Chapter 2

Observational methods

The vast majority of the knowledge we have today about comets comes from remote observations. A wide array of observational techniques is used, covering most of the electro-magnetic spectrum. This chapter will give a short overview of the observational techniques for the different spectral regions. For a more detailed discussion see for example the review by Rauer [2002].

For many years optical observations have been the main tool for comet observers. Two techniques are used, optical spectroscopy and imaging. The spectrum of a comet in the optical wavelengths range is dominated by the solar spectrum reflected and scattered on the dust particles in the coma. A number of radicals like CN, C_2, C_3, NH_2, CH, OH, NH show emission features in the optical wavelengths range, but also some atoms like H, O and Na in addition to some ions such as CO^+, CO_2^+ and H_2O^+. The swan system of C_2 was the first spectral band to be observed and identified in a comet [Donati, 1864; Huggins, 1867]. Baldet [1926] published already a detailed description of spectra of nearly 40 comets observed by spectroscopy. A wide variety of techniques is used for optical spectroscopic observations of comets. For this work medium resolution optical long slit spectroscopy has been used. Therefore this technique will be discussed in greater detail in chapter 5.2 and following. Using high resolution optical long slit spectroscopy the excitation mechanisms of the radicals can be studied in detail. For C_2 this has been done for example by Rousselot *et al.* [2000] for C_3 in Rousselot *et al.* [2001]. Wide band spectrophotometry using a standard set of filters (International Halley Watch - IHW filters) is a technique usable on small telescopes as well. The filters are centered on specific emission bands or on emission free regions to study the dust. The properties of the dust can be inferred by analyzing the reflected solar continuum (see for example Weiler [2002]). Optical imaging allows to study the morphology of the coma. This is presumably the oldest technique if one includes drawings of cometary comae already made in China around 1000 AD.

Radio telescopes study the sub-millimeter to centimeter emissions of molecules in the cometary coma. The first success of this method was the detection of the 18cm lines of the OH radical in comet Kohoutek in 1973 using the Nançay radio telescope (France) (see [Blamont and Festou, 1974]). This radical is formed by photodissociation of H_2O, and thus this measurement allowed an indirect estimate of the water production of the comet. In November 1985 the 3mm lines of the HCN molecule were detected in comet Halley, by Despois *et al.* [1986] using the IRAM (Institut de Radioastronomie Millimétrique) 30m radio telescope in Spain. This was the first definitive detection of a parent molecule using a radio telescope. It was followed by the detection of a number of other molecules including H_2CO (Danks *et al.* [1986]). Another highlight was the detection of radio lines of CO in comet Schwassmann-Wachmann 1 by Larson [1980] using the James Clark Maxwell telescope (JCMT) on Hawaii. This comet is on a nearly circular orbit outside of 6 AU from the Sun. This detection shows the power of radio telescopes to detect the rotational lines which are the only excited levels in most parent molecules in cold media. Comets Hyakutake and Hale-Bopp finally allowed the detection of a number of new molecules. Among these are large organic molecules like isocyanid acid (NH_2CHO) [Mehringer *et al.*, 1997] or acetaldehyde (CH_3CHO) [Crovisier *et al.*, 2000] but also NH_3 could be firmly detected for the first time by Woodney *et al.* [1997]. For a more complete list see the overview by Bockelée-Morvan *et al.* [2000] and references therein. Radio observations have been used to routinely monitor comets. For an excellent example see the work by Biver *et al.* [1997]. They monitored many of the parent species in Hale-Bopp over a wide range of heliocentric distance. The high spectral resolution of radio observations allows also to determine radial velocities of the molecules. The data set is complementary to the data from the optical longterm monitoring which has been used in this work.

Infrared telescopes, both ground and space based, yield additional information on the parent molecules. Infrared spectroscopy has been applied first to comet Halley. This led to the first direct detection of the water molecule by Mumma *et al.* [1986] using the Kuiper Airborne Telescope. Recently, several hydrocarbons like ethane, acetylene or methane have been detected in a number of bright comets, starting with comets Hyakutake and Hale-Bopp (for a more detailed description of these observations see section 6 on page 49). Observations in the infrared wavelengths range are complicated by a number of facts. The main problem for ground based infrared observations is the Earth atmosphere. Due to its high content of water vapor, most of the infrared spectrum is absorbed. Only small spectral windows are left and observations are possible only from observatories at high elevation (like Mauna Kea on Hawaii or Paranal in Chile). The use of space based infrared telescopes like the Infrared Astronomy Satellite (IRAS), operated January to November 1983, the Infrared Space Observatory (ISO, decommissioned April 1998, after all helium had evaporated) or the upcoming NASA Space Infrared Telescope Facility (SIRTF), eliminate these problems entirely. During a systematic exploration of the sky IRAS detected 30 comets, among which 6 were new comets now carrying the name IRAS, sometimes together with the name of other observers. The operational period of ISO coincided with the apparition of comet Hale-Bopp. Unfortunately, due to technical limitations, ISO could observe Hale-Bopp only at heliocentric distances greater than 2.9 AU. At 2.9 AU the whole infrared spectrum (2.4-190 μm) of comet Hale-Bopp could be observed. A wealth of information could be gathered from these observations. For a detailed discussion see Crovisier [1997]. An intermediate solution between space and ground based telescopes are airborne telescopes, like the upcoming SOFIA telescope or the Kuiper airborne observatory (KAO) which was extensively used for observations of comet Halley. Advance in the telescope instrumentation and theoretical working on modeling the infrared emission process will lead to an increasing importance of infrared

observations in the future.
Ultraviolet spectroscopy is impossible from the ground because the Earth atmosphere is almost opaque in this wavelengths range. While first experiments were done using sounding rockets, a systematic study was possible only after the launch of the International Ultraviolet Explorer (IUE). During its 18 years of service several dozen comets have been observed. After the end of its mission in 1996 only the Hubble Space Telescope (HST) and sounding rockets allow the systematic study of comets in the UV. These studies are supplemented by 'one-shot' observations from sounding rockets, the Space Shuttle or space probes, like the VEGA probes at comet Halley. A main advantage of the UV wavelengths range is the fact that the activity of the Sun in this range is rather low. Thus the reflected continuum from the dust is negligible (see chapter 4). The UV spectrum of comets is dominated by the Lyman-α line of the hydrogen atom at 121.5 nm and the OH radical electronic band near 300 nm. The first detection of the Lyman-α line in comets revealed a huge cloud of atomic hydrogen surrounding the comet (e. g. for comet Bennet by Keller and Thomas [1973]). This cloud extends outward to over ten million kilometers. Its enormous size arises from the very long lifetime of the hydrogen atom. The OH emission system lies in the near UV, a wavelengths range which is just observable from the ground. Like the 18 cm radio lines, these measurements can be used as an indicator for the water production rate. Finally also CO is observable in the UV. Of special interest here are the so-called Cameron bands around 220 nm. These have been related to electronically excited CO, produced by the photodissociation of CO_2. Therefore these measurements give some indications on CO_2.
A surprising result was the detection of X-ray emission by comets. First observed in comet Hyakutake (Lisse *et al.* [1996]), this observation was confirmed for comet Hale-Bopp (Krasnopolsky *et al.* [1997], Owens *et al.* [1998]). At least three mechanisms creating this emission are considered: charge exchange between solar wind heavy ions and cometary neutrals, bremsstrahlung emission, and magnetic field recombination. For a more detailed discussion of these mechanisms see for example Krasnopolsky [1997a,b], Häberli *et al.* [1997] or Wegmann *et al.* [1998].