Discovery of X-ray and Extreme Ultraviolet Emission from Comet C/Hyakutake 1996 B2
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During its close approach to Earth, comet C/Hyakutake 1996 B2 was observed at extreme ultraviolet and x-ray wavelengths with the Röntgen X-ray Satellite and Rossi X-ray Timing Explorer. The emission morphology was symmetric with respect to a vector from the comet's nucleus toward the sun, but not symmetric around the direction of motion of the comet with respect to interplanetary dust. A slowly varying emission and a large impulsive event that varied on time scales of 1 to 2 hours were observed. An interaction between the comet and the solar wind/solar magnetic field seems to be the most likely mechanism for the observed emission.

The close perigee [minimum geocentric distance $\Delta = 0.102$ AU (astronomical unit)] of the long-period comet C/Hyakutake 1996 B2 at universal time (UT) 25.3 March 1996 presented a unique opportunity to search for unusual and low luminosity phenomena in the comet. We searched for emission from the comet at wavelengths where cometary emission was unknown, in the x-ray, using the Röntgen X-ray Satellite (ROSAT) (1) high-resolution imager (HRI) and wide-field camera (WFC) (2), and using the Rossi X-ray Timing Explorer (XTE) proportional counter array (PCA) (3). Appreciable x-ray emission from an object is usually associated with the presence of a hot plasma, highly energetic particles, or with material optically thick enough to scatter x-rays from a nearby external source. We were motivated by the work of Ibadov (4), who predicted that x-rays should be generated by high-speed collisions between dust released by the comet and particles in the interplanetary dust (IPD) cloud, and by the observation of a large number of energetic electrons in the ionosphere of P/Halley during the 1986 flybys (5). Prior to our work, only comet Bradfield 1979X had been intentionally observed by an x-ray detector, the Einstein X-ray Observatory imaging proportion-al counter (IPC) (6); no emission was detected from this comet at a geocentric distance of 0.47 AU, with a 5$\sigma$ upper limit to the x-ray luminosity of $1.1 \times 10^{14}$ ergs s$^{-1}$ in the 0.2- to 4.0-keV bandpass (7).

Observations of x-rays in Hyakutake. Pre-perihelion, Hyakutake entered the ROSAT observing window (solar elongation from 75° to 105°) on UT 26 March 1996 and left it on UT 29 March 1996. We obtained 20 ks of time for ROSAT observations of Hyakutake, which took place during nine intervals between UT 26 to 28 March 1996 (Table 1). The HRI and WFC detected the comet in the 0.09- to 2.0-keV band against the instrumental and cosmic backgrounds. No detection of the comet was made by the PCA on UT 31 March 1996. WFC and HRI images (Fig. 1) were created by correcting the position of each photon for the motion of the comet across the field of view (FOV), and then smoothing the result using a 9 $\times$ 9 pixel gaussian filter (8). The HRI and WFC images show a similar pattern. The emission is clearly offset sunward in all images but one [this observation was of short duration and thus low signal to noise (S/N) (Table 1)], with a symmetry with respect to the sun-comet line, and an intensity that is variable on a time scale of 1 to 2 hours. This time scale is shorter than the 6.2-hour rotation period of the nucleus (9) and is also shorter than the minimum coma crossing time of $\approx$7 hours (assuming a gas velocity of 0.8 km s$^{-1}$) for material emitted by the nucleus. The viewing geometry was such that the sun-comet-Earth angle was close to 90°, so that foreshortening of the comet's tail was not important. Compared to optical emission from the comet, the x-ray and extreme ultraviolet (EUV) emissions are offset toward the sun. The spatial extent of the flux in the HRI and WFC images is about the same out of about 50% of the peak brightness in each image, though the low-level emission in the WFC images is more extended and can be traced out to $>200,000$ km from the nucleus in the brighter images (Fig. 2). The brightness centroid versus time for the x-ray emission is stable at $\approx 18,000$ km sunward of the nucleus and a few thousand km below the sun-comet line, while the intensity of the x-ray flux is variable (Figs. 3 and 4).

Light curves were produced from the HRI and WFC observations by counting all photons within an aperture of a 120,000-km radius [the aperture defined by the spatial extent of our HRI observation on UT 28.42 March (Fig. 4)]. The light curves show an impulsive cometary x-ray emission with up to 13 counts s$^{-1}$ and a variability on 1- to 2-hour time scales superimposed on a slowly varying level of emission at $\approx$4 counts s$^{-1}$. The WFC light curve is similar to the HRI, although the WFC emission appears softer during the UT 27 March outburst, suggest-

### Table 1. Observational geometry, exposure time, and observed counts.

| Observation time* | r (AU) | $\Delta$ (AU) | Exposure time (s) | HRI (Count/s)$\dagger$ | WFC (Count/s)$\dagger$ |
|-------------------|-------|----------------|-------------------|------------------------|------------------------|
| 26.52             | 1.017 | 0.109          | 2921              | 6.27                   | 0.113                  |
| 26.65             | 1.014 | 0.111          | 3009              | 8.93                   | 0.174                  |
| 26.71             | 1.013 | 0.112          | 2872              | 5.86                   | 0.00907                |
| 26.89             | 1.008 | 0.115          | 897               | 3.14                   | 0.0803                 |
| 27.571            | 0.994 | 0.125          | 2303              | 14.9                   | 0.444                  |
| 27.711            | 0.990 | 0.130          | 3009              | 11.0                   | 0.249                  |
| 27.781            | 0.989 | 0.131          | 2642              | 19.2                   | 0.554                  |
| 27.841            | 0.987 | 0.133          | 1556              | 16.1                   | 0.501                  |
| 28.431            | 0.975 | 0.146          | 1295              | 7.20                   | 0.138                  |
| 31.281            | 0.913 | 0.222          | 16                | N/A                    | N/A                    |

*Observation time for UT March 1996 in hours.  †Outburst.  ‡Count rates scaled for distance variations by $\Delta^{-2}$.  §March 31.28: PCA observation, count rate was < 10.5 counts/s (2 to 10 keV, 3σ upper limit).  ||March 26.71: High HRI noise. cuts times, low S/N.

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ing that two different emission mechanisms may produce the slowly varying and impulsive emission. Assuming an average photon energy of 0.25 keV in the HRI bandpass, the total luminosity \( L \) of the slowly varying emission is \( 4 \times 10^{33} \) ergs s\(^{-1}\), about 6000 times the luminosity of the moon as measured by ROSAT \( (10) \).

The PCA scanned across Hyakutake on UT 31.28 March 1996. Three of the five on-board detectors recorded the energy and time of each detected x-ray photon. No evidence for x-ray emission from the comet was seen, but upper limits were found for the high-energy tail of the x-ray emission \( (11, 12) \). A crude "spectrum" created by combining the HRI, WFC, and PCA photon count rates for the slowly varying emission from Hyakutake (Fig. 5) is consistent with thermal bremsstrahlung models with \( kT = 0.2 \) to 0.7 keV or with power-law models with \( dN/dE = E^{-\Gamma} \), where \( \Gamma = 2.2 \) to 2.5. An HRI flux due solely to fluorescent line emission does not fit the data \( (13) \).

Possible mechanisms for the cometary x-rays. One possible mechanism for the observed radiation is fluorescent scattering of solar x-rays by material in the comet's coma. This mechanism has been shown to be active on the moon \( (10) \) and would produce soft x-rays, consistent with the PCA upper limits. Assuming that the comet has a composition similar to the sun for atomic number \( Z > 2 \), then the bulk of the scattering should be produced by carbon atoms at an energy of 0.28 keV or oxygen atoms at an energy of 0.53 keV. The maximum emission seen in the HRI and WFC images is not at the nucleus, where the column density of carbon and oxygen is highest, but is displaced sunward. One possible explanation for the observed morphology is that we are observing an optically thick shell of material around the nucleus illuminated from the direction of the sun. The shell must be moving at a velocity of less than 0.02 km s\(^{-1}\) with respect to the nucleus in order to explain the lack of movement of the brightness centroid seen in the images, implying that the material was emitted more than 10 days before the observation period. The rapid variability seen on UT 27 March 1996 would be due not to changes in the density of material flowing sunward from the nucleus, but to rapid changes in the solar x-ray flux.

There are serious problems with this model. The mass of material required to reach an optical depth \( \tau = 1 \) in a shell of material with radius of 18,000 km is \( -1 \times 10^{15} \) g [assuming a photo-ionization cross section of \( 1 \times 10^{-18} \) cm\(^2\) per atom \( (14) \)]. Assuming a conservative density of 0.5 g cm\(^{-3}\) for the comet's nucleus, the total mass of the comet is \( 2 \times 10^{15} \) \( r_n^3 \) where \( r_n \) is the radius of the comet's nucleus in kilometers. The mass of material typically shed by comets throughout an apparition is

\[ 0.25 \text{ keV} \]

Fig. 2. Overlay of the UT 27.8 March 1996 HRI contours (green) and WFC contours (yellow) on a visible light image of the comet taken on UT 27.8 March 1996. The coordinate system is the same as in Fig. 1. The contour levels are 35, 50, 65, 80, and 95% of the peak HRI emission, and 10, 20, and 30% of the peak WFC flux.

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**Fig. 1.** Time series of (A) HRI 0.1 to 2.0 keV x-ray and (B) WFC 0.09 to 0.2 keV EUV images of Hyakutake on UT 26 to 28 March 1996 (Table 1). The images are in a reference frame moving with the comet's apparent sky position. The projected direction toward the sun and the orbital velocity of the comet are shown by arrows. The emission intensity has been autoscaled to the maximum level in each image to produce the highest contrast.
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ting the observations (9,18). Comparison of our HRI and WFC light curves with the solar x-ray flux measured by the Geostationary Observational Environmental Satellite--8 (GOES-8) satellite (19) shows no correlation—the solar x-ray flux is relatively low during the cometary x-ray outburst on UT 27 March 1996. Finally, the bulk of the observed x-rays should be in the carbon and oxygen lines, while the observed spectrum is consistent with continuum-dominated emission (Fig. 5).

A related mechanism, scattering of solar x-rays by arctrogram-size dust, has similar problems. Whereas the amount of mass required for this mechanism depends inversely on the Rayleigh scattering efficiency, which can be quite high, the expected morphology for the emission should be similar to that of dust particles in the coma and tail of the comet. The spectrum of the observed emission is similar to the solar continuum and should track the temporal behavior of the solar x-ray flux, unlike our observations.

A second possible mechanism is that high relative velocity impacts between cometary and the IPD create a soft x-ray-emitting plasma (4). Dust-dust collisions should produce an emission morphology symmetric about the velocity of the IPD particles with respect to the comet. Assuming that the bulk of the dust particles are moving at velocities similar to Earth's (that is, with small inclination to the ecliptic versus Hyakutake's large inclination of 124.9°), the velocity direction subtends an angle of ~25° with respect to the sun-comet direction. Since the maximum emission seen in the HRI images is not at the nucleus, but is displaced sunward from the maximum dust density in the comet, the cometary dust must be optically thick with respect to scattering by the IPD at 18,000 km. However, Ibadov (4) estimates that the region of the comet that is opaque to scattering by the IPD has a radius <100 km. Because the observed emission is stationary with respect to the nucleus, the rapid variability seen on UT 27 March 1996 must be due to changes in the density of the IPD on length scales of ~50 km s\(^{-1}\) * 1 hour = 180,000 km; the spatial structure of the IPD is poorly understood. Although the dust-dust mechanism produces a soft x-ray continuum similar to our observations, the predicted luminosity of \(7 \times 10^{35}\) erg s\(^{-1}\) is smaller than the \(4 \times 10^{35}\) ergs s\(^{-1}\) observed in the slowly varying emission. Another simple test of this mechanism was performed when we re-acquired the comet post-perihelion, on UT 22 to 23 June 1996. After perihelion, the orbital velocity of the comet shifts ~180° with respect to the sun-comet direction, and the offset of emission from the nucleus should also shift by ~180° if dust-dust collisions are the production mechanism. No shift was observed in the observed x-ray emission in June 1996.

A third possible mechanism is that the x-ray emission is derived from energy deposition by solar wind particles. In this model, the sunward position of the x-ray emission is due to the concentration of hot electrons between the comet's bowshock and contact surface (the boundary between the neutral coma and ionosphere). The position of the bowshock and contact surface in Hyakutake can be inferred from the P/Halley encounters, scaling the distances by the ratio of the production rates of gas in Hyakutake versus P/Halley (20). This ratio is ~5 and is accurate to within a factor of 2 (18). Using this method, Hyakutake's contact surface should be at ~100 km from the nucleus, the bowshock at ~100,000 km (5,21), and the x-ray emission should be located between the two (Fig. 2). The slight offset of the emission centroid below the sun-comet line by 5° may be due to the aberration of the solar wind by the comet's orbital velocity, about a 3° effect in the same direction. The rapid variability observed on UT 27 March 1996 may be explained as variations in the solar wind density; similar variations were seen in UV emission from the ionosphere of P/Halley (22). A large enhancement in the solar x-ray flux was observed by GOES 8 on UT 22 to 23 March 1996 (23); the arrival time for any particles associated with the outburst and moving at the 300 to 500 km s\(^{-1}\) velocity of the solar wind is 3.5 to 5.8 days later. Soft continuum x-rays would dominate the bremsstrahlung emission generated from the ~10^6 K solar wind ions, consistent with the PCA upper limits and continuum dominated emission seen in the HRI and WFC observations.

A related emission mechanism is disruption of the current flow in the cometary magnetosphere by sector boundary crossings or solar flares. The emission should be concentrated between the bowshock and ionosphere boundary, and have a maximum near the "magnetic pileup region", ~30,000 to 40,000 km sunward for Hyakutake (Fig. 2). Hudson et al. (6) have argued that the total magnetic energy stored in a comet is ~4 × 10^20 ergs. A third possibility is that the comet's bowshock and contact surface are offset from the comet's center of mass, due to the comet's diameter being small compared with its distance from the sun. However, this model is not consistent with the observed x-ray morphology.
10^{22} \text{ L}^1 \text{ ergs}, which can be disrupted on time scales of ~1000 s, for a total power output of ~4 \times 10^{16} \text{ L (ergs s}^{-1}, where L is the plasma tail length in 10^6 km). The microphysics of energy transfer and current disruption are, however, unclear. Assuming L = 18 \times 10 \text{ km (50° apparent length on the sky) and a conversion efficiency into bremsstrahlung of ~2 \times 10^{-6}, we can account for the observed slowly varying emission. A higher conversion efficiency or power is necessary to explain the rapidly varying emission of UT 27 March 1996. However, no large solar magnetic field changes or disconnection events in the tail of Hyakutake were observed UT 26 to 28 March 1996. Also, while we can expect large amounts of radio emission from large-scale disruptions of the comet's magnetosphere (24), Fernandez et al. (25) and Minter and Langston (26) have reported no detection of the comet to the few hundred millijansky (1 Jy = 10^{-26} \text{ W m}^{-2} \text{ Hz}^{-1}) level at 8.35 and 14.35 GHz on UT 26 to 27 March, 1996.

The major difficulty with the solar wind/magnetic field emission model is the lack of a plausible detailed emission mechanism. If one assumes thermal bremsstrahlung as the mechanism, then for T \sim 10^5 \sim 10^6 \text{ K, L}_e \sim 1 \times 10^{-23} N_e N_V, where N_e is the hot electron density, N_V the target ion density, and V is the volume of the emitting region. For the observed luminosity of ~4 \times 10^{15} \text{ erg s}^{-1}, and a spherical emission region with radius of 60,000 km, N_e N_V \sim 4 \times 10^8 \text{ cm}^{-6} (5, 22). Current models of ion density derived from the P/Halley encounters suggest ion and electron temperatures in this range, but have electron densities N_e \sim 10^{-100} \text{ cm}^{-3} and target densities N_V \sim 10^{-10} \text{ cm}^{-3} at distances scaled to the maximum of emission seen at Hyakutake. There is, however, enough uncertainty in our current understanding of the complex interaction between cometary ionospheres and the solar wind/magnetic field that regions of locally enhanced electron energy and density due to shock heating, Fermi acceleration, and magnetic field reconnection may exist (27, 28).

Other comets. Prompted by our discovery of x-ray emission from Hyakutake, Dennerl et al. (29) have searched the archive of the ROSAT x-ray all-sky survey, conducted in 1990–91 with the Position Sensitive Proportional Counter (PSPC) instrument (1). This search has resulted in the discovery of x-ray emission from comets C/1984 X1-Kicchi, C/1985 X1-Cheyne, C/1985 X2-Arai, C/1985 X4-Keil, and C/1986 T2-Aschenbach. We have assumed that the emission from the comet had the same physical size as the ROSAT observation.

10. A 90% confidence upper limit of 4.5 cps was calculated by adding 1.645 times the standard deviation of the average count rate for other 16-20 intervals (1.38 cps), and thus includes variations due to fluctuations of the x-ray sky. Similarly, the 90% confidence limit for the 10 to 15 keV band is 1.54 cps. 3-\alpha upper limits were then calculated from the 90% confidence limit values by assuming a gaussian behavior and multiplying by a factor of 0.01/2.8.

In this case the HRI/FOV count rate ratio would be >3000, while the observed ratio is <50.

11. The closest approach of the comet to the solar system is about 0.127 AU. Ultraviolet bremsstrahlung fits to the data with plasma temperature KT = 0.2 (open triangles), 0.4 (crosses), and 0.7 keV (open diamonds). Power-law fits to the data with photon index Γ = 2.2 (open circles) and 2.5 (X's). All models have been scaled to a rate of 4 HRI counts/s.

REFERENCES AND NOTES

1. J. Trümper, Adv. Space. Res. 2, 241 (1983).
2. J. H. M. M. Schmitt, ibid, 11, 125 (1991). The ROSAT HRI is a microchannel plate detector coupled to a grazing incidence telescope with an effective area of ~20 cm^2 at 0.1 to 2.0 keV, a circular FOV of 38° in diameter, and an angular resolution of 6 inches HEW (half-energy width) (1, 2). Coarse pulse height discrimination is used to distinguish UV sources from x-ray emitting objects. The ROSAT WFC has three concentric gold-plated mirrors coupled to a curved microchannel plate at the focal plane, providing a circular FOV of 5° in diameter with an angular resolution of 2° HEW (M. R. Simms et al., Opt. Eng. 29, 649 (1990) and J. P. Pye et al., Mon. Not. R. Astron. Soc. 274, 1165, (1996)). All of our WFC observations were obtained with the 51A filter, with a nominal bandpass at 10% of peak effective area of 90 to 205 eV and an on-axis effective area of ~1 cm^2. Lack of contamination from UV red leaks (wavelength >1000 Å) has been verified by tests of the mirror response from the bright OS star Vega at a 90% confidence upper limit of 5 \times 10^{-4} counts s^{-1}. The optical axis of the HRI and the WFC are co-aligned to within 10°, providing similar areal coverage in the EUV and x-ray. The backgrounds in both instruments are dominated by particles, and must be removed by modeling (I. L. Snowden, personal communication and R. G. West, Thesis, University of Leicester (1993)).

24. Another efficient production mechanism for radio frequency emission associated with x-ray luminous objects, synchrotron emission, is unimportant since \nu_{\text{sync}} \sim B^2 and cometary magnetic fields are
An αβ T Cell Receptor Structure at 2.5 Å and Its Orientation in the TCR-MHC Complex

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The central event in the cellular immune response to invading microorganisms is the specific recognition of foreign peptides bound to major histocompatibility complex (MHC) molecules by the αβ T cell receptor (TCR). The x-ray structure of the complete extracellular fragment of a glycosylated αβ TCR was determined at 2.5 Å angstroms, and its orientation bound to a class I MHC-peptide (pMHC) complex was elucidated from crystals of the TCR-pMHC complex. The TCR resembles an antibody in the variable Vα and Vβ domains but deviates in the constant Cα domain and in the interdomain pairing of Cα with Cβ. Four of seven possible asparagine-linked glycosylation sites have ordered carbohydrate moieties, one of which lies in the Cα-Cβ interface. The TCR combining site is relatively flat except for a deep hydrophobic cavity between the hypervariable CDR3s (complementarity-determining regions) of the α and β chains. The 2C TCR covers the class I MHC H-2K^b binding groove so that the Vα CDRs 1 and 2 are positioned over the amino-terminal region of the bound dEV8 peptide, the Vβ chain CDRs 1 and 2 are over the carboxyl-terminal region of the peptide, and the Vα and Vβ CDR3s straddle the peptide between the helices around the central position of the peptide.

Lymphocytes respond to a wide variety of foreign antigens that are presented as peptides in the context of major histocompatibility molecules (MHC) (1). Specific recognition of peptide-MHC (pMHC) complexes is accomplished by a membrane-bound, multicomponent, cell surface glycoprotein termed the T cell receptor (TCR). The TCR complex consists of highly diverse, clonotypic αβ or γδ heterodimers and the γ, δ, ε, and ξ chains of the invariant accessory protein complex CD3 (2). The α and β chains participate in the interaction with the pMHC complex, whereas the CD3 chains participate in signal transduction. The genes encoding the TCR resemble immunoglobulin (Ig) genes not only in sequence, but in their assembly by somatic rearrangement of linked variable (V), diversity (D), joining (J), and constant (C) gene segments during lymphocyte development (3, 4). The formation of functional α chain polypeptide requires the in-frame rearrangement of a V-region gene segment to a J-region gene segment, whereas functional β chain polypeptide is formed by two successive rearrangements of V-, D-, and J-region gene elements (5). The rearranged V-J and V-D-J regions are then attached to their respective C regions to assemble the mature α and β chain gene products. A vast number of potential protein sequences can result from these recombinations (4), as with Igs. Although not as striking as in Igs, four regions of hypervariable amino acid sequence are found on both the α and β chains, three of which are analogous to the antibody complementarity-determining regions (CDRs) (6), which serve as the primary contact points between antibody and antigen (7). Both CDRs 1 and 2 are encoded within the V genes; CDR3 occurs at the V-J junction in the α chain and at the V-D-J junction in the β chain (4).

The high degree of sequence identity between various V and C elements of TCRs and Igs (30 to 70 percent) suggested that TCR domains are folded into β-sheet sandwich structures (8, 9), resembling Ig domains (10), that would pair in a manner similar to the heavy (H) and light (L) chains of antibodies. However, the recognition requirements of a TCR are more restricted than that of an antibody. Antibodies can bind ligands of extensive chemical and structural diversity, as reflected in the different shapes of antibody combining sites, from flat surfaces to deep grooves (7). The function of the TCR is to discriminate among different peptide antigens embedded in the largely flat, undulating surfaces of MHC molecules, whose dimensions and shape are relatively constant. Therefore, a more conserved binding site topology among different TCRs could be expected. Limited sequence diversity of the CDRs 1 and 2 suggested that most of the peptide specificity of the TCR would reside in CDR3, which is the most variable because of the junctional diversity of the V(D)J recombination (4). Site-directed mutagenesis studies confirmed that substitutions in CDR3 can either alter antigen specificity or abolish the response (11). Various models have been proposed for TCR recognition of pMHC in which the CDR3s of Vα and Vβ contact the peptide, whereas CDRs 1 and 2 interact primarily with the MHC α helices (4, 12, 13) or the ends of the peptide (14).

The x-ray structures of an individual TCR β chain from a T cell clone termed 14.3.d (15) and an isolated Vα fragment from a T cell clone termed 1934.4 (16) have confirmed that the TCR does indeed contain Ig-like domains. The Vα and Vβ domains resemble a v-type lq fold (17), whereas Cβ more distantly resembles a c-type lq fold (17). The monomeric β chain was proposed to be rather rigid because of extensive contacts between Vβ and Cβ, and a large protruding loop from Cβ that might limit "elbow" motion between Vβ and Cβ domains (15). Both CDRs 1 and 2 appear to be conformationally restricted by main-chain interactions with framework residues but, in the absence of the buttressing effect of their respective α and β chains, the CDR3s fold away from the domain surface toward the solvent.

The absence of a TCR αβ heterodimer crystal structure until now has been due to difficulties in producing large quantities of...