Asteroids, Comets, Meteors
Proceedings IAU Symposium No. 229, 2005
D. Lazzaro, S. Ferraz-Mello & J.A. Fernández, eds.

doi:10.1017/S1743921305006885

Compositional coma investigations: gas and dust production rates in comets

Rita Schulz
ESA Research and Scientific Support Department, ESTEC, Noordwijk, The Netherlands
email: rschulz@rssd.esa.int

Abstract. Although it is presently not possible to extract the true composition of a comet nucleus from its coma composition, the distribution of physical and chemical coma properties among comets may be expedient to establish a comet classification scheme that reflects their origin and/or evolution. Most of the coma species visible in the optical were extensively observed in the past. The analysis of these gas coma constituents, mainly daughter products produced for the most part by photolytic destruction of their parent species, is therefore of major importance, if we want to draw conclusions on diversities and similarities of comets in terms of coma composition on a statistically relevant basis. Hundreds of gas and dust production rates are published, but have never been combined into a single database that would allow identifying whether and how the abundances of coma species differ from comet to comet and how they vary with heliocentric distance and with the number of apparitions. A common database can however only be established if the production rates are re-calculated with a common model and set of parameters.

Keywords. comets: general, astrochemistry

---

1. Introduction

Comets often show very different phenomenological characteristics, which might indicate the existence of physical and chemical differences of their nuclei. Major efforts have therefore been put over many years into finding criteria for a classification scheme of comets to relate their properties to their place(s) of origin. One that is generally accepted is the classification of comets according to their dynamical characteristics (i.e. dynamically new comets, old long-period comets, young long-period comets, short-period comets of Halley and Jupiter family). Another possibility is the grouping of comets according to their physical and/or chemical properties. Here, the composition of the coma plays an important role, as there is normally no information of the nucleus available. The key to the origin of comets is, however, the composition of their nuclei. Depending on their dynamical characteristics, individual comet nuclei should be in different evolutionary stages. Hence, knowledge of the nucleus composition of comets from different dynamical classes should provide information on how the Solar System was formed, and also lead to clues on the history of the interplanetary environment from the time of planet formation up to the present.

As the composition of a comet nucleus cannot be determined from remote sensing observations, all information has to be derived from coma observations assuming certain physical and chemical conditions in the near-nucleus environment. These conditions vary with heliocentric distance and can a priori be different for different comets. (For instance, the extent of the collision zone is much smaller in weak comets than in very active ones.) Hence, the first step in the compositional analysis of comets is to determine the coma constituents (gas and dust), their abundances, chemistry and dynamics for as many comets as possible. This should be done along the entire part of the orbit for which a comet shows coma activity in order to enable the detection of abundance variations as a function of heliocentric distance.

Several compositional surveys were conducted in the past decades (e.g. A'Hearn and Millis (1980), Newburn and Spinrad (1989), Cochran *et al.* (1992), A'Hearn *et al.* (1995), Fink and Hicks (1996)), which led to conclusions on diversities and similarities of comets in terms of coma composition and gas-to-dust ratio. For the gas coma composition, these surveys focused on the abundances of gas species observable in the optical, mainly daughter products, produced for the most part by photolytic destruction of their parent species. A major breakthrough in the compositional study of comets was achieved when cometary parent molecules became directly detectable by remote sensing observations at sub-mm wavelengths. The investigations of molecules observable at sub-mm and infrared wavelengths are presented and discussed by Crovisier (2005, this issue). This review will give an overview on where we stand in terms of compositional coma analysis of the ensemble of comets concentrating on gaseous daughter products and dust observable in the visible spectral range.

2. Determination of Gas Production Rates

2.1. *The Principles*

The visible spectral range is a good tracer for a number of neutral and ionized gas species as well as the micron sized dust (0.4–0.9 μm) in the cometary coma. The constituents of the gas coma that are observable in the optical, are daughter products, such as OH, CN, NH, C_3, C_2 and NH_2, which are produced, for the most part, by photolytic destruction of their parent species. Many of the above-mentioned species are already known to exist in cometary comae for a very long time. C_2 was already observed in the very first spectrum of a comet which was obtained on 5 August, 1864 by G. Donati. Three emission bands were seen in this spectrum, which W. Huggins later identified as bands of the Swan system of C_2 ($\mathrm{d}\ ^3\Pi_g - \mathrm{a}\ ^3\Pi_u$). He also took the first photographic record of a cometary spectrum, in which C_3 and CN could be identified as well (Huggins, 1982). The detection of NH_2 was first reported by Swings.

From the radial distribution of the neutral gas species in the coma, direct information about their production and destruction mechanisms can be obtained. For instance, the lifetimes and velocities of parent and daughter species can be inferred by fitting the radial intensity profiles of gaseous species by a photolytic model. These values can be most accurately determined in comets that do not show any spatial or temporal variations in their coma. The coma of such comets can be considered to be in a steady-state, which is the basic assumption of the photolytic models used to derive lifetimes (scale lengths) of individual gas species. Any structure superimposed on a smooth two-dimensional steady-state coma would adulterate the shape of the radial profiles and therefore falsify the values of the lifetimes resulting from fitting a photolytic model.

The most frequently used photolytic models are the Haser Model (Haser, 1957) and the Vectorial Model (Festou, 1981). The Haser Model assumes an isotropic radial outflow of parent and daughter molecules with a constant outflow velocity. The fitting parameters for the shape of the radial profiles are the scale lengths of the parent and daughter species, which are basically a folding between the respective expansion velocities and lifetimes. The Haser Model suffers from its too simplistic assumptions. It can however be used as a mathematical representation of the density in the inner coma ($\leqslant 10^5$ km). The Vectorial Model is more sophisticated in that it takes into account the isotropic emission of the daughter species from their parent molecules and separates the effects of the lifetimes and velocities. Hence it permits the study of velocity dependent phenomena. The variable parameters are the lifetimes and velocities of the parent and daughter species. In addition non-steady-state conditions can be assumed. Neither the Haser nor the Vectorial Model includes any collision effects. Both models are frequently used to determine the production rates of the observed daughter species.

The determination of gas production rates requires a conversion of the observed coma intensity (flux) into column density, for which the excitation mechanism of the observed transition bands needs to be known. For the optical bands of the species discussed here, the excitation mechanism is resonance fluorescence with solar radiation, hence the conversion is conducted by applying the fluorescence efficiencies (g-factors) of the respective transitions to the observed fluxes. The gas production rates are then practically determined by comparing the absolute values of the column densities calculated with the photolytic model (e.g. Haser, Vectorial) to those derived from the observed fluxes.

2.2. *The Reality*

The principles of how to calculate gas production rates from photometric emission band fluxes are well established. However, as no common agreement has been reached on which procedure and which parameters are to be applied, the gas production rates determined by various teams can usually not be compared or combined into a single data set. The problems to be solved are manifold, but can essentially be divided into three categories: (1) models and parameters, (2) available instrumentation, (3) data reduction procedures.

2.2.1. *Models and parameters*

To convert the photometric fluxes, resulting from the basic data reduction, into column densities, the fluorescence efficiency (g-factor) of each transition has to be applied. Although it has been a general notion for a number of years already that the g-factors are well established, most of the teams continue using their preferred values, which in some cases have been determined decades ago. The g-factors used by various authors show discrepancies, which are in some cases as large as a factor of 10. For instance, the g-factors used by A'Hearn *et al.* (1995) for C_2 and C_3 are a factor of 2 and 10 different from those used by Cochran *et al.* (1992). Unfortunately either team keeps using their published values in any subsequent publication, which means that the column densities (representing the abundance of species) calculated from the observed intensities will remain systematically different in publications of these two teams, even if they observe with exactly the same instrumentation. For instance, the OH and NH production rates published for comet 19P/Borrelly for 10 November 1994 (Cochran and Barker, 1999; Schleicher *et al.*, 2003) differ by factors of 9 and 4, respectively, even though both teams used the Haser model with exactly the same scale lengths to derive these values. Interestingly, the CN and C_2 production rates derived for that date only differ by a factor of 2 although not only very different g-factors (for C_2 the g-factors differ by one order of magnitude), but also different scale lengths were used by the two teams. Hence, for CN and C_2 the use of entirely different parameters during all steps of the calculations accidentally led to more similar end-results.

The differences in the production rates derived with the Haser and the Vectorial Model are only minor as long as the cometary coma is in steady-state condition and the chosen values for the Haser scale length equal lifetime × velocity for the Vectorial Model. CN column density profiles in steady-state condition could for instance be well fitted with both, the Haser and the Vectorial Model and resulted in very similar scale lengths and lifetimes, assuming outflow velocities of 1 km/s (Schulz *et al.*, 1993). The analysis of non-steady state column density profiles of comet C/1996 Q1 (Tabur) confirmed that such profiles could only be fitted with sufficient accuracy by the Vectorial Model with time-dependent production rates. Nevertheless, it could also be demonstrated that the production rates derived with the Haser model (and the scale lengths of A'Hearn *et al.*, (1995)) are within 10hence reasonably close to the time-averaged production rates resulting from the Vectorial Model (Lara *et al.*, 2001). Also the comparison of CN and C_2 production rates of comet 46P/Wirtanen derived from photometric fluxes of Farnham and Schleicher (1998) with both, the Haser and the Vectorial Model resulted in differences of only 10-20% (Schulz *et al.*, 1998). Fink and Combi (2004) recalculated published production rates of H_2O, CN, and C_2 for this comet from the original fluxes and demonstrated that, by using a common set of scale lengths, the results of various investigators can be brought into acceptable accord. Originally, the CN and C_2 production rates of comet 46P/Wirtanen derived from the CN (1-0) and the C_2 ($\Delta\nu = -1$) bands (Fink *et al.*, 1998) were systematically higher (up to a factor of 2) than those derived from the CN (0-0) and the C_2 ($\Delta\nu = 0$) bands (Farnham and Schleicher, 1998) although the observations were obtained at the same heliocentric distance.

2.2.2. *Instrumentation*

Gas production rates are usually determined either by imaging or aperture photometry or by spectrophotometry. Details of these techniques can be obtained from recent reviews (Schleicher and Farnham, 2004; Feldman *et al.*, 2004). The direct comparison of column density profiles derived from narrow-band images and spectra of comet C/1995 O1 (Hale-Bopp) demonstrated that the choice of observational method does not affect the resulting column densities (and with that the resulting production rates if the same model and parameters are applied) as long as the same emission bands are used and fully covered (Schulz *et al.*, 2000). Depending on the available equipment, different teams determine coma gas production rates with different observational methods and also from different emission bands. Water production rates are for instance determined from emissions of OH (radio or UV), H (lyman-α) or O (O(^{1}D)). For some comets, this results in large discrepancies between the absolute values of the water production rates, which makes the merging of such data sets into a common database very difficult, if not impossible. For instance, although the water production rate determined for comet 81P/Wild 2 from H lyman-α (Makinen *et al.*, 2001b) is only about 15% higher than that obtained from O(^{1}D) (Fink *et al.*, 1999), it is about a factor of 2 higher than that determined from OH (Farnham and Schleicher, 2005). For comet 46P/Wirtanen on the other hand, the water production rate from H lyman-α (Makinen *et al.*, 2001b) agrees quite well with that obtained from OH by Farnham and Schleicher (1998) and recalculated by Fink and Combi (2004), whereas it is almost a factor of 2 lower than that determined from O(^{1}D) (Fink *et al.*, 1998; Fink and Combi, 2004). For comet C/1995 O1 (Hale-Bopp) the water production rates derived around perihelion from H lyman-α (Makinen *et al.*, 2001a) and OH at radio wavelength (e.g. Colom *et al.*, 1997) agree within 10% and are consistent with the expected values extrapolated from OH observations in the UV before perihelion (e.g. Weaver *et al.*, 1997; Schleicher *et al.*, 1997). Hence it appears that the size of the effect depends on the brightness of the observed comet, with weaker comets resulting (as might be expected) in less reliable absolute values for the water production rate. For other species, such as CN and C_2 only few data are available. However, it appears that for those the problem is only minor as long as appropriate g-factor are used. Simultaneous measurements of the integrated band fluxes for the CN $B^2\Sigma^2 - X^2\Sigma^+$ (violet) and $A^2\Pi^2 - X^2\Sigma^+$ (red) systems in comet Austin confirm that the g-factor used for both systems closely describe the radiative properties of CN molecules (Tegler *et al.*, 1992).

2.2.3. *Data Reduction Procedures*

In a few cases discrepancies between published values can be directly related to unconventional procedures in the determination of gas production rates. One example is the difference that resulted in the determination of CN and C_2 production rates in comet C/1996 Q1 (Tabur) by Lara *et al.* (2001) and Turner and Smith (1999). Although both teams used the same observational method (long slit spectroscopy), the same emission bands as well as the same g-factors and Haser scale length, the production rates derived by Turner and Smith (1999) are about a factor of 2 lower than those by Lara *et al.* (2001). A closer look reveals that Turner and Smith (1999) averaged the flux along the entire slit as input for the Haser model, which of course results in decreased (average) flux values, hence smaller production rates. Such unconventional procedures however occur rather rarely and can easily be identified.

3. Determination of Dust Production Rates

In order to be able to compare measurements of cometary dust obtained in different apertures and spectral regions, the quantity $Af\rho$ has been introduced by A'Hearn *et al.* (1984) and is now widely used to measure dust production of dust in comets. It is the product of the Albedo for the scattering angle of the observation ($A(\Theta)$), filling factor of grains in the aperture (f), and effective aperture radius (ρ). The filling factor equals to $f = \frac{N\sigma}{pi\rho^2}$ with σ being the average grain cross section and N being the total number of grains in the aperture. $Af\rho$ is proportional to the observed continuum flux and if the projected density of the dust decreases as ρ^{-1}, it is even independent of the geocentric distance or the aperture size. The relationship between $Af\rho$ and the production of dust varies systematically with the phase angle. There are many more assumptions in using $Af\rho$ as a measure of dust production, which have been summarized by A'Hearn *et al.* (1995). According to Weaver *et al.* (1999), $Af\rho$ can be correlated to the dust mass production rate, Q_{dust} through:

$$Q_{dust} = \frac{0.67 \cdot a \cdot d \cdot v \cdot Af\rho}{A} \tag{3.1}$$

with: Q_{dust} = dust mass production rate in $\mathrm{kg\,s^{-1}}$
a = average particles radius in $\mu\mathrm{m}$
d = density in $\mathrm{g\,cm^{-3}}$
A_p = geometric albedo
v = outflow velocity from the nucleus in kms^{-1}
$Af\rho$ = aperture-independent measure of dust production rate in m.

$Af\rho$ has been used for more than a decade now as a measure of the dust production rate in comets. Almost everybody is using this quantity when publishing dust production rates, which allows comparing and combining the results of various teams. There is of course a number of practical problems, e.g. that some teams do not perform a phase function correction.

The $Af\rho$ system has a very important drawback in that it is not independent of the aperture size any more if the projected density of the dust does not decrease as ρ^{-1}, which is however the reality for most comets observed. Hence the determination of $Af\rho$ will be affected with systematical errors that depend on the slope of the dust coma profiles, if different apertures are used. In summary, with the general use of $Af\rho$ as a measure for the dust production rate of a comet, it was achieved to allow the comparison of values determined by different teams for the same comet in steady-state conditions. Comparison of dust activities of different comets or comets showing short-term variability will however remain very difficult.

3.1. *In-situ dust measurements*

The first in-situ measurements of cometary dust particles were obtained for comet 1P/Halley in 1986. These measurements made by three spacecraft (Vega 1 & 2 and Giotto) were used to determine the particle size range, the process of dust production, and the composition of the dust. The particles showed a wide distribution of sizes, 0.01–100 μm (McDonnell *et al.*, 1991) and were for the most part composed of silicate refractory and organic molecules (Kissel *et al.*, 1986). In-situ dust measurements were also carried out during the Giotto Extended Mission to comet 26P/Grigg-Skjellerup, however only 3 particles were registered during the fly-by (McDonnell *et al.*, 1993). The data obtained during these fly-by missions indeed remained the only available in-situ measurements of dust particles in comets for a long time.

New in-situ data only became available in 2004, when the Stardust measured the the flux, mass distribution and composition of dust coma particles in comet 81P/Wild 2. The dust coma of this comet was characterized by swarms of particles and bursts of activity, which may be explained by jets and fragmentation (Tuzzolino *et al.*, 2004; Green *et al.*, 2004). The overall mass distribution was similar to that seen in comet 1P/Halley, despite the very large variations detected on small scales. The in-situ compositional analysis of the dust in comet 81P/Wild 2 confirm the predominance of organic matter, which seems to be nitrogen richer and oxygen poorer than interstellar dust (Kissel *et al.*, 2004).

Stardust has collected dust particles from the coma of comet 81P/Wild 2 and will return them to Earth stowed into aerogel in a sample return capsule. The in depth analysis of this dust sample, when returned to the Earth on 15 January 2006, will provide independent information on the physical and compositional properties of the dust in comet 81P/Wild 2, hence provide the ground truth necessary to confirm results and interpretation of in-situ measurements from spacecraft.

4. Coma Evolution along the Orbit

It has been realized over the years that studying the evolution of the activity of a comet as it moves along its orbit is of utmost importance to understand the properties of the comet nucleus. Conclusions on the composition of the nucleus can only be drawn if the coma composition is integrated over the entire orbit of the comet (Prialnik, 2005, this issue). The variation of gas and dust production rates as a function of heliocentric distance has been a subject of investigations for many years. The observations indicate that in general gaseous emissions are a stronger function of heliocentric distance than the dust continuum, e.g. most comets show pure continuum spectra at distance beyond 3 AU (most Jupiter-family comets already beyond 2.5 AU). However, as any gas must drag out the dust, this may well just be the practical manifestation of the sensitivity limits of our observational setups. For example, in bright comet C/1995 O1 (Hale-Bopp) CN could be detected in optical spectra from about 5 AU preperihelion (Schleicher *et al.*, 1997) to 9.8 AU postperihelion (Rauer *et al.*, 2003). It is known for many years that in optical spectra the CN emission usually appears first as a comet approaches the sun, while other emissions, like for instance the C_2 bands, are detected only later (Swings and Haser, 1956). It is common that the dust-to-gas ratio becomes systematically smaller with decreasing heliocentric distance (A'Hearn *et al.*, 1995).

4.1. *Production Rate Ratios*

The gas and dust production rates vary with heliocentric distance, r_h, and the approximate r_h-dependence is most often represented by fitting a power law, r_h^{-k}, to the available measurements. The slopes of these fits may vary significantly from comet to comet and from species to species, e.g. the values for k published in the survey by A'Hearn *et al.* (1995) vary from $0.5 < k < 12$. If the production rates of different species vary with different k, the abundance ratio of these species will change as a function of the heliocentric distance. One of the first studies of abundance variations in cometary comae with heliocentric distance led to indications that the C_2/CN production rate ratio is much smaller at heliocentric distances $> 2\,AU$ than at distances $< 1.5\,AU$ (A'Hearn and Millis, 1980). The result was disputed by Combi and Delsemme (1986) arguing that the drop of the C_2 production rate for larger heliocentric distances is an artifact of inappropriate scale lengths law. However, Newburn and Spinrad (1989) were using the revised scale lengths laws in their spectrophotometric survey and still find that the C_2/CN production rate ratio changed continuously with heliocentric distance in the five comets for which they had measurements at different distances. The C_2/CN ratio decreased with increasing r_h in all cases. Unfortunately, the observations only covered a relatively small range of heliocentric distances and no data beyond 2 AU were available. The change in the C_2/CN ratio described by Newburn and Spinrad (1989) is qualitatively also seen in the data of A'Hearn *et al.* (1995), however the size of the effect was much smaller. A significant increase of the C_2/CN abundance ratio was measured for comet 46P/Wirtanen between 1.8 AU and 1.6 AU during a preperihelion monitoring starting at 2.8 AU (Schulz *et al.*, 1998). The effect remains in the production rates recalculated by Fink and Combi (2004) with a common set of scale lengths.

The survey by Cochran *et al.* (1992) revealed evidence for a heliocentric distance dependence of the NH_2/CN ratio. Later a hint was reported that the C_3/CN and CH/CN production rate ratios in comet 19P/Borrelly may also vary with heliocentric distance (Cochran and Barker, 1999), however, the heliocentric distance covered was too small to permit unambiguous conclusions. The analysis of gas production rates in comet 1P/Halley from 2.6 AU preperihelion to 5.1 AU postperihelion showed that the relative abundances of CN, C_2, and C_3 remained essentially constant with respect to each other, but change markedly with respect to OH (Schleicher *et al.*, 1998).

4.2. *Available Data as f(r_h)*

Although the production rates of a large number of comets have been surveyed, the systematic sampling of production rates as a function of heliocentric distance is very poor. Only a hand full of individual comets has been monitored along a sufficiently long part of the orbit, to allow a more detailed analysis of the shape of their activity curves. At least three of these comets clearly show activity curves of complex shape that cannot be fitted by a simple power law and include a sudden preperihelion increase or postperihelion decrease of activity at a certain heliocentric distance. Prominent Comet C/1995 O1 (Hale-Bopp) is one of them, but also the rather faint comets 46P/Wirtanen and 67P/Churyumov-Gerasimenko have been studied extensively, because they were selected as the target for a space mission. To fit the evolution of the OH production rate in Comet C/1995 O1 (Hale-Bopp) the preperihelion data had to be split into three distance regimes and each was fitted separately. The OH production rates increase as $r_h^{-6.8}$ for $r_h > 3$ AU; $r_h^{-1.8}$ for 3 AU $> r_h >$ 1.3 AU; and $r_h^{-3.7}$ for $r_h < 1.3$ AU (Colom *et al.*, 1997). The postperihelion data show only two such distinct regimes (Biver *et al.*, 2002). Preperihelion gas and dust production rate curves obtained of comet 46P/Wirtanen during its 1996/97 apparition showed a steep increase between 1.8 AU and 1.6 AU (Schulz *et al.*, 1998;

Schulz & Schwehm, 1999), which was indicated already in the visual light curve during previous apparitions (Morris 1994). Comet 67P/Churyumov-Gerasimenko had a major drop of gas and dust production rates between 2.5 and 2.9 AU postperihelion (Schulz *et al.*, 2004). A comparison of pre- and postperihelion production rate curves of Comet 1P/Halley confirmed that, unlike Hale-Bopp, this comet was significantly more active after perihelion (Schleicher *et al.*, 1998). Fits to the production rate curves showed that for each species the postperihelion curve is flatter that the preperihelion one. However, one has to keep in mind that comet 1P/Halley showed strong short-term variability, which makes any accurate determination of the shape of its production curves, as a function of heliocentric distance very difficult. In summary, the study of those comets for which sufficient data exist reveals a rather complex activity evolution along the orbit. It is therefore absolutely necessary to continue these investigations on a statistically more relevant sample.

5. Classification of Comets

One of the most discussed questions in view to the origin of comets is whether all or at least some of the Jupiter-family comets come from the Edgeworth-Kuiper Belt rather than from the Oort Cloud. Rather convincing evidence for this assumption has already been establish from dynamical investigations (e.g. Levison and Duncan, 1994). A'Hearn *et al.* (1995) therefore evaluated their production rate survey of 85 comets also in this respect and reported the discovery of significant compositional groupings of comets apparently related to their place of formation. One of their main conclusions is that a significant amount of the short-period comets (most of them Jupiter-family) shows a depletion in carbon-chain molecules, best recognizable from the C_2/CN production rate ratio. On this premises they have introduced a new comet taxonomy, distinguishing comets with *typical* abundance ratios from *carbon-chain depleted* comets and have postulated that the latter comets and only those originate in the Kuiper Belt. The distinction between *typical* and *depleted* abundance ratios in comets has clearly proved to be reasonable and useful, the hypothesis that *depleted* comets might originate in the Edgeworth-Kuiper Belt, however, shows a number of inconsistencies. Firstly, most, but not all *depleted* comets are Jupiter-family comets. About one third of the comets designated as *depleted* were long-period or even dynamically new comets with highly inclined orbits. Secondly, among the Jupiter-family comets, *typical* and *depleted* C_2/CN abundance ratios seem to be more or less evenly distributed (16 typical versus 20 depleted Jupiter-family comets). Thirdly, most of the 85 comets studied by A'Hearn *et al.* (1995) were observed at a rather limited range of heliocentric distances although the production rates of C_2 and CN are known to vary along the orbit. Therefore, much more work is required to understand why and under which circumstances comets show *typical* or *depleted* abundance ratios and whether this criterion may be connected to their place of formation. For this it is vital to first fully understand the compositional evolution of a cometary coma with heliocentric distance.

6. Summary, Suggestions and Conclusions

A huge amount of gas and dust production rates has been collected over the past three decades. Values exist for about 2/3 of the 168 currently known numbered periodic comets and for more than 60 unnumbered ones. For short-period comets, mostly of the Jupiter-family, data are also available over multiple apparitions. Observations of the same comet obtained by various teams very often excellently complement each other.

Nevertheless, all these data have never been combined into a common database, because production rates are only directly comparable if they have been determined from the measured photometric fluxes using the same photolytic model and parameters. Unfortunately this is not the case. The various teams conducting compositional surveys are not even using the same values for the fluorescence efficiencies (g-factors) for the molecular bands they observe. Sentences like: "the adopted constants for converting from fluxes to column densities may not be identical to the constants adopted by other groups", "comparison with other observers is not straightforward because of differences in models to compute production rates", "considerable different scale lengths causes the production rates to diverge by factors of 3" or "users must be cautious when comparing observations from different groups" can be found in almost every publication made on production rates.

However, if we want to draw conclusions on diversities and similarities of comets in terms of their composition, we need to combine the available data for each comet and the ensemble of comets into a common database. No single data set will be sufficient to reach statistically sound conclusions. By know we have realized that although most of the species visible in the optical were extensively observed in the past, we are still far from a perfect understanding of exactly how these species are produced and destructed, whether and how their abundances differ from comet to comet or how they vary with heliocentric distance and with the number of apparitions of a comet. To ensure that data of the individual comets can be combined into a larger database, or at least to permit a direct comparison of the results of the various groups, we need to re-calculate the gas production rates of all comets from the measured photometric fluxes with a single model and a single set of parameters.

Many teams have been publishing the measured fluxes in addition to production rates that can in principle be used to create a common set of all these data. For instance, most of the teams that have recently published production rates of Comet 81P/Wild 2 have also included the measured photometric fluxes (e.g. Fink *et al.*, 1999; Schulz *et al.*, 2003; Farnham and Schleicher, 2004). To facilitate comparison with other data sets, Lara *et al.* (2004) have started to publish not just the gas production rates they have determined with their favorite model and parameters, but also those that would result with the parameters used in the study by A'Hearn *et al.* (1995), the so far most extensive data base of a single team. This may be the first step into establishing the common database of gas production rates, which is definitely needed if we not just want to collect data, but actually benefit from the huge data pool we have already at hand. In the not too long term, we need to agree on a standard model and a set of parameters for the determination of gas production rates. The least we should do is publishing not just production rates, but also fluxes and when we write a publication, use previously published flux values of other teams to re-calculate for comparison with and complementation of our data set.

References

A'Hearn, M.F. & Millis, R.L. 1980, *A.J.* 85, 1528–1537

A'Hearn, M.F., Schleicher, D.G., Feldman, P.D., Millis, R.L., & Thompson, D.T. 1984, *A. J.* 89, 579–591

A'Hearn, M.F., Schleicher, D.G., Millis, R.L., Feldman, P.D., & Thompson, D.T. 1984, *A. J.* 89, 579–591

A'Hearn, M.F., Millis, R.L., Schleicher, D.G., Osip, D.J., & Birch, P.V. 1995, *Icarus* 118, 223–270

Biver, N., Bockelée-Morvan, D., Colom, P., Crovisier, J., Henry, F., Lellouch, E., Winnberg, A., Johansson, L.E.B., Gunnarson, M., Rickman, H., Rantakyrö, F., Davies, J.K., Dent, W.R.F., Paubert, G., Moreno, R., Wink, J., Despois, D., Benford, D., Gardner, M., Lis, D.C., Mehringer, D., Phillips, T.G., & Rauer, H. 2002, *Earth, Moon & Planets* 90, 5–14

Combi, M.R. & Delsemme, A.H. 1986, *Ap. J.* 308, 472-484

Cochran, A.L., Barker, E.S., Ramseyer, T.F., & Storrs, A.D. 1992, *Icarus* 98, 151–162

Cochran, A.L. & Barker, E.S. 1999, *Icarus* 141, 307–315

Colom, P., Gérard, E., Crovisier, J., & Bockelée-Morvan, D. 1997, *Icarus* 141, 307

Crovisier, J. 2005, *this issue*

Farnham, T.L. & Schleicher, D.G. 1998, *A. & A.* 335, L50

Farnham, T.L. & Schleicher, D.G. 2004, *Icarus* 173, 533

Feldman, P.D., Cochran, A.L., & Combi, M.R. 2004, in: M.C. Festou, H.U. Keller, H.A. Weaver (eds.), *Comets II*, (Tucson: University of Arizona Press), p. 425

Festou, M.C. 1981, *A. & A.* 95, 69

Fink, U. & Hicks, M.D. 1996, *Ap. J.* 459, 729

Fink, U., Hicks, M.D., Fevig, R.A., & Collins, J. 1998, *A. & A.* 335, L37

Fink, U., Hicks, M.D., & Fevig, R.A. 1999, *Icarus* 141, 331

Fink, U. & Combi, M.R. 2004, *Planetary & Space Science* 52, 573

Green, S.F., McDonnell, J.A.M., McBride, N., Colwell, M.T.S.H. Tuzzolino, A.J., Economou, T.E., Tsou, P., Clark, B.C., & Brownlee, D.E. 2004, *JGR* 109, E12S04

Haser, L. 1957, *Bull. Acad. Roy. Belgique, Classe de Sciences* 43, 740

Huggins, W. 1882, *Proc. Roy. Soc.* 33, 1

Kissel, J., Sagdeev, R.Z., Bertaux, J.L., Angarov, V.N., Audouze, J., Blamont, J.E., Büchler, K., Evlanov, E.N., Fechtig, H., Fomenkova, M.N., von Hoerner, H., Inogamov, N.A., Khromov, V.N., Knabe, W., Krueger, F.R., Langevin, Y., Leonas, V.B., Levasseur-Regourd, A.C., Managdze, G.G., Podkolzin, S.N., Shapiro, V.D., Tabaldyev, S.R., & Zubkuv, B.V. 1986, *Nature* 321, 280

Kissel, J., Krueger, F.R., Silen, J., & Clark, B.C. 2004, *Science* 304, 1774

Lara, L.M., Schulz, R., Stüwe, J.A., & Tozzi, G.P. 2001, *Icarus* 150, 124

Lara, L.M., Tozzi, G.P., Boehnhardt, H., DiMartino, M., & Schulz, R. 2004, *A. & A.* 422, 717

Levison, H.F. & Duncan, M.J. 1987, *Icarus* 108, 18-36

Makinen, J.T.T., Bertaux, J.-L., Pulkkinen, T.I., Schmidt, W., Kyrölä, E., Summanen, T., Quèmerais, E., & Lallement, R. 2001a, *A. & A.* 368, 292

Makinen, J.T.T., Silèn, J., Schmidt, W., Kyrölä, E., & Summanen, T. 2001b, *Icarus* 152, 268

McDonnell, J.A.M., Lamy, P.L., & Pankiewicz, G.S. 1991, in: R.L. Newburn Jr., M. Neugebauer & J. Rahe (eds.), *Comets in the Post Halley Era*, (Kluwer Academic Publishers), p. 1043

McDonnell, J.A.M., McBride, N., Beard, R., Bussoletti, E., Colangeli, L., Eberhardt, P., Firth, J. G., Grard, R., Green, S.F., & Greenberg, J.M. 1993, *Nature*, 362, 732

Morris, C. 1994, *International Comet Quarterly* 92, 178

Newburn, R.L., Jr. & Spinrad, H. 1989, *A. J.* 97, 552

Prialnik, D. 2005, *this issue*

Rauer, H., Helbert, J., Arpigny, C., Benkhoff, J., Bockelèe-Morvan, D., Boehnhardt, H., Colas, F., Crovisier, J., Hainaut, O., Jorda, L., Kueppers, M., Manfroid, J., & Thomas, N. 2003, *A. & A.* 397, 1109

Schleicher, D.G., Lederer, S.M., Millis, R.L., & Farnham, T.L. 1997, *Science* 275, 1913

Schleicher, D.G., Millis, R.L., & Birch, P.V. 1998 *Icarus* 132, 397

Schleicher, D.G., Woodney, L.M., & Millis, R.L. 2003, *Icarus* 162, 415

Schleicher, D.G. & Farnham, T.L. 2004, in: M.C. Festou, H.U. Keller, H.A. Weaver (eds.), *Comets II* (Tucson: University of Arizona Press), p. 449

Schulz, R., A'Hearn, M.F., Birch, P.V., Bowers, C., Kempin, M., & Martin, R. 1993b, *Icarus* 104, 206

Schulz, R., Arpigny, C., Manfroid, J., Stüwe, J.A., Tozzi, G.P., Rembor, K., Cremonese, G., & Peschke, S. 1998, *A. & A.* 335, L46

Schulz, R. & Schwehm, G. 1999, *Space Science Review* 90, 321

Schulz, R., Tozzi, G.P., Stüwe, J.A., & Owens, A. 2000, *A. & A.* 361, 359

Schulz, R., Stüwe, J.A., Boehnhardt, H., Gaessler, W., & Tozzi, G.P. 2003, *A. & A.* 398, 345

Schulz, R., Stüwe, J.A., & Boehnhardt, H. 2004, *A. & A.* 422, L19

Swings, P. 1943, *M.N.R.A.S.* 103, 86

Swings, P. & Haser L. 1956, *University of Liège Astrophysical Institute, Tech. Rept. AF61* 514

Tegler, S.C., Campins, H., Larson, S., Kleine, M., Kelley, D., & Rieke, M. 1992, *Ap.J.* 396, 711

Turner, N.J. & Smith, G.H. 1999, *A.J.* 118, 3039

Tuzzolino, A.J., Economou, T.E., Clark, B.C., Tsou, P., Brownlee, D.E., Green, S.F., McDonnell, J.A.M., McBride, N., & Colwell, M.T.S.H. 2004, *Science* 304, 1778

Weaver, H.A., Feldman, P.D., A'Hearn, M.F., Arpigny, C., Brandt, J.C., & Stern, S.A. 1999, *Icarus* 141, 1

Weaver, H.A., Feldman, P.D., A'Hearn, M.F., Arpigny, C., Brandt, J.C., Festou, M.C., Haken, M., McPhate, J.B., Stern, S.A., & Tozzi, G.P. 1997, *Science* 271, 1900