Charge Exchange Cross Sections Relevant to Cometary X-ray Emission

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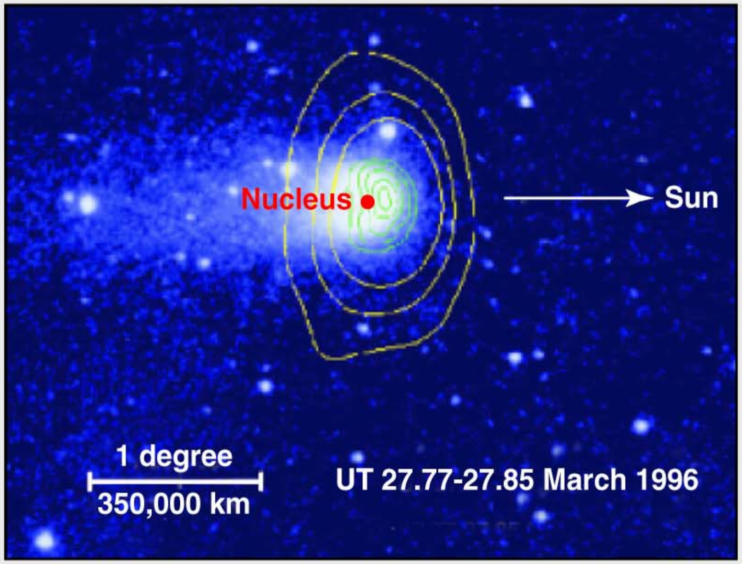
Outline

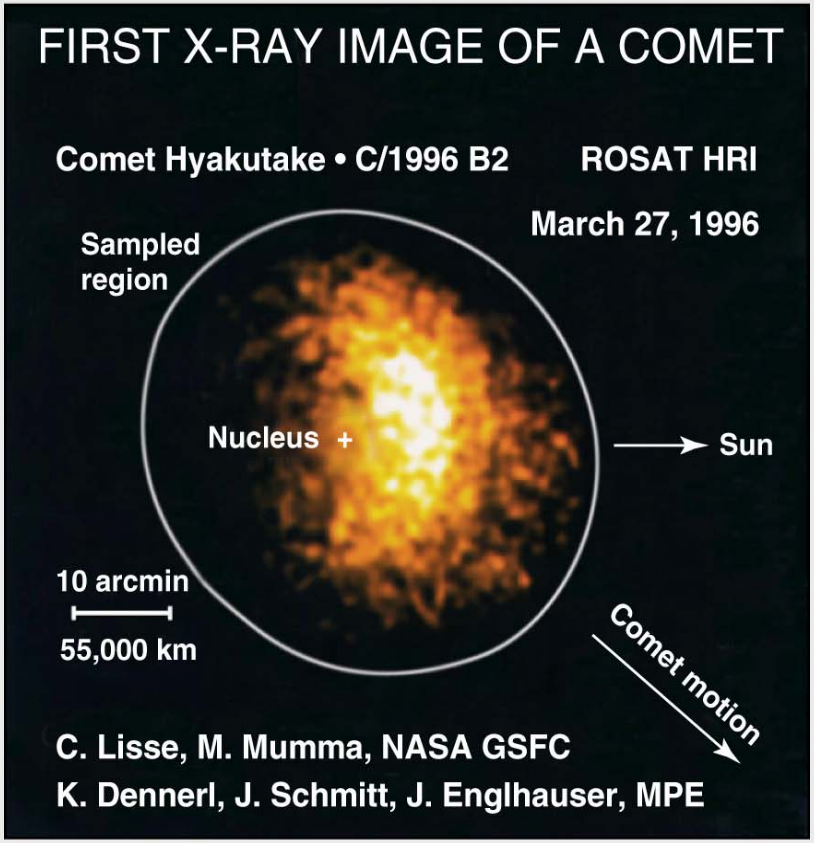
- Unexpected X-ray emission observed from comets
- The role of charge exchange collisions between highly-charged solar wind ions and cometary gases
- CTMC charge exchange cross sections
- Calculations versus collision experiments
- Prediction and comparison to satellite observations

X-Ray Emission Discovered From Hyakutake

- 1996 discovery: Comet Hyakutake observed with the German x-ray satellite ROSAT Wide-Field Camera and High-Resolution Imager emits x-rays in the 0.1-2.0 keV band
- Twenty years earlier, measurements of comet Bradford 1979X had found no such emission



Lisse et al., Science **274** (1996) 205.



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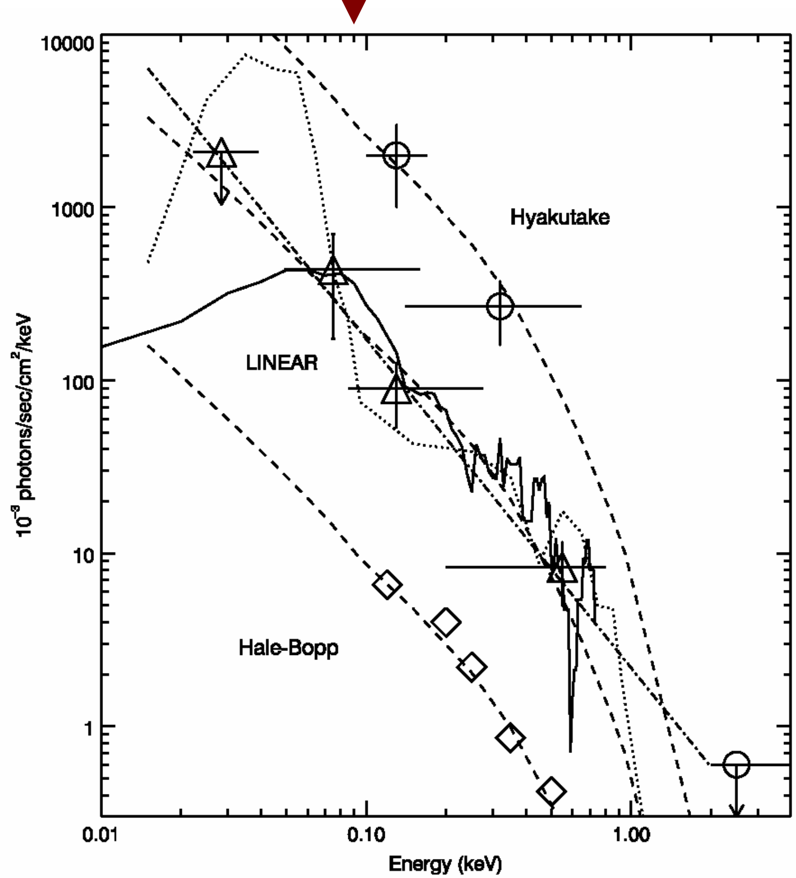
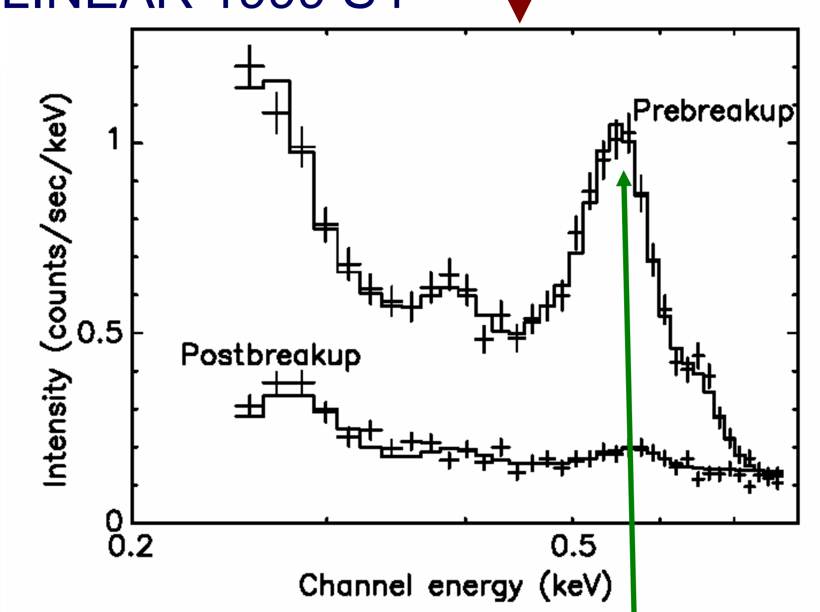
The first few years

ROSAT
BEPPO-SAX
(1996-97)



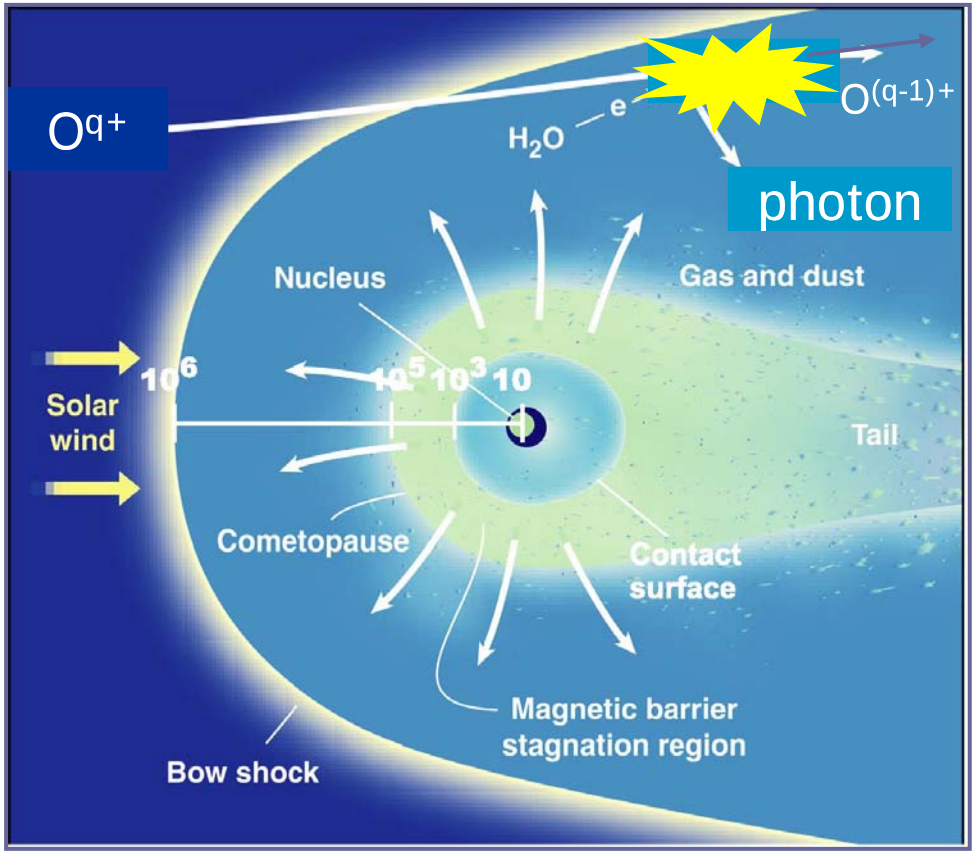
Chandra X-Ray Observatory (CXO)
(2000)
C/LINEAR 1999 S4



Strongly peaked in the $^3S \longrightarrow {}^1S$ forbidden transition!
Together with the evidence of multiple emission lines, this defines CHARGE EXCHANGE AS THE MAIN EMISSION MECHANISM.

Charge Exchange between the cometary gases and the solar wind ions

- 10 km Nucleus
- 10^3 km Contact surface
- 10^6 km Bowshock
- 10^8 km Tails



Heavy Solar Wind Ions SSW ~400 km/s ≈ 0.8 keV/u
FSW ~750 km/s ≈ 2.9 keV/u

Atomic Collisions

Charge Exchange

$$A^{q+} + B \rightarrow A^{(q-1)+*}(nl) + B^{+}$$

A^{q+} solar wind ions

B comet vapors H_2O, CO_2, etc.

Relaxation to ground state via photon emission

$$A^{(q-i)+*}(nl) \rightarrow A^{(q-1)+}(1s) + h\nu$$

Photons $h\nu$: visible – X-rays

Classical Trajectory Monte Carlo

$$H = \frac{p_p^2}{2m_p} + \frac{p_n^2}{2m_n} + \frac{p_e^2}{2m_e} + \frac{Z_p Z_e}{r_{pe}} + \frac{Z_p Z_n}{r_{pn}} + \frac{Z_n Z_e}{r_{ne}}$$

$$\frac{dq_i}{dt} = \frac{\partial H}{\partial p_i}; \qquad \frac{dp_i}{dt} = -\frac{\partial H}{\partial q_i}$$

i.e. 6-coupled first-order differential equations per body

Final State Analysis in charge exchange

$$n_c^2 = -q^2 /(2E_{pe})$$

$$[(n-1)(n-1/2)n]^{1/3} \le n_c < [(n-1)(n+1/2)n]^{1/3}$$

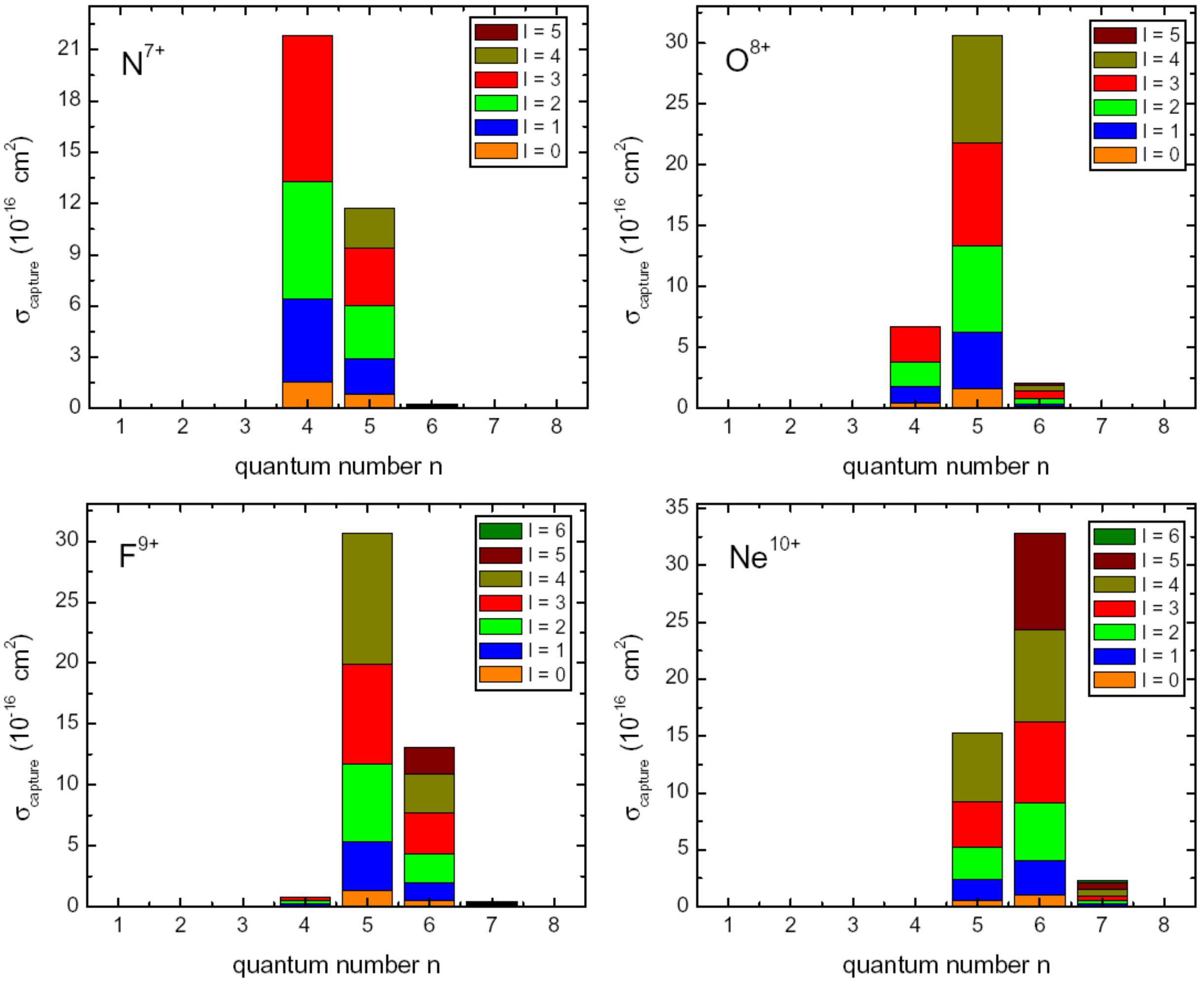
$$l_c = \left(n/n_c\right)(\mathbf{r}_{pe} \times \mathbf{k}_{pe})$$

$$l \le l_c < l+1$$

$$\frac{2m_l - 1}{2l+1} \le \frac{l_z}{l_c} < \frac{2m_l + 1}{2l+1}$$

$$\rightarrow (n, l, m_l)$$

CTMC Single charge exchange cross sections



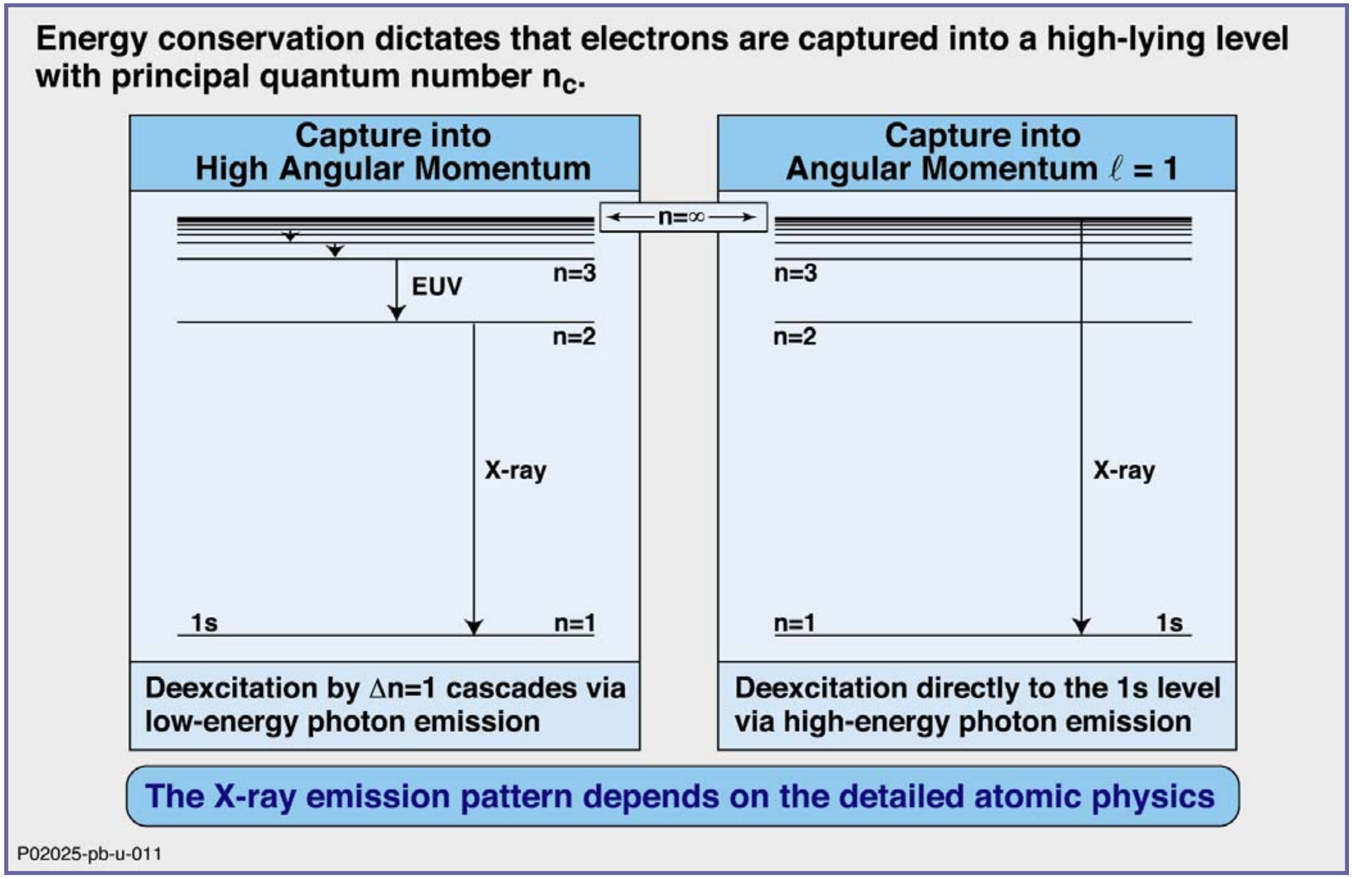
1 keV/u X^{q+}+H_2O

$n_{max} \propto q^{3/4}$ scaling!

(electron tries to preserve the orbital dimension $n_{max} \propto q^{1/2}$ and orbital energy $n_{max} \propto q$)

Statistical limit not yet reached at this energy!

Deexcitation following charge exchange



High impact energies | Low impact energies

What happens at intermediate energies?

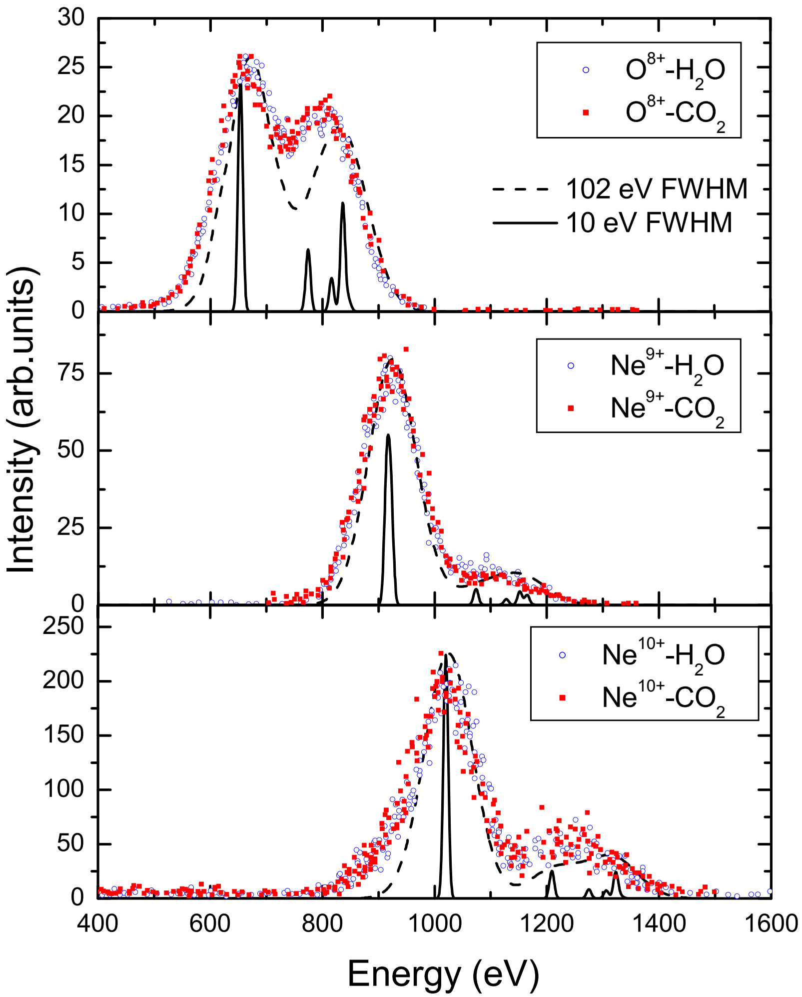
Laboratory Data

Jet Propulsion Laboratory

Capture cross sections and emission cross sections for ions and targets of astrophysical interest.

The CTMC theoretical results have been convoluted by means of 102 eV and 10 eV FWHM Gaussians.

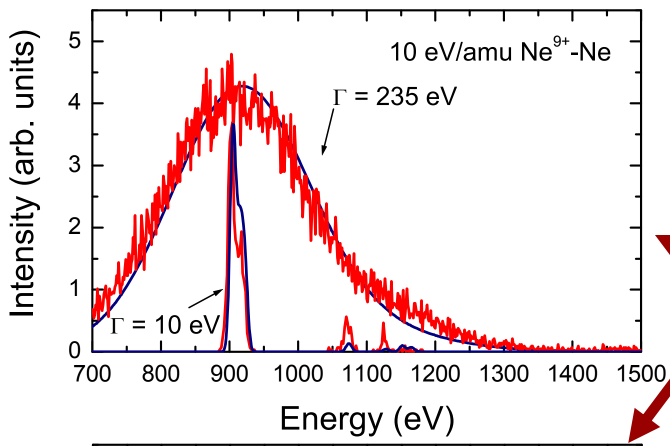
H_2O IP = 12.56 eV
CO_2 IP = 13.77 eV



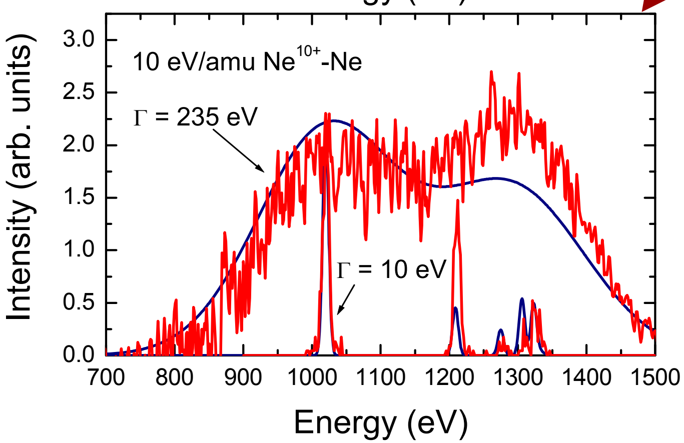
Laboratory Data

Lawrence Livermore National Laboratory

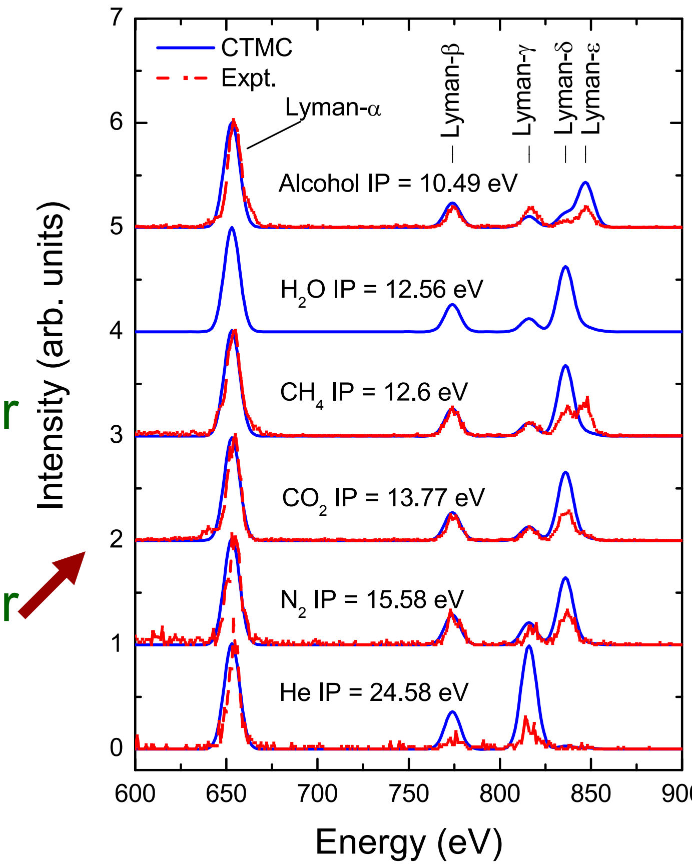
Collision energy ~10 eV/amu



SiLi detector and Microcalorimeter

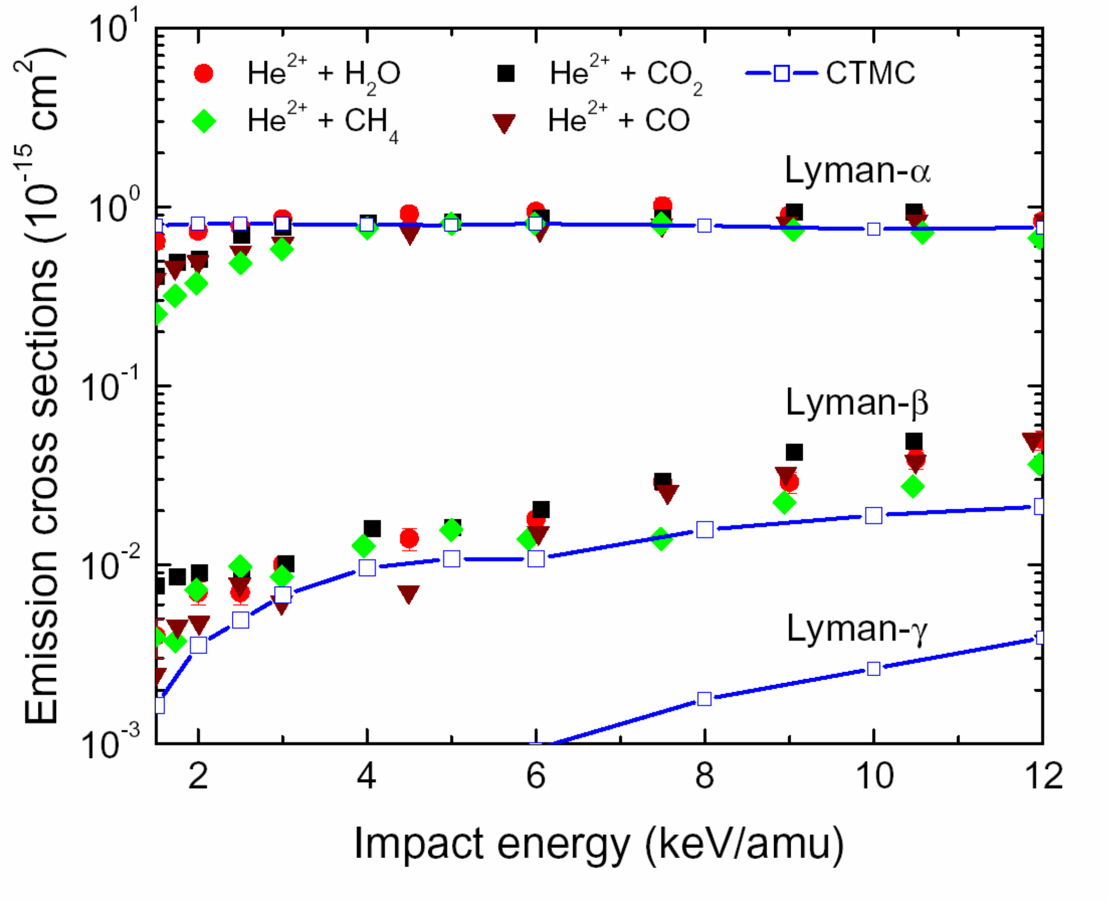


Microcalorimeter



Laboratory Data

KVI Gröningen

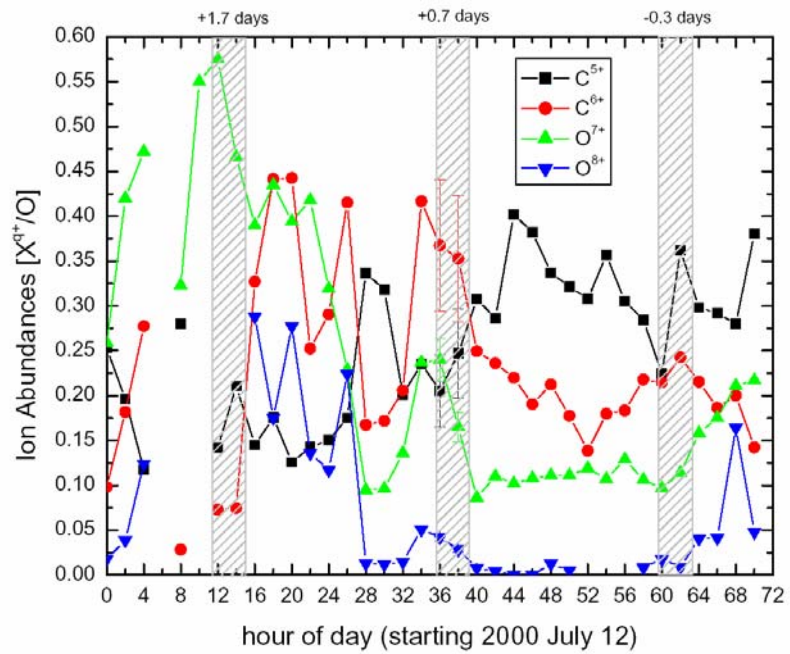


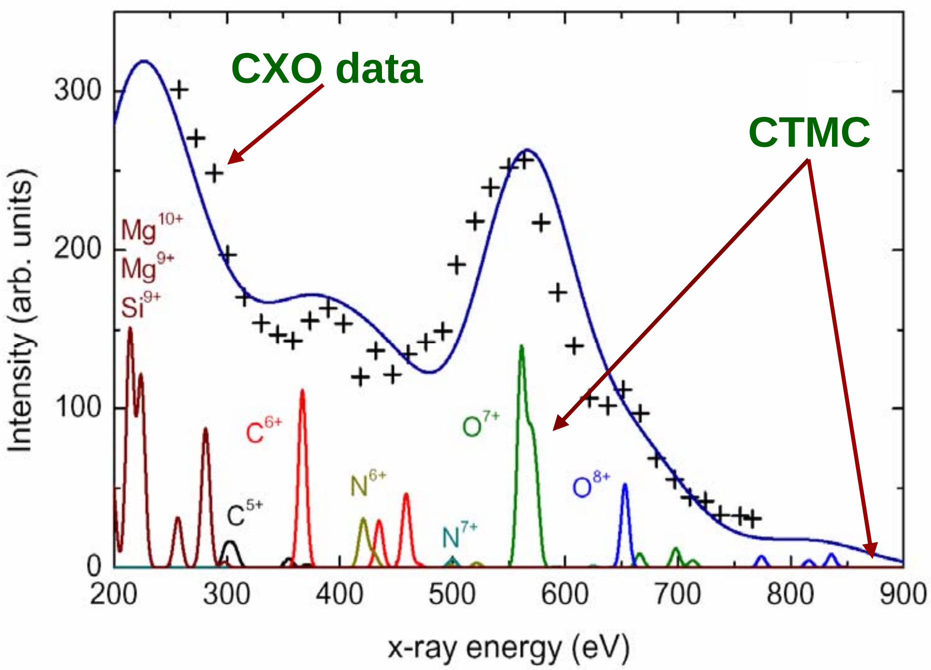
Qualitative agreement for targets with similar binding energies

CTMC results shown for H_2O only!

Astrophysical Data

Comet C/LINEAR 1999 S4



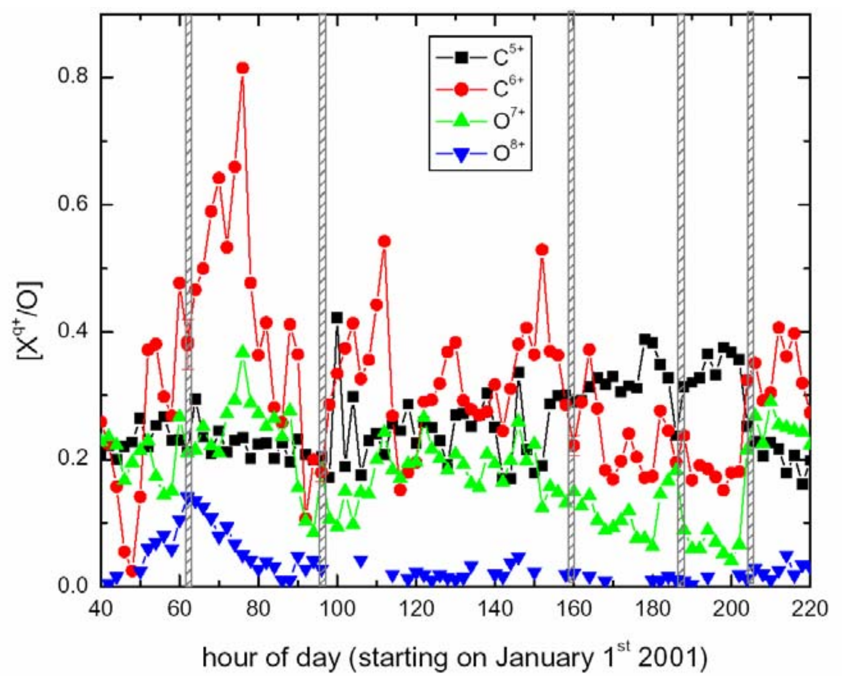


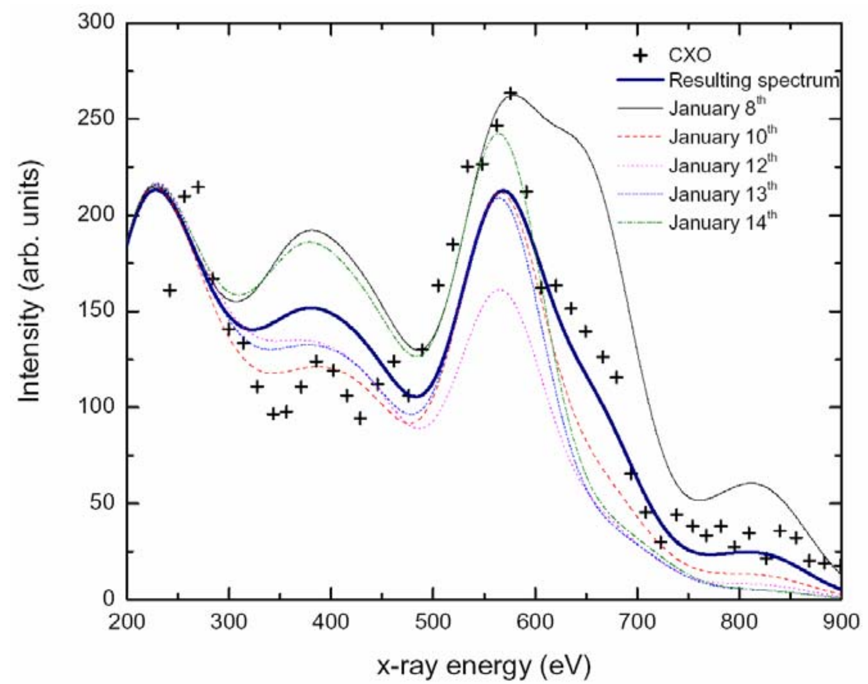
Measurements took place during almost 4.5 hs (July 14, 4:30-8:04 UT)

Solar wind events delay must be taken into account when considering ACE/SWICS-SWIMS data as well as the ACIS-S effective area

Astrophysical Data

Comet McNaught-Hartley C/1999 T1

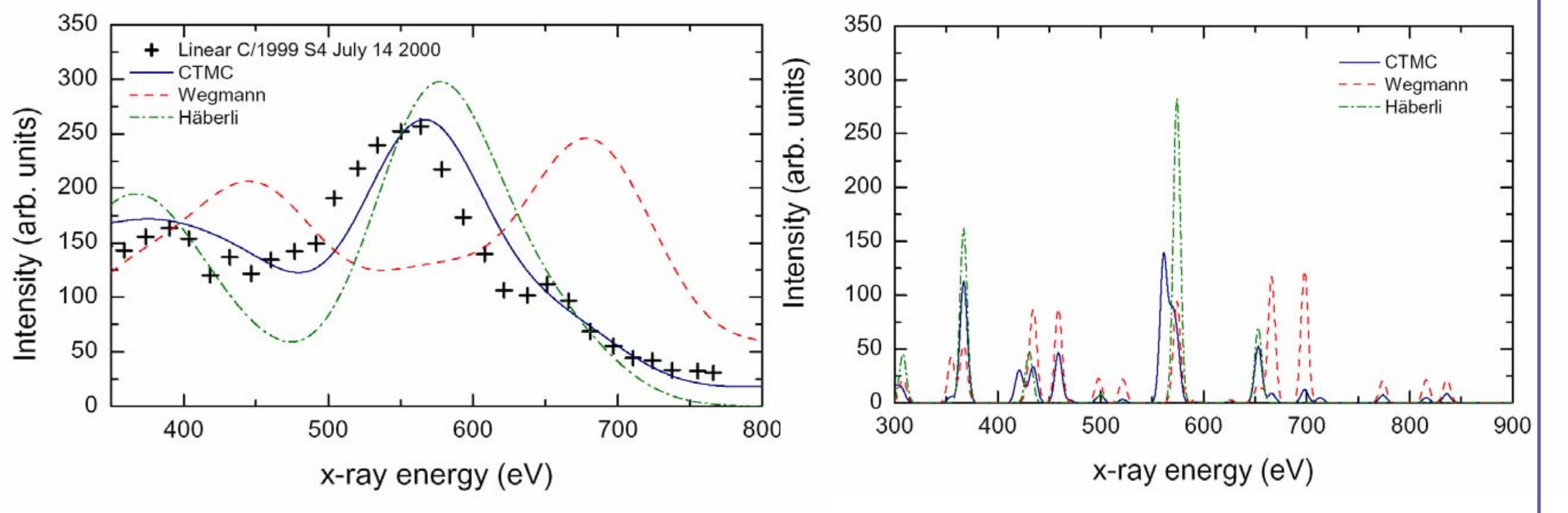




Measurements took place during almost 1 week (1 hour intervals)

Much more difficult situation to model!

What's the convenience of using CTMC?



No assumptions needed for the projectile *l*-state population

Häberli assumed a high energy statistical approach (leads to Lyman-α only)

Wegmann assumed equally probable emissions from n=2,3,….n_{max} to the ground state (overestimates the higher Lyman-β,γ..etc. lines)

Other methods like Landau-Zener are used "adjusting" the *l*-values to fit data

Conclusions

- Chandra X-Ray Observatory (CXO) comet line emission qualitatively reproduced using measured ion abundances and calculated line emission cross sections, i.e. no fitting!
- Microcalorimeter spectra with FWHM line widths of ~10 eV will challenge our understanding of state-selective electron capture reactions
- Data needs to be obtained in short periods of time in order to gain insight into the ion abundances
- Multiple capture still an issue

References

- T. E. Cravens, *Science* 296, 1042 (2002) (Excellent review!)

- Beiersdorfer et al. *Phys. Rev. Lett*. 24 (2000) 5090
- Beiersdorfer et al. *Astrophysical J*. 540 (2001) L147
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- Beiersdorfer et al. *Science* 300 (2003) 1461
- Wargelin et al. *Astrophysical J*. 634 (2005) 687
- Otranto et al. *Phys. Rev. A* 73 (2006) 022723
- Otranto et al. *J. Phys. B* 40 (2007) 1755

- ACE/SWICS-SWIMS data (Caltech web page).

- **DOE – Office of Fusion Energy Sciences (USA)**

- **ANPCyT (Argentina)**