Cometary X-ray and Far UV emission depend on properties of the comet and solar wind, and on the characteristics of their interaction. This chapter presents a brief overview of the fundamental concepts relevant in cometary and solar wind studies. In Chapter 8, these will be used as the foundations of our comet-wind interaction model.

2.1 Solar Wind

The solar wind is the expansion of the solar corona into the interplanetary medium. Every second, approximately $10^9$ kg of material is ejected by the Sun as solar wind. Around Earth, the solar wind consists of circa 9 protons, 10 electrons and 0.5 alpha-particles per cm$^3$. It also contains a small fraction of heavier ions (C, N, O, Ne, ...). They pass Earth with an average velocity of 450 km s$^{-1}$. To most people, the solar wind is best known for its harmless manifestation in the northern light. The Sun's solar wind may have been about 1000 times more massive in the distant past, which must then have affected the history of our solar system. It has even been suggested that Mars' atmosphere has been eroded by the solar wind. Nowadays, space weather effects can still disrupt power grids, disturb radio communication, cause the failure of spacecraft electronics or impose a health hazard for astronauts or even airline passengers.

The solar wind was first predicted when in the early 50's, Biermann (1951) and others tried to explain the kinematics of cometary ion tails. In the next decades, space exploration led to the actual discovery of the solar wind and many experiments were performed to measure its composition and its temporal and spatial behavior. Currently, the solar wind is continuously monitored by a small armada of space crafts. SOHO and ACE are positioned at the Lagrangian point L1, roughly one million kilometers upstream the solar wind, and provide real time solar wind data such as the proton velocity and density, but also compositional data on helium and minor ions. Ulysses, launched in 1990, orbits the Sun in a polar orbit and thus measures latitudinal structures in the wind. Recently, the STEREO instrument was launched, which will provide accurate observations of the outflow directions of coronal mass ejections.

The solar wind is a collisionless plasma of which the composition and charge state
Comets and the Solar Wind

Figure 2.1: Solar wind velocities during solar minimum (left panel) and maximum (right panel). During most of the solar cycle, the wind is organized in a bimodal structure with slow, variable wind around the helioequator and fast, steady wind at higher latitudes. During solar maximum, the slow irregular wind is dominant at all latitudes (Courtesy of Southwest Research Institute and the Ulysses/SWOOPS team).

are frozen in within a few solar radii from the Sun. The composition of the solar wind is therefore a measure of its source region. A parameter often used is the freeze-in (or freezing-in) temperature of two charge states of an ionic species. This quantity is defined as the electron temperature at which the abundance ratio of two neighboring charge states is in ionizational/recombinational equilibrium (Hundhausen et al., 1968). This freeze-in temperature is different for each element, because due to different ionization and recombination time scales, their charge states are frozen in in different parts of the corona. For

Table 2.1: Characteristics of the two types of solar wind, after Axford and McKenzie (1997).

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Slow wind</th>
<th>Fast wind</th>
</tr>
</thead>
<tbody>
<tr>
<td>Speed</td>
<td>300-400 km s⁻¹</td>
<td>700 – 800 km s⁻¹</td>
</tr>
<tr>
<td>Density</td>
<td>10 cm⁻³</td>
<td>3 cm⁻³</td>
</tr>
<tr>
<td>Flux</td>
<td>3 × 10⁸ cm⁻² s⁻¹</td>
<td>2 × 10⁸ cm⁻² s⁻¹</td>
</tr>
<tr>
<td>Structure</td>
<td>highly variable</td>
<td>uniform, slow changes only</td>
</tr>
<tr>
<td>He/H</td>
<td>1-30%</td>
<td>5%</td>
</tr>
<tr>
<td>Minor ions</td>
<td>highly variable</td>
<td>almost constant</td>
</tr>
<tr>
<td>(T_f (O^+7/O^+6))</td>
<td>1.2 – 1.7 MK</td>
<td>≤ 1.2 MK</td>
</tr>
<tr>
<td>Coronal source</td>
<td>Streamer belt</td>
<td>Coronal holes</td>
</tr>
<tr>
<td>Latitude at minimum</td>
<td>≤ 15°</td>
<td>&gt; 30°</td>
</tr>
<tr>
<td>Latitude at maximum</td>
<td>all latitudes</td>
<td>less common, often transient</td>
</tr>
</tbody>
</table>
2.1 Solar Wind

ion pairs of the same element however, a single freeze-in temperature often describes the charge state distribution well (Geiss et al., 1995).

During solar minimum, the solar wind is organized in a bimodal structure with a slow, 300 km s$^{-1}$ wind around the solar equator, and a fast, 700 km s$^{-1}$ wind at latitudes above 30 degrees that is associated with polar coronal holes. This is illustrated in Fig. 2.1, which summarizes solar wind velocities measured by the Ulysses spacecraft. The fast and slow wind not only differ in velocity, but also in their charge state composition, reflecting the different origins of these wind types. The different properties of the two wind types are summarized in Table 2.1. The freeze-in temperature $T_f (O^{7+}/O^{6+})$ for the fast wind is approximately 1.2 MK and relatively constant. For the slow wind, it is around 1.7 MK and highly variable (Geiss et al., 1995; Zurbuchen et al., 2002). The fast, polar wind is thus ‘colder’ than the slow, equatorial wind and its heavy ions are on average of lower charge state than those in the equatorial wind.

Looking in more detail to the solar wind, this simple bimodal picture turns out to be more complex. During solar minimum, the slow wind is highly variable and structured. Coronal holes around the equator eject streams of faster wind, which are generally slower than the polar fast wind. When these streams interact with the slow (background) solar wind, corotating interaction regions (CIRs) are formed. In addition, bubbles of gas and energy called coronal mass ejections (CMEs), shooting away from the Sun in any direction, provide very hot, very fast streams of solar wind. During solar maximum, the bimodality seems to disappear completely and although the general condition of the wind resembles that of the slow wind around solar minimum, the 3D structure of the solar wind is chaotic and highly variable. Also, CMEs are far more common around solar maximum.

2.1.1 Corotational Mapping

The two solar wind observatories ACE and SOHO are both located near Earth, at its Lagrangian point L1 (roughly $10^6$ km upstream the solar wind). In order to get an idea about local solar wind conditions at the position of a comet, the solar wind information obtained by the space probes needs to be extrapolated to the position of the comet, i.e. the time difference between solar wind observation and the actual interaction with a distant comet, has to be determined. A first approximation for this time difference is described by Neugebauer et al. (2000). Their calculations are based on the comet ephemeris, the location of L1 and the measured wind speed. With this procedure, the time difference between an element of the corotating solar wind arriving at L1 and at the comet (or of any object of interest) can be predicted. Structures in the solar wind move radially outward, but also follow the rotation of the Sun, which rotates around its axis in 27 days ($T_{sun}$). This results in an Archimedean spiral, and the time shift $\Delta t$ between comet and L1 has a radial and corotational component:

$$\Delta t = \Delta t_{\text{rad}} + \Delta t_{\text{rot}}$$

(2.1)

where the radial time shift $\Delta t_{\text{rad}}$ is determined by the radial separation between comet and L1, $\Delta d$, and the velocity of the solar wind, $v_{\text{sw}}$:

$$\Delta t_{\text{rad}} = \frac{\Delta d}{v_{\text{sw}}}$$

(2.2)
The velocity of the comet is negligible, because it is very low compared to the speed of the solar wind. The corotational time shift $\Delta t_{\text{rot}}$ is found by dividing the heliolongitudinal separation of comet and L1 ($\Delta \text{Lon}$) by the rotational frequency of the Sun:

$$\Delta t_{\text{rot}} = \frac{T_{\text{sun}} \Delta \text{Lon}}{2\pi} \quad (2.3)$$

This method works well for a quiet, smooth solar wind interacting with a comet near to Earth. However, a disadvantage of this procedure is that it cannot account for latitudinal structures in the wind or the magnetohydrodynamical behavior of the wind (i.e. the propagation of shocks and CMEs). These shortcomings imply that especially for comets observed at large longitudinal, latitudinal and/or radial separations from the observatories located at L1, the solar wind data is at best an estimate of the local wind conditions.

### 2.2 Comets

Comets are generally considered dirty snowballs, sized 1 – 15 km and consist of a mixture of non-volatile ices and frozen grains. Close encounters with spacecraft showed irregularly shaped bodies, with surfaces that suggest a complex history of wearing, collisions and chemical processing (Fig. 2.2). Comets that revolve around the Sun in less than 200 y are called ‘short period’ comets, those with longer orbital periods are referred to as ‘long period’ comets. Long period comets are classically associated with the Oort-cloud (Oort, 1950), a reservoir at at least $10^5$ AU from the Sun that has been estimated to contain between $10^{11} – 10^{12}$ cometary nuclei, with a total mass between 1-50 earth masses (Stern, 2003; Dones et al., 2004). Short period comets originate in the Kuiper belt (Kuiper, 1951), which starts beyond Neptune (30 AU) and hosts many different objects, amongst which the dwarf planets Pluto and its moon Charon. This second reservoir is more disc-like and as a consequence, comets from the Kuiper-belt typically have lower inclinations ($<30^\circ$) than comets from the spherical Oort-cloud.

When a comet approaches the Sun, gases start to sublimate from the nucleus, forming a cloud of gas and dust known as the coma. Because the comet’s gravity is far too weak to bind these gases, the atmosphere expands until the gases are ionized or fragmented by sun light.

Depending on its outgassing activity, the comet will form its characteristic tails. Usually, two tails can be distinguished; a white dust tail, from scattered sun light, and a blueish ion tail from fluorescence processes. Dust particles in the dust tail are pushed out of the coma by light pressure and the tail is curved according to Keplerian mechanics. The kinematics of the ion tail were not understood until the discovery of the solar wind by Biermann (1951). The solar wind sweeps up ions from the coma and blows them in an almost straight tail, which therefore always points away from the Sun. Ionic tails can extend over more than 1 AU. The interaction between comets and wind is discussed in depth in the next section.

Due to their storage far away from the Sun, comets might provide access to pristine material from the early days of the solar system. Also, comets have been suggested as potential sources of life on Earth. Comets have therefore attracted a lot of scientific attention,
resulting in several dedicated space missions in the last two decades. In 1986, a number of spacecraft such as ESA’s Giotto flew by comet Halley. The Giotto probe provided the first images of a cometary nucleus (Keller et al., 1986), and constituted much of our current knowledge concerning the interactions between comets and the solar wind.

In July 2005, the Deep Impact (DI) mission provided the first look inside a comet by having a 385 kg copper core colliding with the nucleus of comet 9P/Tempel. The DI mission yielded very high resolution imagery of the surface of comet Tempel 1 (Fig. 2.2) and allowed for remote spectroscopy of subsurface material excavated by the impact (A’Hearn, 2005). A big question raised by DI concerns the origin of the sublimating gas. DI provided the first direct detection of water ice on the surface of a comet, but the total area covered with ice is too small to explain the outgassing of Tempel 1 (Sunshine, 2006). The European Rosetta mission will address this question by landing on the surface of comet 67P/Churyumov-Gerasimenko in 2014.

2.2.1 Cometary Atmospheres

As comets approach the Sun, they develop a coma from sublimating gases, mainly water with some CO (< 30%) and CO₂ (< 10%) and small traces of other species. The gases produced directly by the nucleus are referred to as parent species and flow out radially until they are photo-ionized or -dissociated by solar UV flux. At 1 AU, typical lifetimes are around 10⁵ s, but these lifetimes vary greatly amongst species (Huebner et al., 1992). Empirically, outflow velocities of parent molecules have been determined to scale with the comet’s distance to the Sun, \( r_h \) (in AU) as \( v = 0.85 r_h^{-0.5} \) km s⁻¹. The products of the fragmentation of parent molecules are called daughter species, and when in turn these
Comets and the Solar Wind

Figure 2.3: Density distribution in a comet with gas production of $Q=10^{29}$ molecules s$^{-1}$ at 1 AU from the Sun, according to the Haser model (see text).

fragments are dissociated, they produce granddaughter species.

The most relevant case for cometary atmospheres is the destruction of water (parent) into H and OH (daughters), and subsequently, O and H (granddaughters):

\[
\begin{align*}
\text{H}_2\text{O} + \nu & \rightarrow \text{OH} + \text{H} + 3.42 \text{ eV} \quad (1.03 \times 10^{-5} \text{ s}^{-1}) \\
& \rightarrow \text{H}_2 + \text{O}(^1\text{D}) + 3.84 \text{ eV} \quad (5.97 \times 10^{-7} \text{ s}^{-1}) \\
& \rightarrow \text{H} + \text{H} + \text{O} + 0.7 \text{ eV} \quad (7.55 \times 10^{-7} \text{ s}^{-1}) \\
& \rightarrow \text{H}_2\text{O}^+ + \text{e} + 12.4 \text{ eV} \quad (3.31 \times 10^{-7} \text{ s}^{-1})
\end{align*}
\]

where reaction rates at 1 AU, for quiet Sun conditions, are given between brackets (Huebner et al., 1992). The first of these reaction paths, where the water molecule breaks apart into hydroxyl and atomic hydrogen, is the most likely channel, with a branching ratio of 86%. After the break up, the kinetic energy release of 3.42 eV yields velocity kicks of 1.5 km s$^{-1}$ for the OH molecule, and 26 km s$^{-1}$ for the H atom (Combi et al., 2004), hence ejecting the latter out of the inner coma to form a large hydrogen halo surrounding the comet.

\[
\begin{align*}
\text{OH} + \nu & \rightarrow \text{O}(^3\text{P}) + \text{H} + 1.27 \text{ eV} \quad (6.54 \times 10^{-6} \text{ s}^{-1}) \\
& \rightarrow \text{O}(^1\text{D}) + \text{H} + 7.90 \text{ eV} \quad (6.35 \times 10^{-7} \text{ s}^{-1}) \\
& \rightarrow \text{OH}^+ + \text{e} + 19.1 \text{ eV} \quad (2.47 \times 10^{-7} \text{ s}^{-1})
\end{align*}
\]
Just like the initial water molecule, the OH molecule is most likely to photo-dissociate and its reaction products are again accelerated. The cometary atmosphere then expands until the atomic products O and H are finally photo ionized.

The spatial distribution of neutral molecules and atoms in cometary atmospheres can be approached by means of the Haser model (Haser, 1957; Festou, 1981). The Haser model assumes a point source with a constant and isotropic gas production rate. The density of a parent molecule (e.g. water) is described by:

\[ n(r) = \frac{Q}{4\pi vr^2} \exp\left(-\frac{r}{v\tau_P}\right) \] (2.4)

where \(Q\) denotes the production rate of the relevant parent species, \(v\) is this species' outflow velocity, \(r\) is the distance to the nucleus and \(\tau_P\) is the lifetime of the species in the solar UV field. The product of outflow velocity and lifetime is called the scale length of the molecule \(\beta_P\):

\[ \beta_P = (v\tau_P)^{-1} \] (2.5)

The density of the molecules \(R\) originating from the dissociation of molecules \(P\) is:

\[ n^R_P(r) = \frac{Q_P}{4\pi v_R r^2} \frac{\beta^D_P}{\beta_R - \beta_P} \left( e^{-\beta_P r} - e^{-\beta_R r} \right) \] (2.6)

where \(\beta^D_P\) is the total destruction scale length of the parent molecule and where the velocity \(v_R\) is the average velocity for the daughter species, found by summing the outflow velocity and the velocity kick from the dissociation process at right angles. The number density of the products of the second dissociation, the granddaughter products \(S\) which are produced from daughter product \(R\), is given by:

\[ n^R_S(r) = \frac{Q_P}{4\pi v_{SR} r^2} \left( Ae^{-\beta_P r} + Be^{-\beta_R r} + Ce^{-\beta_S r} \right) \] (2.7)

where the coefficients \(A\), \(B\) and \(C\) are:

\[ A = \frac{-\beta_P \beta^D_P}{(\beta_P - \beta_R)(\beta_S - \beta_P)} + \frac{\beta^D_P}{\beta_S - \beta_P} \] (2.8)

\[ B = \frac{-\beta_P \beta^D_P}{(\beta_R - \beta_P)(\beta_S - \beta_P)} + \frac{\beta^D_P \beta_R}{(\beta_S - \beta_P)(\beta_R - \beta_P)} - \frac{\beta^D_P}{(\beta_S - \beta_P)} \] (2.9)

\[ C = -A - B \] (2.10)

An example of a neutral density distribution in the coma of an active comet at 1 AU from the Sun is shown in Fig. 2.3. Up to \(10^5\) km from the nucleus, the coma is dominated by water molecules, whereas further outward the most abundant species are its dissociation products H, OH and O. CO has a much longer lifetime in solar UV fluxes, so that it becomes relatively more abundant in the outer parts of the coma.
2.3 Comet-Wind Interaction

When the solar wind first interacts with the ions in the outer coma, a bow shock is created. The solar wind can only digest a certain amount of cometary pick up ions, and when a critical mass is exceeded a bow shock occurs which transforms the parallel supersonic solar wind flow into a divergent subsonic flow. In this bow shock, the solar wind ions are decelerated and heated at the same time. The charge state composition of the wind is not affected in the shock. As an example, during the Giotto encounter, comet Halley interacted with a slow 390 km s\(^{-1}\) wind, and its bow shock was found to be located at approximately 10\(^6\) km upstream the nucleus (Neubauer et al., 1986; Goldstein et al., 1987).

The stand off distance of the bow shock, \(R_{bs}\), can be estimated by using a rule of thumb derived by Wegmann et al. (2004), which describes the pick up of newly generated cometary ions. The solar wind can only digest a certain amount of cometary ions. When a critical mass is exceeded, a bow shock occurs at a distance \(R_{bs}\) from the nucleus:

\[
R_{bs} \geq (\gamma^2 - 1) \frac{\alpha m_C Q}{4\pi v F(\infty)}
\]  

where \(\gamma\) is the adiabatic index (\(\gamma = 5/3\)), \(F(\infty)\) is the initial solar wind mass flux, \(Q\) is the comet’s gas production rate, \(v\) is the velocity of the out flowing gas, \(m_C\) is the average mass of a cometary ion and \(\alpha\) is the average ionization rate of a cometary ion (Schmidt and Wegmann, 1982).

As the wind further penetrates into the comet’s atmosphere, it gradually picks up more and more slow cometary ions, meanwhile loosing initial fast protons that get neutralized.
by charge exchange processes. The Giotto results showed that this mass loading leads to
deceleration, or cooling, of the wind down to velocities of $\sim 50 \text{ km s}^{-1}$ (Goldstein et al.,
1987).

While the bow shock limits the free flowing solar wind, the contact surface is the bound-
ary between pure cometary gases and the solar wind in the inner parts of the coma. Within
the contact surface, there is no magnetic field and its extent in case of comet Halley was
4700 km (Neubauer et al., 1986). The plasma experiments on board Giotto found that the
interaction region between bow shock and contact surface is highly structured. This struc-
turing is still poorly understood.

Highly charged ions are only a minor constituent of the solar wind and play no promi-
ient role in the macroscopic interaction between comets and the solar wind. When these
ions collide on neutral atoms or molecules in the coma, they are neutralized via charge
exchange reactions. For these reactions, cross sections are more than an order of mag-
nitude larger than those of protons, and therefore interaction ranges for highly charged
ions interacting with the comet can extend far beyond the bow shock. X-ray observations
of comets have demonstrated that via charge exchange emission, the interaction between
comets and the solar wind becomes directly visible.