Highly charged ions are amongst if not the most reactive species in the universe. These ions are produced in hot gases of several millions of degrees. When colliding with a neutral gas, the ions are neutralized via charge exchange reactions. These interactions are therefore a key aspect in many astrophysical environments. In the solar system, collisions between a hot plasma and a neutral gas occur when the solar wind interacts with planets, moons, comets and the in streaming neutral interstellar medium. Charge exchange processes might also occur around other stars with even more violent stellar winds, in planetary nebulae (e.g. interaction of the fast post Asymptotic Giant Branch wind with the slowly-moving wind), when supernova remnants interact with the interstellar medium (e.g. the venting of supernova remnants into the lower galactic halo) and on a truly galactic scale, the interaction of winds - associated with starbursts - with the interstellar medium.

Charge exchange reactions are quasi-resonant processes, and depend strongly on properties of both the neutral and the ionized gas. The resulting emission therefore provides a unique window on their interactions. As such, charge exchange emission (CXE) has an important application in controlled fusion experiments, as both Doppler shifts of CXE lines and their absolute and relative intensities can provide information on local plasma parameters such as temperatures, velocities and abundances and charge state of the interacting plasmas (Isler, 1994; von Hellermann et al., 1991; Hoekstra et al., 1998; Anderson et al., 2000).

1.1 Cometary X-ray and EUV emission

X-ray and Extreme Ultraviolet (EUV) emission is usually associated with high temperature environments. The discovery that comets are bright emitters in this spectral regime was therefore a big surprise (Lisse et al., 1996; Mumma et al., 1997), because comets are generally considered dirty snowballs surrounded by a gaseous coma with a temperature of approximately 50 K. After the first discovery by ROSAT of the X-ray emission from comet C/1996 B2 (Hyakutake), a search through the observatory's archives proved that in fact all comets in the inner solar system (≤ 3 AU) were emitting X-rays (Dennerl et al., 1997). The total X-ray power in the 0.2 – 1.0 keV band was between 0.2 – 1 GW, the emission was
highly variable in time and many of the observed comets displayed a characteristic crescent shape.

To explain these surprising observations, numerous possible scenarios were proposed. Amongst them were scattering/fluorescence of solar X-rays (Krasnopolsky, 1997), thermal bremsstrahlung associated with collisions of solar wind electrons with cometary neutral gas or dust (Bingham et al., 1997; Northrop et al., 1997; Uchida et al., 1998), electron/proton K- and L-shell ionization (Krasnopolsky, 1997), and Rayleigh-scattering of solar X-rays by attogram dust particles (Wickramasinghe and Hoyle, 1996; Owens et al., 1998; Schulz et al., 2000) and charge exchange between highly ionized solar wind minor ions and cometary neutral species (Cravens, 1997). A thorough comparative study by Krasnopolsky (1997) demonstrated that none of these mechanisms except for the charge exchange emission (CXE) model could account for more than 5% of the observed luminosities.

The launch of a new generation of X-ray observatories (Chandra and XMM-Newton) allowed for a definitive answer of the comet-X-ray enigma. The observations of comet C/1999 S4 (LINEAR) in July 2000 demonstrated the presence of carbon and oxygen emission lines in the comet’s X-ray spectrum, thereby underpinning the CXE mechanism (Lisse et al., 2001).

Before space probes that to monitor the solar wind became available, cometary ion tails were the only solar wind probes in space. Even nowadays, they largely remain so for regions outside the ecliptic plane. Cometary X-rays in particular have proven to be excellent probes to study solar wind – neutral gas interactions, because comets have no magnetic field and the wind therefore interacts directly with the neutral gas surrounding the nucleus, the coma. Secondly, the size of the cometary atmosphere (in the order of $10^4 — 10^5$ km) allows remote tracking of the ions as they penetrate into the comet’s atmosphere, offering a close-up view on the interaction of the two plasmas. Thirdly, since the first observations of cometary X-ray emission, more than 20 comets have been observed with various X-ray and Far-UV observatories (Lisse et al., 2004; Krasnopolsky et al., 2004). This observational sample contains a broad variety of comets, solar wind environments and observational conditions. The observations clearly demonstrate that cometary charge exchange emission provides a wealth of diagnostics, which are visible as spatial, temporal and spectral emission features.

First of all, the emission morphology is a tomography of the distribution of neutral gas around the nucleus (Wegmann et al., 2004), see Fig. 1.1. In active comets, the X-ray emission clearly maps a spherical gas distribution. This resulted in a characteristic crescent shape for the larger and hence collisionally thick comets, observed at phase angles of roughly 90 degrees. Good examples are the observations of the comets Hyakutake (Lisse et al., 1996), LINEAR S4 (Lisse et al., 2001) and C/2000 WM1 (Wegmann and Dennerl, 2005). Macroscopic features of the plasma interaction such as the bow shock are observable, too (Wegmann and Dennerl, 2005). In less active comets, gaseous structures in the collisionally thin parts of the coma brighten, as is illustrated in Fig. 1.1 for the jets in 2P/2003 (Encke) (Lisse et al., 2005). The morphology of the emission is not crescent-like, but maps the optical coma, which was faint and dominated by a sunward fan composed of two bright jets. Other examples are the Deep Impact triggered plume in 9P/Tempel 1 (Lisse et al., 2007) and the unusual morphology of comet 6P/d’Arrest (Mumma et al., 1997).

Secondly, by observing the temporal behavior of the comet’s X-ray emission, the ac-
1.1 Cometary X-ray and EUV emission

Figure 1.1: Top panel: Comet Hyakutake in 1996, observed with ROSAT (Lisse et al., 1996). The comet produced enormous amounts of gas during the observations and was therefore collisionally thick for solar wind ions, resulting in a characteristic crescent shape. Bottom panel: Chandra X-ray image of comet 2P/2003 (Encke) from Lisse et al. (2005). The nucleus is in the center of the image. The image in lower panel corresponds to a square of $9 \times 10^4$ km on the sides, the image in the upper panel is 7.5 times larger. In both images, the direction to the Sun is approximately towards the right.
Figure 1.2: X-ray light curve of comet 9P/2005 (Tempel 1) for the period June 30 – July 14, 2005, observed by Chandra (■–Lisse et al., 2007) and Swift (□–Willingale et al., 2006) in the 0.3 – 1.0 keV band. The light curve follows the combined temporal behavior of neutral gas (comet gas production, △) and solar wind ion flux (★). This product is indicated with a solid line. All parameters are plotted on an arbitrary scale.

Activity of the solar wind and comet can be monitored. This was first shown for comet C/1996 B2 (Hyakutake) (Neugebauer et al., 2000) and recently in great detail by long term observations of comet 9P/2005 (Tempel 1) (Willingale et al., 2006; Lisse et al., 2007) and 73P/2006 (Schwassmann-Wachmann 3C) (Brown et al., prep), where cometary X-ray flares could be assigned to either cometary outbursts and/or solar wind enhancements (see Fig. 1.2).

Thirdly, cometary spectra reflect the physical characteristics of the solar wind; e.g. spectra resulting from either fast, cold (polar) wind and slow, warm equatorial solar wind should be clearly different (Schwadron and Cravens, 2000; Kharchenko and Dalgarno, 2001; Bodewits et al., 2004). Several attempts were made to extract ionic abundances from the X-ray spectra. The first generation spectral models have all made strong assumptions when modeling the X-ray spectra (Haberli et al., 1997; Wegmann et al., 1998; Kharchenko and Dalgarno, 2000; Schwadron and Cravens, 2000; Lisse et al., 2001; Kharchenko and Dalgarno, 2001; Krasnopolsky et al., 2002; Beiersdorfer et al., 2003; Wegmann et al., 2004; Bodewits et al., 2004; Krasnopolsky, 2004; Lisse et al., 2005). Because many different analytical methods were used, it has been very difficult to study the existing spectra compar-


1.2 Thesis Outline

This thesis discusses the diagnostic use of charge exchange emission, in particular applied to the interaction between comets and the solar wind. In Chapter 2, an overview is given of the fundamental concepts of comets, the solar wind, and their interaction. In Chapter 3, the main charge exchange processes relevant to comet–solar wind interactions are introduced and explained by means of the Classical Over-the-Barrier and Bohr-Lindhard models. In Chapter 4, the experimental set up is described, together with the main features of the experimental techniques used throughout this thesis. Experimental results for collisions between solar wind ions and species which are abundant in the inner coma of cometary atmospheres are presented in Chapters 5–7. In Chapter 8, an interaction model is introduced which uses state selective electron capture cross sections to predict and explain cometary charge exchange emission. This model is then applied to EUV (Chapter 9) and X-ray observations (Chapter 10). Finally, a summary and outlook are given in Chapter 11.