Chapter 1

Cometary diversity and cometary families

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Abstract Comets are classified from their orbital characteristics into two separate classes: nearly-isotropic, mainly long-period comets and ecliptic, short-period comets. Members from the former class are coming from the Oort cloud. Those of the latter class were first believed to have migrated from the Kuiper belt where they could have been accreted in situ, but recent orbital evolution simulations showed that they rather come from the trans-Neptunian scattered disc. These two reservoirs are not where the comets formed: they were expelled from the inner Solar System following interaction with the giant planets. If comets formed at different places in the Solar System, one would expect they show different chemical and physical properties. In the present paper, I review which differences are effectively observed: chemical and isotopic compositions, spin temperatures, dust particle properties, nucleus properties... and investigate whether these differences are correlated with the different dynamical classes. The difficulty of such a study is that long-period, nearly-isotropic comets from the Oort cloud are better known, from Earth-based observations, than the weak nearly-isotropic, short-period comets. On the other hand, only the latter are easily accessed by space missions.

1.1 Introduction

There are not two comets alike. These objects show an extraordinary diversity (Fig. 1.1). Besides the multiplicity of their appearance, the diversity of comets is twofold:

- diversity of orbits, from which different dynamical classes of comets have
Figure 1.1: Cometary diversity, from a 17th century engraving. The exact origin is unknown, but a similar plate was published under a different title in “Description de l’Univers” (Paris, 1683) by Allain Manesson Mallet (1630–1706). At that time, the diversity of comets was remarked from their appearance.
been clearly defined;

• physical and chemical diversity. Several attempts to base a taxonomy of comets upon their chemical diversity were made.

Our present knowledge of the nature of comets, of their formation and evolution, is reviewed in the chapters of [1]. Two fundamental questions arise, related to the diversity of comets and to the history of their formation:

• are the different dynamical classes of comets related to different formation scenarios, and more specifically, to different sites of formation?
• is the physical/chemical diversity of comets due to different formation conditions? Is it linked to the dynamical differences?

The ices contained in comet nucleus comprise molecules of very different volatility [2]. One would expect that the spread of sublimation/condensation temperatures of these molecules leads to a correlation between formation sites and composition, and that the snow lines for the different species follow the temperature profile of the Solar System (i.e., the equilibrium temperature as a
function of heliocentric distance $r_h$). The most volatile molecules (the so-called hypervolatiles) such as CO$_2$ and CH$_4$ can only condense only far from the Sun ($r_h > 50$ AU) whereas water condenses at $r_h > 3$ AU (Fig. 1.2).

Chemistry in the protosolar nebula is also expected to be highly $r_h$-dependent. However, an extensive radial mixing of matter in the protoplanetary Solar Nebula is now testified by several clues (e.g., the presence of both amorphous and crystalline silicates). It would tend to make the chemical composition uniform within the Nebula. But it does not preclude a segregation of the various ice components according to their sublimation temperatures.

On the other hand, short-period comets, which experienced many returns close to the Sun, are likely to present significant modifications of their nucleus outer layers due to heating and sublimation fractionation.

The purpose of the present paper is to examine whether the cometary diversity could be linked to different origins of these bodies. The dynamical history of comets and the possible existence of several reservoirs have already been extensively discussed in the literature (e.g., in several chapters of [1]). A summary is given in Section 1.2. A comparative presentation of the available data on the nature of comets, according to their different dynamical classes, is given in Section 1.3. The possible links between cometary diversity, cometary reservoirs, and their sites of formation, deserve to be analysed and discussed in the light of recent results; this is done in Sections 1.4, 1.5 and 1.6.

1.2 Cometary orbits and cometary reservoirs

1.2.1 Cometary orbits

Following the now classical view, there are two main classes of comets according to their orbital characteristics. Nearly-isotropic comets have arbitrary orbital inclinations; they comprise long-period comets ($\gtrsim 200$ years) and Halley-type comets of shorter orbital periods. Ecliptic comets (aka Jupiter-family comets) have short orbital periods (typically $\lesssim 20$ years) and low orbital inclinations (typically $< 20^\circ$); their orbital evolution is governed by interaction with Jupiter.

A convenient dynamical indicator, used to separate these two classes, is the Tisserand parameter:

$$T_J = \frac{a_J}{a} + 2 \sqrt{\frac{a}{a_J}} (1 - e^2) \cos i,$$

where $a_J$ is the semi-major axis of Jupiter (5.20 AU), $a$ that of the comet orbit, $e$ its eccentricity and $i$ its inclination. For Jupiter-family comets, $2 < T_J < 3$, whereas long-period and Halley-type comets have $T_J < 2$ and asteroids have $T_J > 3$.

Levison [4] proposed a slightly modified family tree for comets, from their Tisserand parameter and their semi-major axis (Fig. 1.3). Chiron-type comets (aka Centaurs — only a handful of them are known to be active) and Encke-type comets (only two members are known to date) are now introduced.
Figure 1.3: Comet families according to Levison [4], using the Tisserand parameter $T$ and the semi-major axis $a$ as criteria.

Quite recently, a new class, Main-belt comets, was introduced [5]. It includes objects with typical orbits of Main Belt asteroids which show a low level of activity. It is possible that many objects presently classified as asteroids belong to this class. Such objects have rather stable orbits and are probably not dynamically related to the other classes of comets. Since there are only three such comets known to date, for which the chemical and physical characteristics are practically unknown, these objects will not be considered here. (Main Belt comets may also be considered as activated asteroids [6].)

1.2.2 Where comets are stored

The origin of comets has been for a long time the subject of debates. Before being recognized as Solar System objects, comets were considered as atmospheric phenomena, or to originate from the Galaxy. Flammarion and Proctor in the 19th century, and more recently Crommelin and Vsekhsvyatskii, argued that Jupiter-family comets were expelled from giant planets [7].

The Oort cloud [8], already described by Schiaparelli and Öpik [9, 10], was introduced to explain the continuous input of new long-period comets.

The belt of trans-Neptunian objects now known as the Kuiper belt [11] was already described by Leonard and Edgeworth [11, 12, 13]. Following the discovery of the first batch of trans-Neptunian objects in the nineties, it was readily accepted as the reservoir of ecliptic comets. However, the orbits of Kuiper-belt objects appear to be very stable and unlikely to evolve into short-period comets. The current idea is that ecliptic comets rather come from another class of trans-Neptunian objects, the scattered disc, whose orbits are more eccentric and show
significant inclination \cite{14, 15, 16}. In fact, the border between the inner part of the Oort cloud and the scattered disc does not seem to be clearly established.

1.2.3 Where comets formed

Numerical simulations of orbital evolutions can now constrain more precisely the possible sites of formations of comets \cite{14, 15, 16, 17}.

Nearly-isotropic comets, formed in the Jupiter–Uranus region, were ejected to the Oort cloud, then coming back as long-period comets and evolving to Halley-type comets.

For some time, it was believed that ecliptic comets were formed in the Kuiper belt beyond Neptune, then migrated to become Jupiter-family comets. Following this paradigm, nearly-isotropic comets were dubbed Oort-cloud comets, and Jupiter-family comets, Kuiper-belt comets. The two classes of comets would have then been formed at quite different distances from the Sun: the “cold” Kuiper-belt comets in the trans-Neptunian region, and the warmer Oort-cloud comets in the Jupiter–Uranus region, expected to be comparatively volatile-depleted.

We now know that ecliptic comets rather come from the scattered disc, and that they were not formed there, but were expelled from the intra-Neptunian Solar System, like the Oort-cloud comets. What are precisely the regions where the two classes of comets formed, and are there indeed different, is presently a moot point. Orbital evolution simulations have shown that the orbits of the giant planets dramatically changed in the first steps of the Solar System history, so that their present places may greatly differ from the places they had when comets formed and were expelled \cite{17}.

To complicate the situation, a comet nucleus may result from the accretion of planetesimals of different origins and different compositions. This could be tested by observing comets that fragmented in different components, as did C/1999 S4 (LINEAR) and 73P/Schwassmann-Wachmann 3.

1.3 Available observations

Jupiter-family and Oort-cloud comets are far from being equally well observed.

To show this for Earth-based observations, we will use the figure of merit $FM = Q[H_2O]/\Delta$, as introduced in \cite{22}. This parameter is roughly proportional to the expected signal, and allows us to evaluate and compare the observability of comets. Table \ref{table1} gives the figure of merit for Earth-based observations of recent long-period comets, as well as for recent and future returns of short-period comets. One can see that unexpected, long-period comets offered much better opportunities than short-period comets. Indeed, the two best comets in the last twenty years were, by far, C/1996 B2 (Hyakutake) and C/1995 O1 (Hale-Bopp). Unprecedented spectroscopic observations led to the detection of many new molecules in these two comets.

Short-period, Jupiter-family comets are all weak comets with $Q [H_2O] \approx a$ few $10^{28}$ s$^{-1}$ at most. The best observing conditions occur for these comets
Table 1.1: Remote sensing observing conditions for a selection of comets

| comet               | date                  | $r_h$ [AU] | $\Delta$ [AU] | $Q$ [$10^{28}$ s$^{-1}$] | $FM$ |
|---------------------|-----------------------|------------|---------------|-------------------------|------|
| 1P/Halley           | January 1986          | 0.7        | 1.5           | 120                     | 80   |
| C/1986 P1 (Wilson)  | May 1987              | 1.3        | 1.0           | 12                      | 12   |
| C/1989 X1 (Austin)  | April 1990            | 1.2        | 0.25          | 2.5                     | 10   |
| C/1990 K1 (Levy)    | August 1990           | 1.3        | 0.45          | 25                      | 55   |
| 109P/Swift-Tuttle   | November 1992         | 1.0        | 1.3           | 50                      | 40   |
| C/1996 B2 (Hyakutake) | March 1996           | 1.1        | 0.11          | 25                      | 225  |
| C/1995 O1 (Hale-Bopp) | April 1997          | 0.9        | 1.4           | 1000                    | 700  |
| C/1999 S4 (LINEAR)  | July 2000             | 0.77       | 0.38          | 10                      | 25   |
| C/1999 T1 (McNaught-Hartley) | December 2000 | 1.2       | 1.6           | 10                      | 6    |
| C/2001 A2 (LINEAR)  | June 2001             | 1.0        | 0.24          | 10                      | 40   |
| C/2000 WM1 (LINEAR) | December 2001        | 1.2        | 0.32          | 4                       | 12   |
| 153P/2002 C1 (Ikeya-Zhang) | April 2002      | 1.0        | 0.40          | 25                      | 60   |
| C/2001 Q4 (NEAT)    | May 2004              | 1.0        | 0.32          | 20                      | 60   |
| C/2002 T7 (LINEAR)  | May 2004              | 0.8        | 0.27          | 10                      | 25   |
| C/2003 K4 (LINEAR)  | December 2004        | 1.4        | 1.2           | 15                      | 12   |
| C/2004 Q2 (Machholz) | January 2005        | 1.2        | 0.35          | 25                      | 70   |
| 22P/Kopff           | April 1996            | 1.7        | 0.9           | 3.5                     | 4    |
| 21P/Giacobini-Zinner| October 1998          | 1.2        | 1.0           | 3                       | 3    |
| 19P/Borrelly        | September 2001        | 1.36       | 1.47          | 3                       | 2    |
| 2P/Encke            | November 2003         | 1.0        | 0.25          | 0.5                     | 2    |
| 9P/Tempel 1         | July 2005             | 1.5        | 0.77          | 1                       | 1.3  |
| 73P/Schwassmann-Wachmann 3 | May 2006      | 1.0        | 0.08          | 2                       | 25   |
| 8P/Tuttle           | January 2008          | 1.1        | 0.25          | 3                       | 12   |
| 85P/Boethin         | December 2008         | 1.1        | 0.9           | 3                       | 3.3  |
| 67P/Churyumov-Gerasimenko | Mars 2009      | 1.24       | 1.7           | 1                       | 0.6  |
| 103P/Hartley 2      | October 2010          | 1.1        | 0.12          | 1.2                     | 10   |
| 45P/Honda-Mrkos-Pajdušáková | August 2011  | 1.0       | 0.06          | 0.5                     | 8    |

Top part: recent nearly-isotropic comets.
Bottom part: recent and future ecliptic comets.
Date is for best observing conditions. $Q =$ water production rate at that date.
$FM = Q/\Delta =$ Figure of merit.
Table 1.2: Space exploration of comets

| Comet            | mission         | date             | $V$ [km s$^{-1}$] | $r_e$ [km] | $Q$ [$10^{28}$s$^{-1}$] | Ref. |
|------------------|-----------------|------------------|-------------------|-----------|-------------------------|------|
| 1P/Halley        | VEGA, Giotto    | March 1986       | 68–79             | 5.5       | 200.                    | [18, 19] |
| 19P/Borrelly     | Deep Space 1    | 22 September 2001| 17                | 2.2       | 3.                      | [20] |
| 81P/Wild 2       | Stardust        | 2 January 2004   | 6                 | 2.1       | 1.                      | [21] |
| 9P/Tempel 1      | Deep Impact     | 4 July 2005      | 11                | 3.0       | 1.                      | [22, 23] |
| 67P/Churyumov-G. | Rosetta         | 2014–2015        | 0                 | 1.0       | 0.–1.                   | [24] |

$V = $ flyby velocity.

$r_e = $ nucleus equivalent radius.

$Q = $ water production rate at time of exploration.

which make a close approach to the Earth. This was recently the case for 73P/Schwassmann-Wachmann 3 (Δ = 0.08 AU on May 2006) and it will also happen for 103P/Hartley 2 in the future (Δ = 0.12 AU on October 2010). But the figure of merit of such Jupiter-family comets is still much lower than that of the best long-period comets.

The situation is opposite with regard to space exploration (Table 1.2): short-period comets, which have expected returns, are the only practicable targets for space missions, which are not yet versatile enough to accommodate unexpected comets. Flybys at a slow velocity and rendezvous are only possible for ecliptic comets, due to the energy limitations of current space technology. 1P/Halley is the only explored comet which does not belong to the Jupiter family: the price to pay was a very large flyby velocity (≈ 70 km s$^{-1}$). Although several studies of space missions towards an unexpected comet were made [26], there is currently no firm plan for such a mission.

On the other hand, short-period comets have very well known orbits, allowing us to perform accurate modelling of non-gravitational forces. Asteroid-like studies of cometary nuclei (i.e., measurement of albedo, size and light curve) are also better done on these weak objects.

### 1.4 Chemical diversity

Only very few comets were explored in situ, so the chemical composition of comets and its diversity are basically investigated by remote sensing using spectroscopy. This investigation is indirect, since only the gas and dust coma is observed, after the nucleus ices have sublimated. Sublimation fractionation may occur (i.e., the most volatile species sublimate first). The production rates of the sublimated molecules (or of their photodissociation products, the so-called *daughter molecules*) are determined. How they are related to the initial
molecular abundances in the nucleus is an open issue. Indeed, the relative production rates vary as a function of heliocentric distances, as was found for comet Hale-Bopp which was observed over a large range of heliocentric distances [27]. Relative molecular production rates — improperly named abundances — are usually given relative to the water production rate, for heliocentric distances \( r_h \approx 1 \text{ AU} \). At such distances, the outgassing of cometary ices is dominated by water sublimation and it is likely that in this regime of strong sublimation, all species more volatile than water are expelled without significant fractionation.

Table 1.3: Relative production rates of radicals.

|         | “typical” | “C\textsubscript{2}-depleted” |
|---------|-----------|-----------------------------|
|         | \( C_2/\text{CN} > 0.66 \) | \( C_2/\text{CN} < 0.66 \) |
| OH      | 100       | 100                         |
| CN      | 0.32 (0.15–0.68) | 0.20 (0.11–0.31) |
| \( C_2 \) | 0.36 (0.13–0.79) | 0.050 (0.007–0.10) |
| \( C_3 \) | 0.025 (0.0055–0.081) | 0.0066 (0.0026–0.020) |
| NH      | 0.42 (0.17–1.6) | 0.33 (0.11–1.2) |

Adapted from [28] where “typical” and “C\textsubscript{2}-depleted” comets are separated according to their \( C_2/\text{CN} \) ratio. Mean production rates and ranges (between parentheses) are listed relative to OH (normalized to 100).

1.4.1 From the visible and the UV: daughter species.

From narrow-band photometric observations of cometary radical, a database of more than one hundred comets has now been constructed, with determinations of the relative production rates of OH, CN, \( C_2 \), \( C_3 \), NH, NH\textsubscript{2} \[28, 29, 30\].

A’Hearn et al. [28] proposed the existence of two classes of comets, depending on their \( C_2/\text{CN} \) ratio, that they named “typical” and “\( C_2 \)-depleted” comets. From their statistics, about one-half of the Jupiter-family comets are \( C_2 \)-depleted, but this fraction is much smaller among nearly-isotropic comets (Table 1.3 and Fig. 1.4).

There are also occasionally comets with strongly anomalous compositions, which are really puzzling monsters. For instance, comet 43P/Wolf-Harrington showed CN, but \( C_2 \) was not observed [31] (Fig. 1.5); comet C/1988 Y1 (Yanaka) showed NH\textsubscript{2}, but no CN nor \( C_2 \) [32] (Fig. 1.5).

Fink [30] suggested a taxonomy similar to [28], but with additional classes: (i) “normal” comets (prototype: 1P/Halley); (ii) comets with low \( C_2 \) and normal NH\textsubscript{2} (prototype: 9P/Tempel 1); (iii) comets with low \( C_2 \) and low NH\textsubscript{2} (prototype: 21P/Giacobini-Zinner); and (iv) comet C/1988 Y1 (Yanaka) which does not fit in the preceding classes. The first three classes comprise respectively 70, 22 and 6 % of the comets in the database.

Unfortunately, these daughter-species studies do not inform us directly on the nature of their parent species. There is little doubt that the OH radical
Figure 1.4: The possible correlation between carbon-depleted comets and Jupiter-family comets (filled symbols, with $T_J > 2$). From [28].

Figure 1.5: Spectra of the anomalous comets 43P/Wolf-Harrington (C$_2$-depleted) and C/1988 Y1 (Yanaka) (NH$_2$-rich), compared to the normal comets C/1989 X1 (Austin) and 1P/Halley. Adapted from [31, 32].
Table 1.4: The composition of cometary volatiles from IR observations$^a$.

| Comet          | CO  | CH$_4$ | C$_2$H$_6$ | C$_2$H$_2$ | HCN  | CH$_3$OH | Ref. |
|----------------|-----|--------|------------|------------|------|----------|------|
| 5 Oort-cloud comets$^b$ | 1.8–17 | 0.5–1.5 | ≈ 0.6      | 0.2–0.3   | 0.2–0.3 | ≈ 2      | 35   |
| 1999 S4 (LINEAR)     | 0.9  | 0.2    | 0.1        | < 0.12    | 0.1   | < 0.1    | 36   |
| C/2001 A2 (LINEAR)   | 3    | 1.4    | 1.6        | 0.4       | 0.5   | 3.5      | 37   |
| 21P/Giacobini-Zinner | < 3  | < 0.08 | < 0.4      | < 0.3     | 1.    |          | 38   |
| 21P/Giacobini-Zinner | 10   | 0.2    |            |           |       |          | 39   |
| 9P/Tempel 1 before DI| 0.2  | 0.2    | 1.1        |          |       |          | 40   |
| 9P/Tempel 1 after DI | 4    | 0.5    | 0.3        | 0.1       | 0.2   | 1.0      | 40   |
| 73P/S.-W. 3-C        | 0.2  | 0.2    | 0.3        |          |       |          | 41   |
| 73P/S.-W. 3-B        | < 2  | 0.14   | ≈ 0.03     | 0.25      | 0.2   |          | 42   |

$^a$ Production rates are given relative to water = 100.

$^b$ C/1999 H1 (Lee), C/1995 O1 (Hale-Bopp), C/1996 B2 (Hyakutake), 153P/2002 C1 (Ikeya-Zhang), C/1999 T1 (McNaught-Hartley).

comes mostly form the photolysis of water and indeed, the OH production rates are used as a proxy for the cometary water production rates. But there is no complete understanding on which are the parents for the C$_2$, C$_3$[33], and even the CN radicals [34]. There are also clues that some of these species come, at least partly, from distributed sources (e.g., from cometary grains), rather than from the nucleus ices.

1.4.2 From the infrared and the radio: parent volatiles.

Except for carbon monoxide which has strong electronic bands in the UV, parent molecules have to be observed through the fluorescence of their vibrational bands in the infrared, or their rotational lines at radio wavelengths [49].

About a dozen comets have been investigated by infrared spectroscopy [35, 41]. A summary of the results is given in Table 1.4. The best studied Jupiter-
family comet is 73P/Schwassmann-Wachmann 3. In addition to molecules such as H$_2$O, HCN, CH$_3$OH, H$_2$CO, NH$_3$ or OCS, infrared spectroscopy can specifically study non-polar molecules, such as hydrocarbons (CH$_4$, C$_2$H$_2$, C$_2$H$_6$), which do not have permitted rotational lines. It can also observe CO$_2$, but only from space due to strong telluric absorption; thus this important cometary volatile has only been observed in a very small number of comets.

Radio spectroscopy achieved detection of about 25 cometary molecules, radicals and ions. Fairly complex molecules, even with small abundances, can be studied provided they have a significant dipolar moment. Molecules as complex as methyl formate (HCOOCH$_3$) or ethylene glycol ((CH$_2$OH)$_2$) have been identified in comet Hale-Bopp. About 30 comets have been investigated by this technique, with resulting information on the production rates of H$_2$O, HCN, HNC, CH$_3$CN, CH$_3$OH, H$_2$CO, CO, CS and H$_2$S. A preliminary analysis of the comet-to-comet chemical diversity is given in [43] with updates in [47, 49, 50]. The summary of the results is presented in Table 1.5. Here again, the best studied Jupiter-family comet is 73P/Schwassmann-Wachmann 3. Whereas the HCN/H$_2$O ratio is relatively constant, several species, such as CH$_3$OH, H$_2$CO and H$_2$S, have important variations from comet to comet. As an example, the distributions of the HCN/H$_2$O and CH$_3$OH/H$_2$O abundance ratios are shown in Fig. 1.6.

An extreme case is that of CO. In distant comets, such as C/1995 O1 (Hale-Bopp) or 73P/Schwassmann-Wachmann 1, CO is the only observed cometary volatile. At $\approx$ 1 AU from the Sun, the production rate of carbon monoxide relative to water ranges from less than 1 % (as observed in the UV by FUSE) to $\approx$ 30 % (C/1995 O1 (Hale-Bopp)). The very origin of cometary CO is a debated topic. In situ observations of 1P/Halley and infrared observations of C/1995 O1 (Hale-Bopp) pointed to a distributed source in addition to the nucleus native source [52], whereas radio interferometric observations of C/1995 O1 (Hale-Bopp) are consistent with a native source only [53].

Two comets were remarked to be strongly “volatile-depleted”: C/1999 S4 (LINEAR) and 73P/Schwassmann-Wachmann 3. Both have very low CO and CH$_3$OH abundances, but normal HCN. We have here an example of a nearly-isotropic and a Jupiter-family comet sharing the same anomalies! (Indeed, these two comets experienced fragmentation.)

The presence – or not – of hypervolatiles in cometary ices could be a stringent clue to the formation temperature of comets. CO, CH$_4$, N$_2$ condense at temperatures lower than $\approx$ 30 K (Fig. 1.2). The presence of N$_2$, tentatively inferred from the observation of N$_2^+$ bands, could not be confirmed in recent, high-quality observations [56]. Noble gases (He, Ne, Ar, Kr...) are still to be detected. However, no clear difference in the abundance of very volatile molecules such as CO, CH$_4$, C$_2$H$_2$, HzS could be found between Jupiter-family and Oort-cloud comets (Tables 1.3 and 1.5).
Figure 1.6: The HCN and CH$_3$OH abundances relative to water from the radio spectroscopic database of comets. The ellipse sizes represent errors. From [55].
Table 1.6: Spin temperatures observed in comets. Adapted from the compilation of [59], and updated with recent results.

| Comet                         | \( \text{H}_2\text{O} \) \([\text{K}]\) | \( \text{NH}_3 \) \([\text{K}]\) | \( \text{CH}_4 \) \([\text{K}]\) | Orbital period \([\text{yr}]\) |
|-------------------------------|------------------------------------------|---------------------------------|---------------------------------|-------------------------------|
| 1P/Halley                     | 29 ± 2                                   |                                 |                                 | 76                            |
| C/1986 P1 (Wilson)            | > 50                                     |                                 |                                 | dynamically new               |
| C/1995 O1 (Hale-Bopp)         | 28 ± 2                                   | 26\(^{+10}_{-4}\)              |                                 | 4000                          |
| 103P/Hartley 2                | 34 ± 3                                   |                                 |                                 | 6.4                           |
| C/1999 H1 (Lee)               | 30\(^{+15}_{-6}\)                       |                                 |                                 | dynamically new               |
| C/1999 S4 (LINEAR)            | ≥ 30                                     | 27\(^{+3}_{-2}\)              |                                 | dynamically new               |
| C/2001 A2 (LINEAR)            | 23\(^{+4}_{-3}\)                        | 25\(^{+1}_{-2}\)              |                                 | 40,000                        |
| C/2000 WM\(_1\) (LINEAR)     | 30\(^{+5}_{-3}\)                        |                                 |                                 | dynamically new               |
| 153P/Ikeya-Zhang              | 32\(^{+5}_{-4}\)                        |                                 |                                 | 365                           |
| 2P/Encke                     | ≥ 33                                     |                                 |                                 | 3.3                           |
| C/2001 Q4 (NEAT)              | 31\(^{+11}_{-5}\)                       | 31\(^{+4}_{2}\)               | 33\(^{+2}_{-1}\)              | dynamically new               |
| 9P/Tempel 1                   | 24\(^{+2}_{-1}\)                        |                                 |                                 | 5.5                           |
| C/2004 Q2 (Machholz)         | > 35                                     |                                 |                                 | dynamically new               |
| 73P/Schwassmann-Wachmann 3    | > 42                                     |                                 |                                 | 5.4                           |

1.5 Diversity from physical indicators and others

1.5.1 Spin temperatures.

Molecules such as \( \text{H}_2\text{O} \), \( \text{NH}_3 \), \( \text{CH}_4 \)… which have several identical hydrogen atoms exist in different spin species (ortho–para, \( A–E \)…). Spin transitions are forbidden, so that spin temperatures could be preserved for a long time. The ortho-to-para ratios (OPR) and spin temperatures observed for water or for other species might thus be primordial. First remarks on this topic were made in [57, 58].

First determinations of the water OPR were made from air-borne infrared observations of comets 1P/Halley and C/1986 P1 (Wilson) [60]. Then accurate measurements were obtained with the Infrared Space Observatory on C/1995 O1 (Hale-Bopp) and Jupiter-family comet 103P/Hartley 2 [61, 62]. Further results on water were obtained by observing vibrational hot bands of water from the ground on bright comets. These results were extended to ammonia. The OPR of \( \text{NH}_3 \) itself cannot (yet) be directly observed, but is derived from the OPR of \( \text{NH}_2 \) determined from its visible spectrum [63]. The spin temperature of methane can also be determined from the \( E, A, F \) spin species relative populations measured from its infrared spectrum.

All these results, recently reviewed in [59] and summarized in Table 1.6, are quite puzzling: the observed spin temperatures are remarkably clustered.
around 30 K, whatever the molecule, the heliocentric distance of the comet or its dynamical history. What is the signification of this temperature? It seems that any possible explanation can be ruled out:

- Equilibration within the coma would lead to spin temperatures depending on the heliocentric distance, as is observed for the rotational temperatures of cometary molecules. Similar spin temperatures were observed for comets at \( r_h \approx 1 \text{ AU} \) and \( r_h \approx 2.9 \text{ AU} \). Laboratory experiments confirm that spin temperatures are preserved in molecular jets.

- Equilibration at the comet surface would also lead to spin temperatures depending on the heliocentric distance, since surface temperatures vary roughly as \( r_h^{-1/2} \). If equilibration occurs at sublimation, one would rather expect \( T_{\text{spin}} \approx 150–200 \text{ K} \), the equilibrium temperature of sublimating water ice in cometary conditions. However, it would be interesting to investigate in the laboratory whether the OPR is preserved during phase transitions.

- A spin temperature in equilibrium with the internal temperature of the nucleus would nicely explain why the spin temperatures are the same for different molecules. However, the comet nucleus internal temperatures depend upon the comet orbital history and are expected to differ between short-period and long-period comets, whereas both classes of comets show the same \( T_{\text{spin}} \). On the other hand, the spin temperatures listed in Table 1.6 pertain to the gas phase; the rotational levels of molecular species have different energies in the solid phase, which leads to a different correspondence between the OPR and \( T_{\text{spin}} \).[64].

- Although inter-spin conversions are forbidden, preservation of the spin state over cosmological times seems to be highly unlikely [64, 65]. This is unfortunately difficult to test in the laboratory! If indeed the present spin temperatures reflect the temperatures at the formation or condensation of the molecules this would imply that all comets formed in very similar physical conditions. Note also that \( \text{H}_2\text{O} \), \( \text{NH}_3 \) and \( \text{CH}_4 \) have very different condensation temperatures: equilibrium at condensation would lead to different \( T_{\text{spin}} \) for these different molecules.

1.5.2 Isotopic ratios.

Isotopic ratios are a crucial diagnostic of the physico-chemical conditions of the early Solar Nebula. This is discussed in detail in [49, 60] and the observational results are summarized in Table 3 of [49].

The only comets for which the D/H ratio in water has been firmly determined — 1P/Halley, C/1996 B2 (Hyakutake) and C/1995 O1 (Hale-Bopp) — are three Oort-cloud comets. All three determinations are close to \( \text{D/H} \approx 3 \times 10^{-4} \) (i.e., twice the terrestrial value and a factor of ten larger than the protosolar
Figure 1.7: Panels a) to d) show different examples of how the formation regions of comets affect the distributions of their observed D/H enrichment $f$. In each of the four panels, the upper diagram shows the used population distributions, and the lower diagram the $f$ distribution that would result. The red line shows Kuiper-belt objects, and the black Oort-cloud objects. From [66].

Table 1.7: Nitrogen and carbon isotopic ratios in comets from observations of the CN radical. Adapted from [67] and [68].

| Comet            | $^{14}$N/$^{15}$N | $^{12}$C/$^{13}$C |
|------------------|------------------|------------------|
| C/1995 O1 (Hale-Bopp) | 140 ± 35         | 90 ± 30          |
| C/2000 WM1 (LINEAR)  | 140 ± 30         | 115 ± 20         |
| 122P/de Vico       | 140 ± 20         | 90 ± 10          |
| 153P/2002 C1 (Ikeya-Zhang) | 170 ± 50        | 90 ± 25          |
| C/2001 Q4 (NEAT)    | 135 ± 20         | 90 ± 15          |
| C/2003 K4 (LINEAR)  | 135 ± 20         | 90 ± 15          |
| C/1999 S4 (LINEAR)  | 150 ± 40         | 100 ± 30         |
| 88P/Howell         | 140 ± 15         | 90 ± 10          |
| 9P/Tempel 1        | 145 ± 20         | 95 ± 15          |
value). It would be crucial to determine D/H for Jupiter-family comets. But the observation of HDO, whose main rotational transitions are in the submillimetric domain, is difficult.

Some chemical models of the primitive Solar Nebula predict a strong dependence of the D/H ratio on the heliocentric distance $r_h$. So, it is in principle possible, from the distribution of the D/H enrichment of a class of comets, to determine the $r_h$ distribution of its formation site. (See [66] and Fig. 1.7).

Puzzling results were obtained for the $^{14}\text{N}/^{15}\text{N}$ isotopic ratio. From high-resolution visible spectra of the CN radical in several comets, $^{14}\text{N}/^{15}\text{N} \approx 150$ was consistently observed (Table 1.7, [67]), whereas $^{14}\text{N}/^{15}\text{N}$ was 300 (close to the terrestrial value) from a radio line of HCN observed in comet Hale-Bopp [70]. In contrast, the $^{12}\text{C}/^{13}\text{C}$ ratio is found to be $90 \pm 4$ in CN for the whole sample, close to the terrestrial ratio (Table 1.7, [67]). This points to an additional source of CN, other than HCN and heavily enriched in $^{15}\text{N}$, which is still to be identified. High molecular weight organics such as polymerized cyanopolyynes were invoked (see [34] for a discussion of the sources of the CN radical). But surprisingly, the $^{14}\text{N}/^{15}\text{N}$ ratio does not vary from comet to comet, whereas these objects had strongly different dust-to-gas ratios. This isotopic ratio is also exactly the same for Jupiter-family and Oort-cloud comets.

1.5.3 Dust properties.

The presence of crystalline silicates in cometary dust is a touchstone for models of cometary formation and Solar System history. The existence in cometary material of silicates in both crystalline and amorphous phases testifies to the existence of radial mixing in the primitive Solar Nebula [71].

Crystalline silicates (forsterite) were clearly identified in the infrared spectrum of comet C/1995 O1 (Hale-Bopp) observed by ISO [62, 72]. They were then observed in several other Oort-cloud comets [73]. The presence of crystalline silicates in Jupiter-family comets was more difficult to assess. They were finally identified in the infrared spectra of 103P/Hartley 2 [72], 78P/Gehrels 2 [74] in 9P/Tempel 1 (Spitzer observations after Deep Impact [75]) and tentatively in 29P/Schwassmann-Wachmann 1 [76]. They are also present in the dust samples of 81P/Wild 2 brought back by Stardust [22, 77].

It seems that crystalline silicates are present in all classes of comets, but that the silicate feature, relative to continuum, is (much) weaker in Jupiter-family comets. So, it was more difficult to identify crystalline silicates in Jupiter-family comets just because these comets are more difficult to observe.

Two different classes of comets are also distinguished from the polarimetric properties of cometary dust [78, 79], apparently correlated with the strength of the silicate feature and the period of the comet. It thus appears that these different dust properties are due to the evolution of the nucleus surface properties and the building up of a mantle for short-period comets.
1.5.4 Nucleus properties

Available data on comet nucleus sizes are reviewed in [80]. Clearly, a selection effect is at work here: whereas many short-period comets were investigated, only the largest nuclei of long-period comets were observed. Thus it is little wonder that the observed sizes are larger for long-period than for short-period comets.

Direct data on comet nucleus density are lacking. Most determinations are based upon the modelling of non-gravitational forces [81]. They are notoriously unreliable due to the complexity of the physical processes at work. Such modelling is almost exclusively available for short-period comets for which several returns are documented. Measurements from space exploration are only expected for Jupiter-family comets (e.g., 67P/Churyumov-Gerasimenko with Rosetta). A determination from the ballistics of the Deep Impact ejecta was attempted for 9P/Tempel 1 [21].

Available data on comet nucleus albedos and colours are also reviewed in [80]. These parameters are similar for nearly-isotropic and ecliptic comets. The range of nucleus albedos is remarkably narrow (0.04 ± 0.02).

1.6 Discussion and conclusions

In the preceding sections, it was shown that comets have indeed a large range of dynamical and physico-chemical properties. It was investigated whether these diversities could be interpreted in the frame of a consistent formation scenario. The following points were assessed:

- Most comets can be unambiguously separated into two classes: nearly-isotropic comets and ecliptic comets. Although there might be some interlopers and ill-classified objects (e.g., Halley-type comets with small inclination), this classification seems to be rather robust.

- These two classes are recognized to originate from two distinct reservoirs. Nearly-isotropic comets are coming from the Oort cloud. Ecliptic comets are coming from a nearer, disc-like trans-Neptunian reservoir which was first identified with the Kuiper belt itself, but which is now believed to be the scattered disc of trans-Neptunian objects.

- In none of these reservoirs, comets appear to have formed in situ. They were formed in the inner Solar System, and then expelled to the outer Solar System (or outside the Solar System) through gravitational interaction with the giant planets. It was formerly believed that nearly-isotropic comets were indeed formed in the Kuiper belt (hence the analogy between Jupiter-family comets and Kuiper-belt comets), but this hypothesis is no longer tenable in view of dynamical simulations.

- The very sites of cometary formation are still ill-determined. The place of the giant planets — their distance to the Sun and even their order —
have evolved in the early stages of the Solar System, complicating the formation scenario.

- Our study of nearly-isotropic and ecliptic comets suffers from a strong observational bias. The former class comprises the brightest objects which allow us to perform the best remote spectroscopic investigations. In contrast, the latter class is the preferred target for space exploration.

- Narrow-band photometry provides us with the largest (in terms of number of comets investigated) statistical investigation of the cometary chemical composition. A class of carbon-depleted (C$_2$–poor) comets has been clearly identified and is possibly associated with Jupiter-family comets. However, we do not know how this translates into abundances of definite nucleus ice molecules.

- Infrared and radio spectroscopy can identify specific ice molecules, but the number of investigated comets is still limited (especially for Jupiter-family comets). A large diversity in parent-molecule relative abundances has been observed, but no obvious correlation with dynamical classes could be found.

- There is no observed correlation between the abundance of hypervolatiles and the dynamical class. For instance, carbon monoxide is present with either low or high abundance in both classes of comets.

- Other indicators, such as the ortho-to-para ratio or the $^{14}$N/$^{15}$N isotopic ratio, which are believed to be linked to cometary origins, are remarkably similar for different dynamical classes, pointing to uniform formation conditions. But we must point out how poor is our understanding of the meaning of the cometary ortho-to-para ratio, and we are still awaiting for an explanation to the different $^{14}$N/$^{15}$N ratios observed for CN and HCN in comet Hale-Bopp.

- The observations of split (or progressively fragmenting) comets show no sign of nucleus heterogeneity, suggesting that these objects accreted from planetesimals formed in uniform conditions.

- The role of aging (and of the so-called “space weathering” process) is uncertain. One would expect short-period comets to experience significant sublimation fractionation and a depletion of hypervolatiles in the outer layer of their nucleus [82, 83]. As noted above, no depletion of the CO production is observed for short-period comets compared to dynamically new comets. No conclusive change in the chemical composition of the material excavated by Deep Impact on comet 9P/Tempel 1 was found, if one excludes an enhancement of organic compounds in the infrared spectra [21] (but in our opinion, this preliminary finding should await confirmation by considering optical depth effects [84]).
Forgetting about dynamical classes, we could investigate whether relative molecular abundances point to different formation regions in a consistent way. Following Fig 1.2 we would expect correlations between the abundance of molecular species and their sublimation temperatures, if comets indeed formed from regions of significantly different temperatures. No such correlation could be yet found. (For instance, from an investigation of 7 Oort-cloud comets, no correlation could be found between the hypervolatiles CO and CH$_4$, whereas their abundances relative to water varied by factors 3–4 [85].) Thus the possible existence of different sites of formation is still an open question.

In conclusion, why comets are so different when some properties are considered — and why some other properties are remarkably uniform — is not yet understood. Further investigations are certainly needed, especially to reliably assess the composition of a large sample of comets. Space exploration is helpful for the deep study of specific, hopefully representative objects. But if we aim at a taxonomic approach, progress will come from the statistical investigation by remote sensing of a large number of objects.
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