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EUVE Search for X-rays from Comets Encke, Mueller (C/1993 A1), Borrelly, and Postperihelion Hale–Bopp

Vladimir A. Krasnopolsky

Catholic University of America, Washington, D.C. 20064
E-mail: vkrasn@altavista.com

Michael J. Mumma

NASA Goddard Space Flight Center, Greenbelt, Maryland

and

Mark J. Abbott

Center for EUV Astrophysics, Berkeley, California

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Our observation of postperihelion Hale–Bopp on November 17–23, 1997, revealed the comet soft X-ray luminosity of $(3.7 \pm 1.2) \times 10^{24}$ photons s^{-1} in an aperture of 6×10^5 km and in the EUVE range of 97–165 eV. We also analyzed observations of three comets from the EUVE archive. The X-ray luminosity of Comet Borrelly on November 20–22, 1994, was $(7.5 \pm 0.6) \times 10^{23}$ photons s^{-1} for the aperture of $\rho = 7 \times 10^4$ km. Upper limits of 2.7×10^{23} and 1.4×10^{24} photons s^{-1} were obtained for Comets Encke and Mueller (C/1993 A1) on November 30, 1993, and June 9–11, 1994, for $\rho = 1.7 \times 10^5$ and 4.1×10^5 km, respectively. This work has doubled the number of comet observations in our EUVE database. Soft X-ray emissions have been detected in five of the eight observations. The measured X-ray luminocities are consistent with a $r^{3/2} Q_{gas}$ dependence having the efficiency of $(6.4 \pm 0.9) \times 10^{-5}$ $AU^{3/2}$ and therefore favors a gas-related mechanism. The only viable candidate is the charge transfer mechanism. Using our X-ray luminosities as functions of aperture and assuming the presentation of the charge transfer spectrum by thermal bremsstrahlung or the power law, it is possible to make careful comparison of X-ray observations made with different instruments. While both our pre- and postperihelion observations of Hale–Bopp demonstrate a regular behavior of X-rays from that comet, the outburst detected with the BeppoSAX and the nondetection with the ROSAT look puzzling. We suggest that the long-term EUVE observations reflect a mean X-ray emission while the comparatively short BeppoSAX and ROSAT observations of Comet Hale–Bopp could coincide with a maximum and a minimum in the heavy ion flux, respectively.

1. INTRODUCTION

Soft X-ray emission from comets is a new phenomenon discovered in the Roentgen Satellite (ROSAT) and Extreme Ultraviolet Explorer (EUVE) observations of Comet Hyakutake (1996 B2) by Lisse *et al.* (1996) and Mumma *et al.* (1997), respectively. Later, X-rays were observed in Comets Hale–Bopp (Krasnopolsky *et al.* 1997, Owens *et al.* 1998), Tabur (Dennerl *et al.* 1997), and Encke (Lisse *et al.* 1999b). Study of the ROSAT all-sky survey by Dennerl *et al.* (1997) revealed X-rays from four other comets. We also detected X-rays from Comet d'Arrest with the EUVE, while X-rays from Comet Bradfield (C/1995 Q1) were below the EUVE detection limit (Mumma *et al.* 1997).

X-ray emission from comets appeared to be much stronger than expected. For example, the X-ray emisions were equal to 1.2×10^{16} and 7.3×10^{11} erg s^{-1} from Comet Hyakutake (Lisse *et al.* 1996, Krasnopolsky 1998) and the Moon (Schmitt *et al.* 1991), respectively. The Moon was observed at a phase angle of $\approx 100^\circ$, and its visual magnitude is equal to -9.7 at this angle (Allen 1973). The mean magnitude of Hyakutake during the ROSAT observation was 0.4 (the data are taken from *International Comet Quarterly* **18**(2)), and the Moon's visual luminosity is higher than that of Hyakutake by a factor of 5 after the correction for the geocentric distances (0.00257 and 0.12 AU, respectively). Therefore the X-ray to visual luminosity ratio for Comet Hyakutake exceeds that for the Moon by a factor of 8×10^4.

The viable excitation processes are charge exchange of solar wind heavy ions (first suggested by Cravens (1997) and later investigated by Häberli *et al.* (1997), Krasnopolsky (1997a,b), and Wegmann *et al.* (1998)) and scattering of the solar X-rays by so-called attogram dust particles (Wickramasinghe and Hoyle 1996, Krasnopolsky 1996, 1997a,b). Some other processes, e.g., electron bremsstrahlung and electron impact excitation, were also suggested. However, their contribution to the observed X-rays

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was proved to be in the order of 1% (Krasnopolsky 1997b, 1998).

Later Ip and Chow (1997) proposed electrostatic charging of small dust particles and their acceleration by electromagnetic interaction with the cometary plasma. Then collisions of these particles with the ordinary dust particles may release X-rays at a level of 5–10% of the observed emission. However, Ip and Chow (1997) took a yield of X-rays at 10^{-2} of the kinetic energy from Ibadov (1990), while Krasnopolsky (1997b) found this yield at $\approx 3 \times 10^{-5}$. The proper correction results in a negligible contribution of this process.

A recent attempt by Uchida *et al.* (1998) to explain the observed X-ray emission of Hyakutake by electron bremsstrahlung is based on some inadequate assumptions. They approximated the emitting coma of Hyakutake as a uniform sphere with a radius of $R = 2 \times 10^5$ km, adopted the effective mean density of oxygen atoms of 10^6 cm^{-3}, and assumed that each electron completely loses its energy in the coma. However, the number of oxygen atoms in their model of the coma exceeds their actual number $Q_{\text{gas}} R/v$ ($Q_{\text{gas}} \approx 2 \times 10^{29}$ s^{-1} is the gas production rate, and v is the gas velocity) by three orders of magnitude. Furthermore, the stopping range of electrons with energy of $\approx$600 eV in H_2O is $N = 1.7 \times 10^{17}$ cm^{-2}, and their assumption of the complete loss of electron energy is valid within a radius $R = Q/4Nv = 30$ km. Then the effective volume of the emitting sphere is smaller than that adopted by Uchida *et al.* (1998) by a factor of $(2 \times 10^5/30)^3 = 3 \times 10^{11}$.

Shapiro *et al.* (1999) also explain the X-ray emission from comets by bremsstrahlung of electrons produced by lower hybrid waves. However, the direct measurements of electron energy distributions in Comet Halley from the Vega and Giotto spacecraft preclude bremsstrahlung at a level exceeding $\approx$1% of the observed X-ray emission (Krasnopolsky 1998).

Further progress in the field requires more observational data. To respond to this problem, we observed Comet Hale–Bopp postperihelion in November 1997 and studied observing data on three other comets from the EUVE archive. This is the subject of this paper.

2. RESULTS OF OBSERVATIONS

Observing conditions for three archive comets and postperihelion Hale–Bopp are given in Table I. The conditions of our previous EUVE observations of four comets (Mumma *et al.* 1997) are also shown in the table. Along with the heliocentric and geocentric distances r and Δ, respectively, the table includes phase (Sun–comet–Earth) angles and elongations (Sun–Earth–comet angles). The observations were made on the shadow parts of the EUVE orbits. We tried to observe comets at their minimum heliocentric and geocentric distances within the EUVE elongation limit $\varepsilon_{\min} \approx 90^\circ$, and this shortened the visibility periods. The effective exposure times were corrected for filtering of the South Atlantic Anomaly and some other unfavorable events and were equal to $\approx$20% of the total observation times.

As in our previous studies, we analyze the data obtained with the deep survey (DS) camera through the lexan/boron filter which has the size of 120×40 arcmin. The observed photon and background events were remapped for motion of the comets, the EUVE orbital parallax, and the EUVE pointing corrections during the observations. This remapping fixed the nucleus of an observed comet at the center of the X-ray image. The overall pointing uncertainty is 30 arcsec due to thermal flexures in the spacecraft (Abbott *et al.* 1996).

The vignetting function for the lexan/boron filter was rather flat, decreasing to 75 and 95% to the edges of the long and short sides of the filter, respectively. Vignetting of the signal differs from that of the background; therefore the corrected background increases from the image center to its periphery (by $\approx$10% at 30 arcmin, see below). However, we analyze the signal mostly within 15 arcmin in the center for all comets except Hyakutake, and this does not affect our results. The signal from Hyakutake was so strong that a possible error in the background correction at the outer image areas was of low importance. The remapped exposure times are also flat within the regions of our analysis. Though some bright EUV sources appeared in the field of view during our observations, they were well seen due to their small spatial extents and never coincided with the observed comets. The remapping routine was developed by one us (M.A.) first

TABLE I
Observing Conditions

Parameter	2P/Encke	C/1993 Al Mueller	19P/Borrelly	6P/d'Arrest	C/1995 Q1 Bradfield	C/1996 B2 Hyakutake	C/1995 O1 Hale–Bopp	C/1995 O1 Hale–Bopp[a]
Dates	30/11–2/12/93	9–11/6/94	20–22/11/94	4–5/9/95	6–7/11/95	21–25/3/96	14–19/9/96	17–23/11/97
r (AU)	1.43	2.64	1.39	1.42	1.50	1.07	3.07	3.45
Δ (AU)	0.95	2.27	0.64	0.47	1.26	0.12	2.91	3.35
ϕ (deg)	44	22	42	21	41	50	19	17
ε (deg)	95	100	114	120	83	124	88	88
τ (s)	3.4×10^4	3.8×10^4	4.1×10^4	4.2×10^4	3.3×10^4	1.0×10^5	9.6×10^4	9.1×10^4

Note. r and Δ are heliocentric and geocentric distances, ϕ is phase angle (Sun–comet–Earth angle), ε is elongation (Sun–Earth–comet angle), and τ is effective exposure time.

[a] Postperihelion observation.

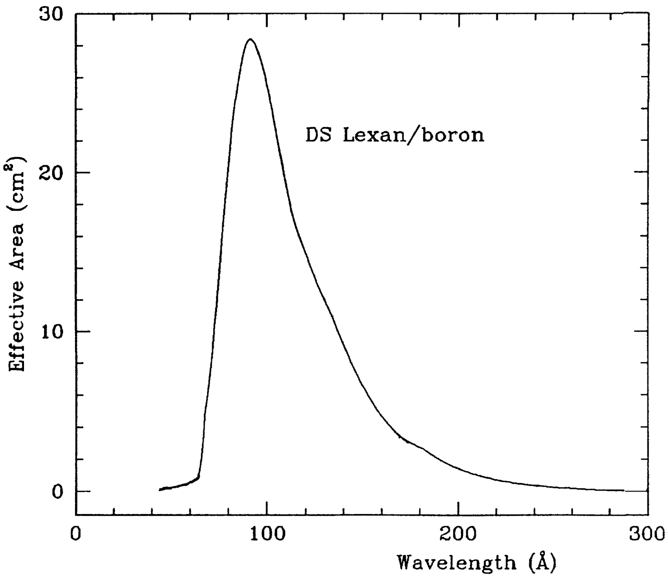

FIG. 1. Effective area of the EUVE Deep Survey camera with the lexan/boron filter.

for our observations of Comet Hale–Bopp and now is used as a standard software for the EUVE observations of moving objects.

The EUVE DS peak effective area (Fig. 1) is 28 cm^2 at 135 eV, its equivalent width is equal to 1910 cm^2 eV, its effective bandpass is $\delta E = 1910/28 = 68$ eV (97–165 eV). The EUVE DS is a narrowband ($E/\delta E = 2$) soft X-ray camera. According to the standard photometric approach, the results of our EUVE observations (Krasnopolsky *et al.* 1997, Mumma *et al.* 1997) are given as photon luminosities within the instrument bandpass assuming a uniform spectrum. These luminosities may be converted to the total luminosities under some assumptions on the X-ray spectrum.

The ROSAT all-sky survey which revealed four comets (Dennerl *et al.* 1997) was done with a proportional counter which had a resolving power $E/\delta E = 1.3$ at $E = 280$ eV. Approximation of the observed data using the thermal bremsstrahlung and the power law spectra resulted in $kT = 230 \pm 40$ eV and a photon index $\alpha = -3$, respectively (Dennerl *et al.* 1997). The observation of Comet Hale–Bopp on September 10, 1996, with the BeppoSAX satellite, which had a better resolving power of $E/\delta E = 3$ at $E = 280$ eV, showed $kT = 290 \pm 60$ eV and $\alpha = -3.1 + 0.6/-0.2$ (Owens *et al.* 1998). The observations of Comet Hyakutake with three instruments (ROSAT HRI, ROSAT WFC, and EUVE DS) require the mean values of $kT = 360$ eV and $\alpha = -2$ (Krasnopolsky 1998).

Wegmann *et al.* (1998) show that a cometary X-ray spectrum, calculated for charge exchange of solar-wind heavy ions and observed with a low-resolution spectrometer, extends up to 700 eV and is very similar to the bremsstrahlung spectrum with $kT \approx 200$ eV. Our inspection of the spectrum of Wegmann *et al.* (1998) shows that the power law spectrum with the photon index of -3 (that is, an energy index of -2) and a cutoff at 700 eV is also a good fit.

The term of thermal bremsstrahlung is confusing because thermal bremsstrahlung is not a physical reality in comets. Even that bremsstrahlung which is expected at a level of ≈1% of the total X-ray in comets, is not thermal. Another inconvenience in using thermal bremsstrahlung is the Gaunt factor which depends weakly on the nucleus charge Z, kT, and E. We take the Gaunt factor for $Z = 8$ (oxygen) from Karzas and Latter (1961), and it varies ±6% from 100 to 700 eV.

The standard photometric approach presuming a uniform spectrum within a narrow bandpass is the best for comparison with detailed spectra which will be acquired in future, and we will follow it. Reductions of the comet luminosities in the range of 97–165 eV for nonuniform spectra are equal to 3, 7.5, and 16% for thermal bremsstrahlung spectra with $kT = 200$–360 eV and the power law spectra with $\alpha = -2$ and -3, respectively. However, the standard photometric approach is inapplicable to instruments having a broad bandpass with a complicated structure like the ROSAT HRI. To facilitate a comparison between the different databases, conversion factors between the photon luminosities and brightnesses in the EUVE DS bandpass and those for the thermal bremsstrahlung and power law spectra are given in Table II. This table shows that the conversion factors are significantly different even for the spectra with $kT = 230$ eV and $\alpha = -3$, which both fit the best the ROSAT all-sky data. X-ray luminosities of comets are given in Table III in the EUVE range of 97–165 eV and also for $E > 100$ eV, assuming thermal bremsstrahlung with $kT = 230$ eV.

Figure 2 shows the X-ray image of Comet Borrelly convolved with a Gaussian having a half-maximum radius of 3×10^4 km. As in preperihelion Hale–Bopp (Krasnopolsky *et al.* 1997), the brightness center is offset from the nucleus in the direction between that to the Sun and the comet velocity vector. The phase angle of $\phi = 42°$ for this observation is larger than those of ≈20° for Hale–Bopp and d'Arrest, and the crescent-like structure of X-ray excitation (revealed in the image of Hyakutake at $\phi = 50°$) is better seen in this comet. The brightness maximum offset is $(3.2 \pm 1.4) \times 10^4$ km in the sky plane, and the correction for the phase angle (Krasnopolsky *et al.* 1997) results in the offset of $(4.6 \pm 2) \times 10^4$ km.

The azimuthally averaged brightness versus distance from the brightness center is shown in Fig. 3. The X-ray luminosity of Comet Borrelly as a fuction of aperture radius ρ is shown in Fig. 4. The data for these figures were extracted from the inconvolved images. Figure 4 is very helpful for comparison of our observations with the other X-ray observations which refer to different apertures. The X-ray luminosity from Comet Borrelly is equal to $(1.6 \pm 0.15) \times 10^{24}$ photons s^{-1} at 97–165 eV and $(1.1 \pm 0.1) \times 10^{15}$ erg s^{-1} at $E > 100$ eV for $\rho = 1.3 \times 10^5$ km (Table III). X-ray luminosities in Table III refer to apertures at levels of 20% of the maximum brightnesses.

The luminosities in Table III are given with 1σ statistical uncertainties which are the vectorial sums of the uncertainties of total (signal plus background) count numbers and the background uncertainties. The former dominate at small apertures, and the latter at large apertures. An optimum is at an intermediate

TABLE II
Conversion Factors

97–165 eV	Spectrum	$E > 100$ eV		100–700 eV	
10^{24} ph/s	$kT = 200$ eV	$1.8 + 24$[a] ph/s	$6.2 + 14$ erg/s	$1.8 + 24$ ph/s	$6.0 + 14$ erg/s
	230	$2.0 + 24$	$7.0 + 14$	$1.9 + 24$	$6.6 + 14$
	290	$2.2 + 24$	$8.6 + 14$	$2.1 + 24$	$7.6 + 14$
	360	$2.4 + 24$	$1.04 + 15$	$2.3 + 24$	$8.6 + 14$
	$\alpha = -2$	$2.2 + 24$	—	$1.9 + 24$	$6.8 + 14$
	$\alpha = -3$	$1.2 + 24$	$3.85 + 14$	$1.2 + 24$	$3.3 + 14$
1 mR[b]	$kT = 200$ eV	1.8 mR	$5.0 - 8$ erg cm^{-2} s^{-1} sr^{-1}	1.8 mR	$4.7 - 8$ erg cm^{-2} s^{-1} sr^{-1}
	230	2.0	$5.6 - 8$	1.9	$5.2 - 8$
	290	2.2	$6.8 - 8$	2.1	$6.1 - 8$
	360	2.4	$8.3 - 8$	2.3	$6.9 - 8$
	$\alpha = -2$	2.2	—	1.9	$5.4 - 8$
	$\alpha = -3$	1.2	$3.1 - 8$	1.2	$2.6 - 8$

[a] $1.8 + 24 = 1.8 \times 10^{24}$.
[b] 1 mR (millirayleigh) $= 10^3$ photons cm^{-2} s^{-1} $(4\pi$ sr$)^{-1}$.

aperture, and these optima are given in Table III as the detection levels in σ. It is equal to 14σ for Comet Borrelly at $\rho = 6.8 \times 10^4$ km. The uncertainty of 25% for the X-ray emission from Comet Hale–Bopp given in Krasnopolsky *et al.* (1997) reflected mostly the model uncertainty (the assumption of a uniform spectrum). The detection level for that comet was 7σ (Table III) at $\rho = 1.9 \times 10^5$ km.

Comparison of the count numbers in the unconvolved frames of 100×100 pixels (440×440 arcsec) and 200×200 pixels results in the optimum conditions for detection of comets which are faint in the soft X-ray. A 2σ detection limit for the effective exposure time of 3.8×10^4 s depends slightly on the observing conditions and is typically 100 counts, that is, 2.6×10^{-3} cps. It corresponds to the X-ray luminosity $Q_X < 2.6 \times 10^{23}\ \Delta^2$ ph s^{-1} at 97–165 eV and $Q_{XE} < 1.9 \times 10^{14}\ \Delta^2$ erg s^{-1} for $E > 100$ eV and $kT = 230$ eV. The observational data for Comets Encke and Mueller show no detectable emissions with the 2σ upper limits of 2.7×10^{23} and 1.4×10^{24} ph s^{-1} (1.9×10^{14} and 10^{15} erg s^{-1}) for $\rho = 1.7 \times 10^5$ and 4.1×10^5 km, respectively.

Counts in the 100×100-pixel bins near the central line of the lexan/boron filter in the remapped DS image of Hale–Bopp, observed by us postperihelion in November 1997, are shown in Fig. 5. Due to imperfect correction of the background by the vignetting function, these counts show a weak (≈10%) minimum near the image center, which may be approximated with the third-degree polynomial. Differences between the measured counts and this approximation are also shown in Fig. 5. These differences result in a pronounced excess in the bin centered

TABLE III
Summary of EUVE Observations of Soft X-rays in Eight Comets

Parameter	2P/Encke	C/1993 Al Mueller	19P/Borrelly	6P/d'Arrest	C/1995 Q1 Bradfield	C/1996 B2 Hyakutake	C/1995 O1 Hale–Bopp[a]	C/1995 O1 Hale–Bopp[b]
r (AU)	1.43	2.64	1.39	1.42	1.50	1.07	3.07	3.45
ρ (10^4 km)	17	41	13	6	23	20	40	40
Q_X (10^{24} ph s^{-1})	<0.27	<1.4	1.6 ± 0.15	0.45 ± 0.05	<0.5	10.3	7.3 ± 1.5	2.65 ± 0.9
Q_{XE} (10^{14} erg s^{-1})	<1.9	<10	11 ± 1	3.1 ± 0.35	<3.5	72	51 ± 10	19 ± 6
ρ_{SP} (10^4 km)	—	—	3.2 ± 1.4	<1	—	4.4 ± 0.3	14 ± 6	—
ρ_B (10^4 km)	—	—	4.6 ± 2	<3	—	6 ± 1	27 ± 12	—
S/σ	<2	<2	14	10.5	<2	>50	7	3
Q_{gas} (s^{-1})	$3.4 + 27$[c]	$9 + 27$	$3.3 + 28$	$1.2 + 28$	$4 + 27$	$2 + 29$	$6 + 29$	$3 + 29$
$Af\rho$ (m)	0.16	—	5.2	0.65	0.85	72	630	500
ε_g	$<1.4 - 4$	$<6.7 - 4$	$7.9 - 5$	$6.4 - 5$	$<2.3 - 4$	$5.7 - 5$	$6.5 - 5$	$5.7 - 5$
ε_d (ph s^{-1} m^{-1})	$<3.5 + 24$	—	$5.9 + 23$	$1.4 + 24$	$<1.3 + 24$	$1.6 + 23$	$1.1 + 23$	$6.3 + 22$

Note. r is the heliocentric distance, ρ is the aperture at 20% the peak brightness (ρ is taken at 250″ for the upper limits), Q_X and Q_{XE} are the X-ray luminosities within the aperture ρ for a flat spectrum in the range of 97–165 eV and for thermal bremsstrahlung with $kT = 230$ eV and $E > 100$ eV, ρ_{SP} and ρ_B are the brightness maximum offset from the nucleus in the sky plane and the corrected value, S/σ is the detection level in σ for the best aperture (see text), Q_{gas} and $Af\rho$ are the gas and dust production rates, respectively, and ε_g and ε_d are the efficiencies of X-ray excitation relative to the gas and dust production rates (see text).
[a] Preperihelion observation.
[b] Postperihelion observation.
[c] $3.4 + 27 = 3.4 \times 10^{27}$.

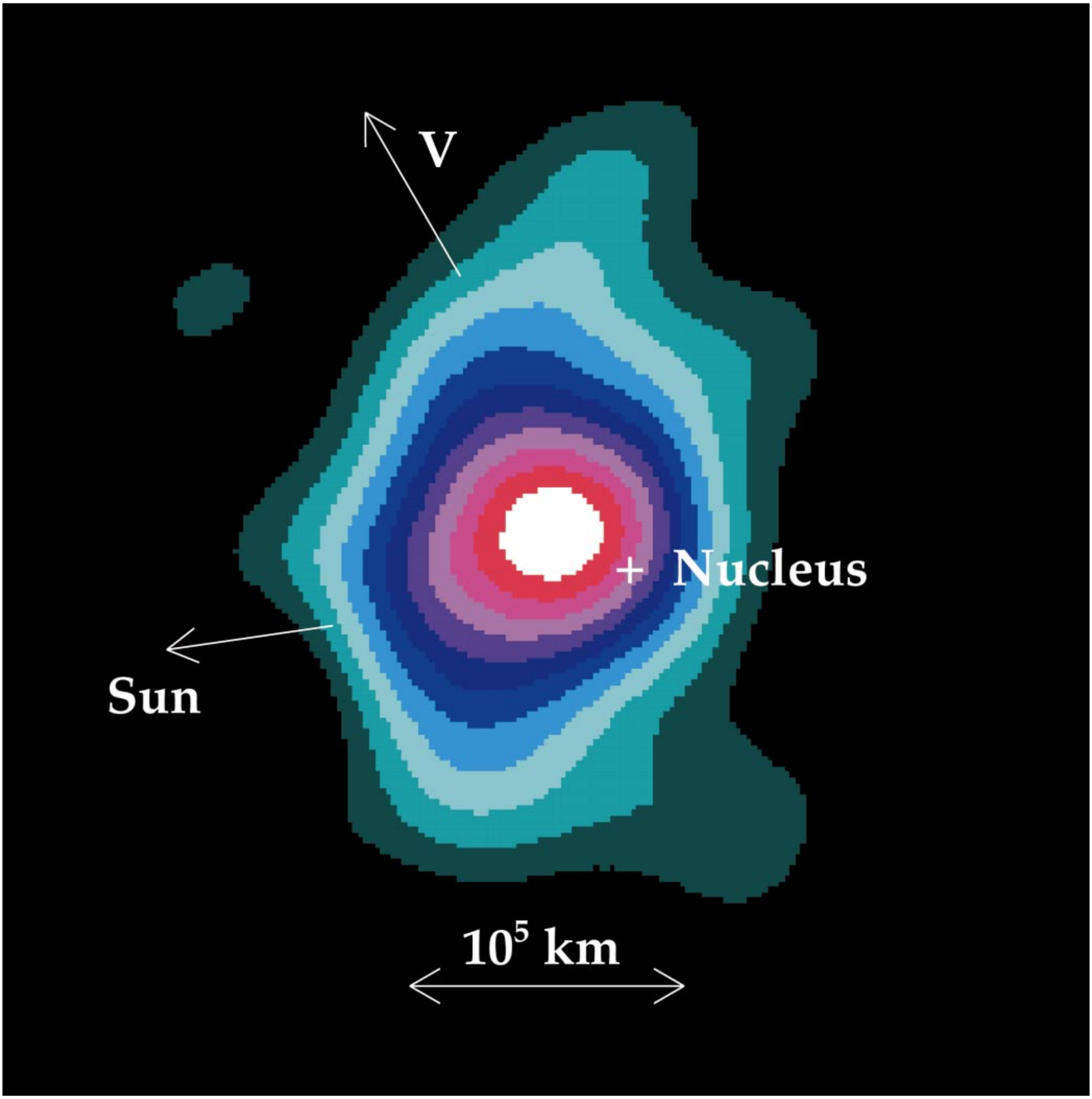

FIG. 2. Comet Borrelly in soft X-rays. V is the comet velocity direction in the geocentric coordinates. North is at the top and east is to the left.

at pixel 970. The detected X-ray luminosity is $(3.7 \pm 1.2) \times 10^{24}$ ph s^{-1} at 97–165 eV and $(2.6 \pm 0.85) \times 10^{15}$ erg s^{-1} at $E > 100$ eV ($kT = 230$ eV) for $\rho = 6 \times 10^5$ km. This luminosity is close to the detection limit, therefore the brightness offset and radial distribution are uncertain and not shown here. However, the brightness offset is also between the sunward and comet velocity directions. We assume that the X-ray spatial distributions are similar in our observations of post- and preperihelion Hale–Bopp. Summary of the EUVE observations of soft X-rays in eight comets is given in Table III.

3. GAS AND DUST PRODUCTION RATES

Observations of Hale–Bopp on 25–29/12/97 from the Infrared Space Observatory gave the production rates $Q_{H_2O} = 2.8 \times 10^{28}$ s^{-1}, $Q_{CO_2} = 3.5 \times 10^{28}$ s^{-1}, and $Q_{CO} = 1.5 \times 10^{29}$ s^{-1} (Bockelee-Morvan *et al.* 1998). Using a r^{-3} dependence for the gas production in dynamically new and long-period comets after perihelion (A'Hearn *et al.* 1995), we obtain $Q_{gas} = 3 \times 10^{29}$ s^{-1} during our observation of Hale–Bopp in November 1997. Microwave measurements of eight species with four radio

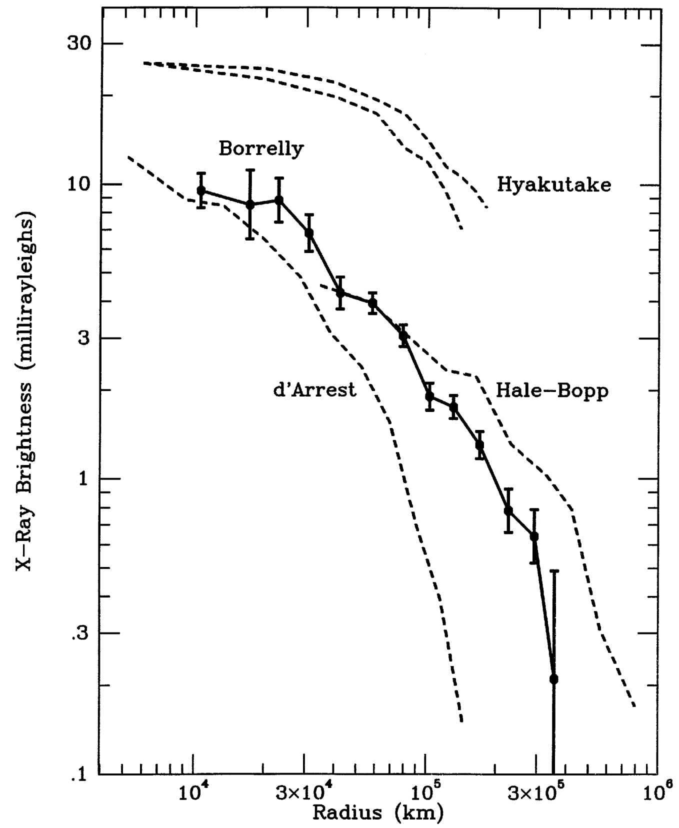

FIG. 3. X-ray brightnesses in Comet Borrelly (solid) and three other comets (dashes) as functions of distances from the brightness maxima. For Hyakutake, brightnesses in both the antisolar direction and the direction normal to the Sun–comet line are shown, Azimuthally averaged brightnesses are shown for the other comets. The data refer to the EUVE range of 97–165 eV.

telescopes did not cover H_2O and CO_2 in the period of our observation, and the CO production rate was at 10^{29} s^{-1} (Biver *et al.* 1999). The HST observations resulted in $Q_{H_2O} = 5.7 \times 10^{28}$ s^{-1} (Weaver *et al.* 1999) interpolated to 20/11/97. Based on these data, we adopt $Q_{gas} \approx 3 \times 10^{29}$ s^{-1}.

A measurable quantity, which is proportional to the dust production rate in comets, is $Af\rho$, where A is the particle albedo, and f is the filling factor for dust particles observed within an aperture ρ (A'Hearn *et al.* 1995). Conversion of $Af\rho$ (in m) to the dust mass production (in kg s^{-1}), which depends on some poorly known parameters of the particle mass distribution, is unimportant for us. Interpolation of the HST observations of Hale–Bopp (Weaver *et al.* 1999) to 20/11/97 gives $Af\rho = 970$ m. The HST values of $Af\rho$ are measured in a small aperture of 1 arcsec and in a broadband filter of 0.55–1.1 μm. Those values are typically greater by a factor of 3 to 3.5 than the groundbased $Af\rho$s, which refer to much larger apertures and narrowband filters. For example, the HST and groundbased $Af\rho$s were equal to 2100 and 630 m near the dates of the EUVE observation of preperihelion Hale–Bopp (see Krasnopolsky *et al.* (1997) and references therein). Most of $Af\rho$ values are from the groundbased observations, and scaling the above values results in $Af\rho = 290$ m on 20/11/97. $Af\rho = 540$ and 570 m were measured by groundbased photometry on 26/10/97 and 1/12/97 (Schleicher, pers. commun.). Based on these data, we adopt $Af\rho \approx 500$ m for the dates of the EUVE observation.

The IUE observations of the OH production rate for comet Borrelly on 18/11/94 and 3/12/94 resulted in $Q_{H_2O} = 2.9 \times 10^{28}$ and 2.3×10^{28} s^{-1}, respectively (Festou, pers. commun.). The OH observations at 18 cm showed $Q_{OH} = 2.4 \times 10^{28}$ s^{-1} at $r \approx$ 1.42 AU (Bockelee-Morvan *et al.* 1995). These values agree with the observations of Comet Borrelly at the previous passages (A'Hearn *et al.* 1995, Newburn and Spinrad 1989). Cochran and Barker (1999) obtained $Q_{OH} = 1.7 \times 10^{27}$ s^{-1} near the dates of the EUVE observation which is much smaller than the other results and therefore neglected. We use factors of 1.2 and 1.3 to convert the H_2O and OH production rates, respectively, to the total gas production rates. This gives $Q_{gas} = 3.3 \times 10^{28}$ s^{-1}.

The measured $Af\rho$s in Comet Borrelly are equal to 6.1 and 3.1 m from Lamy *et al.* (1998) and Cochran and Barker (1999) and may be compared with 6.5 m from the previous passage (A'Hearn *et al.* 1995). We adopt the mean value $Af\rho = 5.2$ m.

The water production rate observed with the IUE in Comet Encke on 27/12/93 at $r = 1.03$ AU is $Q_{H_2O} = 5.1 \times 10^{27}$ s^{-1} (A'Hearn, pers. commun.). The correction for heliocentric distance from A'Hearn *et al.* (1995) results in $Q_{H_2O} = 2.8 \times 10^{27}$ s^{-1} and $Q_{gas} = 3.4 \times 10^{27}$ s^{-1}. This is also close to the values from the previous passages (A'Hearn *et al.* 1995, Newburn

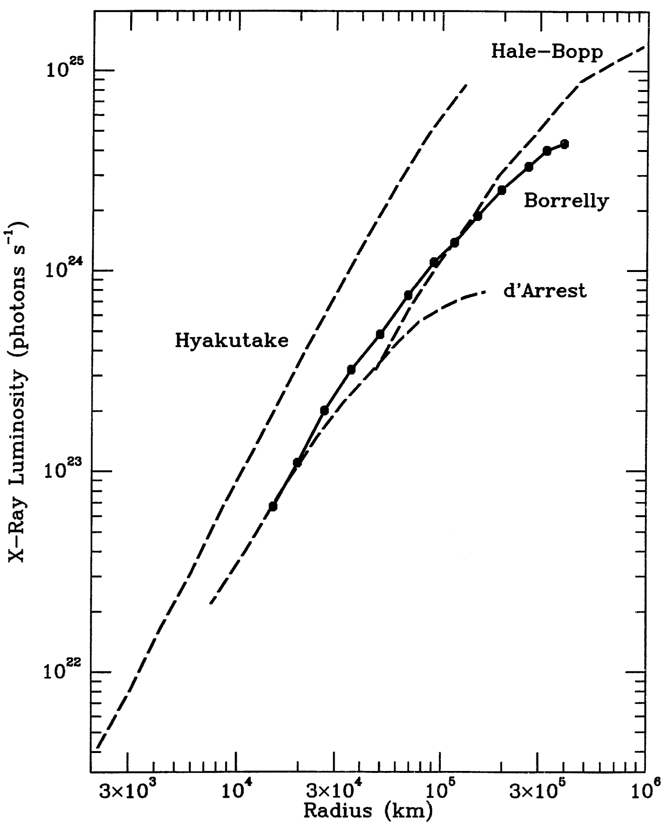

FIG. 4. X-ray luminosities of four comets in the range of 97–165 eV as functions of aperture.

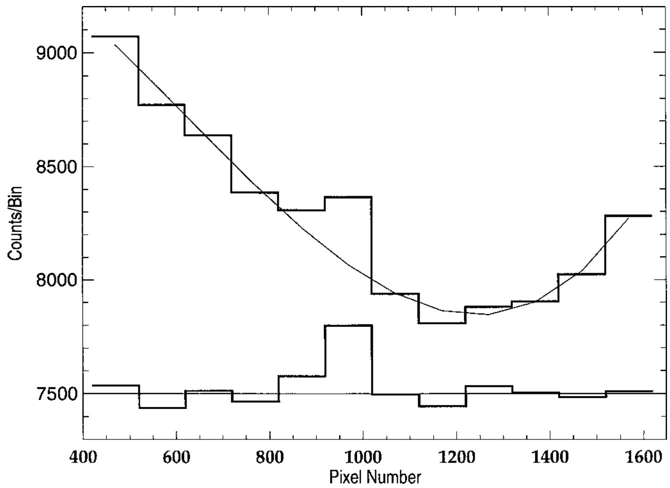

FIG. 5. Detection of X-rays in postperihelion Hale–Bopp. Counts per bins of 100 × 100 pixels near the central line in the remapped image of Comet Hale–Bopp (top solid line). The background is approximated with the third-degree polynomial. The difference between the counts and their approximation (bottom solid line) shows a pronounced signal in the bin centered on pixel 970. For convenience, the zeroth line for this difference is placed at a level of 7500.

and Spinrad 1989). According to A'Hearn *et al.* (1995), $Af\rho$ is equal to 0.16 m for the conditions of our observations.

Three observations of the visual magnitude m_v on June 9–12, 1994, are the only data which we have found for Comet Mueller (1993 A1) near the time of the EUVE observation. They give $m_v = 12.3 \pm 0.3$. A crude method of obtaining the OH production rate from m_v (Festou 1986) with the further correction for the factor of 1.3 gives $Q_{gas} \approx 9 \times 10^{27}$ s^{-1}. The gas and dust production rates in Comets d'Arrest, Bradfield, Hyakutake, and preperihelion Hale–Bopp are considered in Mumma *et al.* (1997) and Krasnopolsky *et al.* (1997).

4. EXCITATION PROCESSES

Studying the correlation of the observed X-ray luminosities with the gas or dust production rates is a way of choosing between gas- and dust-related mechanisms of X-ray excitation, i.e., between charge transfer of solar-wind heavy ions and scattering of the solar X-rays by the attogram dust. A ratio of the attogram dust to ordinary dust is poorly known and may be variable. These variations are also unknown and may downgrade the correlation of X-rays with dust. The correlation of X-rays with gas is less affected by poorly known factors. The long exposure times of 2 to 6 days (the effective exposures are much shorter!) in our observations significantly reduce effects of variations in the solar wind and in the solar X-rays. The apertures of a few times 10^5 km also correspond to averaging of a comet activity in a few days. This time is much longer than typical periods of comet rotation, and the regular spinning jets do not affect the observations.

A problem that we meet in the comparison of the X-ray luminosities with the gas and dust production is a choice of the aperture to which X-ray luminosity refers. We choose these apertures at levels of 20% of the peak brightnesses (Fig. 3). This choice is arbitrary to some extent. Values of ρ are given in Table III, and the appropriate X-ray luminosities are taken from Fig. 4.

The obtained gas- and dust-related efficiency of X-ray excitation, $\varepsilon_g = r^{3/2} Q_X / Q_{gas}$ and $\varepsilon_d = r^2 Q_X / Af\rho$, are shown in Table III. The gas-related efficiencies are corrected to the variation of the gas velocity with heliocentric distance: $v = 0.85 r^{1/2}$ km/s (Cochran and Schleicher 1993). The dust-related efficiencies are based on the observed dust abundances $Af\rho$ and do not need this correction. The values for the comets, which have been detected with the EUVE, result in $\varepsilon_g = (6.4 \pm 0.9) \times 10^{-5}$ and $\varepsilon_d = (4.7 \pm 5.6) \times 10^{23}$ ph s^{-1} m^{-1}. Correlation between the X-ray luminosities and the gas production rates is so good that the uncertainty of 14% in the obtained efficiency is comparable with the uncertainties of both the X-ray luminosities and the gas production rates. The uncertainty of ε_d is so great that only a 2σ upper limit of $\varepsilon_d < 1.5 \times 10^{24}$ ph s^{-1} m^{-1} can be established from the measurements. This favors a gas-related process of X-ray excitation which is charge exchange of solar wind heavy ions with cometary gas.

The upper limits for both ε_g and ε_d in Comets Encke, Mueller, and Bradfield agree with ε_g and ε_d in the other comets. Combining the detection limit of $2.6 \times 10^{23} \Delta^2$ ph s^{-1} with ε_g, we obtain that X-ray from a comet is detectable with the EUVE if $Q_{gas} > 4 \times 10^{27} r^{3/2} \Delta^2$ s^{-1}. Converting this limit to a visual magnitude using the relationship from Festou (1986), we find a limiting magnitude of $11.4 + 1.25 \log r$. It is similar to the detection limit of $m_v = 12$ at $r < 2$ AU in the all-sky ROSAT survey (Dennerl *et al.* 1997).

Inspection of the peak brightnesses scaled to r^2 results in a rather constant value of 26 ± 9 millirayleighs. This means that the comae are fairly thick for an excitation process at $\rho \approx 10^4\ r$ km (Fig. 3). Comae are much thicker collisionally for the solar wind heavy ions than optically for the solar X-ray photons. This also favors the charge exchange mechanism.

5. X-RAYS FROM COMET HALE–BOPP

X-rays from Comet Hale–Bopp were successfully observed by us using the EUVE both pre- and postperihelion, on 14–19/9/96 (Krasnopolsky *et al.* 1997) and on 17–23/11/97 (Figs. 3 to 5). The comet was also observed with the BeppoSAX on 10–11/9/96 (Owens *et al.* 1998) and five times with the ROSAT and ASCA (Lisse *et al.* 1999a).

The pre- and postperihelion X-ray luminosities observed by us within an aperture $\rho = 6 \times 10^5$ km were $(1 \pm 0.23) \times 10^{25}$ (Fig. 4) and $(3.7 \pm 1.2) \times 10^{24}$ ph s^{-1}, respectively, at 97–165 eV. The gas excitation efficiencies for both observations are similar (Table III) and close to the mean value for all observed comets, indicating a regular behavior of X-rays in the comet. However, the X-ray emission measured with the BeppoSAX during 24 h on 10–11/9/96 just a few days before our preperihelion observation was rapidly decreasing with a time constant of 9.3 h. The mean luminosity was 4.8×10^{16} erg s^{-1} in the range of 100–2000 eV for thermal bremsstrahlung with $kT = 290$ eV, and "the source spectrum was extracted within an 8′ radius," that is, $\rho = 10^6$ km. The luminosity observed by us within $\rho = 10^6$ km is equal to 1.4×10^{25} photons s^{-1} (Krasnopolsky *et al.* 1997, Fig. 3; see also Fig. 4 in this paper). Then the energy emitted at $E > 100$ eV is 1.2×10^{16} erg s^{-1} using the conversion factor for $kT = 290$ eV from Table II. The difference of a factor of 4 may be compared with that of 8.3–3.4 obtained by Owens *et al.* (1998) and of ≈10 from Lisse *et al.* (1999a). (Lisse *et al.* compared the BeppoSAX value of 2×10^{16} ergs s^{-1}, instead of the published value of 4.8×10^{16} ergs s^{-1}, with the EUVE value of 2×10^{15} ergs s^{-1} which was not corrected for the aperture and the spectral range.)

Hale–Bopp was also observed with the ROSAT and ASCA twice in September 1996 and then in September, October, and December 1997 (Lisse *et al.* 1999a). X-ray emission has not been detected in all those observations with a 3σ upper limit of 2×10^{15} erg s^{-1} for the ROSAT observation on 19/9/96, which was the last day of the EUVE observation of Hale–Bopp. The obtained upper limit is smaller by a factor of 6 than the X-ray luminosity measured by us within $\rho = 10^6$ km and is equal to the luminosity at $\rho = 1.6 \times 10^5$ km, both for $kT = 290$ eV. (We do not know which aperture and spectral range this limit refers to, and will use it as it is.) The overall high variability of X-rays from Comet Hale–Bopp observed with the BeppoSax, EUVE, and ROSAT in September 1996 looks puzzling and needs explanation in terms of variations of the gas and dust abundances in the comet, fluxes of the solar wind heavy ions and/or the solar X-rays.

The detailed observations by Schulz *et al.* (1999) of the CN 3880 Å band and the continuum at 4470 Å using spectra and images of Comet Hale–Bopp on September 10 to 16 showed a short outburst, which appeard on 9/9/96 at 11 ± 1 UT, just 20 h before the beginning of the BeppoSAX observation. The comet gas and dust production rates during that outburst exceeded their mean values by factors of 3 and 7, respectively. On September 10 the gas and dust densities at $\rho \approx 10^4$ km exceeded the mean values by factors of 6 and 5.5, respectively, and those "bumps" had half-widths of 10^4 km. However, it is difficult to explain the X-ray outburst by this outburst because it increased the total dust and gas abundances within, say, $\rho \approx 5 \times 10^5$ km by 10% only. Furthermore, the X-ray outburst ceased at the end of the BeppoSAX observation on September 11 while the dust/gas bump was spreading in the coma for a few days after that date.

The observations by Schulz *et al.* (1999) did not cover the ROSAT observation on September 19. The only data available to us which covered both EUVE and ROSAT observations in September 1996 are numerous (136 and 17, respectively) visual magnitudes listed in *International Comet Quarterly*. We conclude from these values that the visual luminosity of Hale–Bopp on 19/9/96 was weaker by a factor of 1.14 ± 0.1 than the mean visual luminosity during the EUVE observation. Therefore, we do not expect that a strong decrease in the gas or dust abundance resulted in the nondetection.

The BeppoSAX spectrum with $kT = 290 \pm 60$ eV agrees with the charge exchange spectrum calculated by Wegmann *et al.* (1998) and favors this excitation process. The attogram dust scattering spectrum is much softer, with a photon index of $\alpha \approx -5$ for the intervals of 101–165 and 165–284 eV (Krasnopolsky 1997b, 1998), and disagrees with the observation. A possible explanation of the behavior of Hale–Bopp in X-rays might be a charge-transfer emission during the BeppoSAX observation and a dust-dominated regular emission. Using thermal bremsstrahlung with $kT = 290$ eV for the charge transfer emission and the known spectral dependences of the effective areas of the EUVE DS and the ROSAT HRI, we expect almost equal count rates for both instruments. However, if scattering of the solar X-rays by attogram dust dominates, then the ROSAT count rate is smaller than the EUVE count rate by a factor of 6. Though this hypothesis explains the ROSAT nondetection, it is not supported by the gas-related efficiencies of X-ray excitation (Table III), which favor the charge exchange excitation in the EUVE observations. Moreover, this hypothesis does not explain a source of the strong X-ray outburst observed with the BeppoSAX.

The simplest explanation of the X-ray observations of Comet Hale–Bopp is variations of the heavy ion flux. The duration of the EUVE observations varied from 2 full days for the first five comets to a full 4, 5, and 6 days for Hyakutake and preperihelion and postperihelion Hale–Bopp, respectively. These observations are longer than typical variations of the heavy ion flux in the solar wind which are of a few hours. Therefore, the EUVE observations show a regular behavior of X-ray in the observed comets. The BeppoSAX observation was for 1 day, and the ROSAT observations were probably for a few hours. The heavy ion flux during those observations could be much stronger and weaker, respectively, than the mean flux, and this may explain the results. Comet Hale–Bopp during the X-ray observations was so far from Earth in all three coordinates that it is hardly possible to derive a structure of the heavy ion flux near the comet by near-Earth monitoring of this flux.

A possible weak point in this explanation is the nondetection of Hale–Bopp in all five observations with the ROSAT and ASCA (Lisse *et al.* 1999a). However, upper limits for those observations are unkown. Of some interest could be the upper limit of 0.004 cps for the first channel (0.5–1 keV) of the ASCA observed on 25/9/96 (Lisse *et al.* 1999a). Unfortunately, a spectral shape of the effective area for that channel is not accessible and, as in the case of the ROSAT upper limit, the aperture is unknown.

6. CONCLUSION

The analysis of the EUVE observations of the postperihelion Hale–Bopp and three archive comets in this paper has doubled the number of comet observations in our EUVE database. Five of the eight observations show the detectable soft X-ray emissions. The measured signal is proportional to $r^{3/2}\Delta^2 Q_{\text{gas}}$ (with the efficiency of $(6.4 \pm 0.9) \times 10^{-5}$ AU$^{3/2}$) and therefore favors a gas-related excitation mechanism. The only viable candidate is the charge transfer mechanism. The maximum brightnesses within $\rho \approx 10^4$ km and scaled to r^2 are rather constant and require collisionally/optically thick comae. This can also be the case for the charge transfer and precludes scattering of the solar X-rays by the attogram dust.

Using our X-ray luminosities for various apertures and assuming the presentation of the charge transfer spectrum by thermal bremsstrahlung or the power law, it is possible to make careful comparison of the observations made with different instruments.

While both of our pre- and postperihelion observations of Hale–Bopp demonstrate a regular behavior of X-rays from that comet, the outburst detected with the BeppoSAX and the nondetection with the ROSAT look puzzling. We suggest that the long-term EUVE observations reflect a regular X-ray emission while the comparatively short BeppoSAX and ROSAT observations of Comet Hale–Bopp could coincide with a strong and weak flux of solar-wind-heavy ions, respectively.

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