Cosmic Masers: From Protostars to Black Holes
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Maser emissions from comets

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Abstract.
The 18-cm lines of the OH radical are the only well-documented masers in comets. They have been observed in more than 65 comets since 1973. The good knowledge of their excitation mechanisms and their linear regime allow us to estimate the water production rate and its variation with heliocentric distance from radio observations of OH in comets. Two bright comets, C/1996 B2 (Hyakutake) and C/1995 O1 (Hale-Bopp), recently passed perihelion. We give an account of their observing campaigns and of the new insights they provide in the physics of comets. We also discuss the possibility of masering emission for other cometary molecules: H_2O, CH, CH_3OH.

1. Introduction

Comets are thought to be almost unaffected relics from the early stages of the Solar System formation. One of the main motivations of their study is that they presumably give access to the initial physical conditions and chemical composition of the primitive solar nebula. Another important aspect they offer is the possibility to study a nearby object with an expanding atmosphere (the coma) with many physical and chemical processes at work. When approaching the Sun, the nucleus surface begins to warm and volatile species start to sublimate, dragging along dust particles. The main volatile constituent is water, which governs cometary activity with 4 AU from the Sun, whereas carbon monoxide can sustend the coma more than 10 UA away (Biver et al. 1999).

As the nucleus gravity is far too weak to keep in the atmosphere, the coma is free to expand in space. Under adiabatic conditions, the expansion velocity is increasing whereas the gas temperature is falling down. The coma is illuminated by the solar radiation field, especially in the UV, causing photodissociation and photoionization of the molecules. Water photolysis produces OH and H with a branching ratio of 90% (Crovisier 1989).

Physical conditions in cometary atmospheres (low density, radiative excitation by the Sun) are such that molecules are out of thermodynamical equilibrium, except in the inner coma where collision rates are high. These conditions are adequate for population inversions and the existence of natural masers. However, for being detectable, the column densities corresponding to the masing transitions must be high enough. The continuum background emission, which is to be amplified by cometary masers, is limited to the weak cosmic background or (rarely) external radio sources, the cometary continuum emission being practically negligible for ground-based observations. The OH 18-cm lines are up to now the only masing transitions firmly observed in comets.

In Sections 2, 3 and 4, we discuss recent observations and analyses of the cometary OH 18-cm masers. In Section 5, we examine the case for possible other molecular masers, especially for water at 22 GHz.

2. The OH 18-cm lines and their excitation mechanism

In contrast with interstellar OH masers, the cometary OH maser has a well known excitation mechanism. It is a weak maser operating in the linear regime. Its quantitative modelling permits a reliable estimation of the OH column density in a first step, the production rate of water from the cometary nucleus in a second step.

Since 1973, the 18-cm OH lines have been observed in more than 65 comets. Most of these observations were made with the Nançay radio telescope, constituting a unique data base (Crovisier et al., in preparation) supplementing observations made with other techniques.

Studies with realistic modelling of the OH radio lines in comets started with the discovery by Biraud et al. (1974) and Turner (1974) of the 1667 & 1665 MHz transitions arising from the ground state Λ-doublet in comet Kohoutek (C/1973 E1). Mies (1974) and Biraud et al. (1974) invoked the solar UV pumping of the $A^2\Sigma^+$ excited state from the $X^2\Pi_{3/2}$ ground state, followed by subsequent cascades, as the main mechanism to populate the OH Λ-doublet energy levels. They succeeded to explain the observed line reversals (absorption to emission or vice versa) by the Swings effect, namely the population distribution dependence on the Doppler shifted solar UV spectrum, due to the heliocentric velocity variations.

Mies (1976) stated that, due to the non-isotropic nature of the UV field, one should expect small departures from LTE ratios and up to 10% linear polarization in the OH ground state radio lines. To our knowledge, nobody tried to confirm this latter prediction. Elitzur (1981) explicitly included hyperfine splitting, optical depth and collisional effects in his calculation. He forecasted significant differences between the behavior of the two main lines around crossover velocities. Despois et al. (1981), beside including the v=0 $\rightarrow$ 1 transitions, made an estimation of the quenching radius inside which the maser is quenched by collisions. Schleicher & A'Hearn (1988) extended the pump mechanism, taking into account three vibrational levels in $X^2\Pi$ and $A^2\Sigma^+$ and pure vibrational bands in $X^2\Pi$. Schloerb (1988) significantly improved the quenching treatment by performing non-steady state Monte Carlo simulations of the collisional coma.

In summary, 98-99 % of OH are within the ground state, at 1 AU from the Sun. Line ratios should be close to LTE values, provided the optical depth is weak.

Following Schloerb & Gérard (1985), the flux F of a OH 18-cm line is

$$F = \frac{A_{ul} k T_{BG}}{4\pi\Delta^2} \frac{2F_u + 1}{8} \iint B(x,y) \int i(s) n_{\rm OH}(x,y,s)\, ds\, dx\, dy \qquad (1)$$

where A_{ul} is the Einstein coefficient of the transition, k is the Boltzman's constant, T_{BG} is the background brightness temperature, Δ is the Earth-comet distance, F_u is the total angular momentum quantum number of the transition upper state, $B(x,y)$ is the normalized beam response, $i(s)$ is the inversion of the Λ-doublet ($i = (n_u - n_l)/(n_u + n_l)$) and $n_{\rm OH}(x,y,s)$ being the OH number density in the ground state at position x,y in the sky and at position s along the line of sight. One can see that, in general, both an OH density model and the inversion i variation inside the coma are needed in order to fully explain the observed flux. Neglecting this variation generally leads to a second order error (Despois et al. 1981) and a quite good approximation is obtained replacing $i(s)$ by an average value in Eq. (1).

3. The coma expansion and the OH density modelling

The spatial distribution of OH is needed in order to interpret the OH radio lines, as for any other molecular observation at whatever wavelength. It permits to derive the OH production rate $Q_{\rm OH}$ if production and destruction of OH are taken into account, as did Haser (1957) assuming a radial outflow for the water and OH molecules:

$$n_{\rm OH} = \frac{Q_{\rm OH}}{4\pi r^2 v_{\rm OH}} \frac{L_{\rm OH}}{L_{\rm OH} - L_P} \{\exp(-r/L_{\rm OH}) - \exp(-r/L_P)\} \quad (2)$$

where r is the distance to nucleus, $v_{\rm OH}$ the OH radial velocity, $L_{\rm OH}$ and L_P being the OH and water scalelengths respectively, defined by the product of their photodestruction lifetime by their radial outward velocities.

The Haser model was widely used for coma analysis, owing to its easy implementation. An improvement was proposed by Combi & Delsemme (1980) and Festou (1981): they assume that the additional velocity imparted to the OH molecule at the dissociation is randomly added vectorially to the velocity of water. These vectorial models led to a better determination of both parent and daughter molecules scalelengths.

As the hydroxyl radical is the daughter of the water molecule, lifetime of both are needed in order to get the scalelengths, as well as their velocities. Photodissociation of OH in comets has been studied by van Dishoeck & Dalgarno (1984), Schleicher & A'Hearn (1988) and Budzien et al. (1994). They have shown that the OH lifetime varies greatly with the cometary heliocentric velocity (see Section 2) and with the solar cycle, due to the strong variability of part of the solar UV spectrum. Calculations of both water lifetime and OH ejection velocities can be found in the study of Crovisier (1989). The gas expansion velocity can be measured directly by radio observations of minor parent species (Biver et al. 1999), and indirectly by fitting OH radio line shapes with a vectorial model using the Monte Carlo technique (Tacconi-Garman et al. 1990) or using a simple trapezium shape (Bockelée-Morvan et al. 1990).

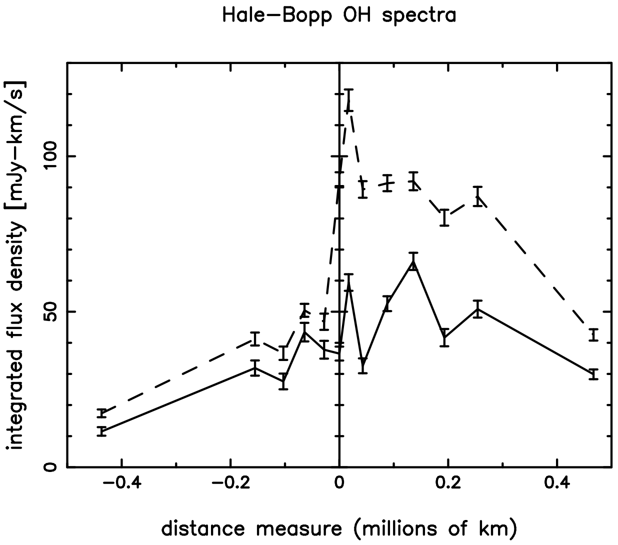

Figure 1. Occultation event observed with the VLA on 12 February 1997: 1667 MHz (dashed line) and 1665 MHz (full line) OH line variations are observed when comet Hale-Bopp (C/1995 O1) was passing in front of the background source J2013+220. The OH main lines areas are shown versus the distance measure, the projected distance between the background source and the point of closest approach at 6.1×10^5 km (Butler et al. 1998).

4. Recent observations: comets Hyakutake and Hale-Bopp

Comet Hyakutake (C/1996 B2) offered the opportunity to observe a bright comet at small geocentric (0.10 AU) and heliocentric (0.32) distances in March-April 1996. Comet Hale-Bopp (C/1995 O1) made a spectacular apparition in the sky in early 1997, and an international observing campain started soon after its discovery in 1995. Many new molecules, most of them observed in the radio range, were found because comet Hyakutake (Bockelée-Morvan 1997) made a close approach to the Earth and comet Hale-Bopp (Bockelée-Morvan et al. 2000) experienced the greatest gaseous production rate ever recorded in modern astronomy history.

4.1. OH occultation observations

As the line intensity is proportional to the background temperature, the signal may be enhanced when the comet is passing in front of the galactic plane, or in front of discrete background radio sources. In the later case, this offers the opportunity to sample different lines of sight around the nucleus and could help to constrain density models or radial-dependent excitation conditions, due to collisional quenching for example (Crovisier et al. 1992). Several such events

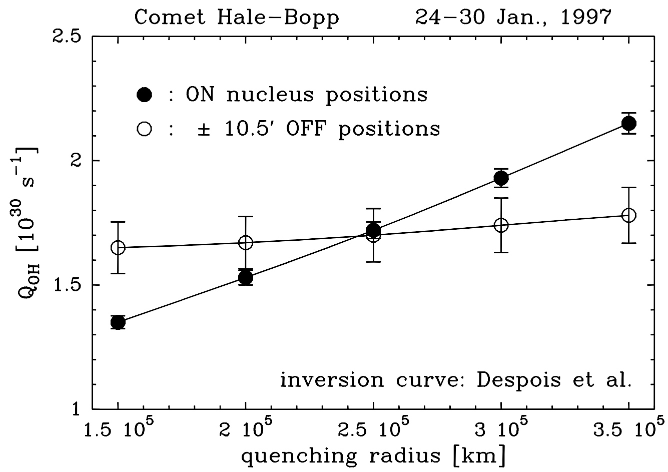

Figure 2. Determination of OH production rate ($Q_{\rm OH}$) and quenching radius (r_q). The offset position spectra are less sensitive to the quenching, the slopes of the $Q_{\rm OH} = f(r_q)$ curves are then different. At the crossing point, we obtain a consistent value of $Q_{\rm OH}$ for both centred and offset positions, and the quenching radius as a by product (Colom et al. 1999).

occurred in the case of comets Hyakutake (Butler et al. 1997) and Hale-Bopp (Butler & Palmer 1997; Butler et al. 1998; Galt 1998). As an example, Figure 1 shows the occultation of 12 February 1997 observed at the VLA in comet Hale-Bopp, during which line variations are clearly shown. Moreover, line ratio variations are also present within the coma, and are partly explained by opacity effects. At this point, one should remind that non-LTE values for OH line ratios were also reported for comet C/1990 K1 (Levy), and variations within the line profile were seen by Gérard et al. (1993). Again, another mechanism than the line optical depth was invoked, and inelastic collisions are proposed as a possible explanation. Finally, this event should help us to constrain both water production rate estimations and the modelling of OH radio emission.

4.2. Sampling the coma with single dishes

Crude mapping with the Nançay telescope was done when the signal was strong enough to allow several offset exposures along with the central one, within the imparted daily one hour observation (Gérard et al. 1998; Colom et al. 1999). Figure 2 shows an example of how the OH production rate and the size of the quenching zone are constrained by this kind of measurements. The radius of this zone, r_q, is defined by the locus where the collisional and UV pumping rates are equal, yielding an effective inversion half the radiative value (Schloerb 1988). Similar observations were conducted with the NRAO 43-m antenna, allowing Schloerb et al. (1999) to fit the observed radial distribution with a vectorial model and to derive very high quenching radii, consistent with the former study. In summary, if the quenching effect were not taken into account, one would underestimate the OH production rate by a factor of up to ten, due to the very high gas density produced by comet Hale-Bopp.

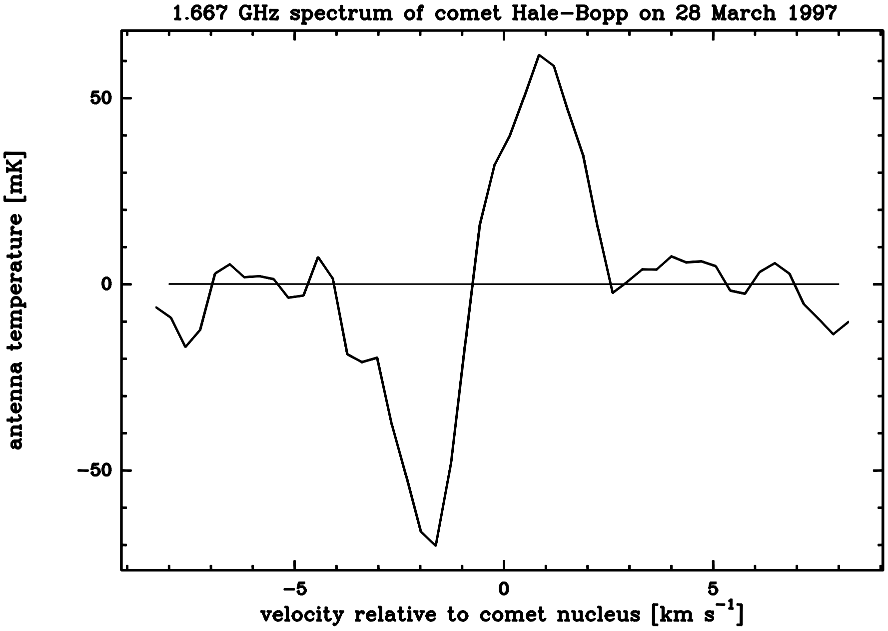

Figure 3. Comet Hale-Bopp (C/1995 O1) observed with the Lovell telescope (Ogley et al. 1997). The line blue wing samples the gas also moving towards the Sun (OH maser in absorption) while the red one samples the gas also expanding away from the Sun (OH maser in emission).

4.3. Inversion reversal

Observation of the inversion reversal has been performed with the Lovell telescope by Ogley et al. (1997). Figure 3 shows that the inversion parameter variations can be seen in a single spectrum, where the heliocentric dependency translates into a line of sight modulation of the sign of the inversion. It is rather unusual to see this S-curve, because it must occur when the inversion is close to zero, hence with rather low signal-to-noise ratio. Clearly Eq. 1 should be fully applied as it is, otherwise it would tell us nothing about the gas content in the coma (see end of Section 2). This kind of spectrum is useful in testing the validity of OH excitation models, at one particular heliocentric velocity.

5. Other cometary masers?

The rotational lines of water between low-energy states are in the far-infrared and submillimetric ranges and were detected only recently by *ISO*, *SWAS*, and *ODIN*. The possibility of maser emission of the 6_{16}–5_{23} line of water at 22.235 GHz in comets, its possible detection in comets C/1974 C1 (Bradfield) and C/1983 H1 (IRAS-Araki-Alcock), has been a debated topic for a long time (Bockelée-Morvan 1987; Crovisier & Schloerb 1991). This transition occurs between high energy levels (about 500 K above the ground state) that are not likely to be significantly populated in cometary atmospheres . According to Graham et al. (2000), this line might be detectable only in comets with very high water production rates under specific viewing conditions (enhanced column densities due to gas jets aligned along the line of sight).

The 6_{16}–5_{23} line was observed by Cosmovici et al. (1998) in comet C/1996 B2 (Hyakutake) close to perihelion and interpreted in terms of masering emissions. However, the line was at anomalous velocities (displaced by ≈ 10 km s^{-1} with respect to the nucleus rest velocity). This is presumably a spurious detection, since radio lines in comets were never observed at similar velocities. In comet C/1995 O1 (Hale-Bopp), this line was marginally detected with the Effelsberg radio telescope with an intensity consistent with LTE emission (Bird et al. 1999), but not with the VLA (Graham et al. 2000).

The CH radical is conspicuous in the optical spectra of comets ($A^2\Delta$–$X^2\Pi_r$ and $B^2\Sigma^-$–$X^2\Pi_r$ systems). It has Λ-doubling transitions at 9 cm within its $X^2\Pi$ rotational ground state, similar to the 18-cm lines of OH. Their excitation should also be similar and governed by fluorescence of the electronic systems: one would expect weakly masering lines, with inversion of the Λ doublet depending upon the heliocentric velocity. The model has never been made, but even in case of maximum inversion, the lines are expected to be much weaker than the OH 18-cm lines because of the small column density of CH (the lifetime of CH is much shorter than that of OH). A sensitive search for these lines in comet Hale-Bopp at the Nançay radio telescope was unsuccessful.

Methanol is an important cometary molecule with ubiquitous rotational lines. It has series of transitions between K-ladders that are masing in the interstellar medium. Such transitions may well be inverted too in cometary atmospheres as the result of spontaneous de-excitation following thermal and fluorescence excitation. Although no conspicuous maser effect has been observed in comets, such inversions are responsible for some anomalies observed in the analysis of the CH_3OH rotation diagrams (Bockelée-Morvan et al. 1994).

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