DETECTION OF SOFT X-RAY EMISSION FROM COMET C/1995 O1 (HALE–BOPP)

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Abstract. We report the detection of soft X-rays from comet C/1995 O1 (Hale–Bopp) by the Low Energy Concentrator Spectrometer (LECS) on-board the X-ray satellite, BeppoSAX. The observations took place on 1996 September 10–11 approximately 1 day after a large dust outburst (Schulz et al., 1997–1999). After correcting for the comets motion, a 7σ enhancement was found centered $(2.1 \pm 1.3) \times 10^5$ km from the position of the nucleus, in the general solar direction. The total X-ray luminosity in the 0.1–2.0 keV energy band is 5×10^{16} erg s^{-1} which is at least a factor of ~ 3 greater than measured by the *Extreme Ultraviolet Explorer* (*EUVE*) 4 days later and suggests that the bulk of the emission measured by the LECS is related to the dust outburst. The extracted LECS spectrum is well fit by a thermal bremsstrahlung-like distribution of temperature of 0.29 ± 0.06 keV – consistent with that observed in other comets. We find no evidence for fluorescent carbon or oxygen emission and place 95% confidence limits of 1.0×10^{15} and 7.8×10^{15} erg s^{-1} to narrow line emission at 0.28 and 0.53 keV, respectively. We calculate that if such lines are present, they constitute at most 18% of the 0.1–2.0 keV continuum luminosity.

Keywords: Comets: general-comets: individual (Hale–Bopp 1995 O1)

JEL codes D24, L60, 047

1. Introduction

The recent *ROSAT* detection of X-ray emission from comets C/1996 B2 (Hyakutake) and C/1990 N1 (Tsuchiya-Kiuchi) was surprising, since theory predicted insignificant fluxes (Lisse et al., 1996; Dennerl et al., 1997). The emissions were centered a few arc-minutes ($\sim 2 \times 10^4$ km) from the nucleus and had an extent of $\sim 5 \times 10^4$ km, being elongated normal to the Sun-nucleus line. The observed fluxes were a factor of $\sim 10^3$ greater than predicted by early models in which X-rays are generated by fluorescent emission and scattering of solar X-rays in the coma. Such models gained acceptance because they provide a natural explanation of the observed crescent-shaped morphology under the assumption that the coma is optically thick to soft X-rays. Alternate models in which the X-rays are generated by solar wind proton, or electron, interactions in the coma also suffer from low efficiencies. However, recently, several models have emerged which predict

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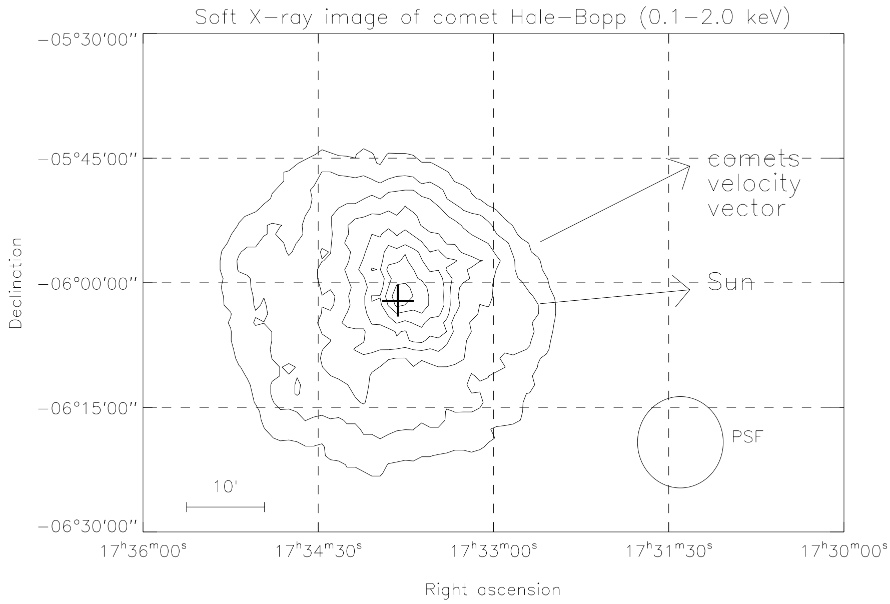

Figure 1. A 0.1–2.0 keV image of the sky containing comet Hale–Bopp. The image has been corrected for the motion of the comet ($\sim 17''$ hr^{-1}). For comparison, the FWHM of the PSF at the mean energy of the source is indicated by the circle in the lower right hand corner. The position of the nucleus is indicated by the cross.

significantly higher cometary X-ray intensities. In the solar wind model of Häberli et al. (1997) and Cravens (1997), X-rays are generated following charge exchange excitations of highly ionized solar wind ions with neutral molecules in the comet's atmosphere. The attogram dust model of Wickramasinghe and Hoyle (1996) produces X-rays from the scattering of solar X-rays in attogram sized ($\sim 10^{-18}$ g) dust particles, such as those detected in the wake of comet Halley (Utterback and Kissel 1990). Interestingly, sub-micron sized grains have recently been observed in the coma of Hale–Bopp (Williams et al., 1997).

2. X-ray Observation

The Low Energy Concentrator Spectrometer (LECS, 0.1-10 keV, Parmar et al., 1997) is one of five instruments on-board *BeppoSAX* (Boella et al., 1997a). It comprises an imaging mirror system and a driftless gas scintillation proportional counter. The energy resolution is 32% at 0.28 keV, the field of view (FOV) is $37'$ diameter (4.6×10^6 km at the comet) and the full width at half-maximum (FWHM) of the encircled energy function is $11.5'$ at 0.2 keV, falling to $5.1'$ at 1 keV. The effective area just below the C edge at 0.28 keV is 20 cm^2. The in-orbit background counting rate is 9.7×10^{-6} $arcmin^{-2}$ s^{-1} keV^{-1}. *BeppoSAX* was launched into a 600 km equatorial orbit on 1996 April 30.

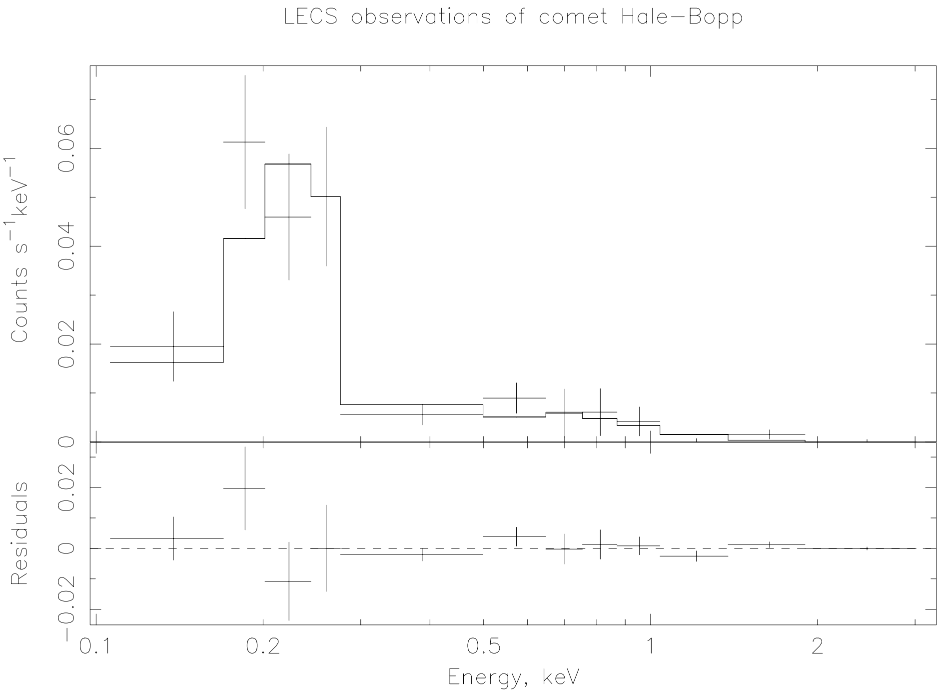

Figure 2. The observed LECS Hale–Bopp spectrum and best-fit thermal bremsstrahlung model (kT = 0.29 keV). The lower panel shows the residuals.

At the time of the *BeppoSAX* observations, the comet was 2.87 AU from the Earth and was in a period of relatively constant brightness of magnitude 6. The size of the coma was visually estimated to be about 20′ and some observers reported a short dust tail of up to 0.5–1°, possibly even 1.5°. Hale−Bopp was observed by *BeppoSAX* between 1996 Sept. 10 04:55 and Sept 11 04:21 UTC. The total LECS exposure was 11.5 ks. A motion corrected X-ray image of the region of sky containing Hale–Bopp is shown in Figure 1. The image has been re-binned to a 56″ × 56″ pixel size and smoothed using a Gaussian filter of width (σ) 1.5′ (1.9 $\times$ 10^5 km). The comet's motion vector and the position of the Sun are indicated. A weak (2.1 $\pm$ 0.3) $\times$ 10^{-12} ergs cm^{-2}s^{-1}; 0.1–2.0 keV) source is visible whose centroid position is 1.7′ $\pm$ 1′, or (2.1 $\pm$ 1.3) $\times$ 10^5 km, from the position of the nucleus, in the solar direction. The extent of the emission is consistent with the LECS PSF of 9.5′ FWHM at the mean energy of the detected emission, although the width normal to the Sun-nucleus axis appears wider than in the direction of motion, similar to that observed in other comets. The 68% confidence limit to any source extent is $<$6′ or $<$8.1 $\times$ 10^5 km.

The extracted spectrum was found to be equally well fit (with χ^2's of 9 for 9 degrees of freedom (dof)) by a thermal bremsstrahlung model of temperature 0.29 ± 0.06 keV (see Figure 2) or a power-law model of photon index $3.1 \pm^{0.6}_{0.2}$. A blackbody gives a less acceptable fit with a χ^2 of 18 for 9 dof (P($>\chi^2$) = 3%). The 0.1–2.0 keV spectrum predicted by the Solar wind model of Häberli et al. (1997) was also fit to the LECS data. This spectrum consists of a series of narrow lines resulting from the excitation of highly charged states of O, C, and Ne ions (see Table II of Häberli et al. (1997). The line species should not vary appreciably from comet to comet, and so the line energies were fixed at the values given in Häberli et al. (1997). The best-fit χ^2 is 44 for 6 dof, with 3 of the lines requiring zero flux. However, we point out that the data are consistent with the later calculations of Ip and Shemansky (1997) which include many more transition lines. The finite energy resolution of the LECS "washes" out any structure and the observed energy-loss mimics a bremstrahlung distribution. The 95% confidence limits to C and O narrow line emission at 0.28 and 0.53 keV are 1.0×10^{15} and 7.8×10^{15} erg s^{-1}. The 0.1–2.0 keV luminosity is 4.8×10^{16} erg s^{-1}, or 2.1×10^{-12} erg cm^{-2} s^{-1}, for the best-fit thermal bremsstrahlung and 5.9×10^{16} erg s^{-1}, or 2.6×10^{-12} erg cm^{-2} s^{-1}, for the best-fit power-law spectrum. The luminosities are $\sim$8 times greater than those measured by *EUVE* 4 days later (Krasnopolsky et al., 1997).

An examination of the *ROSAT* All Sky Survey catalog (Voges et al., 1996) revealed no known X-ray sources at this position. The probability of randomly detecting an X-ray source as bright as this within the extraction region is estimated to be 6×10^{-3}. We exclude a UV leak as being responsible for the counts since the LECS has made a number of deep observations of UV bright stars and no unexpected features were found. In addition, there are no unusual objects in the SIMBAD database and inspection of several deep LECS exposures revealed no "hot spots", or other instrumental features at this position. The Medium Energy Concentrator Spectrometer (MECS) also detected excess 1.3–2.0 keV emission at a position consistent with the LECS detection (at 1.3σ confidence) with an intensity of $(3.3 \pm 2.5)\times 10^{-14}$ erg cm^{-2} s^{-1}. This is in good agreement with LECS 1.3–2.0 keV value of $(1.8 \pm 1.1)\times 10^{-14}$ erg cm^{-2} s^{-1}. Based on the above, the positional coincidence of the source and the spatial distribution of events, we identify Hale−Bopp as the source of the detected X-rays.

3. Optical Observations

Optical observations were carried out on the ESO 2.2 m telescope at La Silla using the multi-mode EFOSC II instrument in 3 narrow bands to differentiate between dust and gas emissions. Hale−Bopp was observed at 01:00 UTC on 1996 Sept. 10 to Sept. 17 with exposure times of 180 s (dust), 180 s (C_2) and 300 s (CN). Each image was divided by the previous one so that temporal changes in the coma become apparent. This technique removes the strong smooth intensity profile of the coma so that superimposed time variable structures become visible (Schulz, 1991). The quotient images shown in Figure 3, reveal that a large dust cloud was ejected

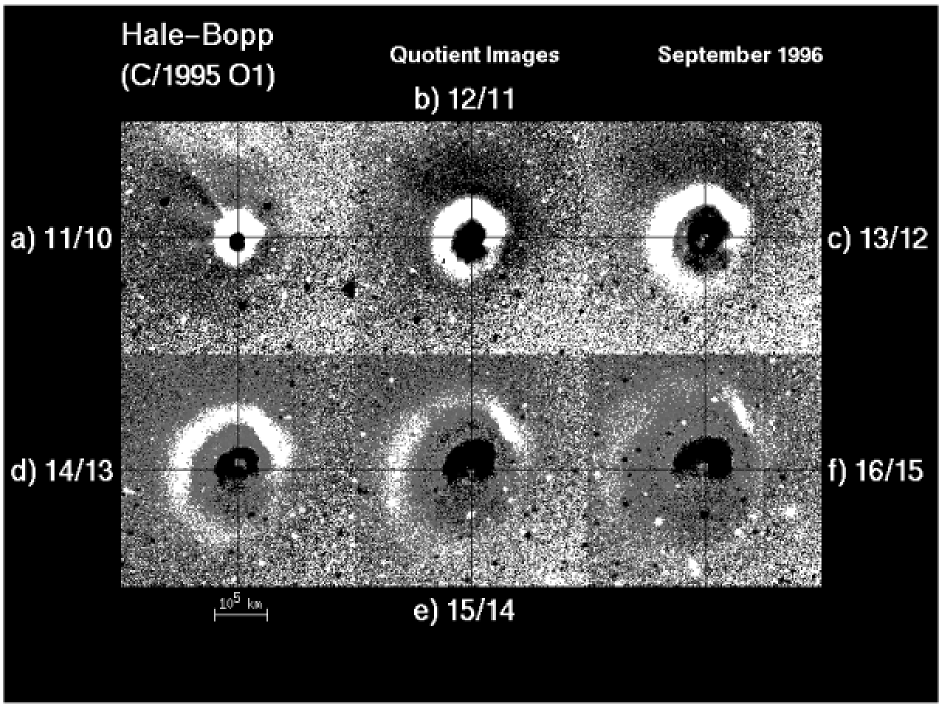

Figure 3. The evolution of the dust shell observed in Hale–Bopp, 1996, Sept. 10–17. Each image is the ratio between an image and that obtained the previous day and highlights changes between consecutive days. The images have the same orientation as Figure 1. The intensity coding has been modified to enhance the resulting shells.

from the nucleus and expanded outwards appearing as a shell when integrated over the line of sight.

4. Discussion

Krasnopolosky (1997) has shown that the attogram dust model can successfully explain the measured fluxes from comet Hyakutake. Scaling the Hyakutake X-ray flux by the quiescent gas and dust production rates and heliospheric distances of Hyakutake and Hale–Bopp, the predicted Hale–Bopp X-ray flux is in good agreement with that measured by *EUVE*, assuming that the X-ray emissivities are similar. Since X-ray intensity is expected to scale with the amount of dust, a factor of $\sim$8 more dust is required to account for the X-ray intensity observed by the LECS assuming the dust size distribution and solar X-ray flux remain the same. The dust production rate before the outburst is estimated to be $\sim 4 \times 10^4$ kg s^{-1} and the ratio of dust to gas production $\sim$3 (Rauer et al., 1997). The estimated dust production rate during the outburst is at least 3×10^5 kg s^{-1}, an increase by a factor of $>$7 than before the outburst. This is sufficient to account for the observed X-ray flux with the attogram dust model. We cannot directly measure the corresponding change in the amount of gas surrounding the comet. However during previous outbursts the gas production rate increased by a factor of only 1–3, depending on species (Weaver et al., 1997).

By the start of the *EUVE* observation the dust density had decreased to a maximum of twice its quiescent level and the cloud had a size of $\sim 3 \times 10^5$ km. By the end of the *EUVE* observation, the cloud filled most of the aperture providing an explanation for the source of extended emission reported in Mumma et al. (1997). The bulk of the dust outburst occurred towards the North and North-West of the nucleus. It is interesting to note that the majority of the X-rays observed by *EUVE* also originate Northwards (see Figure 1 of Krasnopolsky et al., 1997).

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