The Long-Term Evolution of Cometary Outgassing from the Observations of Amateur and Professional Astronomers[1]

Jacques Crovisier
Observatoire de Paris, F-92195 Meudon, France
jacques.crovisier@obspm.fr

Abstract. *Cometary activity is driven by the sublimation of ices in the nucleus: mainly water when the comet is close to the Sun (typically $r_h < 4$ AU), and (presumably) carbon monoxide farther from the Sun. The monitoring of the long-term evolution of cometary activity is fundamental for cometary studies. This evolution differs from comet to comet. It provides clues to the sublimation mechanism of cometary ices and to seasonal effects. Such monitorings serve as a basis for predictions for organizing future observations. They are a requisite for the intercomparison of various phenomena when they are observed at different times. A review of the main methods used for monitoring cometary outgassing is presented. Direct observations of CO and H_2O production rates are rare and difficult because they involve costly and oversubscribed instruments (large telescopes, space observatories). Indirect observations (e.g., the OH radical from its radio lines at 18 cm and from narrow-band photometry in the near UV) are more handy, but they have their own limitations. The huge database of visual magnitude observations by amateur astronomers gives another approach to this topic. For comets from historical times, it provides a precious heritage which is often the only source of information. The empirical relation between visual magnitudes and gas production rates, even if it is physically ill-understood, is a very useful tool. For a systematic and timely exploitation of this database, standardization, fast communication and archiving are crucial points.*

1 Introduction

Recent spectroscopic investigations on the composition of the outgassing products of comets (Bockelée-Morvan et al. 2005), mainly at radio and infrared wavelengths, have confirmed the paradigm of the *dirty snowball model* proposed by Fred Whipple (1950) more than fifty years ago: cometary ices are composed mainly of water. Close to the Sun (i.e., at heliocentric distances $r_h \leq 3$ AU), cometary activity is governed by the sublimation of water. The production rate of water is thus an adequate quantitative indicator of cometary activity. The production rates of other molecules outgassed from cometary ices are currently given relative to water production rates, in order to provide an easy comparison between different comets and to yield relative abundances. Hence the importance of measuring cometary water production and its short- and long-term evolution.

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The activity of comets at large heliocentric distances is governed by the sublimation of species more volatile than water, such as carbon monoxide (the most abundant species observed in distant comets). The correlation between total visual magnitudes and CO production rates was investigated by Biver (2001). It will not be discussed here.

2 How to probe cometary outgassing?

Ironically, although the most abundant cometary volatile, water is one of the species the most difficult to observe, due to the opacity of the Earth's atmosphere to water lines.

2.1 Direct observation of water

Cometary water was first directly observed through its fundamental bands of vibration in the infrared on comet 1P/Halley from the Kuiper Airborne Observatory, a stratospheric aircraft (Mumma et al., 1986) and with the IKS instrument aboard the Vega spacecraft (Combes et al. 1988). The same bands were observed in a very limited number of comets with the Infrared Space Observatory (Crovisier et al. 1997). It is impossible to observe these bands from the ground; however, weaker "hot bands" (i.e., transitions between higher states of vibration, excited by fluorescence) are not absorbed by the terrestrial atmosphere. They could be observed at high spectral resolution with large ground-based infrared telescopes (NASA IRTF, Keck telescope) in a dozen comets (e.g., Dello Russo et al. 2000). All infrared bands of water are emitted by fluorescence, which is a well understood process; thus their observation permits a robust estimation of the water production rate.

More recently, the fundamental rotational line of water at 557 GHz could be observed by heterodyne techniques in several comets with the small submillimetric satellites SWAS and Odin (Neufeld et al. 2000; Lecacheux et al. 2003). This strong line is saturated and the derivation of water production from its observation is model dependent. However, consistent results were obtained, in agreement with other determinations. Very sensitive observations of this line (and of other rotational lines) are expected in the future with the Herschel Space Observatory.

Thus, the direct observation of cometary water relies on space facilities or sophisticated ground-based instruments. It cannot at the present time be used for investigating a large sample of comets or for comprehensive monitorings, but it is invaluable for validating other less direct means of observations.

2.2 Indirect indicators

Water is readily photodissociated by solar UV radiation into fragments – OH, H, O – which can be observed and directly related to their parent molecule (Feldman et al. 2005). OH and O are, in part, created in excited states; their subsequent deexcitation is accompanied by *prompt emission* (in the infrared for vibrationally excited OH, in the visible for electronically excited O). The hydrogen atom can be observed by the strong fluorescence of its Lyman α line in the far UV. OH can be observed through the fluorescence of its electronic bands in the near UV (from space spectroscopy or from the ground with careful narrow-band photometry). OH can also be observed through its 18-cm radio lines (which are emitted by a weak maser process, whose mechanism is governed by the UV fluorescence and is well understood).

Other minor constituents of the cometary gas coma can also be used as indirect indicators. Radicals such as CN, C_2 can be easily observed by narrow-band photometry (e.g., A'Hearn et al. 1995). Molecules such as HCN (hydrogen cyanide) or CH_3OH (methanol) can be observed by ground-based millimetric radio telescopes. There is no strong variation of [CN]/[OH] or [HCN]/[H_2O] (A'Hearn et al. 1995; Biver et al. 2002) observed from comet to comet, so that the production rates of CN and HCN are closely correlated with Q[water].

Possible ways to relate cometary total visual magnitudes to Q[water] are discussed in Section 4.

The dust indicator $Af\rho$ is also a convenient and sensitive tool to trace cometary activity. It is discussed by Jorda (2004).

All these methods for measuring the gas production rates of comets have their own limitations. Most space facilities are subject to solar elongation constraints and cannot observe close to the Sun (which unfortunately corresponds to moments when the comets are at their brightest). They are also oversubscribed instruments for which there is a high competition for observing time. All ground-based observations are affected by weather conditions (except OH 18-cm observations). Modelling issues may also be crucial: a good knowledge of the excitation and distribution of the molecules is requested.

Altogether, these various methods may be considered to be somewhat complementary. They are listed in Table 1 with the size of the corresponding databases.

3 Databases

As discussed in the preceding Section, direct observations of water are only available for a handful of comets.

Observations of the 18-cm lines of OH are not affected by weather conditions or visibility constraints. They are only usable, however, when the OH maser inversion – which depends on the comet heliocentric velocity – is significant. The Nançay database comprises 2416 observations of 65 comets in 1973–1999 (Crovisier et al. 2002a) and more than 1100 observations of 25 comets with the new telescope system since 2000 (Crovisier et al. 2002b). The same lines were occasionally observed in a few comets by other radio telescopes, especially at Green Bank and at Arecibo.

The International Ultraviolet Explorer (IUE) observed the OH near-UV bands in 55 comets from 1978 to 1997 (Festou 1997). The analysis of the complete results in a consistent way is still pending. Only a limited number of comets have been investigated with the Hubble Space Telescope (Feldman et al. 2003).

The SWAN instrument on SOHO routinely provides Lyman α maps of the sky where the hydrogen coma of bright comets is easily visible (Mäkinen et al. 2001). This wealth of information is still to be exploited

Table 1: Methods for estimating gas production rates in comets.

Method	Instrument	Begin. year	N comets	Sensit. [a]	Visib. [b]	Model. [c]	
Direct observation of water							
H_2O IR	space: ISO	1996	3	A	C	A	
	airborne: KAO	1985	2	C	C	A	
	ground	1996	≈ 12	C	B	B	[d]
H_2O radio	space: SWAS, Odin	1999	12	A	C	C	
Observation of water-derived products							
OH 18 cm	Nançay	1973	≈ 90	B	B	C	
	others	1973	≈ 15	B	B	C	
OH IR	ground	1996	≈ 4	C	C	C	
OH UV	ground	1973	≈ 80	A	C	B	
	space: IUE	1978	55	B	C	B	[e]
	space: HST + others		≈ 12	A	B	B	
OI vis.	ground		≈ 50	A	B	C	
Lyman α	space: SOHO/SWAN	1995	≈ 60	B	B	B	[e]
	space: HST + others	1968	≈ 12	A	B	B	
Observation of other gas indicators							
HCN radio	ground: IRAM...	1985	≈ 25	B	A	C	[f]
CN vis.	ground		> 100	A	B	C	[f]
Total visual magnitudes							
visual mag.	amateur network	< 1900	> 1000	A	B	C	[f]

[a] sensitivity to weak comets.
[b] visibility and weather constraints.
[c] modelling issues for retrieving water production rates.
Grades for [a], [b], [c]: A = good; B = medium; C = bad (rather subjective).
[d] water *hot* bands.
[e] database still to be exploited.
[f] not directly linked to water production.

Observations of the oxygen forbidden line *prompt emission* at 630 nm are available for many comets (Fink & Hicks 1996). Their interpretation, however, is plagued by several issues (blended NH_2 line, ill-known branching ratios).

Considerable data on narrow-band photometry of comets with production rates of OH, CN, C_2 radicals exist. However, the only consistent published set of data of some consequence is that of A'Hearn et al. (1995), which deals with 85 comets observed from 1976 to 1992.

Although other databases exist (e.g., Kamél 1992 and Svoreň 2002), the most comprehensive dataset of cometary total visual magnitudes is that gathered by D. Green for the *International Comet Quarterly* (ICQ). This dataset does not yet include all historical observations. It is available as computer files upon request on a comet-by-comet basis.

4 Empirical laws

Table 1 shows that the huge dataset of total visual magnitudes of comets gathered by amateur astronomers is, by far, the most important database on the evolution of comets. For many weak comets and for comets from historical times, it is the

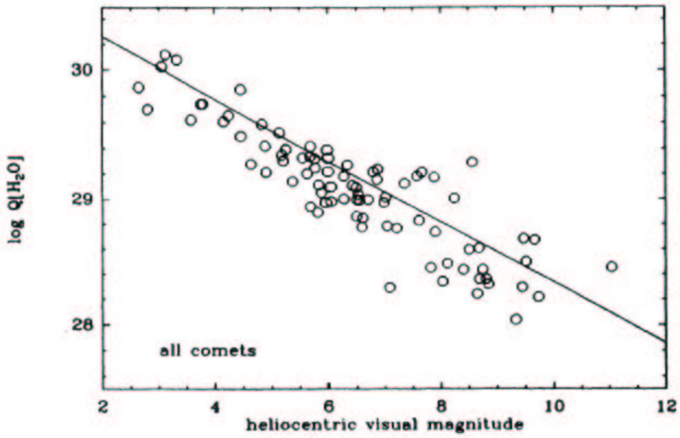

Figure 1: The correlation between heliocentric visual magnitudes and the water production rates observed in 13 comets. From Jorda et al. (1992).

only source of information. To take advantage of this wealth of information, several attempts have been made to relate the total visual magnitude m_h reduced to $\Delta =$ 1 AU and the water production rate $Q[H_2O]$ (Festou 1986; Sekanina 1986; Roettger et al. 1990; Jorda et al. 1992; Jorda 1995; de Almeida et al. 1997; Fig.1). From a statistical analysis of 15 comets, based upon m_h from the ICQ and $Q[H_2O]$ from the Nançay database, Jorda (1995) derived:

$$\log Q[\mathrm{H_2O}] = 30.78 - 0.265 m_h. \quad (1)$$

A new analysis based upon a larger dataset is to be published (Jorda et al., *in preparation*).

This relation (or similar ones) has been broadly used to predict gas productions of comets in the absence of direct measurements (e.g., Jorda & Rickman 1995, de Almeida et al. 1997). Of course, Equation (1) has only a statistical signification, and departures up to a factor of two may be found for individual comets. It should not be applied far from the Sun where the insolation is not high enough to trigger water sublimation. In this case, Biver (2001) tried to relate m_h to $Q[CO]$, but the (radio) observations of CO in distant comets are still sparse.

Naïvely, one would expect the comet brightness to be proportional to its gas production, and therefore a slope -0.4 in Equation (1), rather than -0.26 (see discussions in e.g., Newburn 1984 and Jorda 1995).

5 Marcus' interpretation of the empirical law

In this workshop, Marcus (2004) pointed out that a coefficient, k_2, exceeding the -0.4 value in the relation $\log Q = k_1 + k_2 m_1$ could be explained by a psychophysical artefact of human vision. His model assumes that 1) the coma surface brightness, $j(\varepsilon) = j_c \varepsilon^{-1}$, is inversely proportional to the projected angular distance, ε, in the coma, where j_c is the surface brightness at a standard distance ε_c; 2) the visual coma perimeter, $\varepsilon_{\rm lim}$, is delimited by a threshold, $\gamma_{\rm lim}$, to the gradient contrast

$$\gamma = [{\rm d}j(\varepsilon)/{\rm d}\varepsilon]/[j(\varepsilon)+b], \quad (2)$$

where $b \gg j(\varepsilon_{\rm lim})$ is the sky background; and 3) $\gamma_{\rm lim}$ = constant. If j_c is increased by a factor of x, this third condition constrains the coma to increase only to $x^{1/2}\varepsilon_{\rm lim}$, not to $x\varepsilon_{\rm lim}$, as would be otherwise expected. In further consequence, the model predicts that the total visual coma brightness, I, scales to j_c as $I \sim j_c^{3/2}$, not $\sim j_c$. Because $Q \sim j$ and not $\sim I$, it follows that $Q \sim I^{2/3}$, not $\sim I$. Hence

$$\log Q \sim (2/3)\log I = (2/3)(-0.4)m_1 = -0.27m_1 \neq -0.4m_1 \quad (3)$$

(Marcus, *in preparation*), which is close to what we have found in our production rate–magnitude data sets. In plots against $\log r$, the theory also predicts shallower n slopes for $-2.5\log Q$ than for m_1, as we have also found.

6 Conclusion

- Water can now be observed directly, but sophisticated instrumentation is needed. Thus, such observations are rare and costly. They validate Q[water] obtained by other means.
- Other indirect observations all have their own limitations. They are somewhat complementary. Inter-calibration is needed.
- Systematic exploitation of the large database of total visual magnitudes from the amateur nets is a very helpful approach. The empirical correlation between m_h and Q[water] is physically ill understood, but it works!
- Standardization, fast communication and archiving of the database of cometary magnitudes are crucial points, already addressed in this workshop.

7 Acknowledgements

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