X-RAY EMISSION FROM COMET HALE–BOPP

C. M. LISSE
University of Maryland, Department of Astronomy, College Park, MD 20742
Tel.: (301) 405-1563; Fax: (301) 314-9067, USA; E-mail: lisse@astro.umd.edu

K. DENNERL, J. ENGLHAUSER and J. TRÜMPER
Max-Planck-Institut für extraterrestrische Physik, Postfach 1603, 85740 Garching, Germany

F. E. MARSHALL, R. PETRE and A. VALINIA
NASA/Goddard Spaceflight Center, Code 666, Greenbelt, MD 20771, USA

B. J. KELLETT and R. BINGHAM
Space Science Department, Rutherford Appelton Laboratory, Chilton, OX11 0QX, UK

(Received 16 February 1998; Accepted 16 September 1998)

Abstract. The discovery of X-ray emission from comets has created a number of questions about the physical mechanism producing the radiation. There are now a variety of explanations for the emission, from thermal bremsstrahlung of electrons off neutrals or dust, to charge exchange induced emission from solar wind ions, to scattering of solar X-rays from attogram dust, to reconnection of solar magnetic field lines. In an effort to understand this new phenomenon, we observed but failed to detect in the X-ray the very dusty and active comet C/Hale–Bopp 1995 O1 over a two year period, September 1996 to December 1997, using the ROSAT HRI imaging photometer at 0.1–2.0 keV and the ASCA SIS imaging spectrometer at 0.5–10.0 keV. The results of our Hale–Bopp non-detections, when combined with spectroscopic imaging 0.08–1.0 keV observations of the comet by EUVE and BeppoSAX, show that the emission has the same spectral shape and strong variability seen in other comets. Comparison of the ROSAT photometry of the comet to our ROSAT database of 8 comets strongly suggests that the overall X-ray faintness of the comet was due to an emission mechanism coupled to gas, and not dust, in the comet's coma.

Keywords: Comets: individual, X-rays: solar system

1. Introduction

Since the discovery of X-ray emission from comet C/Hyakutake (1996B2; Lisse et al., 1996), a total of 10 comets have been detected in X-rays. Dennerl et al. (1997) and Lisse et al. (1999) have reported the detection of C/Levy (1990K1), C/Tsuchiya-Kiuchi (1990N1), 45P/Honda–Mrkos–Padjusakova 1990 (P/HMP) and C/Arai (1991A2) using slews from the ROSAT PSPC 0.1–2.0 keV All Sky Survey and C/Tabur (1996Q1), C/Hale–Bopp (1995O1), and P/Encke 1997 using HRI/WFC pointings at 0.09–2 keV. A second light curve similar to Hyakutake's was found for P/Encke with a steady state emission of ~ 0.15 counts/s^{-1} and an impulsive jump to ~ 0.6 cps which decayed with a time constant of 3 hours, and a strong correlation with the solar wind magnetic field and flux, but not with

Earth, Moon and Planets **77:** 283–291, 1999.

the solar X-ray light curve. Mumma et al. (1997) have reported the detection of soft X-ray continuum emission from comets Hyakutake, Hale–Bopp, and d'Arrest using measurements of the continuum in the EUVE DS spectrometers from 0.10–0.17 keV; the measurements are in good agreement with the ROSAT results. Non-detections by our group of comets C/Hyakutake, C/Tabur, C/Hale–Bopp, and P/Temple–Tuttle 1998 using the XTE PCA (2–30 keV) and ASCA SIS (0.6–4 keV) imaging spectrometers hint at the extreme softness of the emitted spectrum.

Except for the puzzling non-detection of comet C/Bradfield 1979Y1 by the Einstein Observatory (in 2.5 ksec of integration time at r = 1.1 AU, Δ = 0.44 AU; Hudson et al., 1981), all comets observed within 2 AU of the Sun and brighter than $V \sim 12$ have been detected, suggesting that X-ray emission is a property of all comets. Comparison of all these detections is beginning to reveal a consistent picture : the X-ray emission is confined to the cometary coma between the nucleus and the Sun in a region 10^4–10^6 km in extent, is not correlated with extended dust or plasma tails, and is symmetrically distributed around the Sun-nucleus line; the spectrum is very soft (kT $\sim$ 0.3 keV) with at most a few % C (0.28 keV) or O (0.53 keV) K-shell line emission, not due to scattering or resonance fluorescence or dust-dust impacts; the emission is composed of both steady state and impulsive components (maximum flux $\sim$3–4 times that of the steady state emission, with rise and fall times on the order of a few hours, occurring $\sim$25% of the time), and is not correlated in time with the solar X-ray flux.

2. Observations of Comet Hale–Bopp

Given that we were beginning to put together a coherent picture of cometary X-ray emission via charge exchange between solar wind minor heavy ions and cometary neutrals, the observational results from comet Hale–Bopp were quite surprising. Our ROSAT and ASCA monitoring observations of the comet over the course of two years (twice in September 1996, once each in September, October, and December 1997) have consistently shown no detection for this bright comet; e.g., in 11 ksec of integration on September 19, 1996, with the comet at r = 3.0 AU, Δ = 2.9 AU, we derive a ROSAT signal of 0.22 $\pm$ 0.15 cps, corresponding to a 3 sigma upper limit luminosity of $L_x = 2 \times 10^{15}$ erg s^{-1} in the HRI passband. No detection was found using 20 ksec of ASCA time on September 25, 1996, but useful upper limits in the 0.5 to 1.0, 1.0 to 2.0, and 2.0 to 10.0 keV bands were obtained. While the 0.5–1.0 limit of 4×10^{-3} cps seems tantalizingly close to a detection, there is no obvious source in our images, and the comet's signal is confused with the faint sky background.

Krasnopolsky et al. (1997) reported the detection of soft X-ray continuum emission from comet Hale–Bopp on September 14–16, 1996 using measurements of the continuum in the EUVE DS spectrometers at 0.10–0.17 keV. The morphology of the emission was found to be very asymmetric with respect to the Sun-nucleus line,

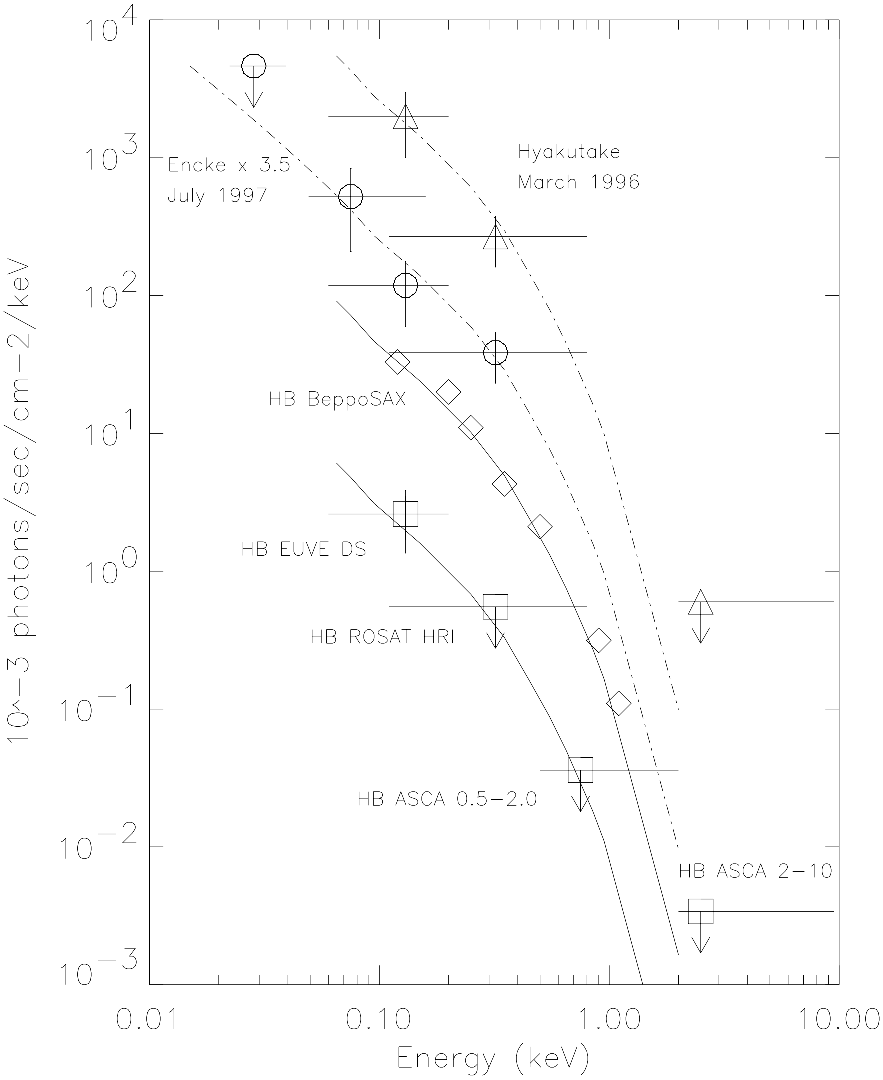

Figure 1. Folded spectra of the x-ray emission from Comet Hale–Bopp. ◇, BeppoSAX LECS measurements on September 10–11, 1996 (Owens et al., 1998). □, EUVE DS spectrometer measurements on September 14–20, 1996 (Krasnopolsky et al., 1997); ROSAT HRI measurements on Sept. 19, 1996; and ASCA 0.5–1.0, 1.0–2.0, and 2.0–10.0 keV upper limits on September 25, 1996. △, ROSAT and XTE March 1996 C/Hyakutake results (Lisse et al., 1996). ○, ROSAT and EUVE July 1997 P/Encke results, multiplied by a factor of 3.5 for clarity (Lisse et al., 1999). Curves, 0.29 keV thermal bremsstrahlung emission models scaled to the data.

concentrated in the NW sector of the image with a maximum at $\sim 1 \times 10^5$ km from the nucleus, and anti-correlated with dust jets observed in the optical, with a total X-ray luminosity $L_x = 2 \times 10^{15}$ erg s^{-1} (using an average in-band photon energy = 0.14 keV). Owens et al. (1998) have recently reported a BeppoSAX detection at 0.1–2.0 keV of the comet using the LECS spectrometer on September 10–11, 1996. While the imaging quality of the instrument is very poor, the observed morphology seems in rough agreement with the EUVE result, although a total X-ray luminosity of $L_x = 2 \times 10^{16}$ erg s^{-1}, 10 times larger than the EUVE result, was found, with a decaying intensity falling exponentially with a 9.3 hour time constant.

The September 1996 spectral results for Hale–Bopp are summarized in Figure 1. The BeppoSAX spectral shape is consistent with the EUVE/ROSAT/ASCA Hale–Bopp results, and our previously measured spectra of Comet Hyakutake; both are well fit by an 0.29 keV thermal bremsstrahlung model, and are poorly fit by an E^{-5} power law, as expected for scattering from attogram dust (Krasnopolsky, 1998). The lack of detection of the comet by ROSAT and ASCA is expected, given the faintness of the EUVE steady-state emission and the ROSAT and ASCA instrument sensitivities. The difference in intensity of the EUVE and BeppoSAX observations is most likely due to an impulsive x-ray emission event on September 10–12, 1996; this is consistent with the BeppoSAX 9.3 hour decay time light curve observed by Owens et al. (1998).

3. Discussion

Since a direct correlation was found between the impulsive X-ray emission and elevated solar wind density/magnetic fields for comet 2P/Encke 1997 (Lisse et al., 1999), we searched the data archives of the solar wind monitoring spacecraft for a large change in the solar wind. Using the SOHO data of R. Lepping (1998; found at URL http://cdaweb.gsfc.nasa.gov/cdaweb/istp_public/), we found increased levels of solar wind flux, velocity, and a rotation of the solar wind velocity vector, all characteristic of a solar wind sector boundary crossing at the Earth on September 8.9–11.2, 1996 (Figure 2). But could such a crossing at the Earth explain a near-simultaneous X-ray outburst at the comet, almost 3 AU away? A simple model of the solar wind sector boundary assumes a current sheet symmetric in heliographic latitude with propagation of the boundary due to solar rotation and solar wind radial outflow such that

$$\Delta t_{\mathrm{Total}} = \Delta t_{\mathrm{CR}} + \Delta t_r,$$

where Δt_{CR} is the time difference due to rotation of the Carrington Spiral, $(\mathrm{longitude}_{\mathrm{comet}} - \mathrm{longitude}_{\mathrm{earth}})/14.7^\circ$ day^{-1}; Δt_r is the time difference due to propagation of the boundary radially outward from the Sun, $(r_{\mathrm{comet}} - r_{\mathrm{earth}})/0.35$ AU day^{-1}; $\Delta t_{\mathrm{total}}$ is the total time difference expected between the

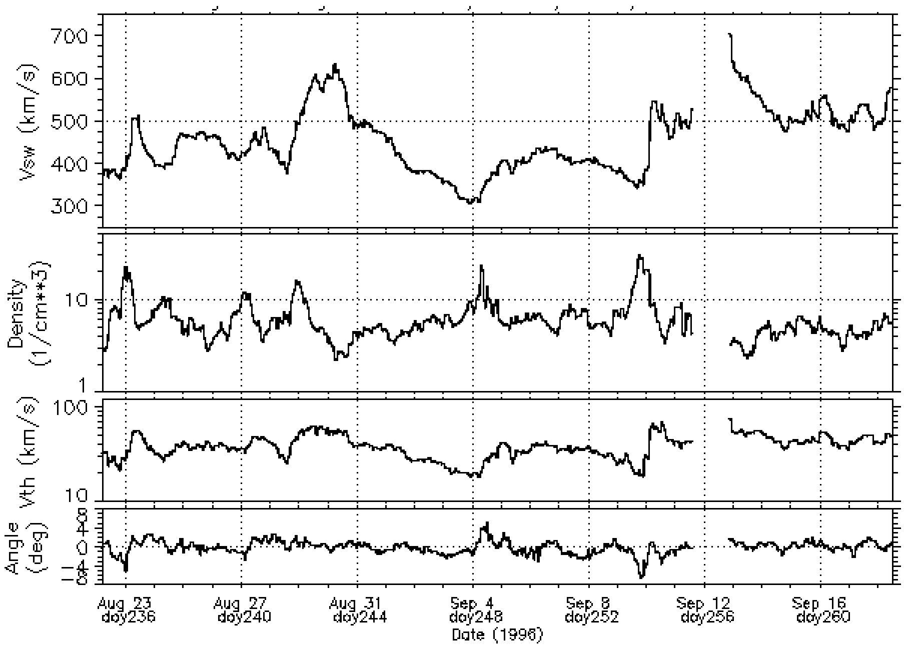

Figure 2. Solar wind velocity, density, thermal velocity, and angle versus time (in days) as measured by the SOHO spacecraft, 23 August September 1996 00:00 UT to 19 September 1996 00:00 UT. There is a clear signature of a sector boundary crossing in all 4 quantities, starting on 9 September 1996.

sector boundary crossing at the comet vs at the Earth, the longitudes and radial distances are heliographic, and we have assumed an average solar wind radial speed of 600 $\pm$ 100 km/sec with respect to the comet (Figure 2).

The Δt_{total} calculated using this model for Hale–Bopp is +1.4 $\pm$ 1.0 days; i.e., the sector boundary crossing should occur at the comet approximately 36 hours after it reaches Earth, on September 10.5–12.5, in reasonable agreement with the lightcurve results of Owens et al. (1998), the faint EUVE detection of September 14–20, 1996, and our ROSAT non-detection of September 19, 1996. The uncertainty in Δt_{Total} is dominated by the poorly known solar wind velocity at the comet's moderately high +22° heliographic latitude; it is known, however, from recent Ulysses measurements that this velocity increases monotonically with heliographic latitude from the minimum value measured at the heliographic equator (i.e., at the Earth and SOHO; Neugebauer et al., 1998). We also have confidence in this model since it gave excellent results for our extensive X-ray light curve measurements of comet P/Encke 1997 (Lisse et al., 1999).

For such an active and bright comet, we also found the faintness of the steady-state X-ray emission from Hale–Bopp in our ROSAT observations puzzling. A possible solution to this problem was found by Dennerl et al. (1997) in their intercomparison of the steady-state X-ray and optical luminosities for 6 ROSAT

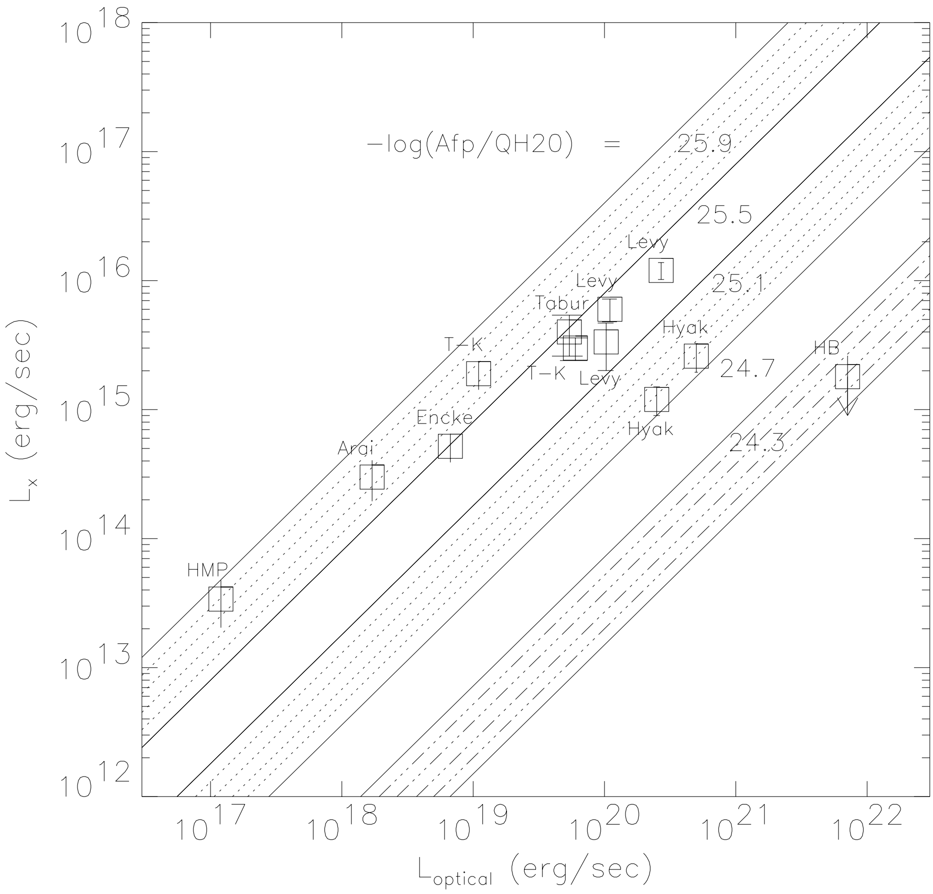

Figure 3. Steady-state X-ray vs. optical luminosity for the 8 comets detected by ROSAT, following Dennerl et al. (1997). If we assume $L_x \propto Q_{\mathrm{gas}}$ and $L_{\mathrm{opt.}} \propto (Q_{\mathrm{dust}} \times \sigma_{\mathrm{dust}} + Q_{gas} \times \sigma_{gas})$, where σ is the cross section for scattering sunlight, then we expect $L_x/L_{\mathrm{opt.}} \propto (\sigma_{\mathrm{dust}} \times (D/G) + \sigma_{\mathrm{gas}})^{-1}$, and an anti-correlation of L_x vs. D/G ratio, as is found.

comets: $L_x \sim L_{\mathrm{optical}}$, as long as the comet's dust-to-gas ratio was constant; for higher values of dust-to-gas, the x-ray emission is attenuated versus the optical. A major advantage of this comparison is that each comet was observed by the same instrument with the same sensitivity and field of view. In Figure 3, we have updated the plot of L_x vs. L_{optical} with our more extensive results for the very dusty comet Hale–Bopp and the very dust-poor comet P/Encke (log (Afρ/Q_{OH}) = −26.4). One of the key findings for comet Hale–Bopp was that despite its normal composition (Schleicher et al., private communication), it was an incredibly dusty comet (Jewitt and Matthew, 1999; Lisse et al., 1997–1999), with log(Afρ/Q_{OH}) = −24.3. Encke clearly lies near the trend line for dust-poor comets, while Hale–Bopp is clearly seen to be an outlier compared to the other comets; the anti-correlation with L_x and Afρ/Q_{OH} is quite clear. On the other hand, Hale–Bopp's measured X-ray

TABLE I

Testable theoretical predictions. References: e-Neutral, Bingham et al.; Northrop et al.; Uchida et al.; Charge Transfer, Cravens et al.; Haeberli et al.; Wegmann et al.; Magnetic Reconnection, Brandt et al.; Hudson et al.; Mendis et al.; Attogram Dust, Wickramasinghe and Hoyle; Krasnopolsky. [N.B. : brem = bremsstrahlung model; hyb = hybrid wave model; v_{comet} = comet velocity; B = magnetic field; L = length of plasma tail; SW = solar wind ion flux, Q_x = solar xray flux; Q_{gas} = comet gas production rate; Q_{dust} = comet dust production rate.]

Observable	Theory			
	e-Neutral	Charge transfer	Magnetic reconnection	Attogram dust
Variation wrt:				
r, helioc. distance	r^{-2}	r^{-2}	r^{-0}	r^{-2}
Q_{dust}, Q_{dust} $B_{SW}(t)$	$Q_{gas}^2 \cdot B_{SW}(t)$	$Q_{gas} \cdot \mathrm{SW}(t)$	$L^3 \cdot B_{SW}^2(t)$	Q_{dust}
Spectrum				
Soft/hard	Soft, kT ∼ 0.3 keV	Soft brems.?	Power law?	Bluened solar
Line/continuum	Continuum	Lines	Continuum?	Solar
Spatial structure				
Total extent	$\sim 10^5$ km	$\sim 10^6$ km	$\sim 10^5$ km	Dust coma
X-ray/EUV Hardness (Color) map	increases towards comet	decreases towards comet	maximum at maximum mag field	increases towards comet
Size of emitting regions	$>10^3$ km	$>10^5$ km	$>10^4$ km?	$>10^5$ km
Temporal signature				
Stochastic Stochastic/steady	$\mathrm{SW}(t) \cdot Q_{gas} \cdot B_{SW}(t)$	$\mathrm{SW}(t) \cdot Q_{gas}$	$f(B_{SW}(t), v_{comet})$	$Q_x \cdot Q_{dust}$

luminosity and gas production rate ($Q_{OH} = 2 \times 10^{29}$ molecules s^{-1}) were quite close to C/Hyakutake's at perigee in March 1996, strongly suggesting the emission depends on the gas production rate.

4. Conclusions

A number of theories have been created to explain the emission: from thermal bremsstrahlung of electrons off neutrals or dust, to charge exchange induced emission from solar wind ions, to scattering of solar X-rays from attogram dust in the comet's coma, to reconnection of solar magnetic field lines (Table I). While all of the proposed mechanisms have in common an interaction between the Sun and the comet as the source of the observed X-rays/EUV, they vary in their prediction for the details of the emission spectrum, spatial hardness distribution, and temporal behavior. For example, the charge exchange models of Cravens (1996) and Wegmann et al. (1998) predict multiple emission lines and an X-ray hardness maximum at the sunward edge of the emission; while the bremsstrahlung models of Bingham et al. (1996) and Northrop et al. (1997) predict a smooth continuum, with hardness maximum near the middle of the spatial distribution.

Assuming all the observational data to be valid, the results on Comet Hale–Bopp can help us narrow down the possible dominant emission mechanisms. Since the spectral shape of the emission appears similar between Hale–Bopp and other comets (Figure 1), we conclude that the same mechanism(s) are active for all comets. Since the ROSAT emission luminosity anti-correlates with cometary dust-to-gas ratio (Figure 3), we conclude that the emission is not produced by interactions with cometary dust, and may even be attenuated by the presence of dust (hence the unusual asymmetric X-ray emission morphology and spatial anti-correlation between the optical continuum and EUVE X-ray images presented in Krasnopolsky et al. (1997)); thus scattering by attogram dust or the more exotic plasma-dust interaction mechanism proposed by Ip and Chow (1997) cannot be the cause of the emission. A scattering mechanism is further ruled out by the lack of correlation between the C/Hyakutake and P/Encke X-ray light curves and the solar X-ray light curve (Lisse et al., 1999), and explanation of the temporal variations of Hale–Bopp's emission as due to a solar wind sector boundary crossing the comet (Figure 2). We are thus left with either electron bremsstrahlung, charge exchange between highly ionized solar wind species and cometary neutrals, or magnetic reconnection as the three most plausible emission mechanisms.

References

Bingham, R., et al.: 1997, 'The Generation of X-Rays From C/Hyakutake 1996B2', *Science* **275**, 49.

Brandt, J., Lisse, C. M., and Yi, Y.: 1996, 'Small Current Sheets in the Solar Wind as the Cause of X-Ray Emission in Comets', *BAAS* **189** (25.05).

Cravens, T. E.: 1997, 'Comet Hyakutake X-Ray Source : Charge Transfer of Solar Wind Heavy Ions', *GRL* **24**, 105.

Dennerl, K. et al.: 1997, 'X-Ray Emissions from Comets Detected in the Roentgen X-Ray Satellite All-Sky Survey', *Science* **277**, 1623.

Haeberli, R. M. et al.: 1997, 'Modeling of Cometary X-Rays Caused by Solar Wind Minor Ions', *Science* **276**, 939.

Hudson, H. S., Ip, W.-H., and Mendis, D. A.: 1981, 'An Einstein Search for X-Ray Emission from Comet Bradfield 1979L', *Planet. Space Sci.* **29**, 1373.

Ibadov, S.: 1990, 'On the Efficiency of Generation of Short-Wave Radiation in Impacts of Cometary and Zodiacal Dust Particles', *Icarus* **86**, 283.

Ip, W.-H. and Chow, V. W.: 1997, 'NOTE: On Hypervelocity Impact Phenomena of Microdust and Nano X-Ray Flares in Cometary Comae', *Icarus* **130**, 217.

Jewitt, H. and Matthews, H.: 1999, 'Particulate Mass Loss from Comet Hale–Bopp', *Astron. J.* **117**, 1056–1062.

Krasnopolsky, V. A. et al.: 1997, 'Discovery of Soft X-Rays from Comet Hale–Bopp Using EUVE', *Science* **277**, 1488.

Krasnopolsky, V. A. : 1998, 'Excitation of X-Rays in Comet Hyakutake (C/1996 B2)', *JGR* **103**, 2069.

Lisse, C. M. et al.: 1996, 'Discovery of X-Ray and Extreme Ultraviolet Emission from Comet Hyakutake C/1996 B2', *Science* **274**, 205.

Lisse, C. M. et al.: 1999, 'X-Ray and Extreme Ultraviolet Emission from Comet P/Encke 1997', *Icarus* **140**, in press.

Lisse, C. M. et al.: 1997–1999, 'Infrared Observations of the Dust Emitted by Comet Hale–Bopp', *Earth, Moon, and Planets* **78**, in press.

Mumma, M. J. et al.: 1997, 'Soft X-Rays from Four Comets Observed by EUVE', *ApJ Letters* **491**, L125.

Neugebauer, M. et al.: 1998, 'Spatial Structure of the Solar Wind and Comparisons with Solar Data and Models', *JGR* **103**, 14587.

Northrop, T. G. et al.: 1997, 'A Possible Source of the X-Rays from Comet Hyakutake', *Icarus* **127**, 246.

Owens, A. et al.: 1998, 'Evidence for Dust-Related X-Ray Emission from Comet C/1995 O1 (Hale–Bopp)', *ApJ Letters* **493**, L47.

Uchida, M.. et al.: 1998, 'X-Ray Spectra of Comets', *Ap J* **498**, 863

Wegmann, R. et al.: 1998, 'X-Rays from Comets Generated by Energetic Solar Wind Particles', *Planetary and Space Science* **46**, 603.