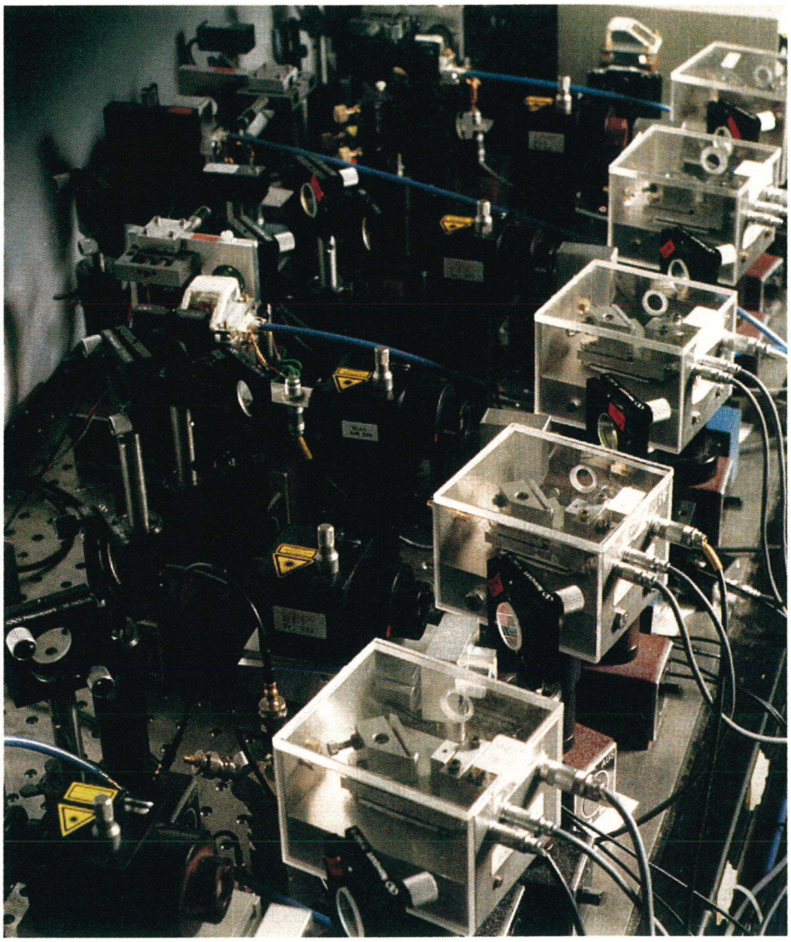

OPTICAL FREQUENCY-INTERVAL divider chain now used in Theodor Hänsch's Garching lab has replaced the large, expensive lasers of reference 1 with the small grating-stabilized diode lasers seen in the 10-cm-long lucite boxes arrayed at right.

ing experiments or by spectroscopy with muonic atoms.

In recent months the Garching group has succeeded in narrowing the 4 kHz of the published resonance curve on page 20 down to only 1 kHz. This they accomplished by chopping the laser illumination into pulses and then imposing a time delay that admits only the slowest hydrogen atoms in the beam. That selection minimizes both second-order Doppler broadening and the "transit broadening" dictated by the uncertainty principle. Hänsch and coworkers have also employed an electro-optic "comb generator" to convince themselves that the divider stages don't lose even a single optical cycle.[2]

Spreading the technique

"If Hänsch's technique can be made practical and portable, we'd be standing first in line to use it," says Kleppner. "But right now his laser chain is so big and complex that I don't know of any American lab that could reproduce it in the present funding climate. The US used to be in the forefront of atomic clock development. But with our declining support, the leadership has passed to Germany and France. Optical frequency research is a perfect example of a new technology being spawned by basic research."

A senior scientist at the US National Institute of Standards and Technology was recently overheard to say, "If anyone at NIST admitted he was setting out to do something as pure as testing QED, he'd be in trouble." But beyond its purely scientific value, the ability to measure optical frequencies to high precision should give us better atomic clocks for a myriad of practical applications. "With the 10^{10} Hz frequency of a cesium atomic clock," explains Hänsch, "you have to wait hours to get a Δt precision of 10^{-14}. But with a clock based on optical transitions, you could get 10^{-15} in one second."

"To make our new technique accessible to other labs," Hänsch told us, "we want to replace all our big, costly lasers with small, compact semiconductor diode lasers. We're already using such diodes in our latest frequency divider chain [see the photo above]. The special grating-stabilized diode lasers we've designed are now being marketed by a German firm."

BERTRAM SCHWARZSCHILD

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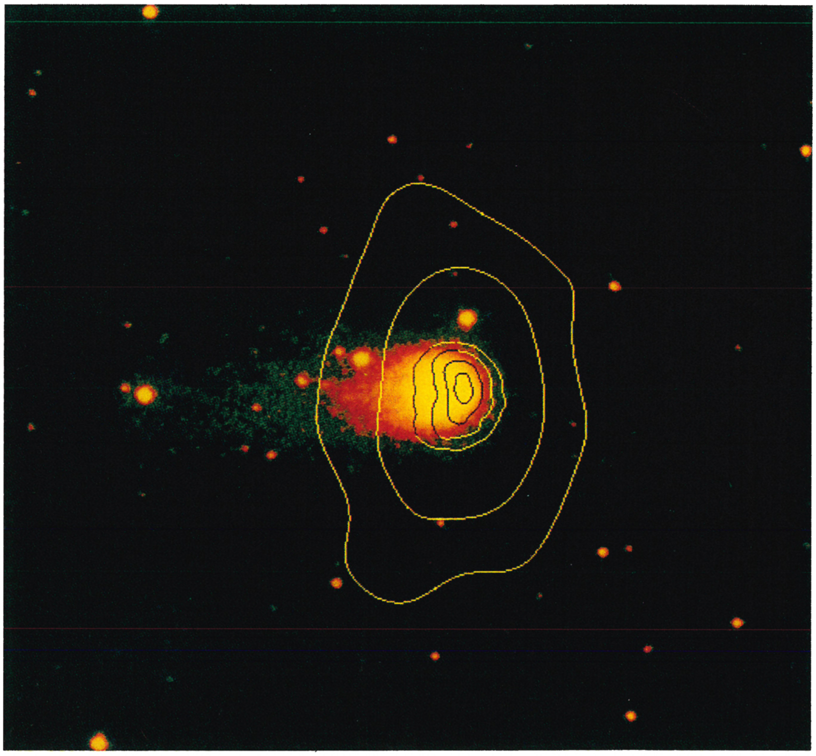
New Results Suggest X-Ray Emission Is a Common Property of Comets

> *The brandisht Sword of God before them blaz'd*
> *Fierce as a Comet; which with torrid heat,*
> *And vapour as the Libyan Air adust,*
> *Began to parch that Temperate Clime . . .*
> —J. Milton, *Paradise Lost*

Comets—dubbed "dirty snowballs" by comet guru Fred Whipple—are among the last celestial bodies you'd expect to emit x rays, which typically come from matter at least as hot as 10^6 K. But last year, to the surprise of astronomers, Carey Lisse (University of Maryland) and Mike Mumma (NASA's Goddard Space Flight Center) discovered faint x-ray emission from comet Hyakutake. They observed the photogenic comet with the ROSAT satellite as the comet flew by Earth in March 1996.[1] That same month, Mumma and Vladimir Krasnopolsky (Catholic University of America) detected the comet with the Extreme Ultraviolet Explorer (EUVE) satellite.[2]

Spurred by ROSAT's discovery, Konrad Dennerl, Jakob Englhauser and Joachim Trümper—all from the Max Planck Institute for Extraterrestrial Physics (MPE) in Garching, Germany—trawled through the archives of ROSAT's 1990–91 all-sky survey and came up with four more x-ray emitting comets, which ROSAT happened to catch in its field of view on seven separate occasions.[3] That's not all. Observing with EUVE, Mumma, Krasnopolsky and Mark Abbott (University of California, Berkeley) detected an additional three comets, including Hale–Bopp,[2,4] which Alan Owens (European Space Agency's space science department) and coworkers also detected with BeppoSAX. Together, these observations not only suggest that x-ray emission is a common cometary property, but also tighten the constraints on models of the emission.



COMET HYAKUTAKE, as observed on 28 March 1996 by ROSAT's High Resolution Imager and Wide Field Camera and by Konrad Dennerl's 35 mm camera. The contours trace the x-ray and extreme ultraviolet emission, whereas the false-color optical image shows the comet's coma—that is, its bright halo of gas and dust—against a starry background. The direction of the comet's motion is toward the bottom right of the figure. However, the halo is blown backward by the solar wind, making the comet look as though it's flying directly toward the Sun, which is off to the right of the figure. The fact that the emission region is symmetric about a line connecting the nucleus to the Sun and is localized between the nucleus and the Sun indicates that the cometary x rays are associated with the Sun's wind or radiation and with the comet's coma—rather than with its plasma and dust tails, which, if viewed with a big telescope instead of a 35 mm camera, would appear 50 times longer than shown here.

Haloes of that kidney

What are the characteristics of the emission? As exemplified by the comet in the adjacent figure, the x rays come from a kidney-shaped region about 10^6 km across that points from the nucleus of the comet towards the Sun. Significantly, the comet's plasma and dust tails are dark in x rays, suggesting that the emission arises from the interaction of the comet's coma (its halo of gas and dust) with the Sun's radiation or the solar wind.

How the x-ray emission behaves as the comet approaches the Sun is therefore a key question. The ROSAT observations, which sampled a range of orbital positions, led to the following findings:

▷ Comets are detectable by ROSAT only when they're closer than about 2 astronomical units from the Sun.

▷ When they're within 2 AU of the Sun, comets have x-ray luminosities in the range 10^{14}–10^{16} erg s^{-1}.

▷ For each comet, the ratio of x-ray luminosity to optical luminosity, L_x / L_{opt}, is roughly constant, but it varies from comet to comet. The L_x / L_{opt} ratio doesn't depend on the orbital position of the comet or the relative velocity of the solar wind with respect to the comet. Rather, it appears to depend on the mix of dust and gas: the dustier the comet, the lower the x-ray luminosity. At present, it's not clear why this is the case.

▷ The comet that was observed most extensively, Hyakutake, flared in x rays. Its flux shot up by a factor of 3–4 on a 1–2 hour timescale.[1] The more recently observed comet Encke also flared.

The other key observational ingredient is the spectrum. When Lisse and Mumma observed Hyakutake, they had to make do with ROSAT's two surviving instruments, the High Resolution Imager and the Wide Field Camera, each of which has only one spectral bin. Dennerl, however, could use data from the Position Sensitive Proportional Counter, which, before it ran out of gas in 1994, provided moderate spectral resolution over its 0.1–2.4 keV energy range.

Dennerl's brightest and best x-ray spectrum came from the comet known as C/1990 K1 (Levy). Its soft spectrum has a characteristic temperature—derived by fitting an optically thin thermal bremsstrahlung model—of around 2 million K. The data, however, are not good enough to pin down spectral models definitively.

The answer, my friend . . .

Can these observational findings be explained by a theoretical model? Last year, when proposing to look for cometary x rays, Lisse remembered a six-year-old paper[5] by Subhon Ibadov of the Institute of Astrophysics in Dushanbe, Tajikistan, and initially thought that colliding dust was responsible. Mumma, on the other hand, was first inspired by the discovery of energetic electrons in the coma of comet Halley. Both notions, however, were quickly ruled out by the observational evidence.

Also excluded by the evidence are models based on reprocessing x rays from the solar corona, which is the most copious source of x rays in the Solar System. Fortuitously, Dennerl's observations took place during solar maximum (when the Sun's x-ray output is greatest), whereas Lisse and Mumma's took place during solar minimum. Yet no systematic difference was found in the x-ray luminosity of comets between the two observing periods.

Of the current models still in the running, two tap energy from the solar wind, the high-speed outflow of electrons and ions from the Sun. Bob Bingham (University of Leicester) and coworkers,[6] Genady Milikh and Surjalal Sharma (University of Maryland) and Ted Northrop (Goddard Space Flight Center) and coworkers[7] have all proposed that solar wind electrons, accelerated near the comet in several possible ways, interact with the nuclei of atoms from the comet's coma. X rays in the form of bremsstrahlung could result. But to produce enough x rays, the electrons must be much more energetic than in the solar wind. An excess of high-energy electrons has indeed been observed—once by Konstantin Gringauz (Space Research Institute, Moscow) in comet Halley.[8] Northrop thinks this hump is large enough to fuel the x-ray emission. Krasnopolsky, however, disagrees.[9,10]

According to Tom Cravens (University of Kansas), it's the ions in the solar wind, not the electrons, that fuel cometary x-ray emission.[11] In his scheme, the x rays are the byproducts of charge exchange reactions between ions, such as O^{6+}, C^{5+}, N^{5+} and Si^{10+}, and neutral molecules and atoms from the cometary coma, such as H_2O, OH, O and H. Charge exchange occurs into discrete levels of the product ion, followed by the emission of an x-ray photon when the product ion de-excites. Consequently, the model predicts an x-ray spectrum made up of line emission—quite unlike the bremsstrahlung model, which predicts a smooth continuum.

Extending Cravens's research, two groups—one led by Roman Häberli (University of Michigan),[12] the other by Rudolf Wegmann (MPE)—have built models that include the magnetohydrodynamics of the comet–solar wind interaction. Their models can reproduce the overall shape of Dennerl's spectral data, which, unfortunately, lack the resolution to see the predicted lines. Another advantage: charge exchange models can comfortably produce the observed x-ray luminosities.

Unruly Sun

To explain the observations completely, the x-ray flaring has to be accounted for. Since no optical flares were seen at the same time (indicating that gas production in the coma was steady), sharp variations in the solar wind must be called into play. Such variations are not ruled out by observations, but the issue can be side-stepped by invoking a different model to supply the impulsive x rays. Hugh Hudson (University of Hawaii), who first attempted to observe x rays from a comet in 1980, proposed that the x-ray emission is powered by the comet's motion through the Sun's magnetic field.[13] As the comet proceeds, field lines drape around it, setting up currents whose stored energy, in principle, could be released gradually to fuel the steady emission or abruptly to fuel the flares. The difficulty with this idea lies in finding an actual mechanism to convert the electrical energy into x-ray photons. But it's attractive because comets cross what are known as sector boundaries. These are manifestations of the wobbly boundary surface between the outwardly and inwardly directed magnetic fields that characterize the two solar hemispheres.

Crossing the bar

In fact, comet Encke, which Lisse observed with ROSAT in July, did cross a sector boundary around the same time that an x-ray flare was observed. However, as yet, Encke's flare and boundary crossing haven't been conclusively tied to one another. And in the case of Hyakutake, the flare apparently occurred without a boundary crossing. It's possible that electron bremsstrahlung could be the source of the flaring.

Whichever model is correct, it appears that cometary x-ray emission will tell us at least as much about the solar wind as about comets themselves. In their deep, inclined orbits, comets plow through parts of the solar wind that spacecraft can't reach. By observing comets with the next generation of x-ray telescopes—Astro-E, the Advanced X-ray Astrophysics Facility and X-ray Multi-Mirror observatory—not only shall we be able to discriminate between the various models, but we may also be able to trace the composition and state of the solar wind in these remote regions.

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