A Search for Water Masers in the Saturnian System

Shigeru TAKAHASHI, Shuji DEGUCHI, Nario KUNO, and Tomomi SHIMOIKURA*

Nobeyama Radio Observatory, National Astronomical Observatory of Japan,
462-2 Nobeyama, Minamimaki, Minamisaku, Nagano 384-1305
shigeru@nro.nao.ac.jp

and

Fumi YOSHIDA

National Astronomical Observatory of Japan, 2-21-1 Osawa, Mitaka, Tokyo 181-8588

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Abstract

We have searched for H$_2$O 6(1,6)–5(2,3) maser emission at 22.235 GHz from several Saturnian satellites with the Nobeyama 45 m radio telescope in 2009 May. Objects of our observation are Titan, Hyperion, Enceladus, and Atlas, from which Pogrebenko et al. (2009, A&A, 494, L1) reported having detected water masers at 22.235 GHz, and in addition are Iapetus and other inner satellites. We detected no emission of the water-maser line from all of the satellites observed, although the sensitivities of our observation are comparable to, or even better than, those of Pogrebenko et al. (2009, A&A, 494, L1). We infer from our observation that the water-maser emission from the Saturnian system is extremely weak, or sporadic in itself. Both monitoring over a long period and obtaining statistical results are important for gaining a further understanding of the water-maser emission in the Saturnian system.

Key words: planets and satellites: individual (Titan, Hyperion, Iapetus, Enceladus, Atlas)

1. Introduction

Maser emissions are widely found in celestial objects, such as dense cores of molecular clouds and circumstellar envelopes of late-type stars (Reid & Moran 1981). Masers have been used as probes of gas with an H$_2$ number density of typically $10^4$–$10^{10}$ cm$^{-3}$. For solar-system objects, several maser and laser phenomena have been found; e.g., CO$_2$ (Venus and Mars: Mumma 1993) and OH (for many comets: e.g., Crovisier et al. 2002). Each phenomenon would be induced by different physical processes. While a thermal 22.235 GHz water line was possibly detected for the comet Hale–Bopp (Bird et al. 1997), the first detection of an H$_2$O maser in the solar system was reported upon the catastrophic impact of comet Shoemaker–Levy 9 and Jupiter (Cosmovici et al. 1996). This report suggests that such an incident can induce collisional pumping for water masers. Recently, Pogrebenko et al. (2009) (abbreviated as POG hereafter) have reported the detection of H$_2$O masers from the Saturnian satellites (Titan, Hyperion, Enceladus, and Atlas) with the Medicina 32 m and Metsiluovi 14 m telescopes. This is interesting because, unlike such temporal phenomena as the breakup and disruption of a comet, we can perform lengthy monitoring of H$_2$O emission using ground-based telescopes, space telescopes (e.g., Herschel Space Telescope), and spacecrafts.

So far, we do not have much knowledge about the maser mechanism in the solar system, although many water-maser phenomena have been observationally studied for extrasolar objects. The combination of ground, space, and in-situ observations would contribute to our understanding of the nature of water-maser emission if its presence in the Saturnian system is verified.

Therefore, we must accumulate more data of the water-maser lines in the Saturnian system. In this letter, we report our trial of detecting water-maser satellites with the 45 m radio telescope at Nobeyama Radio Observatory (NRO). We observed the major Saturnian satellites from which POG reported detections of maser emission; in addition to those, we observed a few other inner satellites.

2. Observations

We observed the Saturnian satellites with the NRO 45 m telescope at the water-maser frequency 22.23508 GHz on 2009 May 15–17, 24, 27, and 28. We used a cooled HEMT amplifier as the receiver front ends and an acousto-optical spectrometer (AOS-H) as back ends. The total band width of AOS-H was 40 MHz, and the frequency resolution was 37 KHz, which corresponds to a velocity resolution of $\sim$0.6 km s$^{-1}$. All of the observations were made by using the position-switching method. We pointed the telescope at the center of Titan and Saturn. A typical integration time of one scan was 20 s. Since the half-power beam width (HPBW) of the telescope ($\sim$72” at 23 GHz) was larger than the angular diameter of Saturn (41” including the ring), we observed several satellites simultaneously. For example, we could observe Hyperion when we observed Titan on May 16, 17, 18, and 28, and Enceladus and Atlas when we observed Saturn throughout the observational days, though a slight offset of pointing resulted in a worse detection of the upper limit. Furthermore, we selected Iapetus as the OFF point of the position switching. We picked up individual satellites selecting the different Doppler-shift frequencies in the data analysis. The telescope pointing was checked

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* Present address: Department of Astronomy and Earth Sciences, Tokyo Gakugei University, 4-1-1 Nukui-Kita-machi, Koganei, Tokyo 184-8501.
by directing the telescope at some nearby strong H$_2$O maser stars. The antenna temperature, $T_A^*$, was obtained by the chopper wheel method with corrections for atmospheric and antenna ohmic losses. A typical range of the system temperature was 120–300 K, which depends on the weather conditions and the airmass at the observations. Table 1 gives a summary of the observations.

We performed base-line fitting with a 3rd-order polynomial to eliminate the continuum emission from the sky and Saturn. Then, we coadded and binned these spectra taking the Doppler shift for each object into consideration. The radial velocities of the Saturnian satellites were calculated by using the JPL Horizons On-Line Ephemeris System (Giorgini et al. 1996). The resultant velocity resolution was $\Delta v \simeq 1\,\text{km}\,\text{s}^{-1}$. These processes were done on the software package NEWSTAR, and procedures to obtain the final spectra after the Doppler correction were carried out on the software that was developed for the solar-system objects.

### 3. Results and Discussion

Figure 1 shows the obtained spectra (upper-left, upper-right and lower-left panels) and an illustration of the satellite positions (lower-right panel) at the time of observations of Titan, Hyperion, and Iapetus. Figure 2 also shows the spectra (upper panels) and illustrations of the positions (lower panels) for Enceladus and Atlas. The Saturnocentric position of satellite, $\theta$, is defined as the angle that the directions of Earth and a satellite make (i.e., $\theta = 0$ when the object transits on Saturn seen from Earth). Table 2 gives a typical 1 $\sigma$ upper limit of the signal, considering the factor of a satellite position inside the telescope beam. The observational results show the data combined on each day and the entire days during the period of observation. For Titan, we show the result at each position.

Table 1. Observational summary.

<table>
<thead>
<tr>
<th>Day</th>
<th>Time (UT)</th>
<th>IT (s)*</th>
<th>IS (s)†</th>
</tr>
</thead>
<tbody>
<tr>
<td>May 15</td>
<td>08:49–13:51</td>
<td>—</td>
<td>6200</td>
</tr>
<tr>
<td>16</td>
<td>05:49–11:12</td>
<td>5260</td>
<td>—</td>
</tr>
<tr>
<td>17</td>
<td>07:48–13:48</td>
<td>3140</td>
<td>—</td>
</tr>
<tr>
<td>18</td>
<td>09:28–10:44</td>
<td>2180</td>
<td>—</td>
</tr>
<tr>
<td>23</td>
<td>05:19–06:40</td>
<td>—</td>
<td>1560</td>
</tr>
<tr>
<td>24</td>
<td>06:43–13:29</td>
<td>4000</td>
<td>3000</td>
</tr>
<tr>
<td>27</td>
<td>07:29–11:15</td>
<td>2000</td>
<td>2020</td>
</tr>
<tr>
<td>28</td>
<td>07:16–11:44</td>
<td>2000</td>
<td>2320</td>
</tr>
<tr>
<td>Total</td>
<td>20580</td>
<td>17100</td>
<td></td>
</tr>
</tbody>
</table>

* ON-source integration time of Titan.
† ON-source integration time of Saturn.

Table 2. Observational results.

<table>
<thead>
<tr>
<th>Satellite</th>
<th>Date (or Data)</th>
<th>$1\sigma$ upper limit*</th>
</tr>
</thead>
<tbody>
<tr>
<td>Titan</td>
<td>16–19,24,27,28</td>
<td>65 mJy</td>
</tr>
<tr>
<td>Hyperion</td>
<td>16–18,28</td>
<td>80 mJy</td>
</tr>
<tr>
<td>Iapetus</td>
<td>16–19,24,27,28</td>
<td>70 mJy</td>
</tr>
<tr>
<td>Enceladus</td>
<td>15,19,23,24,27,28</td>
<td>260 mJy</td>
</tr>
<tr>
<td>Atlas</td>
<td>Pos.1,2,3</td>
<td>170,140,170 mJy</td>
</tr>
<tr>
<td></td>
<td>19be.,19af.</td>
<td>140,150 mJy</td>
</tr>
<tr>
<td></td>
<td>All</td>
<td>130 mJy</td>
</tr>
<tr>
<td>Other satellites</td>
<td>16–19,24,27,28</td>
<td>70–170 mJy</td>
</tr>
</tbody>
</table>

* A typical 1 $\sigma$ upper limit of the signal, considering the factor of a satellite position inside the telescope beam. The observational results show the data combined on each day and the entire days during the period of observation. For Atlas, we show the result at each position.

POG reported the water-line detections of Titan and Hyperion were $\sim 30\,\text{mK}$ ($3.8\,\sigma$ for 8 hr integration) and $\sim 50\,\text{mK}$ ($4.0\,\sigma$ for 6 hr integration), respectively, which correspond to 300 mJy and 500 mJy, respectively. They found that these emissions were seen at almost the same satellite positions for both objects; based on these results, they inferred a common mechanism of the emission, such as Saturnian magnetosphere bow shock. On 2009 May 16–18 and 28, because Titan and Hyperion were near conjunction we could observe them simultaneously in the telescope beam. During May 16–18, especially, these objects were at almost the same position. Therefore, if the maser emissions had been caused by the common mechanism, we would have detected them simultaneously for these two objects. However, our observations at this time could not detect the signals of the emissions, and all of the data combined also showed no symptom. We estimated typical values of the $3\sigma$ upper limit for each daily data. We also obtained $3\sigma$ upper limits during the period of observation using all of the daily data combined. The typical (all) $3\sigma$ upper limits were 200(60) mJy for Titan and 240(80) mJy for Hyperion, which means that we could certainly detect the line emissions if the levels of the flux densities were as high as those of POG.

Although POG did not report the water-maser emission on Iapetus, we monitored this satellite during the period of our observation, aiming this object at the OFF point of the position-switching observations. We could not find any signal stronger than $\sim 210(75)$ mJy ($3\sigma$ upper limit).

The H$_2$O ice and vapor plume on Enceladus has been reported by the Cassini Ultraviolet Imaging Spectrometer (Hansen et al. 2006, 2008), and a hypothesis that there exists liquid water in the crust has been proposed (Porco et al. 2006). As for the water-maser emission, the mass ratio of water vapor to ice in the plume is important because a majority of water molecules must be in the form of vapor in order for maser emission to originate in the Enceladus plume. A recent theoretical study indicates that the plume would be dominated by vapor from the perspective of thermodynamics (Kieffer et al. 2009). The maser-line intensity reported by POG was 500 mJy ($4.2\,\sigma$), and they estimated the column density of water vapor from the observed maser intensity, which agrees with that of the water-vapor plume observed in UV ($n = 1.5 \times 10^{16}\,\text{cm}^{-2}$; Hansen et al. 2006). Nevertheless, we did not...
furthermore we tested the data on May 19 because Atlas passed in figure 2). For each position, we combined the data, and geometrical edges of the Saturn’s rings seen from the Earth; i.e., Position 1 and Position 3, positions passing before the hot line at the time of the ring’s disappearance; that is, we saw the Saturn ring from an almost edge-on view, and we obtained data which had comparable to, or even better sensitivities than, those by POG for almost all of the satellites, though our observations were made during a limited period in 2009 May. If maser emission is stationary in intensity at the levels, like those reported by POG, we could detect them. However, the results were negative for all of the observed Saturnian satellites. From these results, we conclude that the water maser in the Saturnian system may be sporadic in itself and it is strongly restricted to the time and position of the satellites. We have to monitor the satellites for longer periods and to obtain statistical

Fig. 1. Observational results and Saturnocentric positions of Titan, Hyperion, and Iapetus. Each data set has been shifted and plotted every 50 mK. Horizontal axis is target-centric velocity offset. The date of observation in 2009 May (as shown in table 1) is indicated on each spectrum. The Saturnocentric position of satellite, \( \theta \), is defined as the angle that the directions of Earth and a satellite make (i.e., \( \theta = 0 \) when the object transits on Saturn seen from Earth). The radius of orbit in the position plot (lower-right panel) is not drawn to scale.

find appreciable maser emission in our data. The \( 3\sigma \) upper limits were 780(540) mJy. Our data compared unfavorably with those of POG, because Enceladus was located around the edge of the telescope beam for much of the observational time. However, these results might indicate that the flux of the plume is varying, or that the plume is sporadic, like a geyser.

POG reported the most certain detections for Atlas. The averaged spectrum showed a peak with 32 mK and \( S/N = 7.0 \). From the satellite positions, they found that the maser emissions occurred on the trailing side, which was several thousand km away from Atlas, and suggested that the disturbance of Atlas’s motion had caused the emission in the edge regions of Saturnian rings A and F. We attempted to verify this subject in our data. We divided the positions of Atlas into 3 parts: i.e., Position 1 and Position 3, positions passing before the geometrical edges of the Saturn’s rings seen from the Earth; and Position 2, those after the edge (see the positions of Atlas in figure 2). For each position, we combined the data, and furthermore we tested the data on May 19 because Atlas passed by the geometrical edges of the rings (\( \theta = 90^\circ \)) during the observations. However, we could not obtain positive results for each case. All of the combined data showed no prominent feature of the emission. The \( 3\sigma \) detection limits for each data set were in the range of 430–520(400) mJy.

We also checked several inner satellites of which equatorial diameters are larger than \( \sim 10 \) km: Mimas, Janus, Epimetheus, Prometheus, Pandora, and Pan. For all of the satellites, the acquired data was not indicative of maser emission. The typical value of the \( 3\sigma \) upper limit was 500(210) mJy.

We had an opportunity to observe the Saturnian water-maser line at the time of the ring’s disappearance; that is, we saw the Saturn ring from an almost edge-on view, and we obtained data which had comparable to, or even better sensitivities than, those by POG for almost all of the satellites, though our observations were made during a limited period in 2009 May. If maser emission is stationary in intensity at the levels, like those reported by POG, we could detect them. However, the results were negative for all of the observed Saturnian satellites. From these results, we conclude that the water maser in the Saturnian system may be sporadic in itself and it is strongly restricted to the time and position of the satellites. We have to monitor the satellites for longer periods and to obtain statistical
results. These studies would be useful for understanding the water-maser emission reported in the Saturnian system. In addition, we should also perform monitoring observations of other icy bodies; Jovian satellites, comets, outer asteroids, and Kuiper belt objects would be within our scope. As suggested by Cosmovici et al. (1996), maser emission may be induced by catastrophic events. Such events, as a disruption and eruption, can occasionally be found among the solar-system objects [e.g., C/1999 S4 Linear: disruption and dissipation; 29P/Schwassmann–Wachmann: outburst; 7968 Elst–Pizarro: impact or cometary activity (Toth 2000; Hsieh et al. 2004)]. We should not miss events that will occasionally happen, and carry out the observations to accumulate data.

4. Summary

- A search for water maser emission (22.22351 GHz) from five Saturnian satellites (Titan, Hyperion, Enceladus, Atlas, and Iapetus) and from six other inner satellites with an equatorial diameter larger than 10 km (Mimas, Janus, Epimetheus, Prometheus, Pandora, and Pan) was carried out with the 45m radio telescope at Nobeyama radio observatory.
- We could not confirm any emission line from any of the satellites. The typical 3σ upper limits of daily (average) data of Titan, Hyperion, Enceladus, and Atlas were 200(60), 240(80), 780(540), and 430–520(400) mJy, respectively, and for the other inner satellites, the S/N obtained were almost the same.
- The sensitivities were comparable to, or even better than, those of POG for most of the satellites.
- We infer from our observation that the water-maser emission in the Saturnian system is sporadic in itself.

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