Chandra Observations of Comets, Poster #06-01

C. Lisse (APL, carey.lisse@jhuapl.edu), K. Dennerl (MPE), S. Wolk & B. Snios (CfA), D. Christian (CalState Northridge), D. Bodewits (Auburn)

Abstract. Chandra proved that charge exchange was the main mechanism producing X-rays from comets in 2001 by observing comet C/2001 Linear with ACIS-S, simultaneously imaging the comet, measuring its X-ray luminosity, and obtaining a 200-2000 eV spectrum. This spectrum was incompatible with proposed solar X-ray scattering and solar wind bremsstrahlung models of X-ray production, but highly consistent with emission produced by C,N,O and Ne charge exchange lines, where a highly charged/stripped/ionized atom encounters a neutral atom within ~10 atomic diameters and steals/takes/extracts an electron from it. Specifically, charge exchange lines due to hydrogenic and heliogenic (CV,CVI, NVI, NVII, OVII, OVIII, NeIX and NeX) were found - all species common in the solar wind. Chandra has imaged many (10's) of comets since then, demonstrating that the CXE X-rays are produced in the cometary coma, and as the comet gets brighter and more active in a coma arc forward of the comet's nucleus. Temporal variations of the comet's x-ray production L_x are seen that correlate with the product of the comet's gas production and the solar wind flux Qgas * $n_{sw}v_s$.

Introduction

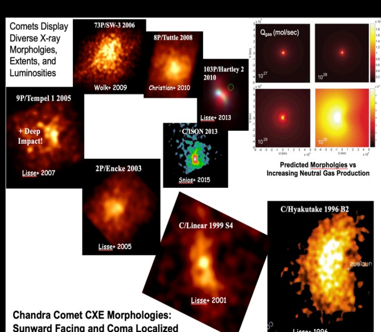
X-ray astronomy started in 1962, and has made incredibly fast progress since then in expanding our knowledge about where in the universe X-rays are generated by which processes. But it took 1 generation before the importance of a fundamentally different process was recognized. This happened in our immediate neighborhood, when in 1996 comets were discovered as a new class of X-ray sources, directing our attention to charge exchange reactions. Charge exchange is fundamentally different from other processes which lead to the generation of X-rays, because the X-rays are not produced by hot electrons, but by ions picking up electrons from cold gas. Thus it opens up a new window, making it possible to detect cool gas in X-rays (like in comets), while all the other processes require extremely high temperatures or otherwise extreme conditions.

After having been overlooked for a long time, the astrophysical importance of charge exchange for the generation of X-rays is now receiving increased general attention. Once it was realized that the X-rays were indeed produced by the interaction of a hot plasma and a cold neutral gas source of electrons (the Sun provides the MK hot ionized plasma, the comet the cold gas),

(1) $A^{q+} + B \rightarrow A^{(q-1)+*} + B^+,\ A^{(q-1)+*} \rightarrow A^{(q-1)+} + h\nu_{x\text{-}ray}$

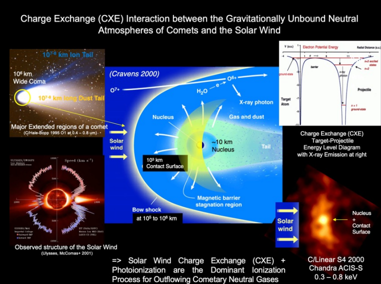
(where A denotes the solar wind projectile ion [e.g., C, N, O….], q is the projectile charge [e.g., q = 5, 6, 7] and B denotes the neutral target species [e.g., H_2O, OH, CO, O, H, etc. in the cometary coma] cometary X-rays were recognized as the first, closest example of astrophysical charge exchange emission.

Since the 1990s, charge exchange ray emission has now been detected at the planets (Venus, Mars, Uranus, Pluto [Dennerl+ 2002, 2004; Dunn+ 2020; Lisse+ 2017), in the heliosphere (Cravens, +2001 Koutroumpa + 2007, 2009), in the ISM (Lallement+ 1998, 2023; Koutroumpa +2011), in starburst galaxies (Gu+ 2017, 2019), and in more than 30 comets (including 15 by Chandra)



Chandra Comet CXE Morphologies: Sunward Facing and Coma Localized

Comet-Solar Wind X-ray Production



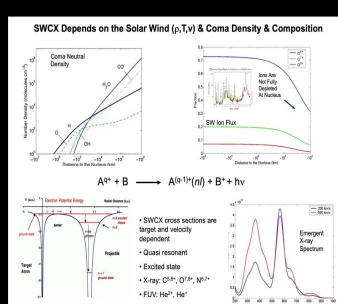
=> Solar Wind Charge Exchange (CXE) + Photoionization are the Dominant Ionization Process for Outflowing Cometary Neutral Gases

To first order, the CXE local x-ray power density P_x can be estimated assuming only one CXE collision per solar wind ion per coma passage. This approximation yields the expression:

(2) $P_x = \alpha * n_{sw} * v_{sw} * n_{neutral}$

where n_{sw} v_{sw} and $n_{neutral}$ are the solar wind proton density, solar wind speed, and neutral target density, respectively (Cravens 1997a, 2002a, Lisse et al. 2004).

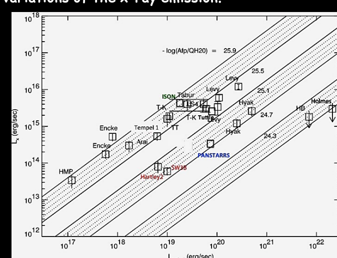
All the "atomic and molecular details" as well as the solar wind heavy ion fraction f_h, are combined into the parameter $\alpha = f_h <\sigma_{cxe}> E_{avg}$, where $<\sigma_{cxe}>$ is an average CXE cross section for all species and charge states, and E_{avg} an average photon energy.



A simple spherically symmetric approximation to the neutral density in a comet's coma is given by $n_{neutral} = Q_{gas} / [4\pi\ v_{gas}\ r^2]$, for r less than the ionization scale length $R = v_{gas}\,\tau$, where $\tau \sim 10^6$ s is the emitted gas ionization lifetime (Schleicher & A'Hearn 1988) and $v_{gas} \sim 1$ km/s the neutral gas outflow speed, both at ~1 AU. Integration of P_x over the volume of the neutral coma yields an x-ray luminosity, L_{xray}, typically within a factor of 2-3 of the observed luminosity (Cravens 1997a, 2000a; Lisse et al. 2001).

L_{xray} vs $L_{optical}$ for a Comet

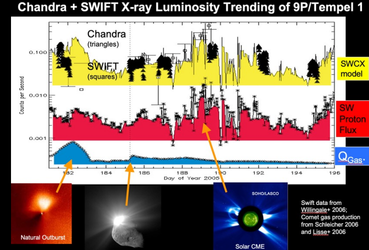
The observed total x-ray luminosity is a function of both the solar wind flux density $n_{sw}w_{sw}$ and the cometary neutral gas production rate Q_{gas} up to the limit of 100% charge exchange efficiency of all solar wind minor ions within an ionization scale length of < 10^6km (Figure 3). The maximum expected x-ray luminosity at 1 AU and 0.2 – 0.5 keV is thus ~ 10^{16} erg/sec, and temporal variations of the solar wind flux directly translate into time variations of the x-ray emission.



As determined by Chandra, comets' CXE luminosity is roughly 10^{-4} of their optical luminosity. L_{xray} seems to scale linearly with L_{opt} up to a point, at which it saturates and gets no larger for the brightest and most active comets. L_{opt} is a measure of the comet's total gas and dust production. The fact that L_{xray} levels off while L_{opt} can still increase is an indication that the total amount of highly charged minor ions in a cylinder < 10^6 km in radius the solar wind are a limiting factor. Increasing dustiness of a comet's coma may also limit its x-ray production, as CXE interactions with dust particles tend to produce Auger electrons instead of x-rays.

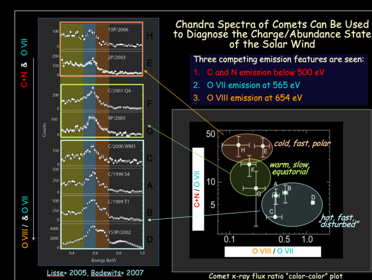
X-ray Production Time Dependence

Chandra + SWIFT X-ray Luminosity Trending of 9P/Tempel 1



Temporal variations of a comet's x-ray production L_x are seen. First found in ROSAT observations of comets in the late 1990's (Lisse et al. 1996, 1999), the demonstration of direct correlation with the product of the comet's gas production and the solar wind flux Qgas * $n_{sw}v_s$.. Was definitively demonstrated by Chandra monitoring observations of thee NASA Deep Impact mission excavation experiment from comet 9P/Tempel 1 in July 2005.

Cometary X-ray Spectroscopy



Since cometary X-ray emission is the result of charge exchange between heavy solar wind ions and neutral gas, it can be used as a probe for monitoring the heavy ion content of the solar wind (Dennerl+ 1997; Kharchenko & Dalgarno 2000; Lisse+ 2005; Bodewits+ 2007), because each ion leaves its characteristic signature in the X-ray spectrum. Around solar minimum, two types of solar wind are present: a fast (v~700 km/s), steady polar component at latitudes above 20 degrees, characterized by low density and low ionization, and an equatorial component, which is typically slow (v ~ 400 km/s), dense, and highly ionized, but also highly variable in these parameters. Outside solar minimum, the equatorial component is expanding to higher latitudes, so that the clear distinction between both components disappears around solar maximum.

Applications of Cometary X-ray Measurements

-Fundamental research on the nature of astrophysical charge exchange using emission from nearby objects in a well described radiation/plasma environment.

-Understanding of x-ray background fluxes (ROSAT long term enhancements, 1/4 keV and 1/2 keV sky, heliopause/IBEX ribbon, etc.)

-Measurement of solar wind flux in remote regions of the solar system, wherever comets may be optically (for Qgas measure) and X-ray observed. (100s of Oort Cloud comets and 40-50 JFC comets come to perihelion in the inner solar system each year.)

-Detection of N_2 or H_2 ice dominated objects, like interstellar object 1I/Oumuamua (Cabot et al 2023).

-Detection of KBO atmospheres via charge exchange between the solar wind and escaping atmospheric particles (Lisse et al 2017, Huey et al 2018, Wolk talk on Thursday)

Acknowledgement: The authors would like to recognize and thank the Chandra project for supporting this work under numerous grants from 2001 to 2016.