WATER PRODUCTION OF COMETS DERIVED FROM OBSERVATIONS OF [OI] (6300 Å) AND H_2O^+ (6150 Å): COMETS C/1998 U5 (LINEAR) AND C/1999 J3 (LINEAR)

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The gas production rates of comets C/1998 U5 (Linear) and C/1999 J3 (Linear) are determined from observations obtained at the 2m-RCC telescope of Pik Terskol Observatory. In case of Comet C/1998 U5 the water production rate is derived from a classical Fabry-Perot interferogram of the [OI] $^1D \rightarrow {}^3P$ transition at 6300 Å. The interferogram shows the cometary [OI] line well separated from the night glow line because of the comet's radial velocity of 21.7 km s^{-1}. The high spectral resolution of the interferogram allows to resolve the cometary [OI] line with respect to neighbouring NH_2 lines. The [OI] emission is detected up to distances of 30,000 km from the nucleus. The water production rate amounts to 1.0×10^{28} molecules s^{-1}. An H_2O^+ column density map of Comet C/1999 J3 (Linear) is used to infer the total gas production rate of this comet using the MHD similarity law. This method is based on the theory of comet-solar wind interaction. Assuming average solar wind behavior we determine a gas production rate of 1.6×10^{28} molecules s^{-1}.

INTRODUCTION

There is now general agreement that water is the main constituent of comets. For the first time water was detected convincingly in 1986 in Comet Halley with the Kuiper Airborne Observatory [10], shortly before the in-situ measurements by the GIOTTO space probe [8]. Spacecraft observations of water have been reported in [4] (Infrared Space Observatory) and [11] (Submillimeter Wave Astronomy Satellite). Besides of these direct, but expensive observations from the stratosphere and from space, ground-based, more indirect determinations of the cometary water production still remain of value, like observations of OH at 18 cm [3] or 3090 Å [5], and observations of [OI] at 6300 Å ([6], [12]). In this paper we derive the water production rate of Comet C/1998 U5 (Linear) from a Fabry-Perot interferogram of the [OI] line at 6300 Å. In the interferogram the cometary [OI] emission is not blended by adjacent NH_2 lines, and, because of the Doppler shift caused by the comet's radial velocity, the cometary emission is well separated from the [OI] night glow. A second method to derive the water production in comets, proposed in [13], is based on the MHD similarity law of the solar wind-comet interaction. We apply this method to observations of H_2O^+ column densities in the coma of Comet C/1999 J3 (Linear).

H_2O PRODUCTION DERIVED FROM AN [OI] FABRY-PEROT INTERFEROGRAM OF COMET C/1998 U5 (LINEAR)

Comet C/1998 U5 (Linear) was observed with the Two-Channel Focal Reducer of the Max-Planck-Institute for Aeronomy at the 2m-RCC telescope of Pik Terskol Observatory on Nov. 20, 1998 (for a description of instrument, filters and etalon see [7]). At this time the comet's heliocentric distance was 1.32 AU, its geocentric distance 0.48 AU, and its radial velocity 21.7 km s^{-1}. Two exposures of the comet were taken. The first one of 30 min duration was through a solid fused silica Fabry-Perot etalon with spectral resolution $\lambda/\delta\lambda \approx 30,000$ and an interference prefilter with central wavelength 6308 Å and 31 Å FWHM (full width at half maximum). The second exposure of 15 min duration was through a filter transmitting a red continuum window at 642 nm. It was used to remove the continuum from the first image. The resulting continuum–free interferogram is shown in Fig. 1. The fringe system of the atmospheric night glow at 6300 Å is most prominent. Because the etalon is tilted by 4° the fringes are not circles. The tilt avoids reflections between etalon and filter and increases the number of recorded fringes (adapts the resolution of the etalon to the pixel size of the CCD). A second, more diffuse fringe system is caused by atmospheric OH emission at 6306.87 and 6306.98 Å. The cometary emissions are spatially localized. The strongest line is due to the cometary [OI] 6300 Å emission. Other cometary lines in the interferogram come from the 0,8,0 band of the NH_2 molecule [1]. The cometary [OI] line appears unblended. It is shifted from the airglow line because of the radial velocity of the comet of 21.7 km s^{-1}.

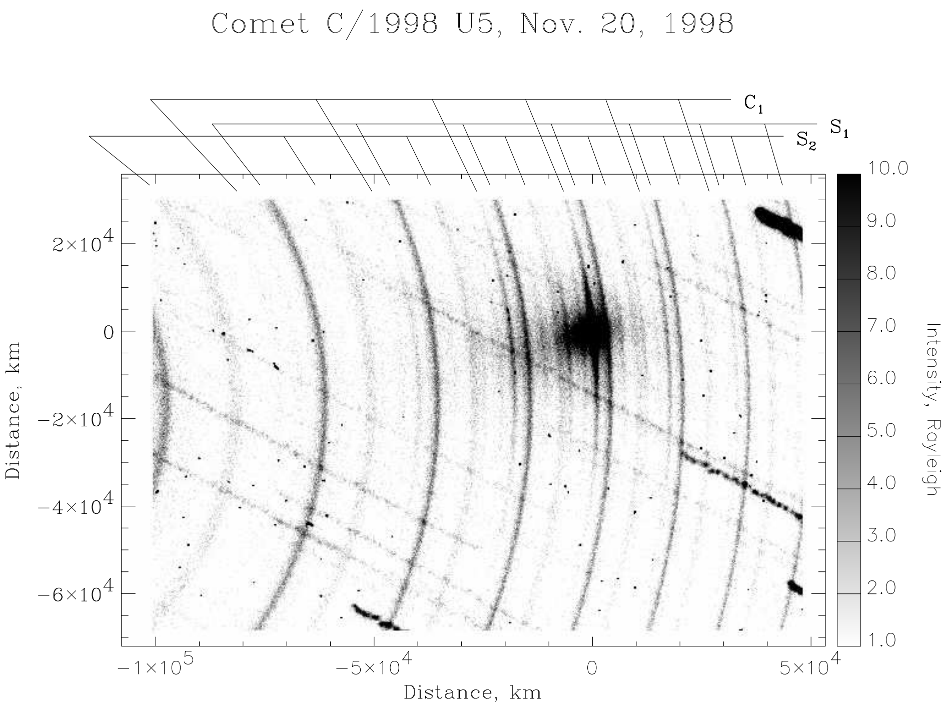

Figure 1: Fabry-Perot interferogram of Comet C/1998 U5 (Linear) in a wavelength range around 6300 Å taken Nov. 20, 1998 (see text)

With the help of observations of spectroscopic standard stars the relative intensities have been transferred to Rayleighs. Intensities in Rayleighs extracted from the interferogram are plotted in the left panel of Fig. 2 as a function of projected distance R_C from the cometary nucleus. The oxygen atom originating from dissociation of water into H_2 and O is created in the ^{1}D state. When it decays into the ^{3}P state it emits a single $\lambda =$ 6300 Å photon. Therefore, in the absence of quenching by electron collision the observed [OI] distribution is proportional to the H_2O distribution. Therefore, for distances less than the scale length of water (1.5×10^5 km at a heliocentric distance of 1.3 AU) the cometary [OI] intensity must decrease $\sim R_C^{-1}$, as observed. According to [6] the water production rate Q_{H_2O} equals 16 times the total luminosity of the [OI] emitting water vapor cloud in photons s^{-1}. If we integrate the fitted $1/R_C$ distribution out to the scale length of 1.5×10^5 km we obtain $Q_{H_2O} = 1.0\times10^{28}$ s^{-1}.

H_2O PRODUCTION DERIVED FROM AN H_2O^+ COLUMN DENSITY MAP OF COMET C/1999 J3 (LINEAR)

Comet C/1999 J3 (Linear) was observed with the Two-Channel Focal Reducer on Sept. 17, 1999, when its heliocentric distance was 0.98 AU and its geocentric distance 1.03 AU. An H_2O^+ image (exposure time 10 min) of the comet was obtained through an interference filter transmitting the short wavelength half of the 0,10,0 band of H_2O^+ (center wavelength 6149 Å, FWHM 32 Å). Like in case of the [OI] emission, a second exposure of 10 min duration through a filter transmitting a red continuum window at 642 nm was used to remove the continuum from the H_2O^+ image. The remaining H_2O^+ image was transferred to absolute intensities with the aid of observations of standard stars. To calculate column densities we assumed equal total intensities of both subbands of the 0,10,0 band of H_2O^+ and used the g-factor provided in [9]. Fig. 2 shows in the right panel

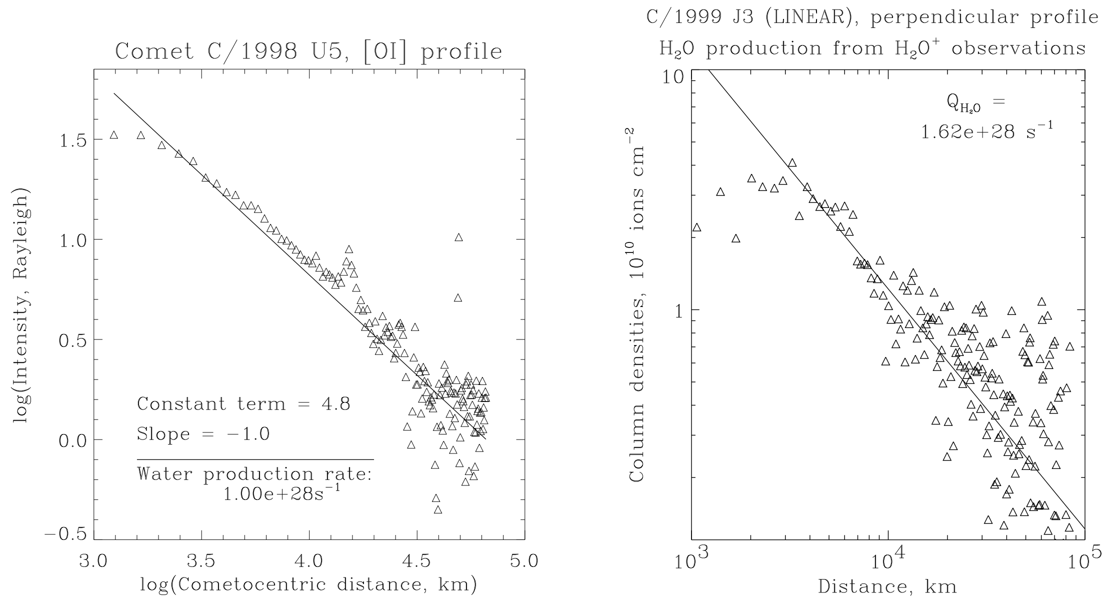

Figure 2: Two ways to derive the water production rate of a comet: Left side: Comet C/1998 U5 (Linear): Fabry-Perot interferometry of the [OI] line at 6300 Å. The intensity of the [OI] line emission is plotted versus sky projected distance R_C from the nucleus. Right side: Comet C/1999 J3 (Linear): MHD similarity law. The profile of H_2O^+ column densities through the cometary nucleus perpendicular to the solar-antisolar direction is shown. In both cases a slope $\sim R_C^{-1}$ has been fitted to the data

the column density profile, extracted along the perpendicular at the comet nucleus with respect to the comet-Sun line. Again a curve $\sim R_C^{-1}$ has been fitted.

In [13] a method was devised to derive water production rates from H_2O^+ column density maps using the MHD similarity law. If σ denotes the ionization rate, m_C the average mass of a cometary ion, Q the total gas production rate, w the outflow speed of neutrals from the nucleus (usually assumed = 1 km s^{-1}), and $\rho_\odot$ and $u_\odot$ the solar wind density and speed, we can define the interaction scale length R_I as follows:

$$R_I = \frac{\sigma m_C Q}{4\pi w \rho_\odot u_\odot}. \tag{1}$$

Then we can make the MDH equations dimensionless by introducing the following dimensionless variables:

$$\mathbf{x}' = \mathbf{x}/R_I,\ t' = tu_\odot/R_I,\ \rho' = \rho/\rho_\odot,\ n' = nm_C/\rho_\odot,\ \mathbf{u}' = \mathbf{u}/u_\odot,\ p' = p/\rho_\odot u_\odot^2. \tag{2}$$

$\mathbf{x}$ and $\mathbf{u}$ are the position and velocity vectors, t the time, ρ and n the mass and number densities, and p the pressure. The dashed quantities are the dimensionless ones. In the hypersonic limit (negligible solar wind thermal pressure), if magnetic field and sources or sinks of momentum and energy are absent, and if the neutral density follows an R^{-2} law, the resulting dimensionless equations do not depend on any dimensional quantities. As the interaction scale length R_I linearly depends on the total gas production rate Q we can say that the comet's "size" linearly increases with its production rate. Let us briefly discuss the conditions of validity of the similarity law with the aim to arrive at a practical way to use it to derive a production rate. The solar wind is a high Mach number flow, *i.e.*, $p_\odot = 0$ is satisfied. Similarly, the main effect of the comet on the solar wind flow is its mass addition to the flow. Since the initial momentum and energy of a cometary particle is small as compared to the momentum and energy of a solar wind particle the comet does not change the momentum and energy balance appreciably. As demonstrated by numerical calculations, the effect of the omnipresent solar wind magnetic field is smallest on the upstream side of the comet, whereas it leads to a flattening of the tail which increases with increasing distance downstream of the nucleus. Therefore, for the derivation of the production rate we use a cut through the nucleus perpendicular to the radius vector. A serious restriction comes from the requirement of a distribution of the neutral water source $\sim R_C^{-2}$. This condition becomes invalid if $R_I \geq R_D$, the dissociation scale length of water. At a heliocentric distance of 1 AU, with $R_D = 8.6\times10^4$ km, ionization rate $\sigma = 10^{-6}$ s^{-1}, $m_C = 20$ amu (to account for other, more heavy cometary ions) , $w = 1$ km s^{-1}, number density $n_\odot = 7$ cm^{-3}, and $u_\odot = 400$ km s^{-1} (in the absence of knowledge about the solar wind conditions average values of the solar wind number density and speed are assumed), a correction for the finite dissociation length scale must be applied for $Q > 10^{29}$. Because of lack of space we must refer to [13] for the details. A further correction must be applied to account for phase angles $\neq 90°$. Then, the essence of the derivation of a production rate using the similarity law rests in a comparison with a well measured comet, which is taken as reference. This comet is Comet Halley, of which we have spacecraft measurements. The production rate is obtained from $Q = 5{\times}10^{-11}\sqrt{C_2}$ [13], where the constant C_2 is derived from a fit of the function $C_2 R_C^{-1}$ to the measured profile through the nucleus (see Fig. 2, right panel). If R_C is measured in cm, Q is in units 10^{29} molecules s^{-1}. In this way we find for Comet C/1999 J3 a total gas production rate $Q = 1.6{\times}10^{28}$ molecules s^{-1}.

DISCUSSION AND CONCLUSION

Two methods of the determination of gas production rates have been applied to cometary observations obtained at Pik Terskol Observatory. The idea of the first method (study of [OI] emission) dates back to the early era of cometary exploration [2]. The use of a solid fused silica etalon in a focal reducer is a simple technique which allows to obtain the [OI] 6300 Å line well separated from the nightglow line (if the radial velocity of the comet exceeds 15 km s^{-1}) and from NH_2. As compared to [12] our method is more sensitive at the expense that we do not get an image of the [OI] emission but can sample the emission only along the etalon fringes. The second method is quite new. It deepens our understanding of the comet-solar wind interaction. Combination of both methods may in the future allow to explore the changing solar wind conditions at comets with ground-based astronomical observations.

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