Chapter 20

Relative abundance ratios

20.1 Abundance ratios relative to water and carbon monoxide

Figure 20.1 shows the ratios of the production rates of C_2H_2, C_2H_6 and C_3H_4 relative to the water and the CO production rates, plotted versus heliocentric distance. For completeness the values determined by Dello Russo *et al.* [2001] measured at perihelion have been included as well. The ratio to CO is in good agreement with the values derived in this work for larger heliocentric distances. As neither H_2O nor CO production rates have been measured at the heliocentric distances of the C_2 and C_3 observations, the values used as input for the ComChem model have been adopted. Chapter 14 describes in details how these values have been derived.

As has been discussed in section 4 water is the main driver for the cometary activity up to 3–4 AU heliocentric distance. At larger heliocentric distances the main driver for cometary activity is carbon monoxide (CO). The upper panel of Figure 20.1 shows a steep increase in the ratios for heliocentric distances greater than 3 AU as the water production rate decreases. The activity of C_2H_2, C_2H_6 and C_3H_4 is at these distances clearly not controlled by water sublimation. For C_2H_2 and C_2H_6 this comes as no surprise, because the sublimation temperatures for pure ices are approximately 49 K and 52 K, respectively. Therefore these molecules have a higher volatility than water. The ratio of the C_3H_4 production rate to the water production rate suggests that C_3H_4 is also a highly volatile species. Up to now there is only very little data on the volatility of allene or propyne. However the existing measurements indicate also a high volatility support the identification of these molecules as possible C_3 parents.

The lower panel of Figure 20.1 shows the ratios of the production rates relative to CO. Within the error bars the ratios for all three species are constant up to 4.74 AU. This confirms that C_2H_2, C_2H_6 and C_3H_4 are very volatile species.

Table 20.1 shows the derived ratios and the associated errors. For a comparison table 20.2 show the upper limits for the ratios of C_2H_2 and C_2H_6 relative to CO measured for NGC

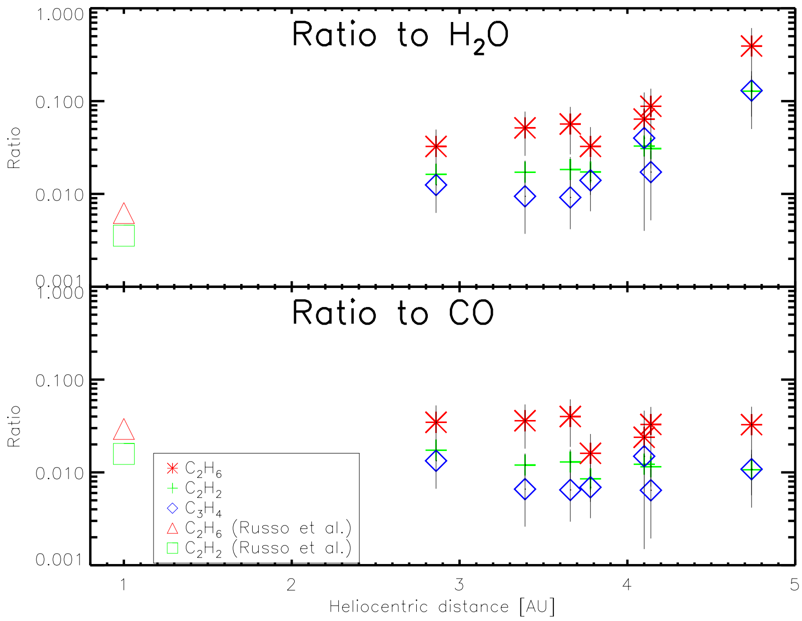

Figure 20.1: Evolution of abundance ratios relative to water and to carbon monoxide over heliocentric distance

$Q(C_2H_2)/Q(CO)$	=	0.01 ± 0.001
$Q(C_2H_6)/Q(CO)$	=	0.03 ± 0.004
$Q(C_3H_4)/Q(CO)$	=	0.008 ± 0.004

Table 20.1: Abundance ratios relative to carbon monoxide derived in this work

7538:IRS9 as determined by Boudin *et al.* [1998]. According to Werner *et al.* [1979] this is a massive protostellar object with an associated infrared reflection nebula deeply embedded in a dense molecular cloud. It has been well studied in the entire mid-infrared range from ground based observatories and by the Infrared Space Observatory (e.g. Allamandola *et al.* [1992], Whittet *et al.* [1996]). While the ratio for C_2H_2 is in agreement with the value derived for comet Hale-Bopp, the ratio for C_2H_6 indicates an enrichment of ethane in comet Hale-Bopp. However one has to be careful by comparing with only one protostellar region. Unfortunately there are only very few measurements of the abundance of hydrocarbons in dense molecular clouds available.

20.2 Abundance ratios relative to acetylene

Figure 20.2 shows the evolution of the abundance ratio of ethane relative to acetylene over heliocentric distance. The ratio is within the errors constant over the whole range of heliocentric distances covered in this study. From the measurements in this work a mean ratio of $Q(C_2H_6)/Q(C_2H_2)=2.3\pm1.0$ can be derived. This value shows clearly that comet Hale-Bopp is overabundant in ethane compared to acetylene. The derived ratio is in agreement with the value of $Q(C_2H_6)/Q(C_2H_2)=2.4\pm0.7$ derived by Dello Russo *et al.* [2001] for comet Hale-Bopp at perihelion.
Table 20.3 show the abundance ratio determined in this work in comparison to ratios derived for other comets. Three other long-period comets show also a similar high abundance of ethane. Only comet C/1999 S4 might be depleted in ethane relative to acetylene, however in this case only a lower limit has been derived. However this comet seems to be depleted in many other volatile species as well [Mumma *et al.*, 2001].
Mumma *et al.* [2000] reported the detection of ethane in comet Giacobini-Zinner, a probable Kuiper-belt comet. Their measurements indicate that this comet was depleted in C_2H_6. Weaver *et al.* [1999a] did not detect C_2H_6 in this comet and derived an upper limit for the production rate of C_2H_6 which was lower than the production rate derived by Mumma.
The ratios obtained in this work and the values determined for other Oort cloud comets indicate that an overabundance of ethane is the rule and not the exception for this class of comets. The statistical base is still too small, to draw any similar conclusions on the chemical composition of Kuiper belt comets.
Possible implications for the formation of the nucleus of comet Hale-Bopp are discussed in section 21.
Based on the production rates derived for C_3H_4 in this work it is possible for the first time to derive abundance ratios for C_3H_4 relative to C_2H_2 and C_2H_6. The ratios are within the errors constant over the whole heliocentric distance range studied in this work. C_3H_4 is less abundant than the other two species. Unfortunately none of the isomeric forms of C_3H_4 has been detected in a cometary coma until today. The fact that C_3H_4 is only slightly less abundant than C_2H_2 and C_2H_6 indicate that this might be mainly an observational problem. In the radio range the energy is distributed over many lines, therefore the strength of an individual line is low. In the infrared wavelengths range there is a blend between the C_3H_4 emission lines and the broad emissions of the CH-bending modes. The abundance ratio of C_3H_4 might set limits to the formation region of comet Hale-Bopp as will be discussed in section 21.

$Q(C_2H_2)/Q(CO)$	$\leq$	0.014
$Q(C_2H_6)/Q(CO)$	$\leq$	0.002

Table 20.2: Upper limits for the abundance ratios relative to CO of solid acetylene and ethane in NGC 7538:IRS9 derived by Boudin *et al.* [1998]

Comet	$Q(C_2H_6)/Q(C_2H_2)$
Hale-Bopp (this work)	**2.3 ± 1.0**
Hale-Bopp	2.4±0.7
C/1996 B2	∼ 0.5 - 4
Hyakutake	4 ± 2
Lee	2.6 ± 0.3
C/1999 S4 Linear	> 0.9

Table 20.3: Abundance ratio of ethane relative to acetylene derived in this work and for some comets [Dello Russo *et al.*, 2001]

$Q(C_3H_4)/Q(C_2H_2)$	=	0.65±0.37
$Q(C_3H_4)/Q(C_2H_6)$	=	0.28 ± 0.18

Table 20.4: Abundance ratios of C_3H_4 to C_2H_2 and C_2H_6

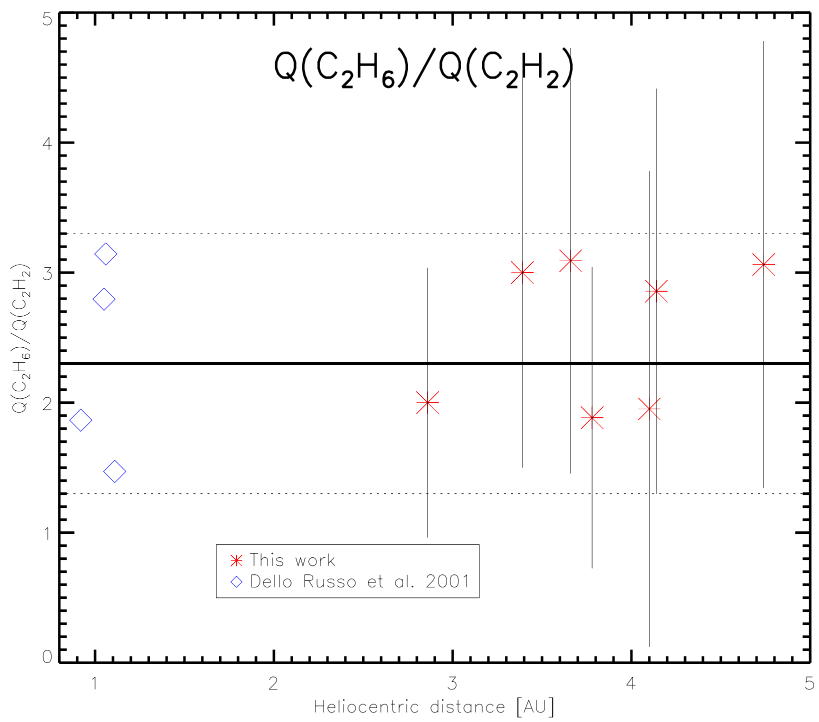

Figure 20.2: Abundance ratio of C_2H_2 relative to C_2H_6 versus heliocentric distance. The solid line is the mean values derived in this work, the dotted lines are the associated errors. The values determined by Dello Russo *et al.* [2001] are displayed for comparison .

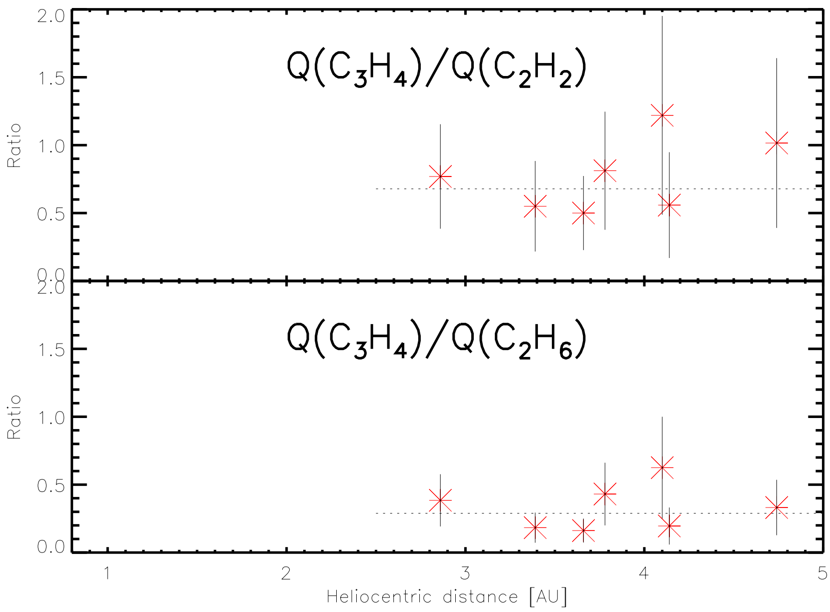

Figure 20.3: Evolution of the abundance ratios of C_3H_4 to C_2H_2 and C_2H_6 over heliocentric distance, the dotted lines are the derived mean values.