Experiments Re-create X Rays from Comets

EARTH is continually showered by x rays traversing the universe from our Sun and other hot stellar objects. A major branch of astronomy is devoted to detecting and studying x rays from distant stars and galaxies, and Lawrence Livermore scientists have long studied the x rays that are produced from nuclear detonations.

However, it came as quite a surprise to scientists in 1996 when the Rosat X-Ray Satellite detected low-energy (less than 1 kiloelectronvolt) x rays streaming from the comet Hyakutake. X-ray emission is usually associated with hot plasmas from stars, nuclear reactions, and black holes, not from ice-cold objects such as comets. Since the original discovery, other x-ray satellites have established that several other comets traveling through our solar system emit x rays with fluxes, or intensities, as high as 10^{25} photons per second.

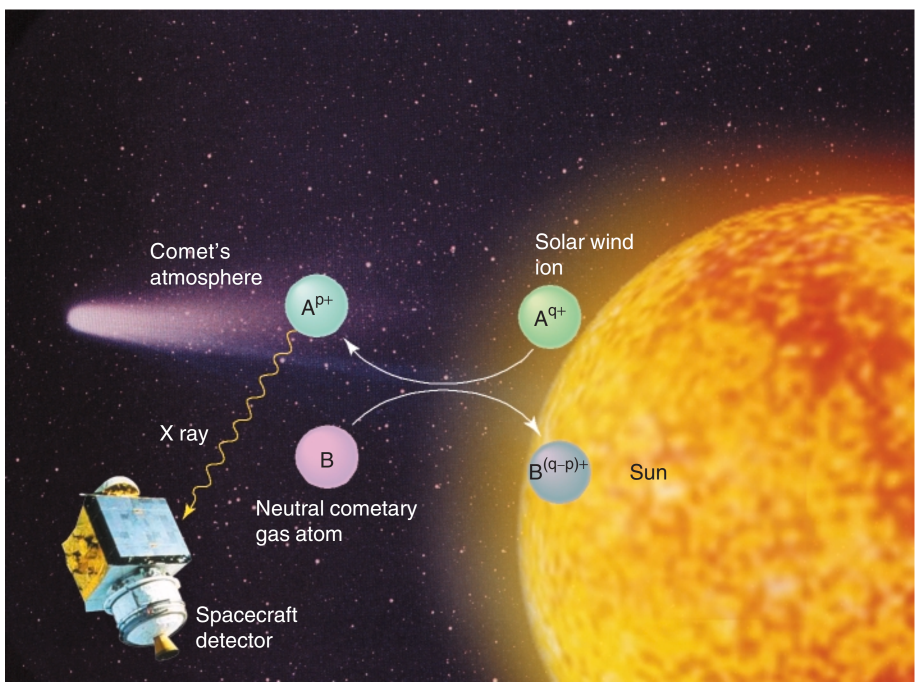
To help resolve the apparent contradiction, a national team of scientists headed by Lawrence Livermore physicist Peter Beiersdorfer is working on the laboratory production of low-energy x rays identical to those produced by comets traveling near the Sun. The team is using Livermore's electron beam ion trap (EBIT) to produce the x rays and an x-ray spectrometer (XRS) designed by the National Aeronautics and Space Administration (NASA) to detect them.

The research is providing much greater understanding about the x rays that are emitted by comets as they pass the Sun. The effort is also providing scientists with valuable information that will help them interpret data to be collected by a joint U.S.–Japan x-ray satellite mission scheduled for launch in 2005.

Primordial Chunks of Ice

Comets are odd-shaped chunks of ice (water and frozen gas) and dust a few kilometers to a few tens of kilometers in diameter. They are the oldest, most primordial objects in the solar system. X rays emanate from a comet's nebulous atmosphere called a coma, which can stretch tens of thousands of kilometers in front of or behind the comet. The coma is formed when the comet gets close enough to the Sun so that some of the ice is vaporized.

More than a dozen theoretical models were first proposed to explain why comets give off x rays. Some models predicted that comet x rays are reradiated x rays from the Sun. Other models were based on some kind of interaction between the molecules



The current explanation for comet x rays is called charge exchange. This process is believed to occur when heavy ions (A^{q+}) from the solar wind flowing from the Sun (right) collide with electrically neutral atoms and molecules (B) in the comet's atmosphere (left). During a collision, a heavy ion captures one or more electrons from a comet's atmospheric atom, ionizing it to $B^{(q-p)+}$. The solar wind ion, now A^{p+}, momentarily enters an excited state and kicks out an x ray as the electrons return to a low-energy state. The x ray can be detected by a spacecraft (lower left).

in the comet's thin atmosphere and ions or electrons from the Sun's solar wind, the stream of particles that blow off the Sun's corona at 400 kilometers per second.

The current leading explanation is called charge exchange. This process is believed to occur when solar wind forces heavy ions of carbon, nitrogen, oxygen, and other elements to collide with the electrically neutral atoms and molecules found in a comet's atmosphere. During a collision, a heavy ion from the solar wind captures an electron from a comet's atmospheric atom or molecule and momentarily enters an excited state. The ion immediately kicks out an x ray as the electron returns to a low-energy state.

"Very little experimental data are available on charge-exchange-induced x rays and what the spectrum emission lines look like," says Beiersdorfer. "The goal of our research is to re-create, in the laboratory, the same x-ray emissions that are produced when the solar wind and comets interact. In this way, we can better understand the nature of charge exchange and help other scientists interpret data taken by x-ray satellites."

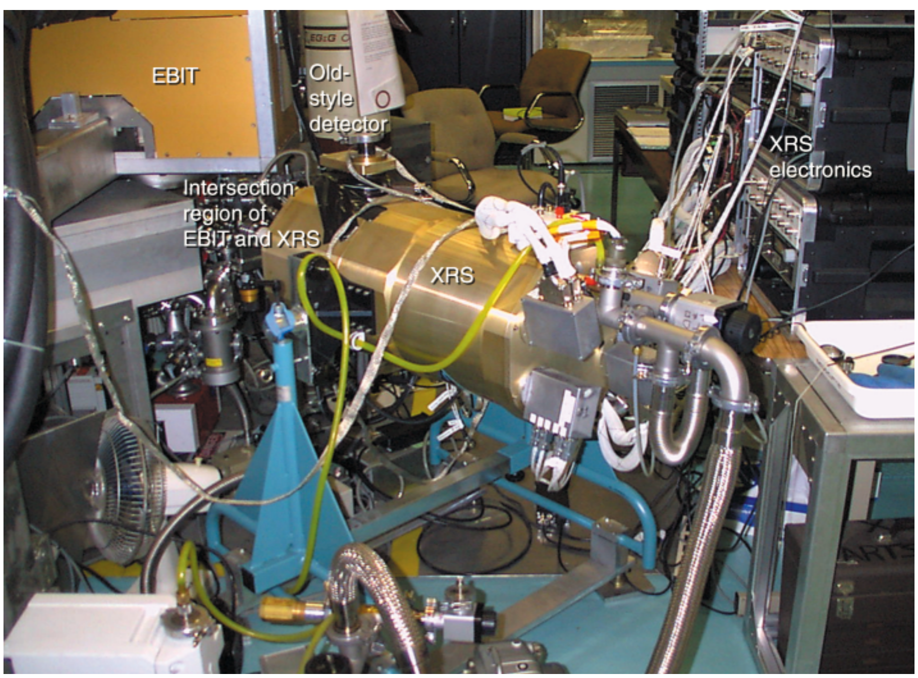
The research, supported by Laboratory Directed Research and Development funding and NASA, is a collaboration between scientists from Livermore, NASA's Goddard Space Flight Center, and Columbia University. The investigators include Daniel Thorn, Mark May, and Hui Chen from the Laboratory; Richard Kelley, Scott Porter, Caroline Stahle, Keith Gendreau, Gregory Brown, Andy Szymkowiak, and Kevin Boyce from Goddard; and Steven Kahn from Colombia. In addition, space researchers Casey Lisse from the University of Maryland and Bradford Wargelin from the Harvard Smithsonian Observatory are aiding the research effort.

The team is using Livermore's EBIT, which produces and traps highly charged ions by means of a high-current-density electron beam instead of traditional high-energy particle accelerators. The instrument was developed in 1985 by Laboratory physicists Mort Levine and Ross Marrs. Other electron beam ion traps, most of which are based on Livermore's design, are used at research centers in the U.S., Europe, and Japan.

EBIT's electron beam collides with selected ions to strip them of one or more electrons, depending on the beam's energy. The current version, named SuperEBIT, can produce an electron beam energy of up to 250 kiloelectronvolts, enough to make uranium (U^{92+}) ions. "SuperEBIT can produce virtually any ion, x ray, or visible photon desired," says Beiersdorfer.

New Generation of Spectrometer

The XRS was designed by NASA for Japan's Astro-E X-Ray Satellite, but a failed rocket launch in February 2000 means a wait of five years before its replacement, the Astro-E2 Satellite, can be placed in orbit. Fortunately, the Astro-E's engineering spare XRS was still available for laboratory x-ray astrophysics measurements. It was sent to Livermore after the failed launch



At Livermore's electron beam ion trap (EBIT) facility, scientists study the charge-exchange process and the effects of different ions and interaction gas molecules on the x-ray emission patterns recorded by the x-ray spectrometer (XRS) (front). The EBIT (in back) provides a source of ions to re-create solar wind particles. At the left is an old-style spectrometer. Also shown is the intersection of the XRS and EBIT.

of Astro-E. The Livermore–Goddard team adapted the instrument to fit on EBIT and uses it to study x-ray detection.

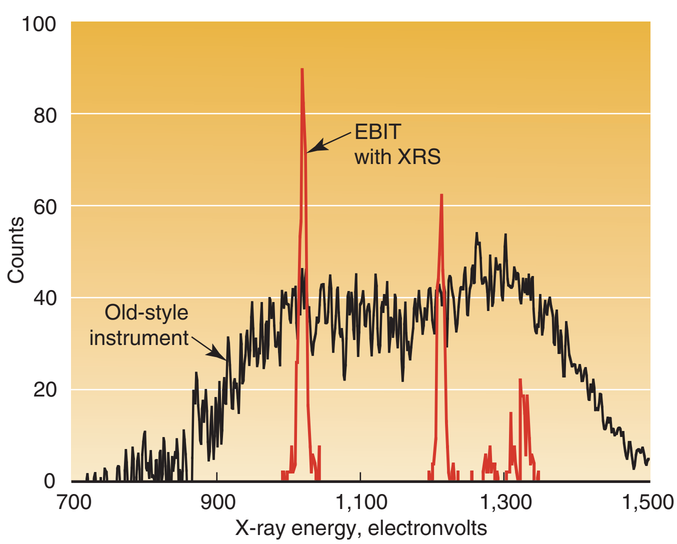
The XRS, a new generation of spectrometer, uses microcalorimeter detectors that are so sensitive they can detect the heat produced by the energy of an individual x-ray photon. To accomplish this, its microcalorimeter array is cooled to an extremely low temperature of –460°F (0.060 kelvin). (The absence of all heat, called absolute zero, is 0.0 kelvin, and has never been achieved.) The XRS has an energy detection range of 0.4 to 10 kiloelectronvolts with an energy resolution of 10 electronvolts, which allows scientists to see much finer detail in the x-ray spectrum.

At the Livermore EBIT facility, scientists study the details of the charge-exchange process and the effects of different ions and interaction gas molecules on the x-ray emission patterns recorded by the XRS. The EBIT facility provides a source of ions to re-create solar wind particles interacting with atoms and molecules in a comet's atmosphere. The XRS records the x-ray spectra, and diagnostic detectors characterize the experimental conditions. In effect, says Beiersdorfer, the EBIT facility has become a test stand for the Astro-E2 satellite, which will carry an enhanced XRS.

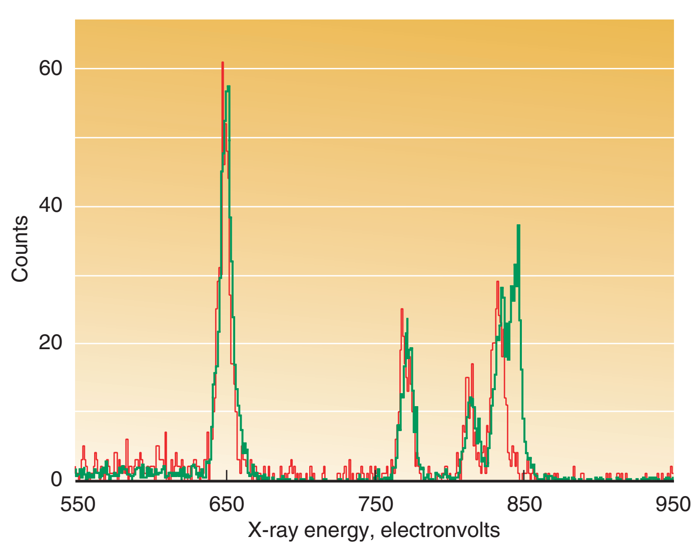
Experiments Mimic Space Interactions

The EBIT experiments begin with the production of several million ions of either carbon, oxygen, neon, magnesium, silicon, or iron. These ions are found in the solar wind and are believed to be involved in charge-exchange reactions with comets. The beam is then turned off, and the trap is operated in the so-called magnetic mode, in which the ions are confined by a magnetic field to a volume of about 2 cubic centimeters. At this density, the physics is the same as that found in the vicinity of a comet passing close by the Sun. (A greater density of ions would introduce completely different physics regimes.) Next, neutral molecules of water, methane, nitrogen, or carbon dioxide, all of which have been identified in comets' atmospheres, are injected into the trap.

For a few hours, the XRS records the x rays produced by charge-transfer collisions between the ions and the neutral molecules. The result is a catalog of emission lines that serve as tell-tale fingerprints of a particular ion's x-ray-producing collision. Beiersdorfer says that the experiments are validating the hypothesis that charge exchange is a viable mechanism for producing comet x rays, although the exact mechanics of the process are probably more complex than is known.



Data on charge-exchange-induced x-ray emissions supplied by electron beam ion trap (EBIT) experiments with the x-ray spectrometer (XRS) are enormously more detailed than data supplied by old-style detectors. This graph compares the data supplied by each instrument in registering x-ray emissions caused by charge-exchange reactions involving an ion of neon (Ne^{9+}).



Plots of x-ray emissions from an ion of oxygen (O^{7+}) caused by interactions of O^{8+} with methane (CH_4, the green trace) or with nitrogen (N_2, the red trace) reveal subtle changes in the x-ray emission lines when these different neutral gases collide with the heavy ions. The changes are found near 850 electronvolts.

The researchers discovered that the x-ray emission pattern changes with the kinetic energy of the ions. They found that the average x-ray energy emitted by the ions shifts to higher values as the kinetic energy of the ions is lowered. They also uncovered subtle changes in the x-ray emission lines when different neutral gases collide with the heavy ions. “The composition of the interaction gas is another important variable,” says Beiersdorfer.

Comets as Probes

Beiersdorfer predicts that careful detection and measurement of x rays produced by the interaction between the solar wind and comets will one day provide a powerful means to monitor space “weather” inside the solar system without the need for spacecraft circling the Sun. In this way, he says, comets could be used as probes to measure the intensity, speed, and composition of the solar wind, its intermittent “quiet time,” and the chemical composition of comet gases.

“Given that more than three bright comets with appreciable x-ray emissions enter the inner solar system each year, their x rays can provide a valuable diagnostic of the solar wind. This capability has opened up a whole new window to our solar system; it’s a very rich field.”

Some astronomers have conjectured that as the solar wind slows down throughout the heliosphere, it may generate weak x rays through charge-exchange reactions with natural gas streaming in from the interstellar medium (mostly hydrogen atoms). If this hypothesis is borne out by x-ray satellite data, astronomers will have to revise their assumption that the soft x-ray background that seems to permeate the universe may in fact be partly due to charge-exchange reactions from the solar wind.

Small Handbook on Comet X Rays

The result of the EBIT experiments will likely be a small handbook for scientists to guide their interpretation and understanding of the comet x-ray data sent back by Astro-E2, beginning in 2005. “The scientific community will be well prepared when Astro-E2 launches,” says Beiersdorfer. In the meantime, NASA has committed a second, advanced XRS for the EBIT team’s research.

As the EBIT experiments continue, other scientists are looking at the theoretical model of charge exchange. Atomic theorists Ronald Olson from the University of Missouri at Rolla; Jim Perez from Luther College in Decorah, Iowa; Charles Weatherford from Florida A&M University in Tallahassee; and Burke Ritchie from Livermore are aiding the research effort. Lawrence Livermore researchers have extensive experience in modeling short-wavelength radiation phenomena, and physicist Ritchie is using high-performance supercomputers to elucidate in greater detail charge-exchange reactions using the quantum theory of atomic collisions.

Clearly, primordial chunks of dirty ice still hold a few surprises for scientists.

—Arnie Heller

Key Words: charge exchange, comets, electron beam ion trap (EBIT), microcalorimeter, solar wind, x rays, x-ray spectrometer (XRS).

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