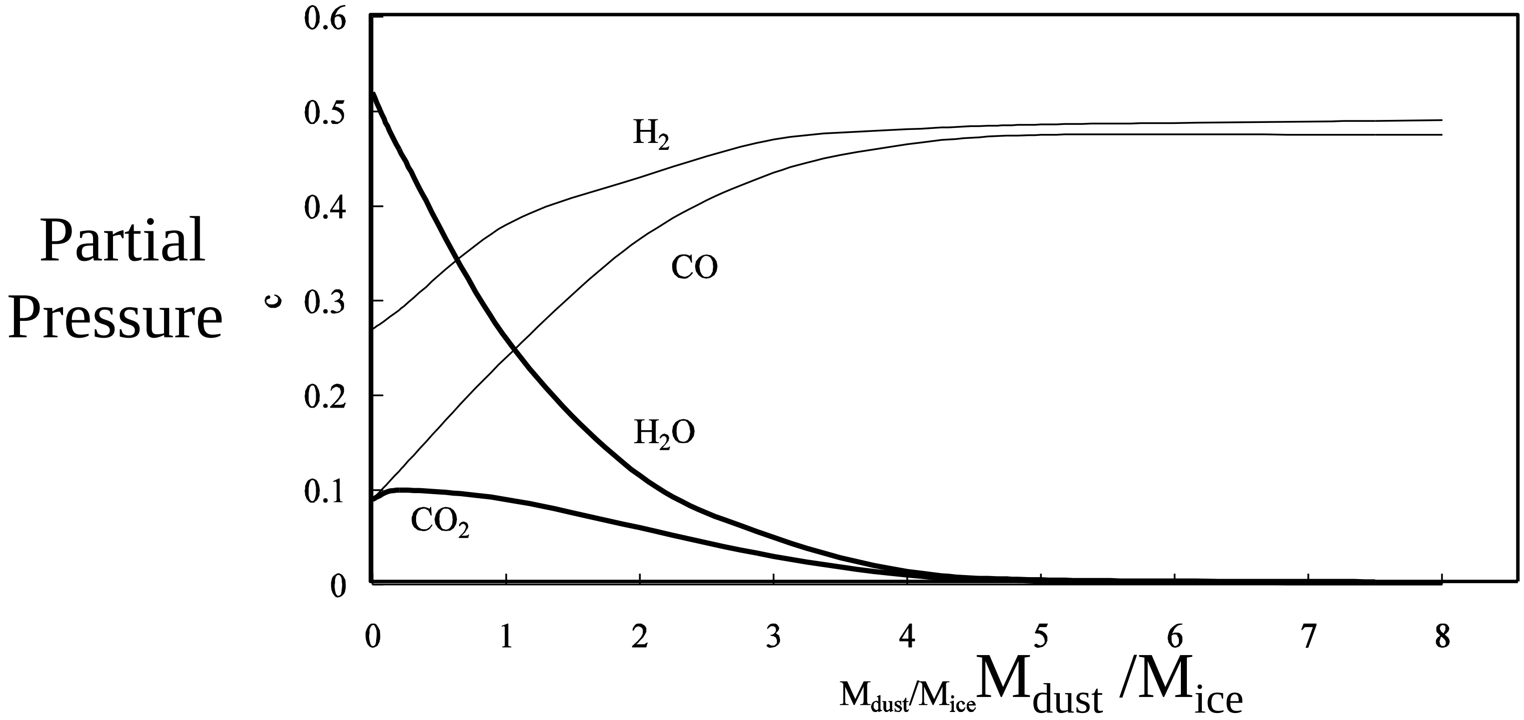


Equilibrium content of the fireball during adiabatic cooling of impact-produced vapor cloud. Water vapor content is assumed to be equal to 100 %. $T_0 = 10^4$ K, $P_0 = 10^4$ bar, $\gamma = 1.2$.

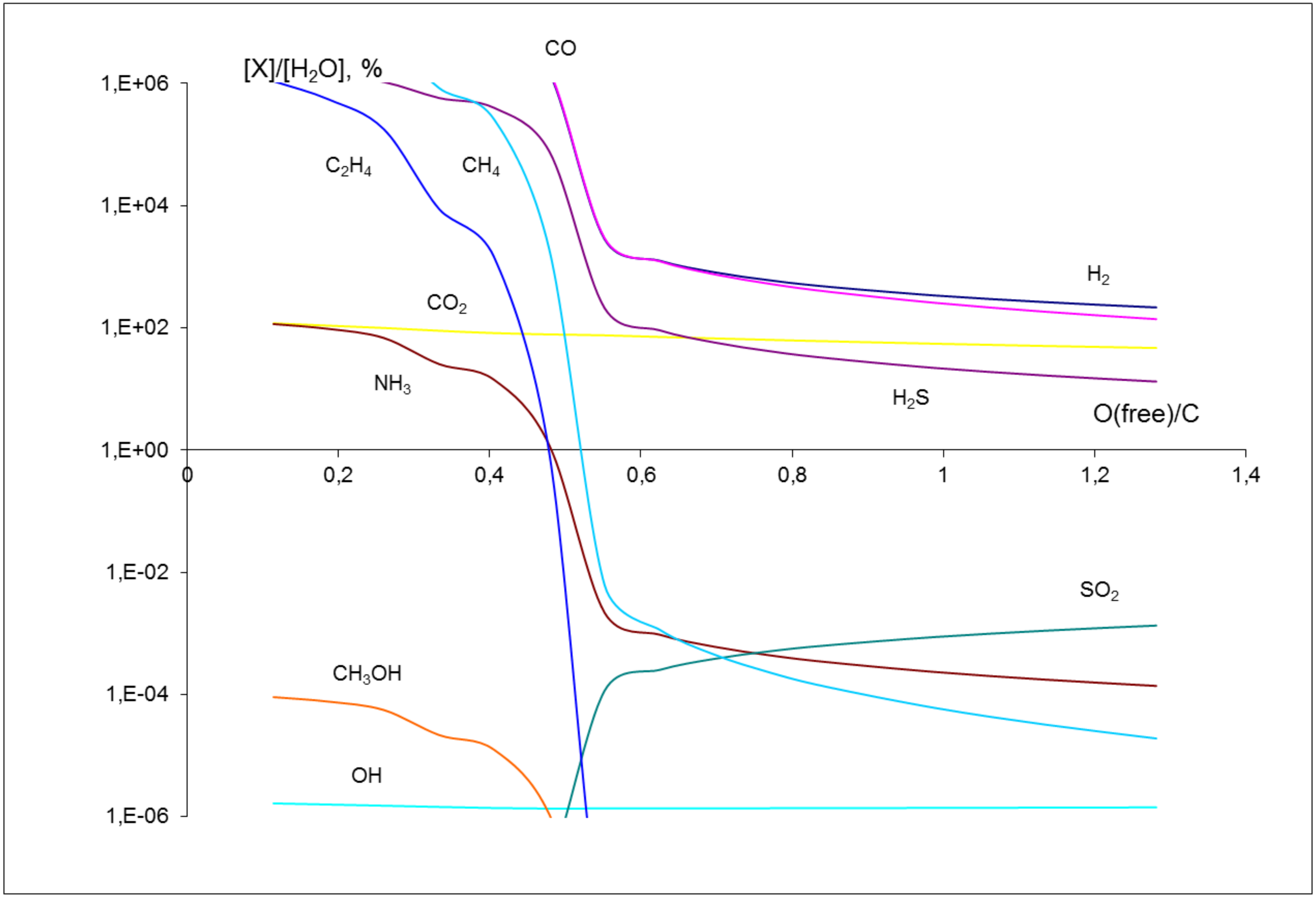
The equilibrium water abundance in the fireball, formed by O-rich comet impact



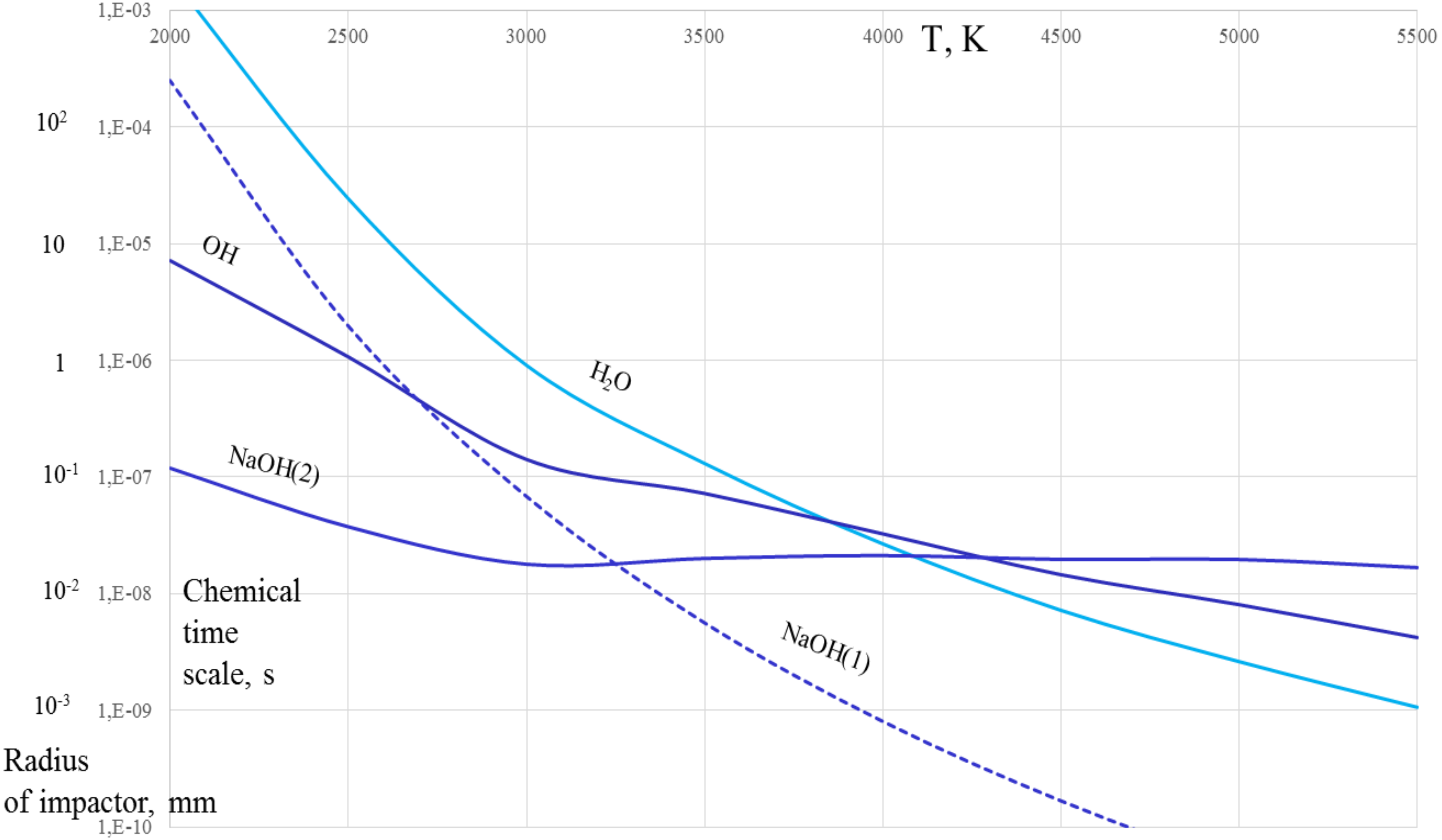
Equilibrium chemical composition of impact-produced fireball at 1300 K and 10^{-3} bar versus dust/gas ratio in cometary matter



The elemental composition of cometary dust and gas components are taken to be equal to those of comet Halley (Delsemme, 1988). Cometary gas is O-rich, cometary dust is C-rich. Thus, H_2O and CO_2 can be delivered to the Moon only by O-rich comets.



Equilibrium content of species detected at the LCROSS impact site, normalized to H_2O content at 1200 K and 0.03 bar, versus O(free)/C ratio in impacting comets.



Chemical time scale of main reactions with participation of H_2O, OH, and NaOH in the impact-produced cloud as a function of temperature in the adiabatically cooling impact-produced cloud.

Gas-phase sulfur compounds are migrated to the temporary lunar atmosphere

- When the fireball temperature is below 1500 K, H_2S is the main S-containing compound
- Fixation of sulfur into solid phase by reaction $H_2S + Fe = FeS + H_2$ is kinetically prohibited due to short hydrodynamic time scale (~ 1-10 s) during the fireball expansion

Creation
of temporary lunar atmosphere

- The formation period of lunar atmosphere is equal to $D/c_s \sim 2*10^4$ s, where $D = 3476$ km is the diameter of the Moon. This period of time is shorter than the photolysis time scale (10^5-10^6 s).
- The maximal number density in collisionless lunar exosphere is 10^8 cm^{-3}, it correspond to an atmospheric mass of $5*10^9$ g (Vondrak, 1974).
- Short-period comets over 10^{11} g and 50 m can produce a thick atmosphere

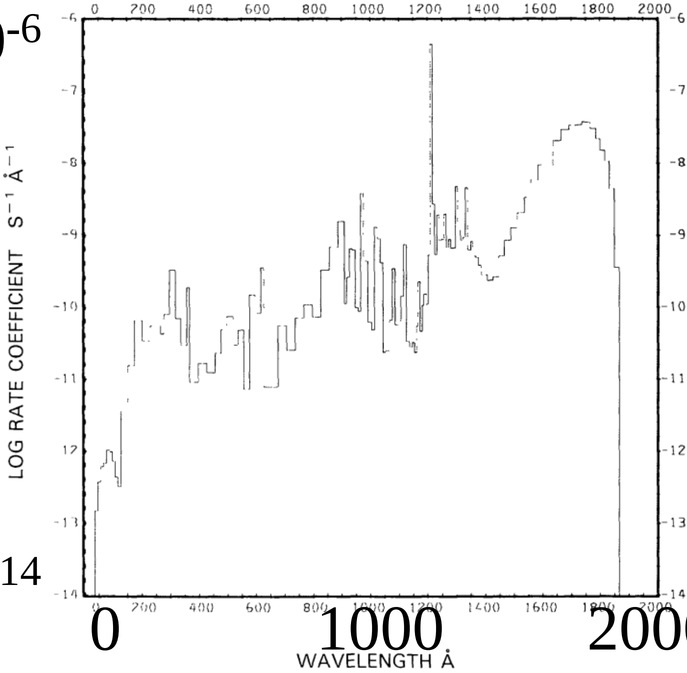
Photolysis of impact-produced species

H_2O + solar photon = OH + H, 10^{-5} s^{-1}
H_2O + solar photon = H + H + O (^3P), $7.5*10^{-7}$ s^{-1}
H_2O + solar photon = H_2 + O, $6*10^{-7}$ s^{-1}

Rate Coefficient, s^{-1} $Å^{-1}$

10^{-6}

10^{-14}



0 1000 2000

Fig. 76. $H_2O + \nu \rightarrow OH + H$, for the quiet Sun.

Wavelength, Å

Rate coefficient
of reaction of water
photolysis
H_2O + photon = OH + H
as a function
of wavelength
(Huebner et al., 1992)

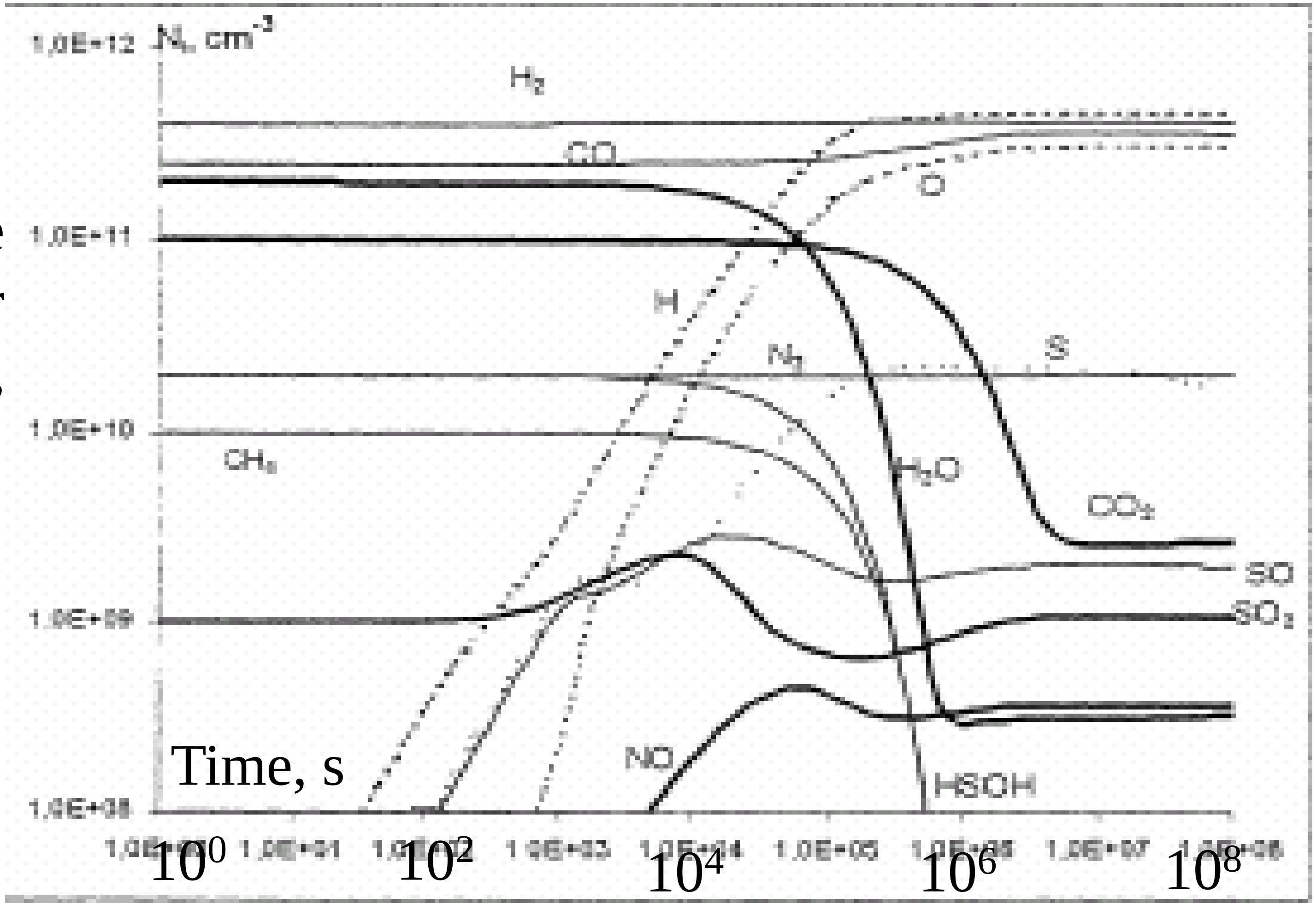
Photochemical model
of temporary lunar atmosphere

- Neutral-neutral and photolysis reactions are included
- H, C, O, N, S – containing species are included
- Rate constants are taken from (Baulch et al., 1976; Nimmo et al., 1998; Le Teuff et al., 2000; Huebner et al., 1992)
- The photolysis rates are assumed to be independent from the number density at the surface
- The set of reactions do not include ion-neutral reactions and the chemical processes on the lunar surface
- The number density is constant versus time

Chemical composition of impact-produced lunar atmosphere, formed by impact of an O-rich comet, versus time

The gas temperature is 300 K, the total surface number density is 10^{12} cm^{-3}.

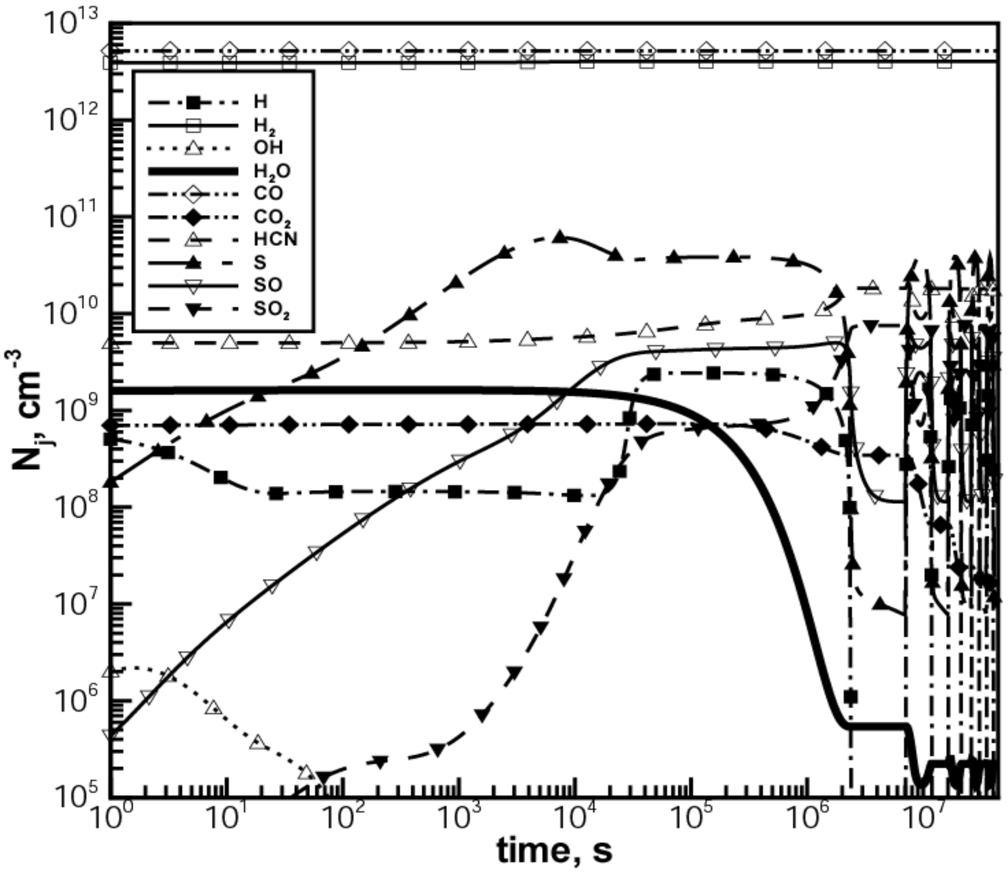
Surface number density, cm^{-3}



Chemical composition of impact-produced lunar atmosphere versus time

The gas temperature is 300 K; the initial total surface number density is 10^{13} cm^{-3}. The fireball was formed after a collision of a C-rich comet with the Moon. The initial abundances of species are equal to the equilibrium abundances in the fireball at 1700 K and 1 bar. Time dependence of photolysis rates is added.

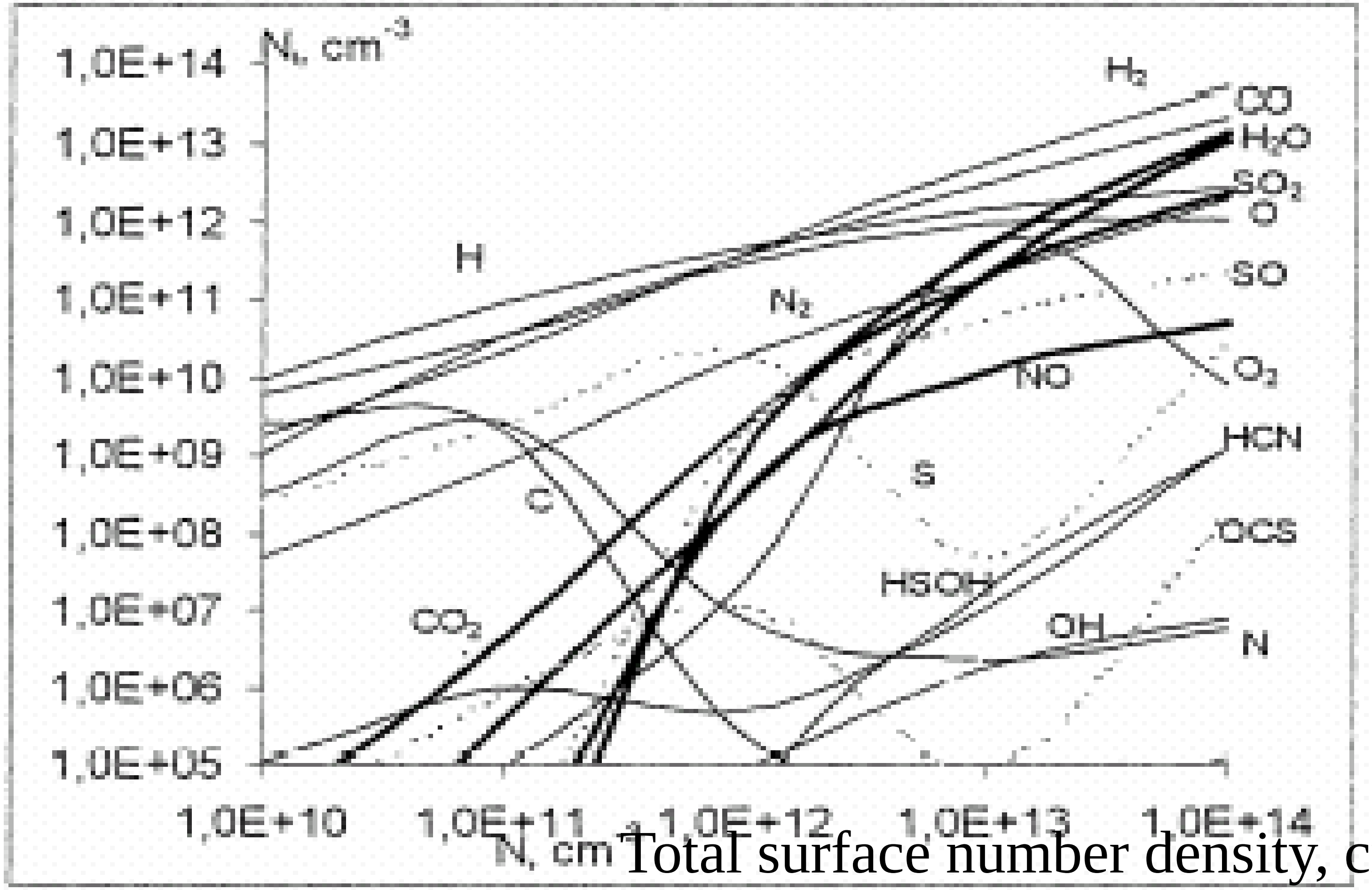
Surface number density, cm^{-3}



Chemical composition of the temporary lunar atmosphere after 10^7 s from the moment of its creation versus the total surface number density

The gas temperature is 300 K.

Surface number density, cm^{-3}



Total surface number density, cm^{-3}

Capture
of temporary lunar atmosphere
by cold traps

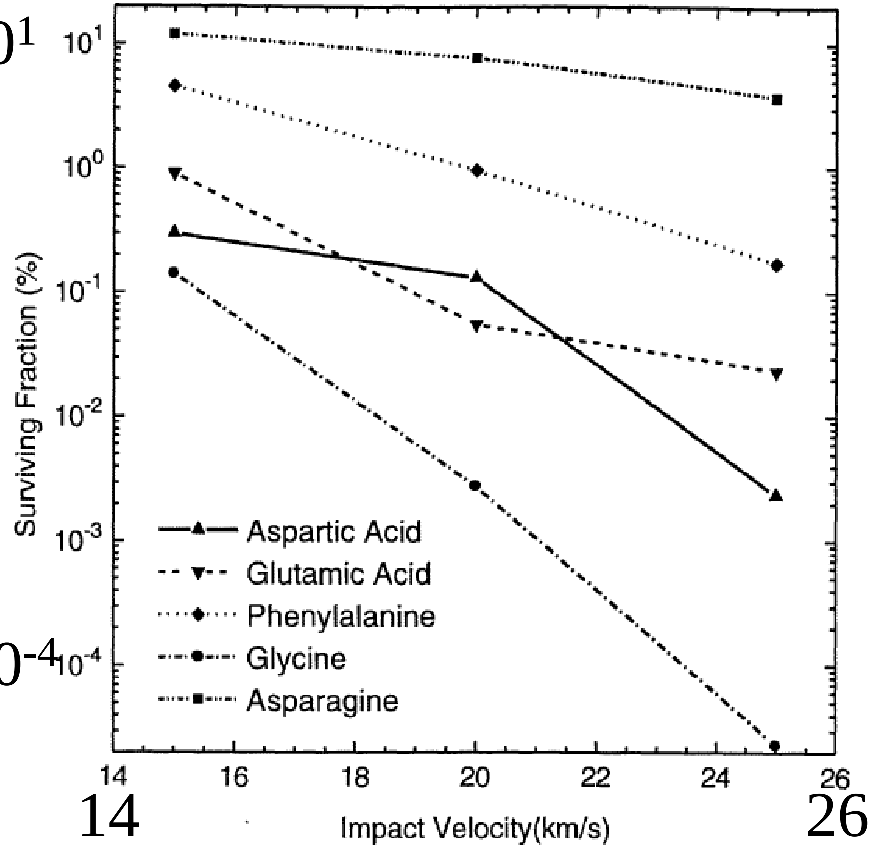
- The lifetime of temporary atmosphere $t_{life} \sim t_{ph} N_a / N_{exs}$, where t_{ph} is the photolysis time scale (10^5-10^6 s), N_a is the initial number density, $N_{exs} \sim 10^8$ cm^{-3} is the maximal surface number density in the lunar exosphere.
- The typical capture time of temporary atmosphere can be determined by use of diffuse theory.
- Then the ratio between capture and lifetime times can be estimated as $(S_m/S_c)D_c/(t_{ph}v) << 1$, where S_m is the area of the total lunar surface, S_c is the area of cold traps, $D_c \sim 1$ km is typical depth of polar craters, v is the thermal velocity of species.
- Condensable species of temporary lunar atmosphere essentially all fall into cold traps.

Survival of amino acids during collisions of comets with Europe as a function of impact velocity and comet radius

(Pierazzo, Chyba, 1999)

Surviving Fraction, %

10^1



10^{-4}

14 26

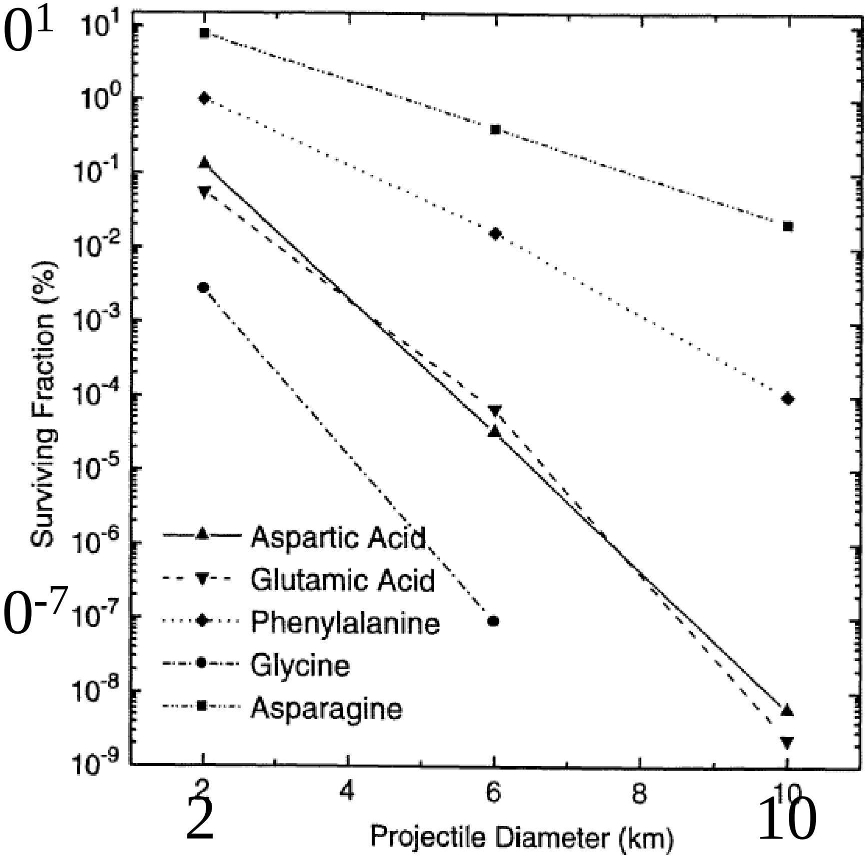
FIG. 3. Amino acid survival in vertical impacts of a 1 km radius comet as function of impact speed.

Impact Velocity, km/s

Surviving Fraction, %

10^1

10^{-7}



2 10

FIG. 4. Amino acid survival in cometary vertical impacts at 20 km/s as function of comet diameter.

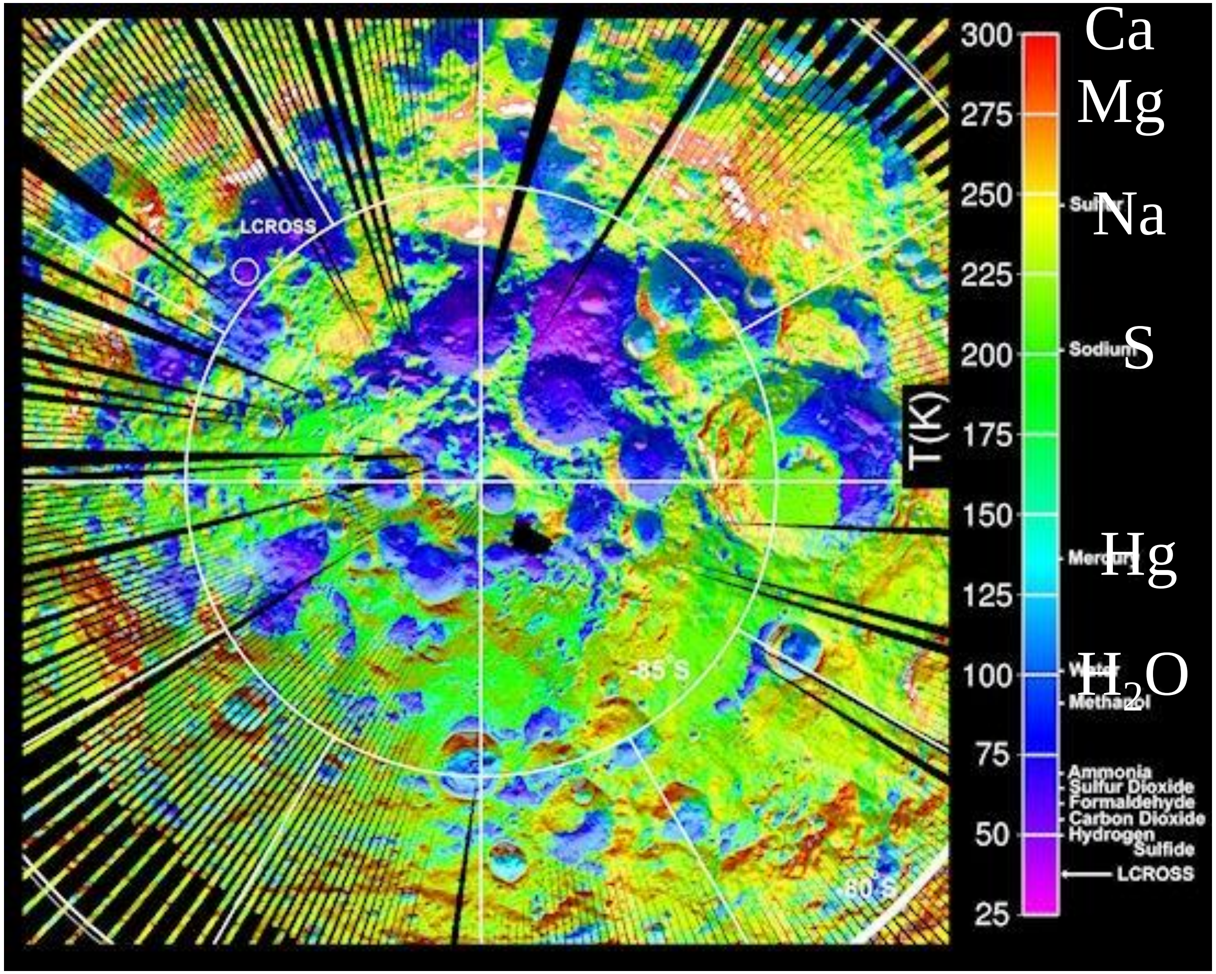
Projectile Diameter, km

Compound	Content in the LCROSS cloud	Content at the poles, wt%	Mass at the poles, kg	Content in comets	Main source	O-comets, kg/year	Asteroids, kg/year	C-comets, kg/year	Low-speed comets, kg/year
H_2O	100	5,6	10^{13}	100	**Asteroids**	10^{5}	2×10^{6}	4×10^{-3}	2×10^{4}
CO	15	0,08	5×10^{8}	10	C, O - comets, asteroids	2×10^{5}	2×10^{5}	2×10^{5}	2×10^{3}
CO_2	2,17	0,04	2×10^{10}	5	**Asteroids**	10^{5}	$1{,}5\times10^{6}$	0,02	4×10^{3}
CH_3OH	1,55	0,1	2×10^{11}	0,2-6	Low-speed comets	2×10^{-7}	2×10^{-8}	4×10^{-8}	4×10^{2}
CH_4	0,65	0,003	2×10^{8}	0,2-1,5	C- comets	10^{-2}	2×10^{-4}	2×10^{4}	70
C_2H_4	3,12	0,02	2×10^{9}	0,3	C- comets	10^{-9}	10^{-13}	10^{4}	60
H_2S	16,75	0,2	4×10^{10}	0,12-0,6	**Asteroids**	5×10^{3}	10^{5}	0,02	30
SO_2	3,19	0,2	10^{11}	0,1	**Asteroids**	3	2×10^{4}	10^{-18}	30
NH_3	6,03	0,07	5×10^{10}	0,1-1,6	Low-speed comets	0,2	0,1	0,01	60

Origin of volatile compounds at the poles of the Moon (Berezhnoy et al., 2012)

Thermal stability of different species at the poles of the Moon (http://science.nasa.gov/science-news)

After LCROSS impact
H_2O, CO, H_2, Ca, Hg, Mg
(Gladstone et al., 2010),
H_2O, H_2S, NH_3, SO_2,
C_2H_4, CH_3OH, CH_4, OH
(Colaprete et al., 2010),
Na (Killen et al., 2010)
were detected
in the LCROSS
impact plume.
These species
may be delivered
to the poles of the Moon
by impacts
of comets, asteroids,
and meteoroids.



Conclusions

- Large amounts of water ice can be delivered to the Moon by 3-5 km asteroids and O-rich short-period comets.
- Such comets and asteroids can deliver to the lunar poles also CO_2 and SO_2 ices as well as H_2, CO, and H_2S.
- C-rich comets are main source of hydrocarbons at the poles of the Moon while low-speed cometary impacts are able to deliver complex organic species, methanol, and ammonia to the lunar poles.