Radiolysis and sputtering of carbon dioxide ice induced by swift (MeV-GeV) ions

C. Mejía[1,2], M. Bender[3], D. Severin[3], C.Trautmann[3,4], Ph. Boduch[1], V. Bordalo[1,5], A. Domaracka[1], X.Y. Lv[1], R. Martinez[1,6], H. Rothard[1,*]

*corresponding author

email: rothard@ganil.fr

(1) Centre de Recherche sur les Ions, les Matériaux et la Photonique CIMAP (CEA-CNRS- ENSICAEN-UCBN), CIMAP-Ganil, BP 5133, Boulevard Henri Becquerel, 14070 Caen Cedex 05, France.

(2) Departamento de Física, Pontifícia Universidade Católica do Rio de Janeiro, Rua Marquês de São Vicente 225,22453-900 Rio de Janeiro, RJ, Brazil.

(3) Materials Research Department, GSI Helmholtzzentrum für Schwerionenforschung GmbH, Planckstraße 1, 64291 Darmstadt, Germany.

(4) Technische Universität Darmstadt, Germany.

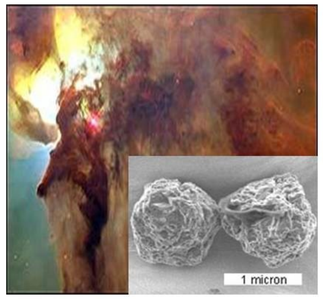
(5) Observatorio Nacional-MCTI, Rio de Janeiro, Brazil.

(6) Physics Department, Universidade Federal do Amapá, Rod. JK Km. 02, Jardim Marco Zero, 22453-900 Macapa, Brazil.

Interstellar dust grains (dense molecular clouds)

… covered with thin Layers of Ices (H_2O, CO, CO_2, NH_3, …)

are exposed to
- Cosmic rays; (protons, helium, heavy ions)
- Solar/stellar wind (H, He, C, O, S …)
- UV photons
- Electrons



Irradiation leads to …

Radiolysis

Fragmentation/Destruction

Formation of Molecules (Radiation Chemistry)

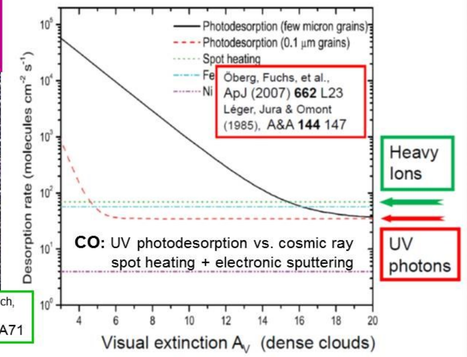
Desorption / Sputtering

Compaction / Amorphization

Astrophysical Application …

Presence of Molecules in the gas phase in "dense" (10^4–10^6 mol. cm^{-3}) Molecular Clouds **?**

Electronic Sputtering !



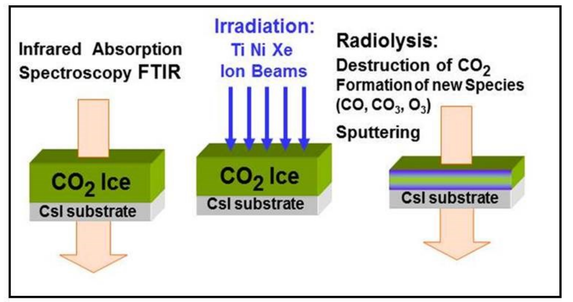
E. Seperuelo Duarte, A. Domaracka, P. Boduch, H. Rothard, E. Dartois, E.F. da Silveira
Astronomy & Astrophysics 512 (2010) A71

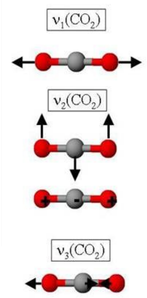
Projectiles: energies (E) and electronic stopping power (S_e),
CO_2 Ice: initial column density (N_o) and corresponding thickness (l).

Ice temperature: 15 K, except for Ti (30K). Experiments marked (*) performed with $^{12}C^{18}O_2$ instead of $^{12}C^{16}O_2$. Additional data taken from
(a) U. Raut and R.A. Baragiola, Astrophysical Journal (2013) 772:53
(b) E. Seperuelo Duarte, P. Boduch, H. Rothard, T. Been, E. Dartois, L.S.Farenzena, E.F. da Silveira, Astronomy & Astrophys. 502 (2009) 599
Electronic stopping: SRIM software [http://www.srim.org/].

Ion beam	E	S_e	N_o	l	
	(MeV)	(10^{-15} eV cm^2/molec)	(x10^{17} molec/cm^2)	(μm)	
H^+	0.1	46	0.50	0.024	(a)
$^{50}Ti^{12+}$	550	1050	5.00	0.24	
$^{50}Ti^{21+}$	550	1050	5.60	0.27	
$^{58}Ni^{11+}$	46	2600	14.1	0.69	(*,b)
$^{58}Ni^{13+}$	52.2	2630	14.0	0.68	(*)
$^{58}Ni^{13+}$	52.2	2630	8.30	0.40	
$^{129}Xe^{23+}$	91.6	4460	16.8	0.82	
$^{132}Xe^{21+}$	630	5680	0.68	0.033	
$^{132}Xe^{38+}$	630	5680	1.13	0.055	

Experiment: FTIR analysis of thin ice layers

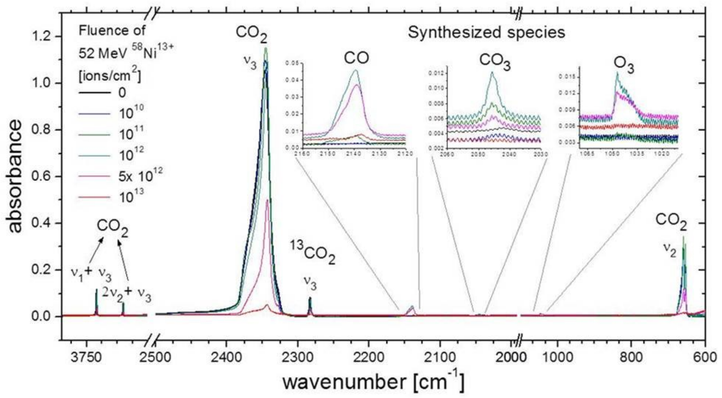




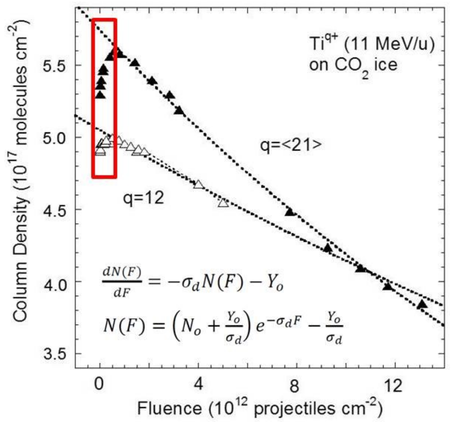
Molecular vibrations: plenty of information

Integral (Surface):
columnar density (thickness)
evolution with projectile fluence: disappearance (fragmentation, sputtering) and synthesis of new molecules

Absorption Line Position + Shape:
identification of molecules,
environment ("dangling bonds": porosity)
structure (crystal, amorphous)



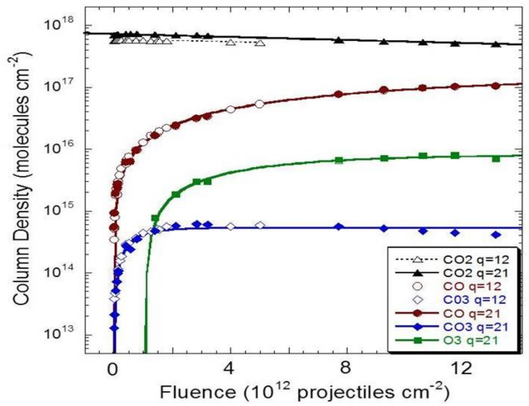
Projectile fluence dependence



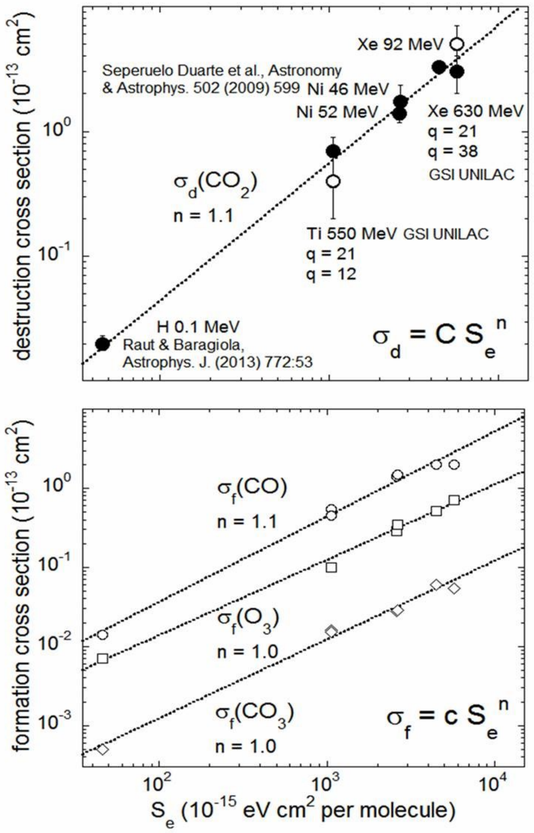
CO_2:
Compaction* **destruction** (fragmentation) **sputtering**

Formation of **CO**, **O_3**, **CO_3**

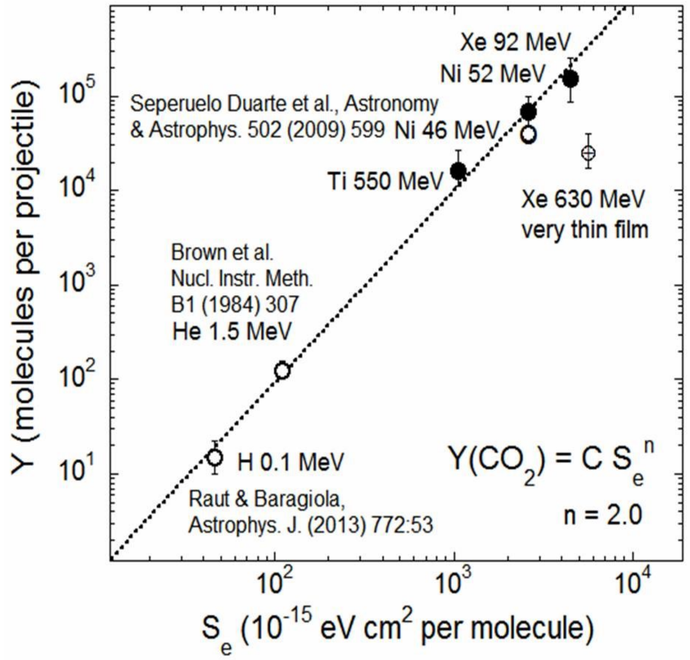
*C.F. Mejía, A.L.F. de Barros, E. Seperuelo Duarte, E.F. da Silveira, E. Dartois, A. Domaracka, H. Rothard, P. Boduch, **Compaction of porous ices rich in water by swift heavy ions** Icarus 250 (2015) 222



Formation and destruction cross sections



Sputtering yield



The chemical and physical changes induced by heavy irradiation of pure solid CO_2 at low temperature (T=15-25 K) are analyzed. The experiments were performed with Ti (570 MeV) and Xe (630 MeV) ions at the M-branch of GSI/Darmstadt and with Ni ions (46 and 52 MeV) at IRRSUD GANIL/Caen in order to simulate the effects of cosmic rays. The evolution of the thin CO_2 ice films (deposited on a CsI window) was monitored by mid-infrared absorption spectroscopy (FTIR) [1]. The dissociation rate of CO_2, determined from the fluence dependence of the IR absorption peak intensity, is found to be proportional to the electronic stopping power S_e. We also confirm that the sputtering yield shows a quadric increase with electronic stopping power [1,2,3]. Furthermore, the production rates of daughter molecules such as CO, CO_3, C_3 and O_3 were analyzed and found to be proportional to S_e [3].

[1] H. Rothard, A. Domaracka, P. Boduch, M. E. Palumbo, G. Strazzulla, E. F. da Silveira, and E. Dartois,
Modification of ices by cosmic rays and solar wind, J. Phys. B: At. Mol. Opt. Phys. 50 (2017) 062001 (Topical Review)

[2] W.L. Brown, W.M. Augustyniak, K.J. Marcantonio, E.H. Simmons, J.W. Boring, R.E. Johnson and C.T. Reimann, Nucl. Instr. Meth. B1 (1984) 307

[3] C. Mejía, M. Bender, D. Severin, C.Trautmann, Ph. Boduch, V. Bordalo, A. Domaracka, X.Y. Lv, R. Martinez, H. Rothard,
Radiolysis and sputtering of carbon dioxide ice induced by swift Ti, Ni, and Xe ions, Nucl. Instrum. Meth. B365 (2015) 477-481.

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