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Water masers in the Kronian system

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Abstract. The presence of water has been considered for a long time as a key condition for life in planetary environments. The Cassini mission discovered water vapour in the Kronian system by detecting absorption of UV emission from a background star (Hansen *et al.* 2006). Prompted by this discovery, we started an observational campaign for search of another manifestation of the water vapour in the Kronian system, its maser emission at the frequency of 22 GHz (1.35 cm wavelength). Observations with the 32 m Medicina radio telescope (INAF-IRA, Italy) started in 2006 using Mk5A data recording and the JIVE-Huygens software correlator. Later on, an on-line spectrometer was used at Medicina. The 14 m Metsähovi radio telescope (TKK-MRO, Finland) joined the observational campaign in 2008 using a locally developed data capture unit and software spectrometer. More than 300 hours of observations were collected in 2006-2008 campaign with the two radio telescopes. The data were analysed at JIVE using the Doppler tracking technique to compensate the observed spectra for the radial Doppler shift for various bodies in the Kronian system (Pogrebenko *et al.* 2009). Here we report the observational results for Hyperion, Titan, Enceladus and Atlas, and their physical interpretation. Encouraged by these results we started a campaign of follow up observations including other radio telescopes.

Keywords. Planets and satellites, masers, molecular data.

1. Introduction

The Cassini Ultraviolete Imaging Spectrometer (UVIS) detected water vapour in a plume emanating from Enceladus via absorption of UV emission from a background star (Hansen *et al.* 2006). This discovery confirmed Enceladus as a supplier of water into the Saturns ring system and triggered search for other manifestations of water in the Kronian system. One of these manifestations is the maser emission of water molecules at the frequency of 22 GHz (1.35 cm wavelength). Possibilities of natural masers associated with different bodies of the Solar System were first discussed by Mumma (1993) and the first detection of the 22 GHz water maser emission from the planetary system was made during the collision of the Shoemaker-Levy comet with Jupiter (Cosmovici *et al.* 1996). To achieve the maser amplification optical depth of $\tau > 1$, with collisional pumping for H_2O molecules at a kinetic temperature around 200 K, several requirements should be met (Elitzur 1992, Elitzur & Fuqua 1989, Elitzur *et al.* 1992). If the water molecules are the dominant component (Waite *et al.* 2009) in the masing cloud, water-water collisions can ignite the maser emission if the water number density is $n_{H2O} = 10^9$ cm^{-3}. The presence of free electrons with energies in the range of 0.1 - 0.2 eV and number density $n_e = 10^3$ - 10^5 cm^{-3} relaxes the requirements (Elitzur & Fuqua 1989), to a cloud size of 300 km and the water molecules number density of $n_{H2O} = 10^7$ cm^{-3}, or the column number density of $n_{H2O} = 3{\times}10^{14}$ cm^{-2}. This low energy electron density, required for effective pumping of the maser, is consistent with in situ measurements made by the Cassini mission (Schippers *et al.* 2008), while the water molecules column density is consistent with the data from Hansen *et al.* (2006) and Hansen *et al.* (2008)

2. Observations, data processing and results

The observational campaign was conducted in 2006 - 2008, using the 32 m Medicina (INAF-IRA, Italy) and 14 m Metsähovi (AUST-MRO, Finland) radio telescopes. We observed with the bandwidth of 8 MHz, which corresponds to the radial Doppler velocity coverage of 100 km/s at the observational frequency of 22 GHz. The system temperature of the antennas during the observations was in the range of 140-250 K for the Medicina telescope and 90-150 K for the Metsähovi. The Metsähovi radio telescope observed with both right and left circular polarizations, while the Medicina telescope used the right circular polarization only. For spectrum acquisition we used the real-time online spectrometer at the Medicina station (Montebugnoli *et al.* 1996) and an off line software spectrometer at Metsähovi, both with the instrumental spectral resolution of 1 kHz or 13.5 m/s in velocity terms at 22 GHz, while the expected maser line width was in the range of 100-1000 m/s. The antenna beams of 2 arcmin for Medicina and 3.5 arcmin for Metsähovi covered Saturn, most of its inner satellites and rings, partly covering the E-ring and outer satellites at certain orbital phases. We also used a targeted pointing of antennas on individual Kronian satellites. The system temperature range, antenna's efficiency and the polarization factor made the sensitivity of these two antennas comparable in spite of the difference of their diameters.

The data analysis was carried out at JIVE, using a whole data base of observed spectra, more than 300 hours with a 3-10 minutes of integration time per spectrum. The observed spectra were Doppler corrected in frequency domain according to the predicted radial velocity of the satellites in the beam. We used the JPL Solar System Dynamic Group's online Horizons tool (Georgini 1996) to get the station-centric radial Doppler velocity for a number of Kronian satellites. The spectra for each observed satellite were integrated over the time of certain orbital phases of the satellites. We used 16 orbital phases within each satellite's orbital period. The total integration time per orbital phase bin was between 6 and 10 hours. Not all the orbital phases showed the detection, which is an indication of the narrow beaming of the maser emission.

After integrating the radial Doppler corrected spectra for 20 of major Kronian satellites for each of the 16 orbital phases, we found statistically significant detections for 4 satellites.

The 22 GHz water maser line was detected in association with orbital phases and Doppler shifts at a level of 0.3-0.5 K antenna temperature for Enceladus, Atlas, Titan and Hyperion, with a statistical confidence level of 4.2, 7.0, 3.8 and 4.0 sigma, respectively. As an example, a summary plot of our detection for Enceladus is shown in Figure 1.

3. Physical implications

The amount of experimental data available is insufficient to construct a detailed physical model of the masers detected to date. In different regions and bodies of the Kronian system, the cause or character of the maser pumping might vary. Following Elitzur *et al.* 1992, and assuming a spherical geometry and collisions with a neutral molecular agent or low energy electrons as the main pumping mechanism, and a water-vapour ambient temperature in the range of 120 – 200 K, the required column density of water molecules of $5{\times}10^{14}$ – $5{\times}10^{15}$ cm^{-2} will provide a sufficient population inversion to achieve the amplification length with the optical depth of $\tau > 3$.

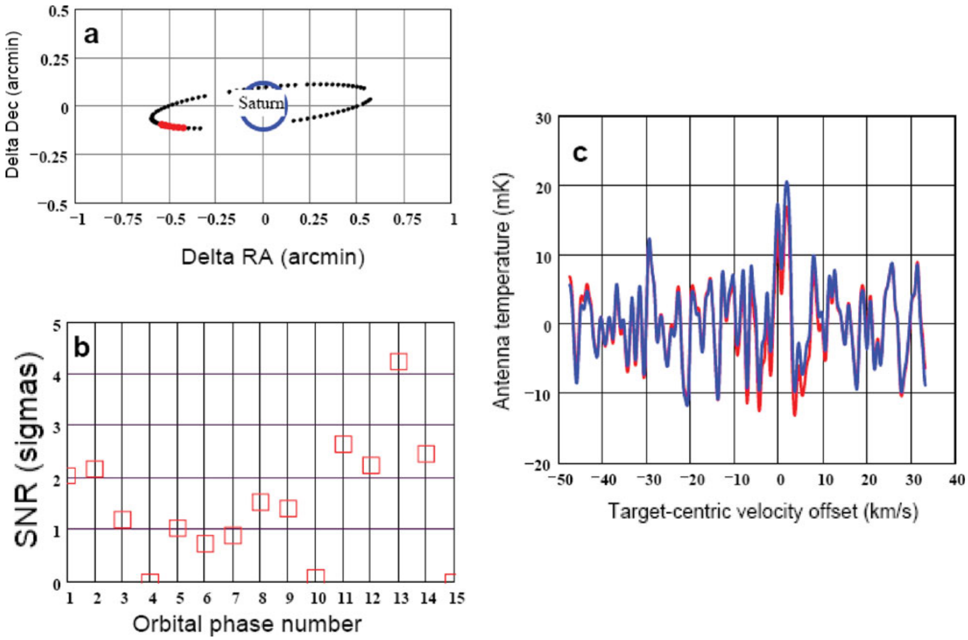

Figure 1. A summary plot for the water maser line detection associated with the orbital motion of Enceladus. Top left: the distribution of the Enceladus position with respect to Saturn during the 3 days in May 2008; black dots represent the positions from which the spectra were acquired, while red dots indicate the positions yielding the best SNR. Bottom left: the detection SNR vs the orbital phase, with the highest level of 4.2 sigma for the 13th orbital phase bin. Right: the spectrum, Doppler corrected and integrated over 4 hours of the orbital phase 13. The red line indicates a raw accumulated spectrum, while the blue line shows the base line ripple corrected one.

We note that such the column density is a small fraction of the peak column density of 1.5×10^{16} cm^{-2} measured by the Cassini UVIS (Hansen *et al.* 2008) for a characteristic length of 100 km. The elongated geometry of the masing cloud, with the major axis directed toward the observer can further relax the requirements on the volume density of water molecules. Other pumping mechanisms, such as interaction with the Kronian magnetosphere, solar-wind plasma and shocks, can also play a determining role.

We consider the results presented here as a strong case for in depth study of the water maser emission in the Kronian system. This study might provide a new insight on the physical conditions in the Kronian system and help to focus further in situ investigations.

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