The discovery of high energy X-ray emission in 1996 from C/1996 B2 (Hyakutake) has created a surprising new class of X-ray emitting objects. The original discovery (Lisse et al., 1996) and subsequent detection of X-rays from 17 other comets (Table 1) have shown that the very soft (E < 1 keV) emission is due to an interaction between the solar wind and the comet’s atmosphere, and that X-ray emission is a fundamental property of comets. Theoretical and observational work has demonstrated that charge exchange collisions of highly charged solar wind ions with cometary neutral species is the best explanation for the emission. Now a rapidly changing and expanding field, the study of cometary X-ray emission appears to be able to lead us to a better understanding of a number of physical phenomena: the nature of the cometary coma, other sources of X-ray emission in the solar system, the structure of the solar wind in the heliosphere, and the source of the local soft X-ray background.

2. OBSERVED CHARACTERISTICS OF COMETARY X-RAY EMISSION

Shortly after the initial C/Hyakutake detection, soft X-ray emission from four other comets was found in the ROSAT archival database, confirming the discovery (Dennerl et al., 1997). X-ray emission has now been detected from 18 comets to date (Table 1) using a variety of X-ray sensitive spacecraft — BeppoSAX, ROSAT, the Extreme Ultraviolet Explorer (EUVE), and more recently, Chandra and XMM-Newton. All comets within 2 AU of the Sun and brighter than V = 12 have been detected when observed. We now recognize that X-ray emission is a characteristic of all active comets.

The observed characteristics of the emission can organized into the following four categories: (1) spatial morphology, (2) total X-ray luminosity, (3) temporal variation, and (4) energy spectrum. Any physical mechanism that purports to explain cometary X-ray emission must account for all these characteristics.
<table>
<thead>
<tr>
<th>Comet</th>
<th>Time</th>
<th>Instrument</th>
<th>Energy (keV)</th>
<th>Detection</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>45P/Honda-Mrkos-Pajdušáková</td>
<td>Jul 1990</td>
<td>ROSAT PSPC/WFC</td>
<td>0.09–2.0</td>
<td>Yes</td>
<td>[1]</td>
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<tr>
<td>C/1990 K1 (Levy)</td>
<td>Sep 1990</td>
<td>ROSAT PSPC/WFC</td>
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<td>Yes</td>
<td>[1]</td>
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<tr>
<td></td>
<td>Jan 1991</td>
<td></td>
<td>0.09–2.0</td>
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<tr>
<td>C/1991 A2 Arai</td>
<td>Nov 1990</td>
<td>ROSAT PSPC/WFC</td>
<td>0.09–2.0</td>
<td>Yes</td>
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<td>C/1990 N1 (Tsuchiya-Kiuchi)</td>
<td>Nov 1990</td>
<td>ROSAT PSPC/WFC</td>
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<td>2P/Encke</td>
<td>Nov 1993</td>
<td>EUVE DS</td>
<td>0.02–0.10</td>
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<td></td>
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<td>0.02–0.18</td>
<td>Yes</td>
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<td>Jul 1997</td>
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<td></td>
<td>Mar 1996</td>
<td>ALEXIS</td>
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<td>No</td>
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<td></td>
<td>Apr 1996</td>
<td>XTE PCA</td>
<td>2.0–10.0</td>
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<td>Jun 1996</td>
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<td></td>
<td>Jun 1996</td>
<td>ROSAT HRI/WFC</td>
<td>0.09–2.0</td>
<td>Yes?</td>
<td>[4]</td>
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<td>C/1995 O1 (Hale-Bopp)</td>
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<td>ROSAT HRI/WFC</td>
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<td></td>
<td>Sep 1996</td>
<td>BeppoSAX</td>
<td>0.1–200</td>
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<td>[6]</td>
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<td></td>
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<td>ROSAT HRI/WFC</td>
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<td>[7]</td>
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<td></td>
<td>Sep 1996</td>
<td>ASCA</td>
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<td></td>
<td>Mar 1997</td>
<td>XTE PCA</td>
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<tr>
<td></td>
<td>Oct 1997</td>
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<td></td>
<td>Nov 1997</td>
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<td>0.02–0.10</td>
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<td></td>
<td>Feb 1998</td>
<td>ROSAT PSPC/WFC</td>
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<td>C/1996 Q1 (Tabur)</td>
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<td>55P/Temple-Tuttle</td>
<td>Jan 1998</td>
<td>EUVE Scanners</td>
<td>0.02–0.18</td>
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<td></td>
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<td>103P/Hartley 2</td>
<td>Feb 1998</td>
<td>ROSAT PSPC/WFC</td>
<td>0.09–2.0</td>
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<td>C/1998 U5 (LINEAR)</td>
<td>Dec 1998</td>
<td>ROSAT PSPC/WFC</td>
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<td>C/2000 S4 (LINEAR)</td>
<td>Jul 2000</td>
<td>Chandra ACIS-S</td>
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<td></td>
<td>Aug 2000</td>
<td>Chandra ACIS-S</td>
<td>0.2–10.0</td>
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<td></td>
<td>Jan 2001</td>
<td>XMM-Newton</td>
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<td></td>
<td>Feb 2001</td>
<td>FUSE</td>
<td>0.113–0.117</td>
<td>No</td>
<td>[12]</td>
</tr>
</tbody>
</table>

TABLE 1. Observation times, instruments, and energies* for comets detected† through December 2002 in the X-ray or extreme ultraviolet.
2.1. Spatial Morphology

X-ray and EUV images of C/1996 B2 (Hyakutake) made by the ROSAT and EUVE satellites look very similar (Lisse et al., 1996; Mumma et al., 1997) (Fig. 1). Except for images of C/1990 N1 (Dennerl et al., 1997) and C/Hale-Bopp 1995 O1 (Krasnopolsky et al., 1997), all EUV and X-ray images of comets have exhibited similar spatial morphologies. The emission is largely confined to the cometary coma between the nucleus and the Sun; no emission is found in the extended dust or plasma tails. The peak X-ray brightness gradually decreases with increasing cometocentric distance $r$ with a dependence of about $r^{-1}$ (Krasnopolsky, 1997). The brightness merges with the soft X-ray background emission (McCammon and Sanders, 1990; McCammon et al., 2002) at distances that exceed $10^4$ km for weakly active comets, and can exceed $10^6$ km for the most luminous (Dennerl et al., 1997) (Fig. 2). The spatial extent for the most extended comets is independent of the rate of gas emission from the comet. The region of peak emission is crescent-shaped with a brightness peak displaced toward the Sun from the nucleus (Lisse et al., 1996, 1999). The distance of this peak from the nucleus appears to increase with increasing values of $Q$, and for Hyakutake was located at $r_{\text{peak}} = 2 \times 10^4$ km.

2.2. Luminosity

The observed X-ray luminosity, $L_x$, of C/1996 B2 (Hyakutake) was $4 \times 10^{15}$ ergs s$^{-1}$ (Lisse et al., 1996) for an aper-

![Fig. 1. Images of C/Hyakutake 1996 B2 on 26–28 March 1996 UT: (a) ROSAT HRI 0.1–2.0 keV X-ray; (b) ROSAT WFC 0.09–0.2 keV extreme ultraviolet; and (c) visible light, showing a coma and tail, with the X-ray emission contours superimposed. The Sun is toward the right, “+” marks the position of the nucleus, and the orbital motion of the comet is toward the lower right in each image. From Lisse et al. (1996).]
ture radius at the comet of $1.2 \times 10^5$ km. [Note that the photometric luminosity depends on the energy bandpass and on the observational aperture at the comet. The quoted value assumes a ROSAT photon emission rate of $P_X \approx 10^{25}$ s$^{-1}$ (0.1–0.6 keV), in comparison to Krasnopolsky et al.’s (2000) EUVE estimate of $P_{EUV} \approx 7.5 \times 10^{25}$ s$^{-1}$ (0.07–0.18 keV and 120,000 km aperture.) A positive correlation between optical and X-ray luminosities was demonstrated using observations of several comets having similar gas ($Q_{H_2O}$) to dust [$A_f \rho / Q_{H_2O}$], following A'Hearn et al. (1984)] emission rate ratios (Fig. 3) (Lisse et al., 1997b, 1999, 2001; Dennerl et al., 1997; Mumma et al., 1997; Krasnopolsky et al., 2000). $L_x$ correlates more strongly with the gas production rate $Q_{\text{gas}}$ than it does with $L_{\text{opt}} \sim Q_{\text{dust}} \sim A_f$ (Figs. 2 and 3). Particularly dusty comets, like Hale-Bopp, appear to have less X-ray emission than would be expected from their overall optical luminosity $L_{\text{opt}}$. The peak X-ray surface brightness decreases with increasing heliocentric distance $r$, independent of $Q$ (Dennerl et al., 1997), although the total luminosity appears roughly independent of $r$. The maximum soft X-ray luminosity observed for a comet to date is $\sim 2 \times 10^{16}$ erg s$^{-1}$ for C/Levy at 0.2–0.5 keV (Dennerl et al., 1997) (Fig. 3).

### 2.3. Temporal Variation

Photometric lightcurves of the X-ray and EUV emission typically show a long-term baseline level with superimposed impulsive spikes of a few hours’ duration, and maximum amplitude 3 to 4 times that of the baseline emission level (Lisse et al., 1996, 1999, 2001). Figure 4 demonstrates the strong correlation found between the time histories of the solar wind proton flux (a proxy for the solar wind minor ion flux), the solar wind magnetic field intensity, and a comet’s X-ray emission for the case of Comet 2P/Encke 1997 (Lisse et al., 1999). Neugebauer et al. (2000) compared the ROSAT and EUVE luminosity of C/1996 B2 (Hyakutake) with time histories of the solar wind proton flux, oxygen ion flux, and solar X-ray flux, as measured by spacecraft residing in the solar wind. They found the strongest correlation between the cometary emission and the solar wind oxygen ion flux, a good correlation between the comet’s emission and the solar wind proton flux, but no correlation between the cometary emission and the solar X-ray flux.

For the four comets for which extended X-ray lightcurves were obtained during quiet Sun conditions, the time delay between the solar wind proton flux and the comet’s X-ray impulse (Table 2) was well predicted by assuming a simple latitude-independent solar wind flow, a quadrupole solar magnetic field, and propagation of the sector boundaries radially at the speed of the solar wind and azimuth-
ally with period one-half the solar rotation period of 28 d
(\text{Lisse et al., 1997b, 1999; Neugebauer et al., 2000})

\[ \Delta t_{\text{total}} = \Delta t_{\text{Carrington rotation}} + \Delta t_{\text{radial}} = \frac{\text{longitude}_{\text{comet}} - \text{longitude}_{\text{Earth}}}{14.7^\circ/d} + \frac{r_{\text{comet}} - r_{\text{Earth}}}{400 \text{ km/s} \cdot 86400 \text{ s/d}} \]

2.4. Spectrum

Until 2001, all published cometary X-ray spectra had very low spectral energy resolution (\(\Delta E/E \sim 1\) at 300–600 eV), and the best spectra were those obtained by ROSAT for C/1990 K1 (Levy) (\text{Dennert et al., 1997}) and by BeppoSAX for Comet C/1995 O1 (Hale-Bopp) (\text{Owens et al., 1998}). These observations were capable of showing that the spectrum was very soft (characteristic thermal bremsstrahlung temperature \(kT \sim 0.23 \pm 0.04\) keV) with intensity increasing toward lower energy in the 0.01–0.60 keV energy range, and established upper limits to the contribution of the flux from K-shell resonance fluorescence of carbon at 0.28 keV and oxygen at 0.53 keV. However, even in these “best” spectra, continuum emission could not be distinguished from a multiline spectrum. Nondetections of Comets C/Hyakutake, C/Tabur, C/Hale-Bopp, and 55P/Temple-Tuttle using the XTE PCA (2–30 keV) and ASCA SIS (0.6–4 keV) imaging spectrometers were consistent with an extremely soft spectrum (\text{Lisse et al., 1996, 1997b}).

Higher-resolution spectra of cometary X-ray emission have just appeared in the literature. The Chandra X-ray Observatory (CXO) detected soft X-ray spectra from Comet C/1999 S4 (LINEAR) over an energy range of 0.2–0.8 keV, using an energy resolution with a full-

### Table 2. Predicted and observed lightcurve phase shifts using the latitude-independent model.

<table>
<thead>
<tr>
<th>Comet</th>
<th>Time of Impulse (00:00H UT)</th>
<th>(\Delta t_{\text{long}}) (d)</th>
<th>(\Delta t_{\text{radial}}) (d)</th>
<th>(\Delta t_{\text{total}}) (d)</th>
<th>(\Delta t_{\text{observed}}) (d)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hyakutake</td>
<td>27 Mar 1996</td>
<td>−0.23</td>
<td>0.032</td>
<td>−0.20</td>
<td>−0.24</td>
</tr>
<tr>
<td>Hale-Bopp</td>
<td>11 Sep 1996</td>
<td>−4.60</td>
<td>5.9</td>
<td>1.30</td>
<td>+1.4</td>
</tr>
<tr>
<td>Encke</td>
<td>7 Jul 1997</td>
<td>−0.26</td>
<td>0.093</td>
<td>−0.17</td>
<td>−0.1</td>
</tr>
<tr>
<td>Temple-Tuttle</td>
<td>29 Jan 1998</td>
<td>−2.31</td>
<td>0.37</td>
<td>−1.94</td>
<td>−2.5</td>
</tr>
</tbody>
</table>

Time shifts assume solar wind velocity as measured near-Earth; positive time shifts = impulse happens at Earth first, comet next; negative time shifts = boundary hits comet first, Earth next.
width half-maximum (FWHM) of $\Delta E = 0.11$ keV (Fig. 5). The spectrum is dominated by line emission, not by continuum. Using the CXO, a new spectrum of Comet C/1999 T1 (McNaught-Hartley) (Krasnopolsky et al., 2002) shows similar line-emission features. Line emission is also found in XMM-Newton spectra of Comet C/1999 T1 (McNaught-Hartley) and, more recently, in CXO spectra of C/2001 WM1 (LINEAR) and C/2002 Ikeya-Zhang (K. Dennerl et al. and C. M. Lisse et al., personal communication, 2003). An XMM-Newton spectrum of C/2001 WM1 (LINEAR) shows characteristic CXE X-ray signatures in unprecedented detail (K. Dennerl et al., personal communication, 2003). A re-

Fig. 6. EUVE observations of line emission from C/1996 B2 (Hyakutake), following Krasnopolsky and Mumma (2001). (a) MW (middle wavelength) 0.034–0.073 keV spectrum on March 23, 1996. (b) LW (long-wavelength) 0.018–0.04 keV. The extreme ultraviolet spectra are clearly dominated by line emission. The best agreement with CXE model predictions are for the O$^{4+}$, C$^{4+}$, and Ne$^{7+}$ lines. (c) FUSE observations of three comets, with a marginal detection of the CXE OVI line in C/2001 WM1 (LINEAR) at 1032 Å (following Weaver et al., 2002). The nondetections in Comets C/2001 A2 (LINEAR) and C/1999 T1 (McNaught-Hartley) and the marginal detection in C/2001 WM1 (LINEAR) are consistent with CXE predictions for the luminosity of these lines.
3. PROPOSED X-RAY MECHANISMS

A large number of explanations for cometary X-rays were suggested following the discovery paper in 1996. These included thermal bremsstrahlung (German for “braking radiation”) emission due to solar wind electron collisions with neutral gas and dust in the coma (Bingham et al., 1997; Dawson et al., 1997; Northrop, 1997; Northrop et al., 1997; Uchida et al., 1998; Shapiro et al., 1999), micrometeoroid impacts (Ibadov, 1990; Ip and Chow, 1997), K-shell ionization of neutrals by electron impact (Krasnopolsky, 1997), scattering or fluorescence of solar X-rays by cometary gas or by small dust grains (Lisse et al., 1996; Wickramasinghe and Hoyle, 1996; Owens et al., 1998), and by charge exchange between highly ionized solar wind ions and neutral species in the cometary coma (CXS) (Cravens, 1997a; Häberli et al., 1997; Wegmann et al., 1998; Kharchenko and Dalgalno, 2000; Kharchenko et al., 2003; Schwadron and Cravens, 2000). In the thermal bremsstrahlung mechanism, fast electrons are deflected in collisions with charged targets, such as the nuclei of atoms, and emit continuum radiation. Electron energies in excess of 100 eV (T > 10^6 K) are needed for the production of X-ray photons. In the K-shell mechanism, a fast electron collision removes an orbital electron from an inner shell of the target atom. Early evaluation of these various mechanisms (Dennerl et al., 1997; Krasnopolsky, 1997; Lisse et al., 1999) favored only three of them: the CXS mechanism, thermal bremsstrahlung, and scattering of solar radiation from very small (i.e., attogram; 1 attogram = 10^-19 g) dust grains.

A significant problem with mechanisms involving solar wind electrons (i.e., bremsstrahlung or K-shell ionization) is that the predicted emission luminosities are too small by factors of 100–1000 compared to observations. The flux of high-energy solar wind electrons near comets is too low (Krasnopolsky, 1997; Cravens, 2000b, 2002a). Furthermore, X-ray emission has been observed out to great distances from the nucleus, beyond the bow shock (Fig. 2), and the thermal energy of unshocked solar wind electrons at these distances is about 10 eV. No emission has ever been found to be associated with the plasma tail of a comet, which has similar plasma densities and temperatures. Finally, the new, high-resolution spectra demonstrating multiple atomic lines are inconsistent with a continuum-type mechanism or a mechanism producing only a couple of K-shell lines as the primary source of cometary X-rays. Lisse et al. (2001) tried several thermal bremsstrahlung continuum model fits to the C/1999 S4 spectrum, and Krasnopolsky and Mumma (2001) tried the same for the C/1996 B2 (Hyakutake) spectrum, but neither was successful.

Mechanisms based on dust grains also have a number of problems. It has been known since 1996 that Rayleigh scattering of solar X-ray radiation from ordinary cometary dust grains (i.e., about 1 µm in size) cannot produce the observed luminosities — the cross section for this process is too small (Lisse et al., 1996). A potential solution to this problem is to invoke a population of very small, attogram (10^-19 g) grains with radii on the order of the wavelengths of the observed X-ray radiation, 10–100 Å, which can resonantly scatter the incident X-ray radiation. The abundance of such attogram dust grains is not well understood in comets, as they are undetectable by remote optical observations; however, there were reports from the VEGA Halley flyby of a detection of an attogram dust component using the PUMA dust monitor (Vaisberg et al., 1987; Sagdeev et al., 1990). However, the statistical studies of the properties of several comets (Figs. 2 and 3) demonstrate that X-ray emission varies with a comet’s gas production rate and not the dust production rate (Dennerl et al., 1997; Lisse et al., 1999, 2001). Furthermore, the cometary X-ray lightcurves (Lisse et al., 1996, 1999, 2001; Neugebauer et al., 2000) correlate with the solar wind ion flux and not with solar X-ray intensity. Finally, dust-scattering mechanisms cannot account for the pronounced lines seen in the new high-resolution spectra — emission resulting from dust scattering of solar X-rays should mimic the Sun’s X-ray spectral continuum, similar to what is observed in the terrestrial atmosphere for Rayleigh scattering of sunlight (Krasnopolsky, 1997).

The CXS mechanism requires that the observed X-ray emission is driven by the solar wind flux and that the bulk of the observed X-ray emission be in lines. Localization of the emission to the sunward half of the coma, a solar wind flux-time dependence, and a line-emission-dominated spectral signature of the observed emission all strongly point to the solar wind charge exchange mechanism as being responsible for cometary X-rays.

4. SOLAR WIND CHARGE EXCHANGE X-RAY MECHANISM

The solar wind is a highly ionized but tenuous gas (i.e., a plasma) (Cravens, 1997b). At its source in the solar corona, the million-degree gas is relatively dense and in collisional equilibrium, but its density drops within a few solar radii into a freeflow regime wherein collisions are infrequent. Both the solar wind and corona have “solar” composition — 92% hydrogen by volume, 8% helium, and 0.1% heavier elements. The heavier, “minor ion” species are highly charged (e.g., oxygen in the form of hydrogen-like O^+ or helium-like O^6+ ions, N^+6/N^5+, C^5+/C^4+, Ne^8+, Si^8+, Fe^{12+}, etc.) due to the high coronal temperatures (Bame, 1972; Bochsler, 1987; Neugebauer et al., 2000). The solar wind flow starts out slowly in the corona but becomes supersonic at a distance of few solar radii (Parker, 1963; Cravens, 1997b). The gas cools as it expands, falling from T = 10^6 K down to about 10^5 K at 1 AU. The average properties of the solar wind at 1 AU are proton number
density = $7 \text{ cm}^{-3}$, speed = $450 \text{ km s}^{-1}$, temperature = $10^5 \text{ K}$, magnetic field strength = $5 \text{ nT}$, and Mach number = $8$ (Hundhausen et al., 1968). However, the composition and charge state distribution far from the Sun are “frozen in” at coronal values due to the low collision frequency outside the corona. The solar wind contains structure, such as slow ($400 \text{ km s}^{-1}$) and fast ($700 \text{ km s}^{-1}$) streams, which can be mapped back to the Sun. The solar wind “terminates” in a shock called the heliopause, where the ram pressure of the streaming solar wind has fallen to that of the interstellar material (ISM) gas (Suess, 1990). The region of space that contains plasma of solar origin, from the corona to the heliopause at ~100 AU, is called the heliosphere. A very small part of the solar wind interacts with the planets and comets; the bulk of the wind interacts with neutral ISM gas in the heliosphere and neutral and ionized ISM material at the heliopause.

As the solar wind streams into a comet’s atmosphere, cometary ion species produced from solar UV photoionization of neutral coma gas species are added to the flow as “pick-up ions.” The resulting mass addition slows down the solar wind due to momentum conservation and a bow shock forms upwind of the comet (Galeev, 1991; Szegö et al., 2000) (Fig. 7). The flow changes from supersonic to subsonic across the shock, and the magnetic field strength increases by a factor of ~5. Closer to the nucleus, where the cometary gas density is higher and collisions more frequent, the flow almost completely stagnates (Flammer, 1991). The outer boundary of this stagnation region is often called the cometopause (cf. review by Cravens, 1991). The observed X-ray brightness peak resides within this boundary. Magnetic field lines pile up into a “magnetic barrier” in this stagnation region and drape around the head of the comet forming the plasma tail in the downwind direction (Brandt, 1982).

From experimental and theoretical work in atomic and molecular physics it is found that solar wind minor ions readily undergo charge transfer (or exchange) reactions (Phaneuf et al., 1982; Dijkkamp et al., 1985; Gilbody, 1986; Janev et al., 1988; Wu et al., 1988) when they are within ~1 nm of a neutral atomic species

$$A^{q+} + B \rightarrow A^{(q-1)+} + B^+ \quad (1)$$

where $A$ denotes the solar wind projectile ion (e.g., O, C, Si . . . ), $q$ is the projectile charge (e.g., $q = 5, 6, 7$) and $B$ denotes the neutral target species (e.g., H$_2$O, OH, CO, O, H . . . for cometary comae) (Fig. 8). The cross section for this process is large, on the order of $10^{-15} \text{ cm}^2$, about 1 order of magnitude larger than the hard-sphere collisional cross section.

The product ion deexcites by emitting one or more photons ($A^{(q-1)+} \rightarrow A^{(q-1)+} + h\nu$, where $h\nu$ represents a photon). It is the characteristic radiation of the product ion that is measured with astronomical X-ray instrumentation, and so one labels the radiation detected by the charge state of the final ion. The deexcitation usually takes place via a cascade through intermediate states rather than in one step to the ground state. For large enough values of $q$, the deexcitation transitions lead to the emission of X-ray photons. For species and charge states relevant to comets, the principal quantum number of the ion $A^{(q-1)+}$ is about $n = 4$ or 5.

![Fig. 7. Spatial schematic of the solar wind-comet interaction. The relative locations of the bow shock, the magnetic barrier, and the tail are shown (not to scale). The Sun is toward the left. Also represented is a charge transfer collision between a heavy solar wind ion and a cometary neutral water molecule, followed by the emission of an X-ray photon. After Cravens (2002b); copyright journal Science (2002).](https://example.com/fig7)

![Fig. 8. Energy level diagram for a CXE process. Electron potential energy (atomic units, a.u.) vs. distance from the target atom nucleus (assumed here to be an H atom) for a charge transfer reaction involving a projectile ion Be$^{4+}$. The internuclear distance chosen is 10 Bohr radii or $5.29 \times 10^{-10} \text{ m}$, the curve-crossing distance for the $n = 3$ ion final state. The target energy level (and binding energy $E_b$) and product ion (Be$^{3+}$) energy levels are shown in units of hartrees (1 hartree = 27.2 eV). A possible cascading pathway for the deexcitation by photon emission is shown. After Cravens (2002b); copyright journal Science (2002).](https://example.com/fig8)
(Ryuifuku et al., 1980; Mann et al., 1981). The cross section for charge exchange between a high charge state solar wind ion and an ionized coma gas species is negligible in comparison, due to the effects of Coulomb repulsion between the two reactants. Once a coma neutral atom is ionized, either by CXE processes or solar UV flux, the CXE mechanism is no longer an important energy transfer process.

### 4.1. Charge Exchange Morphology

Numerical simulations of the solar wind interaction with Hyakutake including CXE have been used to generate X-ray images. A global magnetohydrodynamic (MHD) model (Häberli et al., 1997) and a hydrodynamic model (Wegmann et al., 1998) were used to predict solar wind speeds and densities and the X-ray emission around a comet. The simulated X-ray images are similar to the observed images, which is relatively unsurprising, as any dissipative solar wind–coma process with total optical depth near unity would create the observed morphology (Fig. 1). The emission is found to lie in the sunward hemisphere of the neutral coma, varying from collisionally thin to collisionally thick as the solar wind approaches the nucleus. Emission is predicted to be in the soft X-ray, UV, and optical wavelengths, with the softest photons emitted closest to the nucleus. However, the spatial models to date have included only highly simplified models of the CXE deexcitation cascade, as compared to the detailed spectral models of the global behavior discussed below.

As an example of the potential of studying the behavior of the solar wind inside the coma using CXE reactions, we consider the dissimilar morphologies of the extended Lyman-$\alpha$ coma and the X-ray emitting regions of comets (cf. Keller, 1973; Festou et al., 1979; Combi et al., 2000). The CXE mechanism should not only transfer electrons from cometary neutrals to solar wind minor ions, but to the solar wind majority ions $H^+$ and $He^{++}$ as well. These ions are roughly 1000 times more abundant than the X-ray active highly ionized minor ions. The prompt photon-emission energy produced from CXE by He$^{++}$ ions produces at least three times the energy released by all the minor ions combined (D. Shemansky, personal communication, 2003). Further, the neutral atoms produced are capable of scattering emission from the Sun. At luminosities of $\sim 10^{16}$ erg s$^{-1}$, and production rates of $\sim 10^{27}$ s$^{-1}$, the HI created by CXE would create the observed morphology (Fig. 1). The emission is found to lie in the sunward hemisphere of the neutral coma, varying from collisionally thin to collisionally thick as the solar wind approaches the nucleus. Emission is predicted to be in the soft X-ray, UV, and optical wavelengths, with the softest photons emitted closest to the nucleus. However, the spatial models to date have included only highly simplified models of the CXE deexcitation cascade, as compared to the detailed spectral models of the global behavior discussed below.

### 4.2. Charge Exchange Luminosity and Temporal Variation

To first order, the CXE local X-ray power density $P_x$ can be estimated assuming only one CXE collision per solar wind ion per coma passage. This approximation yields the expression

$$ P_x = \alpha n_{sw} u_{sw} n_n $$

where $n_{sw}$, $u_{sw}$, and $n_n$ are the solar wind proton density, solar wind speed, and neutral target density respectively (Cravens, 1997a, 2002a). All the “atomic and molecular details” as well as the solar wind heavy ion fraction $f_h$ are combined into the parameter $\alpha$, given by $\alpha = f_h(s_{\alpha})E_{ave}$, where $\langle s_{\alpha} \rangle$ is an average CXE cross section for all species and charge states, and $E_{ave}$ an average photon energy. A simple spherically symmetric approximation to the neutral density in the coma is given by $n_n = Q/(4\pi u_r^2)$, for $r$ less than the ionization scale length $R = u_n t$, where $t = 10^6$ s is the ionization lifetime [for 1 AU (Schleicher and A’Heam, 1988)] and $u_n = 1$ km s$^{-1}$ the neutral gas outflow speed. Integration of $P_x$ over the volume of the neutral coma yields an X-ray luminosity typically within a factor of 2–3 of the observed luminosity (Cravens, 1997a, 2002a; Lisse et al., 2001). The observed luminosity is a function of both the solar wind flux density and the cometary neutral gas production rate up to the limit of 100% charge exchange efficiency of all solar wind minor ions within an ionization scale length of $10^6$ km. The maximum expected X-ray luminosity at 1 AU and 0.2–0.5 keV is $\sim 10^{16}$ erg s$^{-1}$ (Fig. 3). Temporal variations of the solar wind flux directly translate into time variations of the X-ray emission (Fig. 4).

### 4.3. Charge Exchange Spectra

Model CXE spectra are in good agreement with the low-resolution X-ray spectra of cometary X-ray emission, and the line centers of the high-resolution spectra have been successfully predicted using CXE theory (Figs. 5 and 6) (Lisse et al., 1999, 2001; Krasnopolsky and Mumma, 2001; Weaver et al., 2002). The application of the CXE model to comets has entailed a number of approaches to date. Some work has included only a few solar wind species but used a careful cascading scheme (Häberli et al., 1997). Other approaches have used a simple cascading scheme and simple collision cross sections, but included a large number of solar wind ions and charge states (Wegmann et al., 1998; Schwadron and Cravens, 2000). Kharchenko and colleagues (Kharchenko and Delgarno, 2000; Kharchenko et al., 2003) have treated the atomic cascading process more carefully than other modelers, although the spatial structure of the solar wind–cometary neutral interaction in their model was highly simplified. They predicted the existence of a large number of atomic lines, including $O^{5+}$ ($1s^25d \rightarrow 1s^22p$) at 106.5 eV, $C^{4+}$ ($1s2s \rightarrow 1s^2$) at 298.9 eV, $C^{5+}$ ($2p \rightarrow 1s$) at 367.3 eV, $C^{5+}$ ($4p \rightarrow 1s$) at 459.2 eV, and $O^{6+}$ ($1s^2p \rightarrow 1s^2$) at 568.4 eV. At least some of these lines appear in the best
cometary X-ray spectra to date, the CXO ACIS-S spectra of C/1999 S4 (LINEAR) and C/1999 T1 (McNaught-Hartley). The peak measured near 0.56 keV is certainly the combination of three closely spaced helium-like O6+ (1s2p and 1s2s → 1s2) transitions (which comes from CXE of solar wind O7+) and the line located at 0.32 keV is due to helium-like C4+ (1s2p and 1s2s → 1s2). Similar identifications have been made for the EUVE spectrum of C/1996 B2 (Hyakutake) (Krasnopolsky and Mumma, 2001). The spectral problem is still far from totally solved, however. Careful comparisons and calculations needed to interpret the subtleties of the high-resolution spectral observations, including the role of collisions after charge transfer, solar wind ion–dust interactions, and the exact species present at each point in the coma, are only now starting to be done (Krasnopolsky et al., 2002; Kellett et al., 2003).

5. THE FUTURE OF COMETARY X-RAY EMISSION STUDIES

The discovery that comets are X-ray sources can now be explained by charge exchange reactions of highly charged solar wind ions with neutral atoms and molecules residing in the cometary coma. The energy required to power this emission originates in the hot solar corona and is stored as solar wind ions with neutral atoms and molecules residing in the cometary coma neutral atoms and molecules, release this potential energy in the form of X-ray and UV radiation. This simple model can explain the gross features of the observed crescent-shaped emission with its sunward displaced peak, the maximum spatial extent of the emission of ~10^6 km (Figs. 1 and 2), the maximum observed luminosity of ~10^16 erg s^-1 (Fig. 3), and spectra dominated by line emission (Fig. 4).

5.1. Plasma-Neutral Interactions in the Cometary Coma

However, a more careful treatment of the CXE mechanism is needed to fully understand the phenomenon of cometary X-ray emission. One complication is that the multiple CXE collisions take place in regions close to the nucleus where the target density is high (the so-called “collisionally thick” case). The charge state for the initially hydrogen-like or helium-like solar wind minor ion is reduced by one during each CXE collision, ultimately leading to its conversion to a neutral atom. When the ion’s charge state becomes too low, X-ray photons are no longer emitted. When the number of neutrals in a volume of space becomes too low, due to coma expansion and ionization of coma gas molecules by solar UV radiation, X-ray photons are no longer detectable. Another complication is that spectral differences are expected for slow and fast solar wind streams, with the slow solar wind, with its higher coronal freeze-in temperature, producing a harder spectrum than does the fast solar wind (Schwadron and Cravens, 2000).

Further theoretical progress will require the integration of several ingredients into a single model: (1) accurate solar wind composition for a range of solar wind types; (2) a suitable MHD model of the solar wind interaction with the coma, in order to accurately predict the densities of ions and neutrals in equation (2); and (3) a more detailed understanding of the atomic processes, in order to improve our understanding of the parameter α in equation (2). Success for the first point requires new and improved measurements of the solar wind throughout the heliosphere, and/or large number statistical studies of cometary X-ray emission throughout the heliosphere; the second point requires improved MHD codes on modern supercomputers; and to achieve the third point, additional laboratory measurements of state-specific CXE cross sections will be required. The first and second points are being actively pursued by astronomers and modelers in the field. New laboratory work is now being undertaken (Beiersdorfer et al., 2000, 2001; Greenwood et al., 2000; Hasan et al., 2001) to measure CXE cross sections for comet target species such as H_2O at collision energies relevant to the solar wind (a few keV/amu). Recent measurements have indicated, for example, that multiple as well as single-electron CXE makes a contribution to the X-ray emission (Hasan et al., 2001; Greenwood et al., 2001; Gao and Kwong, 2002). Given detailed MHD models of the solar wind passing through the coma and accurate cross sections for the CXE process, we will be able to map out the density of solar wind minor ions in the coma.

5.2. Remote Sensing of the Solar Wind

Driven by the solar wind, cometary X-rays provide an observable link between the solar corona, where the solar wind originates, and the solar wind where the comet resides. Once we have understood the CXE mechanism’s behavior in cometary comae in sufficient detail, we will be able to use comets as probes to measure the solar wind throughout the heliosphere. This will be especially useful in monitoring the solar wind in places hard to reach with spacecraft — over the solar poles, at large distances above and below the ecliptic plane, and at heliocentric distances greater than a few AU (Lisse et al., 1996, 2001; Krasnopolsky et al., 2000). For example, approximately one-third of the observed soft X-ray emission is found in the 530–700-eV oxygen O7+ and O6+ lines; observing photons of this energy allows studies of the oxygen ion charge ratio of the solar wind, which is predicted to vary significantly between the slow and fast solar winds (Neugebauer et al., 2000; Schwadron and Cravens, 2000; Kharchenko and Dalgarno, 2001).

5.3. Emission from Other Planetary Systems

The CXE mechanism operates wherever the solar wind (or any highly ionized plasma) interacts with a substantial quantity of neutral gas. Motivated in part by the discovery of the new class of cometary X-ray emitters, further meas-
measurements of potential solar system sources (Holmström et al., 2001; Cravens and Maurellis, 2001) of X-ray emission have been undertaken recently. X-rays have now been observed from Venus as solar X-rays fluently scattered by the thick (compared to comets) venusian atmosphere (Dennerl et al., 2002), and from Mars as ~90% fluently scattered solar X-rays from the thick martian atmosphere and ~10% CXE-derived X-rays (Dennerl, 2002). The solar wind is known to approach very closely to these planets due to their weak intrinsic magnetic fields, which cannot act as effective obstacles to the external flow, allowing for CXE processes to occur. The small spatial extent and high density of the gravitationally bound planetary atmospheres provides a higher X-ray luminosity due to scattering of solar X-rays than from CXE. X-rays have now been detected at Io and Europa and in the Io flux torus using Chandra, although the exact mechanism of emission is still unknown (Elser et al., 2002). Another neutral gas system from which X-ray emission has been predicted is the terrestrial hydrogen geocorona (Cox, 1998; Cravens, 2000a; Dennerl, 1999; Freyberg, 1998; Robertson and Cravens, 2003), although no detection has yet been made.

X-ray emission from the heliosphere is also expected from the interaction of the solar wind with the interstellar neutral gas (mainly HI and He) that streams into the solar system (Cox, 1998; Cravens, 2000a,b). Cravens (2000b) demonstrated that roughly one-half of the observed 0.25-keV X-ray diffuse background can be due to this process. Solar and Heliospheric Observatory (SOHO) observations of neutral hydrogen Lyman α emission show a clear asymmetry in the ISM flow direction, with a clear deficit of neutral hydrogen in the downstream direction of the incoming neutral ISM gas, most likely created by CXE ionization of the ISM as it transits the heliosphere. Cravens et al. (2001) have shown a strong correlation between the solar wind flux density and the ROSAT “long-term enhancements,” systematic variations in the soft X-ray background of the ROSAT X-ray detectors. Photometric imaging observations of the lunar nightside by Chandra made in September 2001 do not show any lunar nightside emission above a CXE background. The soft X-ray emission detected from the darkside of the Moon, using ROSAT, would appear to be due not to electrons spiraling from the sunward to the dark hemisphere, as proposed by Schmitt et al. (1991), but instead be due to CXE in the column of solar wind between Earth and the Moon. The analogous process applied to other stars has been suggested as a means of detecting stellar winds (Lisse, 2002a,b; Wargelin and Drake, 2001).

5.4. Soft X-Ray Background

Heliospheric and geocoronal X-ray emission have been suggested (Cravens, 2000b, 2002b; Dennerl, 1999; Lisse et al., 2001) to make significant contributions to the observed soft X-ray background [previously attributed entirely to hot interstellar gas (Snowden et al., 1990, 1998; McCammon et al., 2002)]. This supposition is supported by the positive correlations that have been found between measured solar wind fluxes and measured X-ray background intensities (Cravens et al., 2001; Robertson et al., 2001). Recent large angular scale measurements of the diffuse soft X-ray background in a 100-s rocket flight by McCammon et al. (2002) and in the Chandra background toward MBM12 (R. Edgar et al., personal communication, 2001) show a clear peak at 560 eV, as expected for CXE-driven emission (Fig. 4). A significant fraction of the line emission observed in the soft X-ray background, e.g., the 560-eV emission, is probably due to CXE emission in our solar system and around other stars.

REFERENCES


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