STUDIES OF VOLATILES AND ORGANIC MATERIALS IN EARLY TERRESTRIAL AND PRESENT-DAY OUTER SOLAR SYSTEM ENVIRONMENTS

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This report constitutes a review and partial summary of individual projects within several areas of research generally involving the origin, distribution, chemistry, and spectral/dielectric properties of volatiles and organic materials in outer solar system and early terrestrial environments. Other collaborators play a prominent role in some of these studies, as indicated in the references for specific topics.

Impact delivery of volatiles and organic compounds to the early terrestrial planets.

Cometary delivery of organic molecules to the early Earth. Here (Chyba et al. 1990) we assess with a state-of-the-art smooth particle hydrodynamic code the survivability of the organic carbon complement of asteroids and comets during the latter part of the heavy bombardment, 4.5 Gyr to 3.8 Gyr ago. Our characterizations of the impactor flux and size distribution show that most of the mass is contributed by large impactors whose organic complement cannot survive the impact process in a 1-bar atmosphere. However, we show that objects ≥100 m in radius aerobraked through the ~10-bar CO₂ atmosphere proposed for this period can contribute organic material at a rate ~10⁵-10⁶ kg yr⁻¹ that exponentially decreases with a half-life of ~10⁶ yr. Total amounts delivered could then be comparable to the contemporary oceanic (3 × 10¹² kg) and total (6 × 10¹⁴ kg) terrestrial biomasses. (Fig. 1, 2.)

Exogenous sources of prebiotic organic molecules on the early Earth. In this work (Chyba and Sagan, 1991) we investigate (in addition to the delivery by direct impacts considered above) the contribution of interplanetary dust particles, airbursts, and organic synthesis driven by atmospheric and impact shock waves. We find that the inclusion of additional direct (non-shock) sources increases the delivery rate to ~10⁸ kg yr⁻¹, comparable to in situ production rates (from lightning, coronal discharge, aurorae, etc.) for CO₂ atmospheres with high H₂ abundance. Of potentially much greater importance is the additional energy source provided by the shock waves associated with impacts, which can induce organic synthesis at rates ~10¹² kg yr⁻¹. At this rate a contemporary biomass is produced every 10⁶ yr; even in CO₂-dominated atmospheres the shock-driven rate is comparable to the highest rates possible from other in situ sources even from highly reducing atmospheres. Impact processes, directly and indirectly, likely were very important for the geochemical carbon cycle and surface organic inventory through the period leading up to the first known biological activity. (Fig. 3.)

Constraints on terrestrial volatile accretion during the heavy bombardment. Further pursuing associated questions arising from earlier work on impact delivery of volatiles (especially H₂O) to the early terrestrial planets, we investigate (Chyba 1991) the consistency between the elemental composition of Earth’s upper mantle and lunar highland material, compared to the contribution we compute from heavy bombardment impacts. The delivery of large amounts of volatiles — in particular, oceanic volumes of H₂O — is consistent with known geochemical constraints. While we point out a critical need for more laboratory measurements of the H₂O content of chondritic material, we show that a nominal model of the impactor flux and composition results in the delivery of sufficient H₂O to account for the present mantle+crust inventory, while contributing quantities of C, N, S, and Cl not exceeding those estimated for the mantle+crust. The abundances of highly siderophilic “noble metals” in Earth’s upper mantle are also consistent with the expected flux of late heavy bombardment meteoritic material.

Extraterrestrial amino acids and terrestrial life. In a note (Chyba 1990), we comment on recent work explaining the distribution of extraterrestrial amino acids in sediments near the K-T boundary in terms of accretion of comet-derived interplanetary dust particles associated with a main impact event, and on other work reporting a predominance of L-amino acids in the Murchison meteorite. The additional possibility of shock-production of amino acids in situ is raised, and is relevant to the concentration of the paper (Chyba and Sagan 1991) summarized above.

Optical constants measurements.

Optical constants of solid methane. Here (Khare et al. 1990) we present results for CH₄ in the VIS-NIR, including measurements of those absorption bands in solid crystalline CH₄ with complex part k > 10⁻⁶ in the wavelength range 1.10–2.65 μm. Since CH₄ is known to be present on the surfaces of Triton and Pluto and C₂H₆ is a major photochemical product, these materials are probably both major
contributors to the still incompletely-understood reflection spectra of Triton and Pluto. (Similar results for C$_2$H$_6$ are soon to be published.)

Spectral classification, chemical processes, and distribution of materials.

Color and chemistry on Triton. Using quantitative multiband spacecraft imaging data, one can identify spectrally distinct units of material, and relate these units to the coupled chemical and volatile transport processes controlling the spectral evolution and deposition of the material. In this work (Thompson and Sagan 1990) we find that Triton's surface can be characterized by 6 major spectral units: (1) lightly colored southern hemisphere cap (SHC) material; (2) a bluish thick frost unit beyond the permanent SHC margin; (3) a thin frost unit incompletely covering the equatorial material; (4) a more strongly colored equatorial unit; (5) extremely bright spectrally neutral units; and (6) units showing anomalous UV or red absorption. We also show that sedimenting photochemical organic dust composed of C$_2$H$_4$ and C$_2$H$_6$ can be rapidly converted to colored products (over a few Triton seasons), while direct surface modification by magnetospheric electrons and cosmic rays requires much longer times. The chemical evidence would then suggest that more strongly colored units are older, while lightly colored units represent seasonal lag deposits and bright units are younger than a few Triton seasons, an interpretation consistent with the major morphological features of Triton's surface.

Triton's streaks as windblown dust. The encounter of the Voyager 2 spacecraft with Neptune's satellite Triton revealed many "dark" (about 10-20% darker than the adjacent frost) surface streaks in Triton's southern hemisphere, resembling the streaks that are due to windblown dust on Mars. It seems therefore that dust transport by winds in Triton's tenuous atmosphere is required, the main question being the mechanism for raising dust from the surface or sub-surface. The two obvious candidates are geyser-like eruptions and direct lofting by surface winds. We have demonstrated (Sagan and Chyba 1990) that, despite Triton's tenuous (16 ± 3 μbar) atmosphere, low-cohesion grains with diameters of ≤5 μm, may be carried into suspension by aeolian surface shear stress, given expected geostrophic wind speeds of ~10 m s$^{-1}$. (The wind velocities needed to lift grains as cohesive as those found on Earth, however, are implausibly high.) For erupting plumes, we show that dust-settling timescales and expected wind velocities yield streak length scales in good agreement with those observed. Both candidate mechanisms therefore seem to be consistent with present observations of Triton.

Radar properties of ice, hydrocarbons, and organic heteropolymers.

Titan and other icy satellites: Dielectric properties of constituent materials and implications for radar sounding. Here (Thompson and Squyres 1990) we assess the state of experimental measurements on the dielectric properties of materials relevant to radar sounding of icy satellites, and especially Titan, in expectation of further ground-based work and of planning for the Cassini spacecraft's radar system. Using straightforward dielectric theory appropriate to each type of material, we present and/or fit available measurements for H$_2$O ice, polyacetylene, tholins, and hydrocarbon liquids without and with polar solutes. Transmission of any surface lakes or oceans on Titan varies from optically thin to optically thick over centimeter to decimeter wavelength ranges. Using a proposed sounding mode for a Cassini radar system, only surface reflections will result at 2.2 cm wavelength, while the sub-liquid layers can be sounded at 13.6 cm. Further, both the ocean-sediment and organic sediment-H$_2$O ice boundaries could be detected. (Fig. 4.)

References.

Fig. 1. Impact velocities as a function of surface atmospheric pressure for generic cometary and chondritic impacts at an incidence angle of 0° with radii of 100, 500, or 1500 m. In this isobaric model, the atmosphere is equivalent to the contemporary terrestrial one, with a surface pressure increased to $P_s$.

Fig. 2. Maximum, minimum, and mean temperatures for a comet impacting an ocean 3 km deep. The results here are independent of comet radius, provided the ocean is at least several comet radius deep. The dotted lines denote temperatures obtained from the Tillman EOS with an assumed constant specific heat capacity for ice. The solid lines represent temperatures for the NAME EOS. The temperatures 1800 and 1200 K are the temperatures for which HCN and simple organics (such as short-chain aliphatics, benzenes, and $\text{H}_2\text{CO}_3$), respectively, survive shock heating for time scales comparable with those of impact. For impact velocities at 10 km s$^{-1}$, a significant fraction of the organic inventory survives impact.

Fig. 3. Exogenous organic carbon provided to Earth as a function of time, from (a) sources delivering intact extraterrestrial organic molecules, and (b) impactor-driven shock synthesis of organics in the terrestrial atmosphere or post-impact vapor plume. Curves are labelled according to source. In (b), the upper curves are for $\text{CH}_4 + (\text{NH}_3/\text{N}_2) + \text{H}_2\text{O}$ reducing atmospheres, and the lower curves are for $\text{CO}_2 + \text{N}_2 + \text{H}_2\text{O}$ neutral oxidation state atmosphere. Solid lines represent the more secure estimates. Dashed lines indicate upper bounds, and the dotted line denotes an estimate that, while uncertain, is largely independent of the oxidation state of the atmosphere.

Fig. 4. Calculated signal to noise ratio (SNR) vs wavelength for radar sounding using a possible Cassini mission radar system in a 1000-km flyby of Titan. (a) low-CH$_4$ ($X_{\text{CH}_4} = 0.05$); (b) high-CH$_4$ ($X_{\text{CH}_4} = 0.8$). (See Table V.) Curves show the SNR for reflections from the upper surface of the ocean, the ocean/solid organs interface, and the solid organs/ice interface (see text for model details). Operating wavelengths for this proposed Cassini radar system are 2.2 and 13.6 cm; the longer wavelength could possibly sound the ocean floor, provided the (poorly understood) absorption of polar solutes is sufficiently low.