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EARLY PHASES OF STAR FORMATION: INSIGHTS FROM HERSCHEL

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Abstract. Herschel will explore the last window on the Universe which has remained until now almost inaccessible to us, namely the Far Infrared to submillimeter wavelength range. This window is perfectly suited to study most of the phases of star formation, which occur at relatively low temperatures. The first step starts in very cold cores, with dust temperatures as low as 6 or 7 K, and proceeds up to the phase of hot corinos, where temperatures reach 100 K. Even larger temperatures, up to a few 1000 K, are found in the outflow shocks caused by the interaction of the outflows emanating from the newly born protostar with the surroundings. All these phases will be studied with the three instruments aboard Herschel: PACS and SPIRE will mostly probe the continuum dust emission, whereas HIFI will be devoted to the study of the molecular emission. This lecture especially focuses on the importance of molecules to study star formation.

1 Introduction

Dark molecular clouds are the places where stars form. At their interiors, where the FUV photons cannot penetrate, the material gets dense and can cool down to very low temperatures ($\leq$10 K). The gas cooling and the damping of the supersonic turbulence in these dense cores are probably necessary to allow density to build up and reach a critical point where the collapse of the material becomes irreversible and leads to the formation of a star. While these first steps are still poorly understood because of the difficulty in studying them (lack of tracers, dust emitting at wavelengths hardly observable from the ground), the following steps are better known. Thanks to the energy which starts to pour out of the protostar and to the

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spectacular outflow phenomenon which drives away part of the infalling material at high speed (creating the conditions for powerful shocks heating the gas up to 2000 or 3000 K), these phases become bright enough to be studied with a variety of instruments. Indeed, there is not a single type of instrument sufficient to study star formation in all its aspects and the quest has started much before Herschel was even planned. Millimeter (mm) and submillimeter (submm) telescopes and interferometers, infrared and X-ray satellites, and even optical telescopes have brought and still bring their contribution to this study. However the submillimeter and far-infrared ranges (between 200 and 600 μm) remain mostly unexplored and a large part of the star formation activity can be traced mostly in this range. Herschel should thus bring us new and exciting information on star formation.

Though dust continuum emission has the great advantage of tracing prestellar cores and of revealing the existence of embedded stars through emission in the millimeter to infrared range, molecular lines offer a wealth of information including the kinematics of the gas. In this lecture, we will mostly concentrate on molecular line studies and briefly review the major steps of low mass star formation and see how Herschel will help explore these phases. The reader is refered to the lectures by F. Motte and P. Hennebelle for complementary aspects such as dust emission and numerical modelling respectively. The interested reader on star formation in general, should consult several review papers such as Bergin & Tafalla (2007), McKee & Ostriker (2007), and the relevent chapters of the last issue of Protostars and Planets (PPV) for a thorough presentation of today's knowledge on the subjects which are only sketched here.

2 Three Reasons to Study Molecules in Star Forming Regions

There are at least three reasons to study the molecules in star forming regions, and we describe them in the following.

2.1 Molecular Complexity

The most abundant molecule in molecular clouds is H_2. Everything else apart from He is a trace component. The next most abundant molecular species is CO, with a relative abundance to H_2 of only 10^{-4} in the best cases. Then, at lower abundance levels, many more molecules exist, from simple diatomic molecules to more complex ones. To date, molecules with up to 13 atoms have been identified in star forming regions (see *e.g.* `http://www.ph1.uni-koeln.de/vorhersagen/index.html` for an updated list). However, we know that much bigger molecules exist in the InterStellar Medium (ISM): the Polycyclic Aromatic Hydrocarbons (PAHs), with 20 to 1000 carbon atoms, believed to be responsible of spectral features between 3 and 20 μm (note that no single Earth-known PAH, like coronene $C_{24}H_{12}$, has yet been identified) and we suspect that very complex organic molecules, much more complex than those so far identified, are also synthesized in star forming regions, although their identification becomes more difficult with the increasing size of the molecule.

In this context, the study of the molecular emission allows to answer some important questions: up to what level of complexity, apart from PAHs, do complex molecules form in star forming regions? How and when do they form? What happens to them? Do they survive to the point of being included in the bricks forming the planetary systems (comets, asteroids and planets)?

2.2 Interplay Between Chemical Composition and Star Formation

Dark clouds, whether small (10–100 $M_\odot$) or big (10^5–10^6 $M_\odot$) in mass, do not collapse monolithically and turn all their mass into stars at once. What prevents them to do so is not known with certainty, but the molecular composition of the gas very likely plays a major role here. All clouds show supersonic turbulent motions, which is an efficient way to sustain clouds against collapse. So far, it is not clear how the supersonic turbulence is injected into the clouds, and how it is maintained at the observed levels, while it is expected to decay rapidly. Protostellar outflows have been suggested, see reviews on turbulence by Elmegreen & Scalo (2004), Mac Low & Klessen (2004), Ballesteros-Paredes *et al.* (2007), but contested, Banerjee *et al.* (2007). It is believed that magnetic fields also provide a support against the collapse. Here, the matter is coupled to the magnetic field via the ions and their collisions with neutral species. Indeed, ambipolar diffusion (drift of neutral species through the magnetic field mesh) is advocated as one possible way of starting the contraction in clouds (*e.g.* Shu *et al.* 1987; Mouschovias 1991). Therefore, the chemical composition, and, specifically the molecular ions play an important role in the star formation process. The molecular composition influences the collapse also in another way: the cooling of the gas (Goldsmith & Langer 1978; Goldsmith 2001), necessary to let the gas contract and evacuate the gravitational energy, and the heating provided by the dissipation of supersonic turbulence, cosmics ray and gas compression.

Both the temperature and ionization degree (defined as the abundance of electrons relative to H_2) depend on the gas chemical composition. An illustrative example is given by the case of the CO abundance. CO is the main coolant in the outer parts of clouds. In the innermost and densest regions (at $A_V \approx 10$ mag typically), CO freezes-out onto the grains mantles and cannot cool the cloud anymore. Although collisions keep gas and dust thermally coupled in dense ($\geq 10^5$ cm^{-3}) enough regions (Goldsmith 2001), as observed in a few cases (L183, Pagani *et al.* 2004, 2007, L1544; Crapsi *et al.* 2007), there may be intermediate regions where CO is frozen out and density too low to allow an effective coupling between gas and dust and as a result, the gas is warmer than the dust (*e.g.* B68, Bergin *et al.* 2006).

2.3 Lines as Diagnostic Tools

First of all, an information unique to molecular lines is the measurement of the dynamics of the gas via the Doppler effect. This allows an estimate of the amount of turbulence, and traces macroscopic motions in the gas such as collapse, rotation, outflows, etc. which obviously are of primeval importance for the understanding of star formation processes.

Second, each molecule has a set of energy levels between which radiative transitions occur (following quantum mechanics selection rules) and the different lines of the same molecule can trace different temperature or density regimes in the cloud. Similarly, different molecules can trace different parts of the cloud. For example, CO and N_2H^+ are not coexistent in dark clouds because N_2H^+ is readily destroyed by CO and is thus maintained to undetectable levels as long as CO is abundant. N_2H^+ starts to appear when CO depletes onto grains, and eventually becomes one of the most easily observable species (with NH_3) in dense and cold prestellar cores.

3 HIFI and the Molecular Emission in Star Forming Regions

HIFI is the ideal instrument to observe lines from molecules, radicals, atoms and ions down to a velocity resolution of 50 m s^{-1} (see T. de Graauw chapter). Below, we list typical species which will be observed with HIFI for different purposes.

1. Major gas coolants: H_2O, CO, OH, C, C^+, … (the major coolants are primarily the most abundant species).
2. Major grain mantle components (when released in the gas phase — the ices themselves are observed in the infrared): H_2O, H_2CO, CH_3OH, NH_3, … (note that CO_2 has no permanent dipole moment, like H_2, and is therefore detectable via its vibrational transitions in the infrared only).
3. Hot gas chemistry tracers: H_2O, SO_2, …
4. Ionization field tracers: C^+, CO^+, OH, CH^+, HI, …
5. Hydrides: CH, NH_3, OH, LiH, FeH, SH, SiH, … Most hydrides are not observable from the ground (this is one of the major advances expected with HIFI).
6. Molecular deuteration : HDO, CH_2D^+, OD, D_2H^+, … (Note: the para ground state transition of H_2D^+ at 1.37 THz lies in a gap between HIFI bands 5 and 6 and cannot be observed, whereas the ortho transition at 372 GHz is observable from the ground).
7. Molecular shock tracers: H_2O, SiO, CO, OH, …

For species with large rotational constants (hydrides, ...), ground state transitions will be mostly observed, while heavy species (SiO, SO_2, organic compounds...) will be observed in relatively highly excited transitions. H_2O has radiative transitions at many wavelengths, connecting levels of either low or high energy. Therefore, it can trace a large variety of physical conditions. This is why H_2O appears as an ubiquitous tracer in the above list combined with the fact that it should be rather abundant in any medium with temperature above about 100 K (temperature at which the water ice sublimates).

In the following sections, we will describe in some detail which lines will be likely targets for Herschel studies, mostly with HIFI, the high spectral resolution spectrometer. We will focus on three specific, important cases: pre-stellar cores (Sect. 4), protostars (Sect. 5) and outflows (Sect. 6).

Before doing that, we want to mention the three Key Programs which will be carried out in the HIFI Guaranteed Time related to Star Formation:

- *Water In Star Forming Regions (WISH)*, led by E. van Dishoeck (Leiden Observatory, NL): it will focus on the observations of water lines of a statistical sample of key objects for understanding low to high mass star formation (pre-stellar cores, protostars, outflows and circumstellar disks). Ancillary observations will include H_2O chemically related species, like H_3O^+, OH etc., including high-J lines of CO.

- *HIFI Spectral Surveys of Star Formation Regions (HS_3F*, led by C. Ceccarelli (Laboratoire d'Astrophysique de Grenoble, France): full HIFI, and in some cases PACS, spectra will be obtained for a sample of representative sources of star forming regions: two pre-stellar cores (with only partial coverage of the HIFI bands), two Class 0 low and intermediate mass sources, one outflow spot, and three high mass protostars with luminosity from 500 to $1 \times 10^6\ L_\odot$.

- *Herschel/HIFI Observations of EXtraOrdinary Sources: The Orion and Sagittarius B2 Starforming Regions (HEXOS)*, led by E.Bergin (University of Michigan, USA): HIFI and PACS spectral surveys of several sources in the Orion and Sgr B2 regions will be obtained, to study the variety of conditions (PDR, cold clouds, hot cores...) present in these two regions which have long been benchmarks for astro-chemistry studies.

4 Prestellar Cores

Diffuse atomic gas and dust somehow gather in some places where the opacity to FUV radiation becomes large enough to allow H_2 to form and remain molecular. Other molecules then start to form, protected from the FUV photons by H_2 and dust. In such molecular regions, the cosmic rays are (almost) the only source of gas heating and the clouds cool at temperatures lower than about 15 K (mostly through the CO lines). Denser condensations, hereafter called "pre-stellar cores", are found within the molecular clouds, and are thought to be the seeds from which stars form. To date there is no consensus on the exact mechanism which starts the collapse. Two major competing theories are invoked. The first one describes the collapse as a quasi static process: the pre-stellar cores are initially supported against their self-gravity by magnetic or turbulent pressure, and progressively evolve towards higher degrees of condensation through either ambipolar diffusion (*e.g.* Mouschovias 1991) and/or the dissipation of turbulence (Nakano 1998). Alternatively, pre-stellar cores form dynamically through local density enhancements due to supersonic turbulent flows, which can eventually collapse if they are large enough (*e.g.* Klessen *et al.* 2000). In both cases, it is difficult to observationally probe the contraction of the pre-stellar cores, for the expected velocities (50–100 $\mathrm{m\,s^{-1}}$) are much lower than the average observed linewidths (dominated by supersonic turbulence).

Very likely, Herschel, and specifically HIFI will be able to observe these early phases in a handful of molecular lines, because many molecules, abundant in those physical conditions, emit only lines from their lowest energy levels, typically in the millimeter/submillimeter range (observable with ground based telescopes). There are possibly a few important exceptions: the ground state lines of ortho D_2H^+ (at 1477 GHz), NH_3 (at 572 GHz), and ortho and para H_2O (at 557 and 1113 GHz respectively).

To have an idea of the possibility of detecting lines by HIFI in the Terahertz range, consider a gas at respectively $T_{kin} = 10, 12$ and 15 K and a line at the frequency of 1.5 THz. The antenna temperature ΔT_a^* is a function of the line excitation temperature T_{ex}:

$$\Delta T_a^* = \eta_c(1 - e^{-\tau})(J(T_{ex}) - J(T_{cbg})) \tag{4.1}$$

where $J(T)$, the Rayleigh-Jeans correction, is given by

$$J(T) = \frac{h\nu}{k}\frac{1}{e^{\frac{h\nu}{kT}} - 1}. \tag{4.2}$$

Here h is the Planck constant, k the Boltzmann constant, ν the frequency of the line, T_{cbg} the cosmic background radiation temperature, and η_c the coupling efficiency of the telescope to the source. ΔT_a^* is maximal when the line is optically thick ($\tau \gg 1$ and $1 - e^{-\tau} = 1$) and when the line is thermalized (*i.e.* $T_{ex} = T_{kin}$). In the 3 cases considered here, the antenna temperature would be respectively ~50, 180 and 600 mK. Considering the overall expected system temperature (including all losses in the detection chain) of 5000 K at 1.5 GHz and using the radiometer equation

$$\Delta T_{rms} = \frac{\eta T_{sys}}{\sqrt{\delta\nu t}} \tag{4.3}$$

these 3 lines will be detected with a signal-to-noise ratio of 5 in a 0.1 $\mathrm{km\,s^{-1}}$ velocity bin in respectively ~400, 30 and 3 hours of observations (where we assumed η, an efficiency factor which depends on the actual observing mode, equal to 1). Thus a 50% increase of the kinetic temperature results in a 12-fold increase in antenna temperature and therefore in a two orders of magnitude decrease in integration time. This gives hints at what kind of cold clouds observations should be done at 1.5 THz.

Figure 1 shows the predicted intensity (main beam temperature) of the ortho-H_2O ground transition at 557 GHz, as a function of the gas temperature and for different gas densities. Those computations refer to a ortho-H_2O column density equal to 5×10^{14} $\mathrm{cm^{-2}}$: assuming a typical H_2 column density of 1×10^{23} $\mathrm{cm^2}$. This corresponds to an abundance of ortho-H_2O of 5×10^{-9} with respect to H_2, in

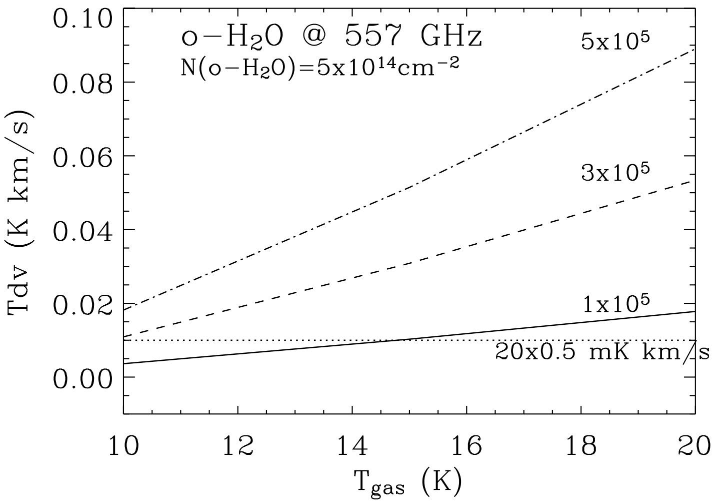

Fig. 1. Predicted intensity seen by HIFI of the ortho-H_2O ground state transition at 557 GHz as a function of the gas temperature. Units are in K km s^{-1}. Different curves refer to different densities: 1×10^5, 3×10^5 and 5×10^5 cm^{-3}. The ortho-H_2O column density is assumed to be 5×10^{14} cm^{-2}. The horizontal dashed line shows the approximate limit of observability by HIFI, assuming a reachable RMS equal to 4 mK in 4 hours of observations.

agreement with the recent measurements by SWAS and ODIN (Snell *et al.* 2000; Pagani *et al.* in prep.). To give an example of the detectability of this line, 4 hours are necessary to reach a rms noise level of 4 mK in a 0.5 km s^{-1} bin.

If observing lines in pre-stellar cores may be at the limit of the HIFI capabilities, SPIRE will be perfectly suited for mapping the cold dust in these objects. The peak emission wavelength for a 10 K black-body is 350 μm, right in the middle of the SPIRE bandpass. Detailed maps of dust column density and dust temperature will be obtainable with a resolution much better than what ISO (Kessler *et al.* 1996, `http://sci.esa.int/iso/`) and Spitzer (Werner *et al.* 2004, `http://www.nasa.gov/mission_pages/spitzer/main/index.html`) could do. For a detailed discussion on dust observations see F. Motte's chapter in this book.

5 Protostars

Pre-stellar cores eventually collapse to form protostars. Protostars are classified in 4 categories from Class 0 to Class III sources, (very likely) reflecting an evolutionary sequence (Adams *et al.* 1987; André *et al.* 1993; André *et al.* 2000). Briefly, Class 0 sources are believed to be the youngest known protostars, which have not accumulated the bulk of their final mass yet: they are completely embedded in their parental cloud. In Class I sources the envelopes are less thick and, therefore, warmer: they continue to be in the accretion phase but at a slower pace. Class II and Class III sources correspond to the pre-main-sequence objects known as Classical and Weak TTauri stars: the envelopes are completely dissipated and the central newly formed star becomes visible along with the circumstellar disk. Simultaneously with the accretion, material is ejected outward by strong stellar winds which allow accreting matter to get rid of angular momentum: this gives rise to the spectacular phenomenon of the molecular outflows. In the following, we will discuss the case of Class 0 sources, as they have the richest submillimeter to far infrared line spectra.

The physics and chemistry of Class 0 protostars will be an important target for HIFI. Class 0 sources, whose prototype for chemical studies can be considered to be IRAS 16293-2422, have a complex structure. The newly born star is totally hidden by the relatively massive (a few $M_{\odot}$) and cold, collapsing envelope from which the central object accretes material; in addition, very likely the central object is surrounded by a gaseous disk; finally, a substantial fraction of the collapsing material is ejected outwards forming the molecular outflow. We will discuss the outflow in the next section (Sect. 6). The disk contribution to the line submillimeter to far infrared spectrum will certainly be very minor with respect to the envelope, if for not other reasons, because of the relatively larger beam dilution caused by the expected sizes of the embedded disk (a few hundreds of AUs at most). Therefore, here we focus especially on the envelope.

Many studies have shown that, from the chemical point of view, the envelopes of Class 0 sources can be thought of as composed by two parts (see for example the recent review by Ceccarelli *et al.* 2007): i) an outer, cold envelope chemically unperturbed by the collapse and therefore reminiscent of the prestellar core conditions; ii) an inner, warm envelope where the dust temperature exceeds the ice sublimation temperature and where the chemistry is, hence, dominated by the grain mantle sublimation. This inner region has been nicknamed "hot corino" (Bottinelli *et al.* 2004; Ceccarelli 2005) because it displays features similar to those of the hot cores, massive regions of warm and dense gas enriched in complex molecules (*e.g.* see the recent review by Beuther *et al.* 2007).

The two parts of the envelope will both contribute to the emerging line spectrum. Generally speaking, because of the different excitation conditions, low lying transitions will arise in the outer (colder and less dense) envelope, whereas high lying lines will probe the inner, hot corino region. Of course, in addition to the excitation conditions, the abundance of the species is different, usually larger (with some very specific exceptions) in the inner than outer envelope. An illustration of this is shown in Figure 2, where we report the case of the H_2CO (Ceccarelli *et al.* 2003). Low lying lines only depend on the abundance in the outer envelope, because they are formed there, whereas high lying lines can be used to constrain the abundance of formaldehyde in the inner envelope (of, course this specific case will best be studied by ground based telescopes).

Since water lines cannot be observed with ground based telescopes, their observation is a major drive for Herschel and HIFI. Figure 3 shows the predicted

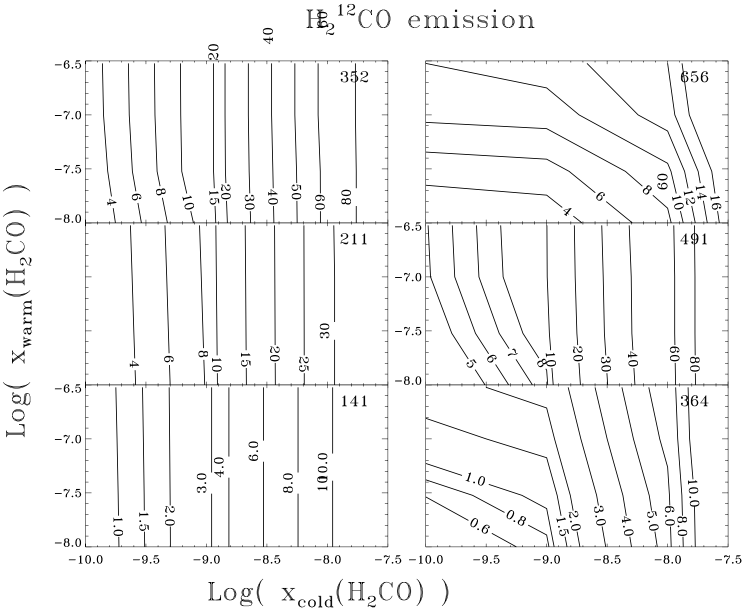

Fig. 2. Contours plot of the intensity of six selected H_2CO lines as a function of the abundance in the inner (X_{warm}) and outer (X_{cold}) envelope respectively (from Ceccarelli *et al.* 2003). The value in the top right corner is the frequency (in GHz) of the transition.

spectra of selected lines from ortho and para water in the case of IRAS 16293, for different inner water abundances (adapted from Ceccarelli *et al.* 2000). As in the case of H_2CO, only high lying H_2O lines are affected by the inner abundance. As a consequence, they not only can be used to constrain the abundance of water in the inner envelope but can also probe the dynamics of that region, where the infall motion is larger than in the outer, almost quiescent envelope.

6 Outflows

It is remarkable that no Class 0 source has been found without an outflow yet. Outflows seem therefore to be tightly linked to the accretion phenomenon, possibly taking away excess angular momentum. Recent 3 dimensional (3D) MagnetoHydroDynamical (MHD) simulations shed some light on a possible scenario for forming a class 0 source, starting from a pre-stellar core, and following with the formation of a disc and an outflow (Banerjee & Pudritz 2006). Implications for angular momentum dissipation, turbulence injection in the cloud and cloud disruption by the outflow are all important aspects yet to be characterized in detail.

At the interface between the outflow and the envelope (or molecular cloud), violent (dissociative or non-dissociative) shocks are created, which transiently heat and compress the quiescent material. These shocks have two effects on the chemical

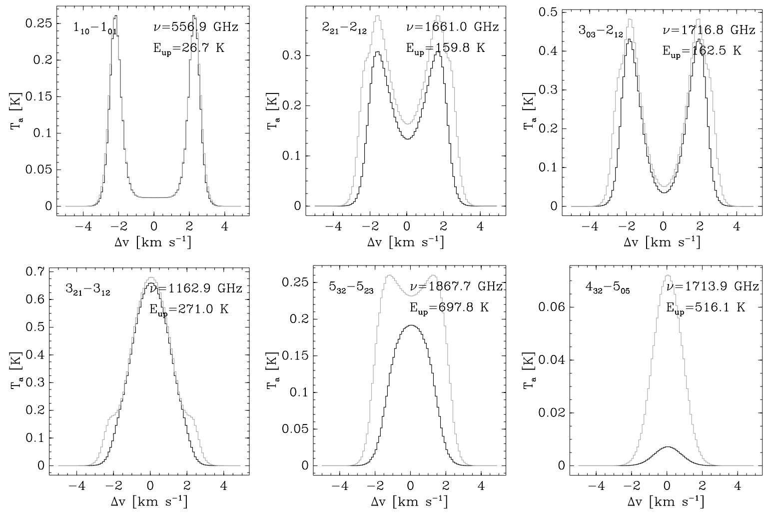

Fig. 3. Selected water line spectra, for two different water abundances of the inner envelope (courtesy by S. Maret).

composition of the gas. First, the grain mantles are partially or entirely destroyed and their components are injected into the gas phase, enriching it of species formed on the grain surfaces (H_2O, CO_2, CO, CH_3OH, H_2CO etc.). Second, gas temperature goes up to a few thousand K, opening up formation routes inhibited at lower temperatures. An outstanding example is that of H_2O: reactions with activation barriers ($O + H_2 \rightarrow OH$ followed by $H + OH \rightarrow H_2O$) become efficient and H_2O is abundantly formed. Actually, in molecular shocks, depending on the shock velocity, water may be the most abundant molecular species, even more abundant than CO, and certainly is a major actor in the post-shocked gas cooling (*e.g.* Kaufman & Neufeld 1996).

In addition to water, given the relatively large temperature, many high lying transitions of species like H_2O, CO, OH etc. which are accessible in the HIFI spectral range will also be excited and the relevant lines may well be detectable, providing strong constraints on the outflow and shock models.

7 From Interstellar Medium to Solar System

What is the fate of all the molecules which we have seen to appear or to deplete through the various phases of star formation? We can have a look at the final stage of the process, *i.e.* the Solar System to try to see what is left over. To illustrate this, we will concentrate on two interesting aspects: the ortho/para ratio of H_2O in comets and the H/D ratio of water in both comets and the terrestrial oceans. Again, a more detailed discussion is available in the PP IV & V books and see also E. Lellouch's chapter in this book.

The ortho-to-para ratio of water is 3 when the temperature is high enough (*i.e.* ≥50 K) to thermalize this ratio. However in comets this ratio has been measured to be only 2.45 to 2.7, corresponding to formation temperatures from 25 to 35 K. This implies that the water now observed in comets, resulting from the sublimation of the ices which surround the rocky material, has been formed at those temperatures.

The molecular deuteration of water, namely the HDO/H_2O ratio, in the terrestrial oceans is 1.558×10^{-4} (Lodders & Feggley 1998), about half times that measured in a few comets (*e.g.* Bockelee-Morvan *et al.* 1998), and 10 times larger than the deuterium/hydrogen elemental ratio (Linsky 2003). This enhanced HDO/H_2O ratio in the oceans points to an "exogeneous" origin, namely the water of the Earth oceans has been acquired after the Earth formed. Several possibilities have been suggested; among them, the hypothesis that comets may have contributed substantially, to the ocean formation, at the very beginning of the Earth life, is much debated though a comet contribution as low as 10% seems to be a prefered solution nowadays (*e.g.* Dauphas *et al.* 2000, see also Cheby & Hand 2005 for a discussion on cometary impact on Earth).

Finally, it is interesting to note that Jupiter and Saturn atmospheres reveal a HD/H_2 ratio of $\sim 2.2 \times 10^{-5}$ and $\sim 1.7 \times 10^{-5}$ (Lellouch *et al.* 2001) which was probably the local interstellar medium value at the time of the solar system formation, 4.5 Gy ago (Deuterium was created during the big-bang nucleosynthesis and is since slowly destroyed in stars, a phenomenon called astration).

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