Microwave spectroscopy as a tool for studying the nuclei of active comets

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Abstract

The nuclei of active comets emit molecules anisotropically from discrete vents. The properties of outgassing (rate and direction) of each active source continuously change in a closed cycle over the course of nucleus rotation. A natural tool for studying these effects is microwave spectroscopy, which is sensitive to cometary molecules through their rotational transitions and which offers unique insights into their kinematics as the spectra are velocity-resolved. Using this technique, we investigated the HCN atmosphere of comet 8P/Tuttle, which had an unusually favorable apparition in winter 2007/2008. We detected short-term evolution of the spectral line profile, suggesting the nucleus rotation period of 5.7 h or 11.4 h, in agreement with the results of other studies. Subsequent modeling with a newly developed algorithm yielded several additional properties of the nucleus, including the spin-axis orientation, the mean-diurnal HCN production rate, the gas-flow velocity, and the distribution of activity sources over the nucleus body. It also clearly favors the 11.4 h rotation period over the shorter solution.

Introduction

8P/Tuttle is a Halley-type comet with an orbital period of 13.6 yr and perihelion at 1.0 AU. Although known since the end of the 18th century, it had remained relatively poorly characterized until the last apparition, which was by far the most favorable since its discovery. Around the New Year's Day of 2008, the comet approached the Earth to only 0.25 AU and at the same time was perfectly placed in the northern hemisphere. This prompted several observing campaigns and resulted in very rich observational material collected across all wavelengths.

Interesting results about the nucleus rotation, unknown prior to this apparition, came from several groups using a handful of different techniques. Schleicher & Woodney [24] and Woodney et al. [26, 27], and independently Waniak et al. [25], carried out narrowband optical imaging of the CN coma. Both groups observed recurrent shells from which they inferred the rotation period of 5.7 h, and concluded that the structure was produced by a single active vent. However, radar observations from Arecibo [15-17] yielded the period of 11.4 h, that is precisely twice as long, which was supported by the nucleus photometry from the Hubble Space Telescope [21], and both teams also reported strongly bifurcated (possibly contact-binary) nucleus shape. An interesting possibility arises then, that perhaps the period was indeed as long as 11.4 h, but the nucleus featured two equally productive vents located symmetrically on the opposite sides. Under certain assumptions concerning the spin-axis orientation and/or sublimation, such a scenario might have created coma pattern barely distinguishable from what would be produced by a single jet recurring every 5.7 h.

The exceptionally close approach of comet Tuttle created a great opportunity to seek the effects generated by nucleus rotation in the cometary molecular emission lines. In this respect, of particular interest are rotational transitions because their low energies are naturally accessible to microwave spectroscopy which offers the highest spectral resolution across all wavelengths and can easily resolve the kinematics of cometary gas. Using this technique, we can investigate the effects caused by variation of the instantaneous outgassing rate and direction, which produce the observable periodic modulation of (*i*) the line area (outgassing rate), (*ii*) the line position (outgassing direction through the Doppler effect), and (*iii*) the complete line profile (both effects). Whereas such rotational modulation has been observed for decades in all kinds of cometary images, the spectroscopic evidence is still poor. Notable exceptions include comet Hale-Bopp, observed to periodically vary in CO [5, 19] and in sulfur-bearing molecules [6], periodic modulation of HCN in comets 9P/Tempel 1 [1], 73P-C/Schwassmann-Wachmann 3 [12] and 2P/Encke [20], and also variation of H_2O observed by Biver et al. [3] in C/2001 Q4 (NEAT) and of multiple molecules detected by Biver et al. [4] in C/2007 N3 (Lulin). Moreover, strong quasi-periodic variation of HCN and CH_3OH was recently observed in comet 103P/Hartley 2 – the target of NASA'S *EPOXI* mission – which made it possible to characterize the nucleus rotation state [13] and compositional structure [14]. In this work, however, we present the preliminary results from our earlier approach dedicated to comet 8P/Tuttle. Conventionally, we used the HCN molecule, whose $J(3–2)$ rotational transition is perhaps the best tracer of nucleus rotation in this part of cometary microwave spectrum which is accessible from the ground (cf. [9]).

The growing observational evidence for rotational modulation of cometary emission lines creates an obvious and immediate demand to establish an adequate modeling approach, which should replace the time-honored isotropic model of Haser [18]. Surprisingly, however, little was done in this matter to date. Therefore, our ambition was also to develop a fully time-dependent construction, accounting for non-isotropic production of molecules from a rotating nucleus, with the aim of applying it to the spectral time series of comet Tuttle and subsequent targets. This combined observational and theoretical effort let us obtain for comet Tuttle the most complete characterization of a cometary nucleus from microwave spectroscopy before the apparition of comet 103P/Hartley 2 in late 2010. In Section 2 we show our observations, in Section 3 explain the fundamentals of our model, in Section 4 the key results of model application, and in Section 5 we summarize this paper and discuss possible future developments and directions.

This project was coordinated with other activities of our team[1], all under the common umbrella of a detailed characterization of comet Tuttle. The other projects include: (*i*) narrowband optical imaging of the CN coma (supplemented with the C_2, C_3, and dust bands) using the 2 m telescope at the Rozhen observatory [25], (*ii*) radio observations of OH at 18 cm with the 32 m radio telescope in Piwnice, and (*iii*) optical spectroscopy with the 2 m telescope at Rozhen [7] and the 0.9 m telescope in Piwnice. The overall observational material is very rich, but in this paper we have focused exclusively on the microwave part of the campaign. Early results from this part were already presented by Drahus et al. [10, 11], a more detailed analysis constitutes a chapter in Drahus [9], and a full analysis is currently in preparation.

Observations

We observed comet Tuttle on three consecutive dates: Dec. 31.0, 2007 UT, and Jan. 1.0 and 2.0, 2008 UT, for 5.0 h, 3.2 h, and 4.6 h, respectively, using remotely the 10 m Submillimeter Telescope (Fig. 1) atop Mount Graham (Arizona, USA). The comet was 1.10 AU from the Sun, 0.25 AU from the Earth, and the phase angle was 56°. We used the 1.3 mm sideband-separating dual-polarization SIS receiver (a prototype for ALMA) tuned consistently to the rest frequency of HCN $J(3\text{–}2)$ equal to 265.886434 GHz. The highest spectral resolution of 250 kHz was provided by a pair of identical Filterbanks, each connected to a different polarization channel of the receiver. Note that this resolution corresponds to 0.28 km/s at the observed frequency (or equivalently $\upsilon/d\upsilon = 1.1\times10^6$), which makes the spectra velocity-resolved, and hence is sufficient to study HCN kinematics. The telescope's half-power beam radius was $14''.5$ that is 2600 km at the comet's distance. The position of the comet was continually calculated from the orbital elements provided by the JPL *Horizons* system. The spectra were taken in a position-switching mode, with $0^\circ.5$ offset in azimuth for sky-background determination (where the coma contribution is negligible). The spectral scales were calibrated following standard procedures (cf. e.g. [12]).

Our observing strategy was the same on each date. After the initial calibrations, the observations were arranged in a closed loop. First, two consecutive 8 min exposures of the comet were taken, and then two short (1.3 or 2 min) exposures of standard source W3(OH) followed. In each case half of the exposure was dedicated to the target and half to the sky background. One complete cycle: Tuttle—Tuttle—W3(OH)—W3(OH) took about 30 min (integrations + calibrations + switching), and eventually comprised one *master spectrum* in our time series. Note, however, that for each single exposure we obtain in fact two independent spectra from the two polarization channels. Thus, each master spectrum was created upon averaging four independent 8 min spectra. The only exception is master spectrum # 17 – the last one from the middle date – which is a single exposure (yet still from both polarization

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[1] Our team consists of W. Waniak, G. Borisov, T. Bonev, C. Jarchow, P. Hartogh, K. Czart, M. Küppers, and the author of this note.

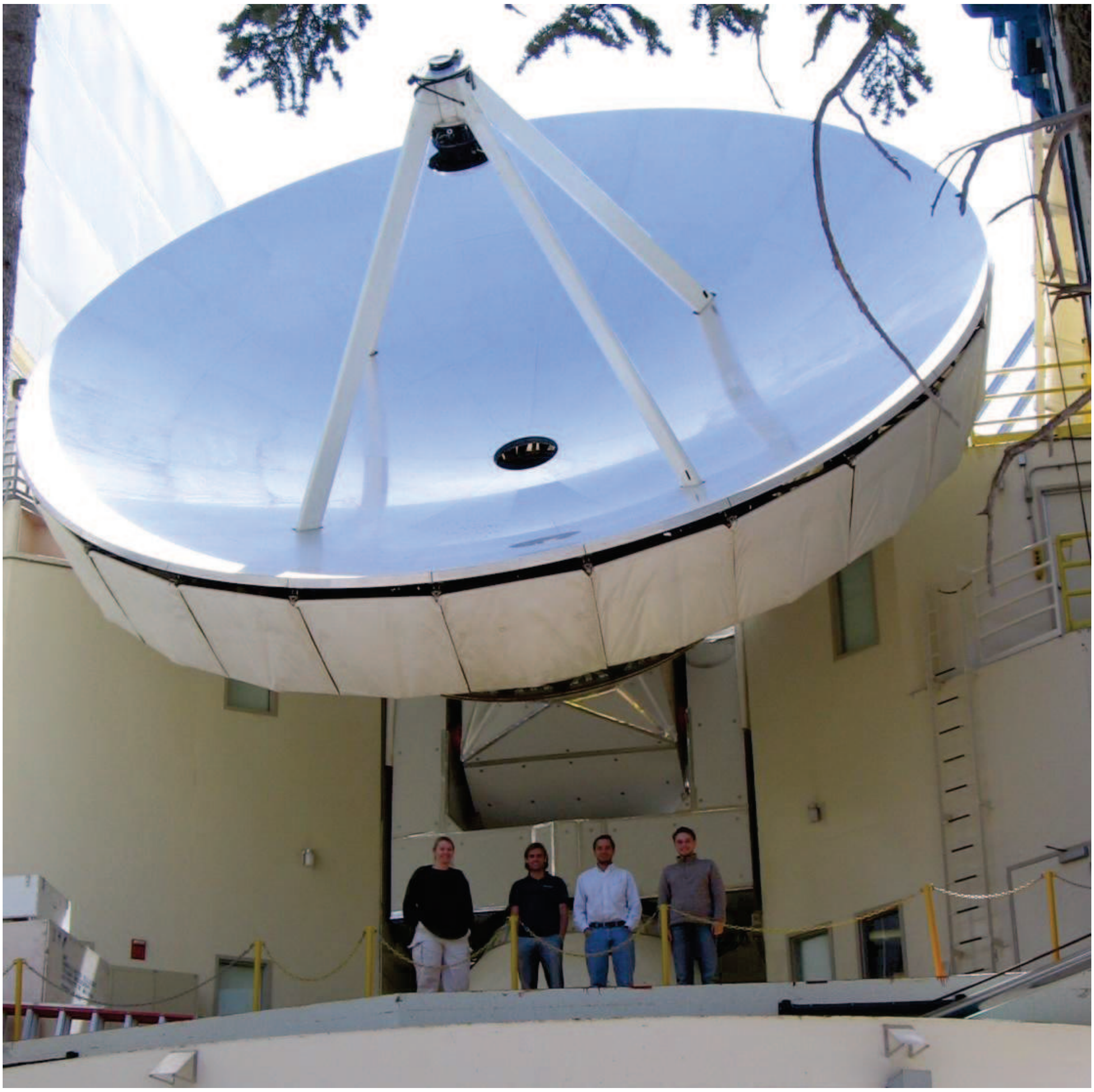

Fig. 1. Submillimeter Telescope at the Mount Graham International Observatory (Arizona, USA).

channels) because there was no observing time left to obtain the second one. In total, we obtained 27 master spectra: 10 on the first date, 7 on the middle, and 10 on the last one. They are presented in Fig. 2.

As for the millimeter astronomy standards the quality of these spectra is exceptionally high. This is because of a few factors which fortunately coincided during our run, most notably:

- an extremely dry atmosphere (the precipitable water vapor typically of 1.5 mm) allowed for as much as 90% zenith transmission at the observed frequency;
- the newly installed ALMA-prototype receiver demonstrated excellent stability and noise level;
- tracking of the telescope was unusually stable;
- we encountered nearly no technical problems, which is rare even nowadays!

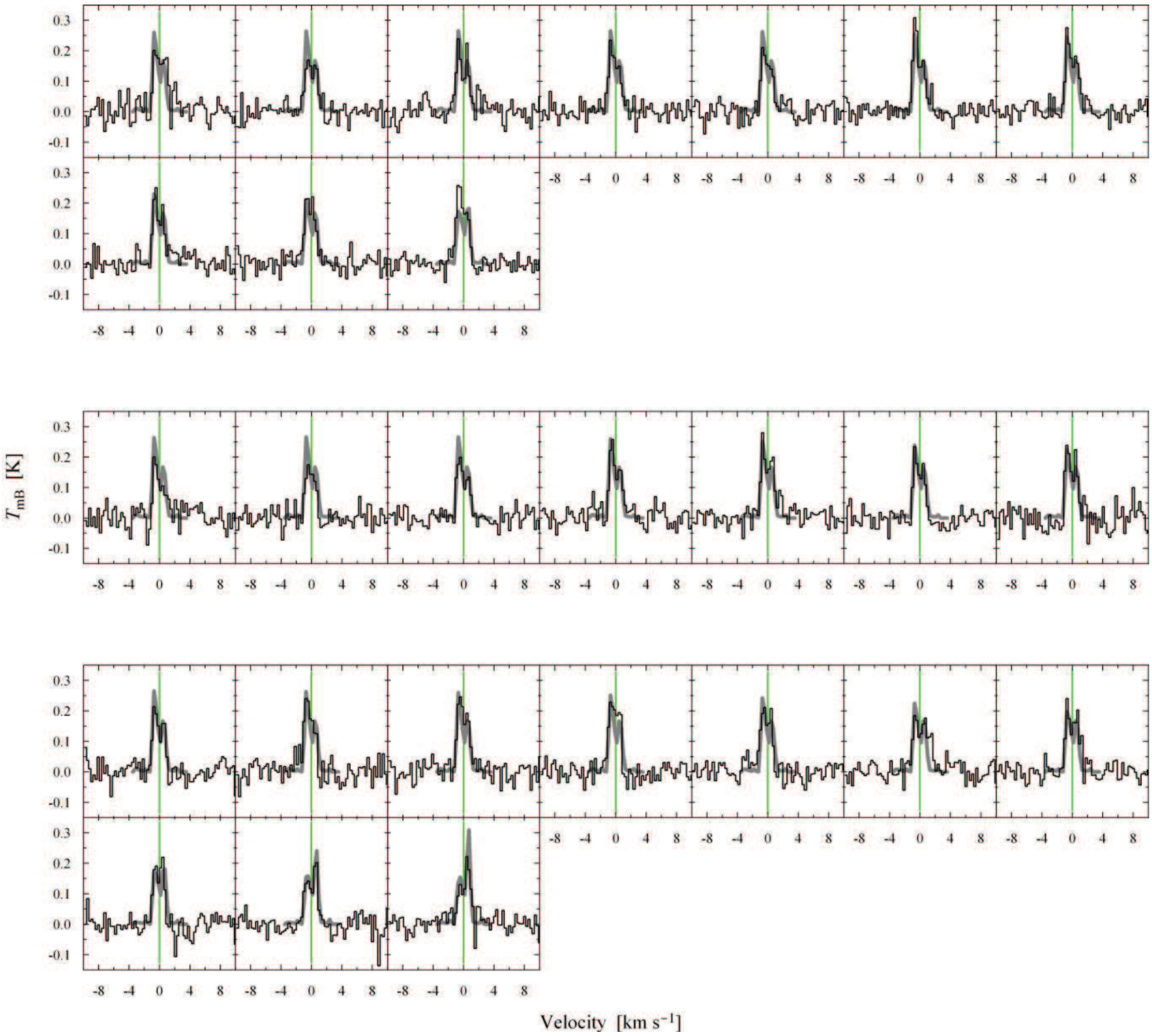

Fig. 2. Master spectra of HCN at 265.9 GHz. The three blocks correspond to the three dates of observation ordered chronologically from top to bottom. Time increases from left to right and the spectra from the same night are approximately 30 min apart. The thick gray lines show the best fit of the model.

The spectra of comet Tuttle in Fig. 2 clearly show that the line profile indeed evolved in an organized manner on a short timescale – presumably due to nucleus rotation. The profile has two distinct components: one blueshifted at about -1 km/s and the other one redshifted at about +0.5 km/s. The blueshifted component dominates in most of the spectra except for the last two where the redshifted one is clearly brighter (especially in the very last spectrum). This basic observation is of a fundamental importance, as it readily implies that the nucleus rotation phases covered by the last two spectra could not have been observed before. Consequently, this leads to the following windows for the rotation period: 5.70-5.75 h, 7.32-7.67 h, 10.35-11.51 h, 13.95-15.35 h, etc., where the first two windows are independent and are followed by their approximate multiples. Higher multiples are also possible, but they suffer from insufficient overlap or/and coverage of the observed rotation phases, thus it is impossible to evaluate their reliability. Overall, the obtained windows are nicely consistent with the results from other techniques (see Section 1). Surprisingly, however, periodographic analysis of the line area and position (cf. [12]) did not yield any statistically-significant solution, although the above periodicities were clearly visible. We interpret this as being caused by (*i*) a small number of the data points and (*ii*) intrinsically small amplitudes of variability of both line parameters.

New model

To adequately interpret the data of comet Tuttle we developed a new model of cometary microwave spectral line profiles. As the only source of activity we assumed a spherical nucleus sublimating strictly normally to the surface. The ejected molecules continue to travel at a constant speed as purely radial gas flow. We also assumed negligible optical depth at the observed frequency and *Local Thermodynamic Equilibrium* (LTE) characterized by a constant gas temperature that we assumed to be equal to 40 K as suggested by Biver et al. [2].

The key feature of this model is how it tackles sublimation from the nucleus. The body is divided into small elements, each parameterized by the coordinates of the center (θ, Φ), surface area dS, and sublimation potential η. Besides these properties – intrinsic to the element – the amount of ejected molecules also depends on the local solar zenith angle z. That is because it is the solar radiation which activates cometary sublimation and the efficiency of this process is introduced through the activation function $\Lambda(z)$. With all this in mind, we can now write the element's contribution to the instantaneous production rate Q of the whole body:

$$dQ(\theta,\phi,t) = \eta(\theta,\phi)\Lambda(z)dS(\theta,\phi) \tag{1}$$

It is very difficult to properly introduce into the model the activation process, as it requires a detailed thermal modeling of the body. Therefore, we approximated it with a simple $\Lambda(z) = \cos(z)$ on the day side and zero otherwise (implying no night-side sublimation), which results from energy balance in the sublimation-dominated regime (e.g. [8]).

We can readily see that this approach tackles the cometary comae as anisotropic and non-steady-state gas environments. The former concept is introduced by the non-uniform distribution of the sublimation potential and activation efficiency. The latter comes from the time-dependence of the activation function, which changes with the rotation phase and (typically much slower) orbital position. However, if we use $\eta(\theta, \Phi)$ = const, the model will reduce itself to a steady-state anisotropic construction, and if we additionally request $\Lambda(z)$ = const, it will become equivalent to the standard isotropic model of Haser [18].

The emitted molecules are then integrated: first along their lines of motion, which ensures constant radial velocity v_r within the integration. At this step we account for the exponential photodecay of the molecules and also for the Gaussian profile of the beam. A sub-spectrum resulting from such integration has a Gaussian shape; it is centered at v_r and has $FWHM = \sqrt{8 \ln 2 kT / m}$, where k is the Boltzmann constant, T is the gas temperature, and m is the mass of a single molecule. Then the spectra from all directions are co-added, and in the last step – with the aid of the JPL spectral line catalog [23] – we convert the number of molecules into their cumulative brightness. A final spectrum accounts also for the hyperfine splitting (cf. [22]).

Application

Applied to the data of comet Tuttle (see Fig. 2), the model clearly favors the 11.4 h rotation period over the one twice as short. The spin axis appears in the Sun–comet–Earth plane, with the northern pole shifted by 20° from the Earthward direction away from the Sun and the southern pole shifted by the same amount from the anti-Earthward direction towards the Sun. We find the mean-diurnal production rate of HCN equal to 2×10^{25} molec/s and the gas flow velocity of 0.85 km/s . The nucleus has a southern polar cap 30° in radius and η enhanced by a factor of 40, and a small ultra-volatile vent within the cap (η enhancement of about a factor of 4000), which is illuminated only during a short fraction of the rotation cycle. Moreover, a large (35° in radius) inactive spot at the same longitude as the vent appears at moderate northern latitudes. (The hemispheres are named according to the sense of rotation with the right-hand rule defining north.)

Interpretation of these parameters is very straightforward. The mean-diurnal production rate controls the average line area. The expansion velocity and (to a smaller extent) the temperature establish its width (both through the Doppler effect, as both represent the gas kinematics – the first one the bulk flow, the second one the superimposed random component). Finally, the rotation period controls the repeatability of the line profile. Given that the comet's phase angle was greater than half, most of the illuminated part of the nucleus, including the sub-solar point, was visible from the Earth, producing the blueshifted molecules. On the other hand, the redshifted molecules originated from a smaller region closer to the southern pole, which received much less sunlight but featured higher volatility. At some point during the rotation cycle, the Sunward outgassing was strongly attenuated by the inactive spot and at the same time the sublimation from the southern polar region became further amplified by the ultra-volatile vent, which produced the observed inversion of the line components. We note that the obtained parameters are very approximate at this point and so is their interpretation. They will be further refined as both the obtained fit occasionally deviates from the data, and also the assumed spherical shape of the nucleus is seemingly inconsistent with the bifurcated nature of this object (cf. Section 1).

The obtained HCN production rate is unusually low for a nucleus as large as the one of comet Tuttle, indicating substantial depletion in volatiles, probably of evolutionary nature, whereas the gas expansion velocity is typical of comets at comparable heliocentric distances. Both results are in full agreement with the study by Biver et al. [2], who used the same technique. Our spin-axis orientation and volatility map of the nucleus are loosely consistent with the preliminary results from CN imaging by Waniak et al. [25], who suggested the spin axis close to the line of sight and bulk outgassing not far from the Earthward direction (which they associated with an active vent located 30° from the Earthward pole). The agreement is much worse with the independent CN study (D. Schleicher, personal communication) and radar observations from Arecibo [16, 17], suggesting the spin axis tilted to the line of sight by 55° to 60°.

Summary and conclusions

On three dates around the New Year's Day of 2008 we obtained a time series of HCN spectra of comet 8P/Tuttle. The velocity-resolved line profiles evolved with time in an organized manner, which we interpreted as caused by nucleus rotation and used to constrain the rotation period. Our estimates are consistent with the determinations from other techniques.

Since such effects have been reported for only a few comets before, a natural question arises: why are not they observed routinely? Clearly, they can be best detected when the observation is limited to the inner coma. However, using large microwave telescopes, which offer beam sizes of the order of 10" at these frequencies, this condition is satisfied for comets as distant from the Earth as 0.5 AU, which appear relatively often. We suspect that over the years these effects were routinely averaged out in hours- or even days-long effective exposures of very faint lines. Alternatively, they could be missed out due to undersampling if the goal was to detect as many molecules as possible in a short time. The latter case is well illustrated by comet Tuttle itself: Biver et al. [2] detected several molecules including HCN, but did not find any convincing evidence for the short-term variations. Indeed, our observations show that the signatures of nucleus rotation were very easy to miss. This leads to the conclusion that careful arrangement of observations is critically important for such a study, and that one should aim at obtaining the longest possible and uninterrupted time series. Unlike in night astronomy, this requirement can be easily satisfied by a single microwave facility, which in many cases can observe day and night for as long as the comet is above the horizon.

In order to interpret the spectra, we developed a new model of cometary spectral line profiles, which is a non-steady-state anisotropic construction. Upon being applied to our data, it yielded the spin-axis orientation and the activity pattern of the nucleus which fall into the broad range of proposed solutions inferred using other methods and techniques. To our best knowledge, orientation of cometary spin axis has never been inferred from microwave spectra before, and overall, the line profiles have never been explored so extensively before the apparition of comet 103P/Hartley 2 three years later. In addition, we retrieved the mean-diurnal HCN production rate and the gas expansion velocity, both in excellent agreement with the independent spectroscopic study at the same wavelengths.

We note that the current application of the model did not explore its full potential. Future studies will take advantage of its capabilities of analyzing spectral maps and time series collected over large arcs on the sky (easily realized for Earth-approaching comets), which should greatly improve the retrieval. Moreover, if applied to long time series, the model will be sensitive to distinguish constant vs. accelerated and simple vs. excited rotation state of the nucleus. When applied to several molecules observed simultaneously, it will verify whether they originate from different active vents (chemical heterogeneity) or the same gas mixture was produced globally (chemical homogeneity). All these new applications have the potential of challenging our current paradigms concerning the properties and physics of cometary nuclei, and consequently, their history and role in the Solar System as the supplier of water and organics.

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