

## Rapidly Varying Anisotropic Methanol (CH<sub>3</sub>OH) Production in the Inner Coma of Comet 46P/Wirtanen as Revealed by the ALMA Atacama Compact Array

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### ABSTRACT

We report the detection of CH<sub>3</sub>OH emission in comet 46P/Wirtanen on UT 2018 December 8 and 9 using the Atacama Compact Array (ACA), part of the Atacama Large Millimeter/Submillimeter Array (ALMA). These interferometric measurements of CH<sub>3</sub>OH along with continuum emission from dust probed the inner coma (**<2000 km from the nucleus**) of 46P/Wirtanen approximately one week before its closest approach to Earth ( $\Delta = 0.089 - 0.092$  au), revealing rapidly varying and

anisotropic CH<sub>3</sub>OH outgassing during five separate ACA executions between UT 23:57 December 7 and UT 04:55 December 9, with clear progression in the spectral line profiles **over a timescale** of minutes. We present spectrally integrated flux maps, production rates, rotational temperatures, and spectral line profiles of CH<sub>3</sub>OH during each ACA execution. The variations in CH<sub>3</sub>OH outgassing are consistent with Wirtanen’s 9 hour nucleus rotational period derived from optical and millimeter wavelength measurements, and thus are likely coupled to the changing illumination of active sites on the nucleus. The consistent blue offset of the line center indicates enhanced CH<sub>3</sub>OH sublimation **from the sunward hemisphere of the comet**, perhaps from icy grains. These results demonstrate the exceptional capabilities of the ACA for time-resolved measurements of comets such as 46P/Wirtanen.

*Keywords:* Molecular spectroscopy (2095) — High resolution spectroscopy (2096) — Radio astronomy (1338) — Comae (271) — Comets (280)

## 1. INTRODUCTION

Comets, kilometer-sized bodies of ice and dust, were assembled in the solar nebula during the era of planet formation and subsequently scattered to the Kuiper disk or the Oort cloud. Stored with minimal processing for the last  $\sim 4.5$  Gyr in the deep freeze of the cold outer solar system, they may serve as “fossils” of solar system formation, with the volatile composition of their nuclei reflecting the chemistry and prevailing conditions present in the midplane of the solar nebula (Bockelée-Morvan et al. 2004; Mumma & Charnley 2011; Bockelée-Morvan & Biver 2017). Volatiles are released as they enter the inner solar system (heliocentric distances,  $r_H < 5$  au) and encounter increasing solar radiation, activating sublimation and leading to the formation of a coma (a freely expanding atmosphere). Remote sensing of coma volatiles over the past three decades has revealed that comets display significant compositional diversity (e.g., A’Hearn et al. 1995; Crovisier et al. 2009; Cochran et al. 2015; Dello Russo et al. 2016a), **providing a window into the diversity of their initial conditions and the degree of chemical processing during their lifetime.**

The composition and structure of the coma can be measured in exceptional detail through pure rotational transitions of coma molecules, such as carbon monoxide (CO), carbon monosulfide (CS), hydrogen cyanide (HCN), formaldehyde (H<sub>2</sub>CO), and methanol (CH<sub>3</sub>OH). Single dish and interferometric observations at millimeter wavelengths (e.g., Bockelée-Morvan et al. 1994; Biver et al. 1999; Milam et al. 2006; Fray et al. 2006; Boissier et al. 2007; Lis et al. 2008; Cordiner et al. 2014) have shown that the distributions of HCN and CH<sub>3</sub>OH in some comets are consistent with direct release from the nucleus, whereas CS, H<sub>2</sub>CO, and HNC are produced by “distributed” sources in the coma. More recently, the high sensitivity and angular resolution of the Atacama Large Millimeter/Submillimeter Array (ALMA) has confirmed these results, and enabled spatially and temporally resolved measurements capable of discerning variations in outgassing on small timescales (Cordiner et al. 2017b).

The 2018 perihelion passage of Jupiter-family comet (JFC) 46P/Wirtanen afforded an opportunity to couple the high spatial and spectral resolution of ALMA with the most favorable apparition of a JFC in the previous decade. Here we report time-resolved pre-perihelion observations of CH<sub>3</sub>OH in 46P/Wirtanen taken with the ALMA Atacama Compact Array (ACA). The  $12 \times 7$ -m antennas of the ACA provide short baselines between 9 and  $\sim 50$  m (corresponding to an angular resolution ranging from  $5''.45$  to  $29''.0$  at 230 GHz), resulting in greater sensitivity to extended flux than the main 12-m array (**which was in configuration C43-4 at the time of our observations with an angular resolution ranging from  $0''.39$  to  $4''.89$  at 230 GHz**). We note that these observations were most sensitive to the inner coma of Wirtanen, and that the largest recoverable scale of the ACA is small compared to the size of Wirtanen’s extended coma (up to several arcminutes). We sampled CH<sub>3</sub>OH emission in the coma of 46P/Wirtanen with multiple executions of the ACA spread over two dates, searching for changes in molecular production rates, outgassing, and spatial distribution of emission. Significant variations in molecular production and anisotropic outgassing of CH<sub>3</sub>OH were measured throughout these data. We report spectrally integrated flux maps, production rates, rotational temperatures, and spectral line profiles of CH<sub>3</sub>OH emission. Section 2 presents the observations and data analysis, results are found in Section 3, and Section 4 discusses the variation in CH<sub>3</sub>OH during these measurements, identifies potential mechanisms, and places these results in the context of **other** comets characterized to date.

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## 2. OBSERVATIONS AND DATA REDUCTION

Comet 46P/Wirtanen (hereafter Wirtanen) is a Jupiter-family comet with a period  $P = 5.4$  years, and was the original target of ESA’s Rosetta mission. During its 2018 apparition, Wirtanen reached perihelion ( $q = 1.05$  au) on UT 2018 December 12, and passed closest to the Earth ( $\Delta_{\min} = 0.0774$  au, approximately 30 lunar distances) on UT 2018 December 16. We conducted pre-perihelion observations towards Wirtanen on UT 2018 December 8 and 9 during Cycle 6 using the ALMA ACA with the Band 6 receiver, covering frequencies between 241.5 and 242.0 GHz ( $\lambda = 1.23 - 1.24$  mm) in one 500 MHz wide spectral window. The observing log is shown in Table 1. We tracked the comet position using JPL Horizons ephemerides (JPL #K181/21). One correlator setting was employed in each execution to simultaneously sample multiple CH<sub>3</sub>OH transitions and continuum. Weather conditions were good (**mean precipitable water vapor at zenith, zenith PWV**, = 0.89 – 1.09 mm on December 8, zenith PWV = 2.15 – 3.23 mm on December 9). Quasar observations were used for bandpass and phase calibration, as well as calibrating Wirtanen’s flux scale. The spatial scale (**the range in semi-minor and semi-major axes of the synthesized beam**) was 3''98 – 7''99 and the channel spacing was 122 kHz, leading to a spectral resolution of 0.15 km s<sup>-1</sup>. The data were flagged, calibrated, and imaged using standard routines in the Common Astronomy Software Applications (CASA) package version 5.6.1 (McMullin et al. 2007). We deconvolved the point-spread function with the Högbom algorithm, using natural visibility weighting and a flux threshold of twice the rms noise in each image. The deconvolved images were then convolved with the synthesized beam and corrected for the (Gaussian) response of the ALMA primary beam. We transformed the images from astrometric coordinates to projected cometocentric distances, with the location of peak continuum flux chosen as the origin, which was in good agreement with the comet’s predicted ephemeris position. **The topocentric frequency of each spectral channel was converted to cometocentric velocity as**

$$V = c \left( \frac{f_{\text{rest}} - f}{f_{\text{rest}}} \right) - \frac{d\Delta}{dt} \quad (1)$$

where  $c$  is the speed of light (km s<sup>-1</sup>),  $f_{\text{rest}}$  is the rest frequency of a given transition (GHz),  $f$  is the frequency of the channel (GHz), and  $d\Delta/dt$  is the geocentric velocity of the comet at the time of the observations (km s<sup>-1</sup>).

**Table 1.** Observing Log

Execution	Date	UT Time	$T_{\text{int}}$	$r_{\text{H}}$	$\Delta$	$\phi$	$\nu$	$N_{\text{ants}}$	Baselines	$\theta_{\text{min}}$	PWV
			(min)	(au)	(au)	(°)	(GHz)		(m)	(")	(mm)
1	2018 Dec 7–8	23:57–00:58	45	1.057	0.092	37.1	241.8	12	8.9–48.9	4.11×7.99	1.09
2	2018 Dec 8	01:25–02:26	45	1.057	0.092	37.0	241.8	12	8.8–48.9	3.98×6.53	0.89
3	2018 Dec 9	00:46–01:47	45	1.056	0.089	35.3	241.8	12	8.8–48.9	4.23×7.27	2.15
4	2018 Dec 9	02:26–03:27	45	1.056	0.089	35.1	241.8	12	8.8–48.9	4.28×6.85	2.58
5	2018 Dec 9	03:54–04:55	45	1.056	0.089	35.0	241.8	12	8.8–48.9	4.33×7.78	3.23

NOTE— $T_{\text{int}}$  is total on-source integration time.  $r_{\text{H}}$ ,  $\Delta$ , and  $\phi$  are the heliocentric distance, geocentric distance, and phase angle (Sun-Comet-Earth), respectively, of Wirtanen at the time of observations.  $\nu$  is the mean frequency of each instrumental setting.  $N_{\text{ants}}$  is the number of antennas utilized during each observation, with the range of baseline lengths indicated for each.  $\theta_{\text{min}}$  is the angular resolution (synthesized beam) at  $\nu$ , and PWV is the mean precipitable water vapor at zenith during the observations.

## 3. RESULTS

We detected molecular emission from multiple strong CH<sub>3</sub>OH transitions near 241.7 GHz as well as continuum emission from dust in the coma of Wirtanen. Molecular line emission was modeled using a three-dimensional radiative transfer method based on the Line Modeling Engine (LIME; Brinch & Hogerheijde 2010) adapted for cometary atmospheres, including a full non-LTE treatment of coma gases, collisions with H<sub>2</sub>O and electrons, and pumping by solar radiation (for further details see Cordiner et al. 2019a). **We calculated the number density of molecules**

released from the nucleus as a function of distance following the Haser formalism (Haser 1957) as

$$n_p(r) = \frac{Q}{4\pi v_{\text{exp}} r^2} \exp\left(-\frac{r\beta}{v_{\text{exp}}}\right), \quad (2)$$

where  $Q$  is the production rate (molecules  $\text{s}^{-1}$ ),  $v_{\text{exp}}$  is the expansion velocity ( $\text{km s}^{-1}$ ) and  $\beta$  is the photodissociation rate adopted from Huebner et al. (1992), with  $Q$  and  $v_{\text{exp}}$  allowed to vary as free parameters.

We assumed that the collision rate between  $\text{CH}_3\text{OH}$  and  $\text{H}_2\text{O}$  is the same as that with  $\text{H}_2$  (taken from the LAMDA database). This assumption has negligible impact on the derived parameters since the coma contained within the ACA beam was close to LTE due to the proximity of Wirtanen and the relatively small beam size. Our models were run through the CASA “simobserve” tool to mimic the effects of the ACA using the exact antenna configuration and hour angle ranges of our observations. We found that interferometric filtering by the ACA resulted in a 24% loss in the peak flux of our models; therefore, an efficiency factor  $\eta = 0.76$  was applied to the radiative transfer models when comparing with observed spectra and calculating production rates. Detected spectral lines, including upper-state energies ( $E_u$ ) and integrated fluxes, are listed in Table 2.

**Table 2.**  $\text{CH}_3\text{OH}$  Lines Detected in Wirtanen

Transition	Frequency (GHz)	$E_u$ (K)	Integrated Flux <sup>a</sup>				
			(K $\text{km s}^{-1}$ )				
Execution			1	2	3	4	5
UT Date (2018)			12/7-8, 23:57–00:58	12/8, 01:25–02:26	12/9, 00:46–01:47	12/9, 02:26–03:27	12/9, 03:54–04:55
$5_0-4_0 A^+$	241.791	34.8	$0.381 \pm 0.011$	$0.305 \pm 0.015$	$0.349 \pm 0.013$	$0.441 \pm 0.012$	$0.345 \pm 0.014$
$5_{-1}-4_{-1} E$	241.767	40.4	$0.317 \pm 0.010$	$0.278 \pm 0.014$	$0.337 \pm 0.015$	$0.360 \pm 0.014$	$0.270 \pm 0.018$
$5_0-4_0 E$	241.700	47.9	$0.313 \pm 0.011$	$0.279 \pm 0.013$	$0.293 \pm 0.015$	$0.357 \pm 0.015$	$0.259 \pm 0.014$
$5_1-4_1 E$	241.879	55.9	$0.260 \pm 0.010$	$0.244 \pm 0.015$	$0.243 \pm 0.012$	$0.283 \pm 0.013$	$0.242 \pm 0.016$
$5_2-4_2 A^+$	241.887	72.5	$0.215 \pm 0.009$	$0.149 \pm 0.011$	$0.122 \pm 0.014$	$0.195 \pm 0.014$	$0.078 \pm 0.019$
$5_{-3}-4_{-3} E$	241.852	97.5	$0.080 \pm 0.011$	$0.093 \pm 0.013$	$0.078 \pm 0.013$	$0.108 \pm 0.014$	$0.084 \pm 0.015$
$T_{\text{rot}}^b$ (K)			$82 \pm 8$	$77 \pm 10$	$52 \pm 5$	$60 \pm 5$	$57 \pm 7$

NOTE—<sup>a</sup> Spectrally integrated flux of spectra extracted from a **nucleus-centered beam at the position of peak continuum flux** (Figures 1 and 2) for the indicated **execution** and UT date labeled in Table 1. <sup>b</sup> Rotational temperature derived using the rotational diagram method (Bockelée-Morvan et al. 1994).

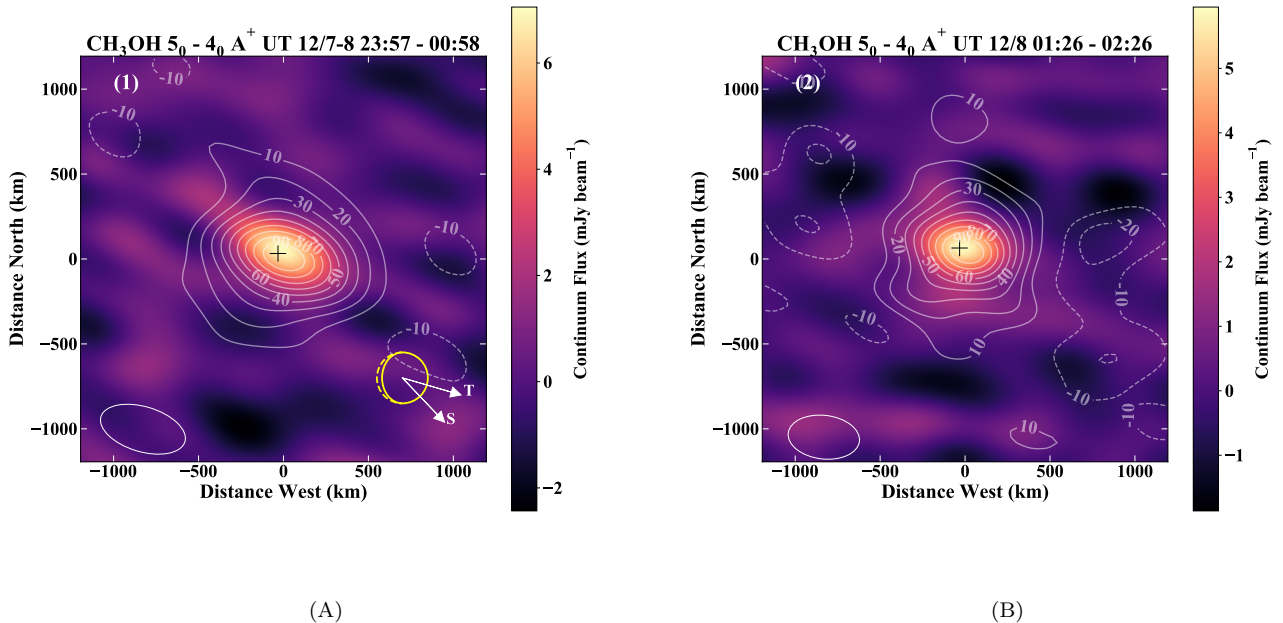
### 3.1. Molecular Maps, Extracted Spectra, and Radial Profiles

Figures 1 and 2 show spectrally integrated flux maps for the  $\text{CH}_3\text{OH } 5_0-4_0 A^+$  transition near 241.791 GHz (the strongest  $\text{CH}_3\text{OH}$  transition in these data) for each ACA execution in Wirtanen. The shape and spatial extent of the emissions are relatively consistent across each execution.

We extracted **nucleus-centered** spectra of the  $5_0-4_0 A^+$  transition in each ACA execution. Figure 3 shows the significant variation in the velocity profile (and to an extent, amplitude) measured in each execution. We found that the velocity profiles of the remaining five detected  $\text{CH}_3\text{OH}$  transitions in each execution (Table 2) were consistent with that of the strongest  $5_0-4_0 A^+$  transition. Taken together, these spectra indicate that  $\text{CH}_3\text{OH}$  outgassing in Wirtanen was anisotropic, and furthermore that this anisotropy varied with time (Section 4).

### 3.2. Rotational and Kinetic Temperatures

We detected emission from six strong  $\text{CH}_3\text{OH}$  transitions in each ACA execution on December 8 and 9. We constrained the coma rotational temperature along the line of sight during each execution using the rotational diagram method (Bockelée-Morvan et al. 1994), and list them in Table 2. Retrieved rotational temperatures are **marginally**



**Figure 1. Executions 1 – 2.** Spectrally integrated flux maps for the  $\text{CH}_3\text{OH } 5_0-4_0 A^+$  transition in Wirtanen on UT 2018 December 8. Contour intervals are 10% of the projected peak of the gas emission in each map. The rms noise ( $\sigma$ ,  $\text{mJy beam}^{-1} \text{ km s}^{-1}$ ) and contour spacing,  $\delta$ , for each map are (A):  $\sigma = 19$ ,  $\delta = 2.7\sigma$  and (B):  $\sigma = 18$ ,  $\delta = 2.2\sigma$ . Continuum emission is shown as a color map behind the contours. Sizes and orientations of the synthesized beam are indicated in the lower left corner of each panel. **The comet’s illumination phase ( $\phi \sim 36^\circ$ ), as well as the direction of the Sun and dust trail, are indicated in the lower right.** The black cross indicates the position of the peak continuum flux from which spectra were extracted. Each execution is numbered in the upper left as denoted in Table 1.

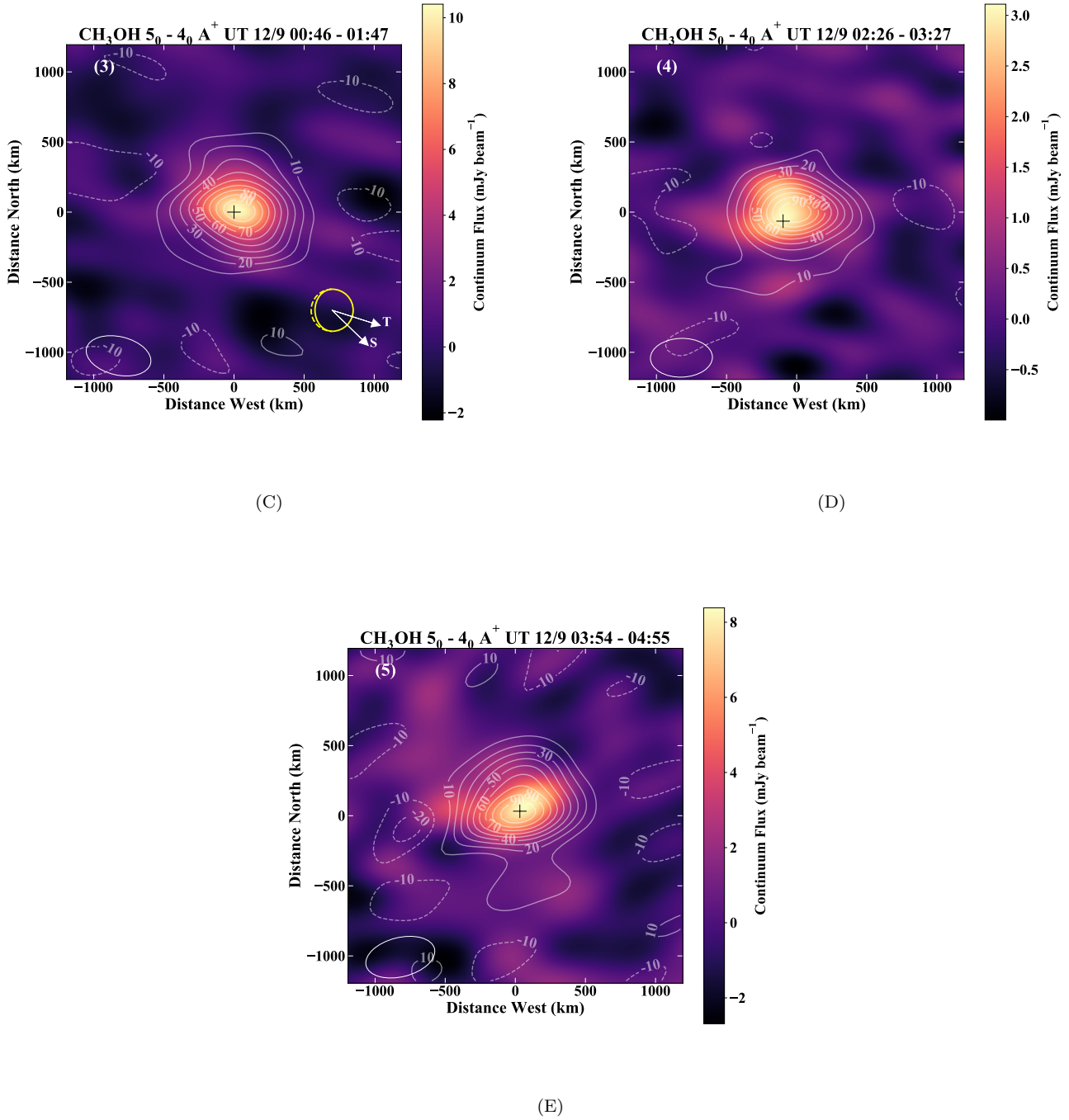
higher on December 8 than on December 9. However, rotational temperatures for executions on a given date are consistent within  $1\sigma$  uncertainty.

Given the very small geocentric distance ( $\Delta \sim 0.09$  au) of Wirtanen during our observations, the **HWHM** of the ACA synthesized central beam extended to nucleocentric distances of  $\sim 132 \times 265$  km. This corresponds to the very inner coma of Wirtanen, where the rotational states should be **in thermal equilibrium due to collisions** at the kinetic temperature of the gas; therefore, the rotational temperature is **expected to be similar** to the kinetic temperature for the  $\text{CH}_3\text{OH}$  sampled by our measurements.

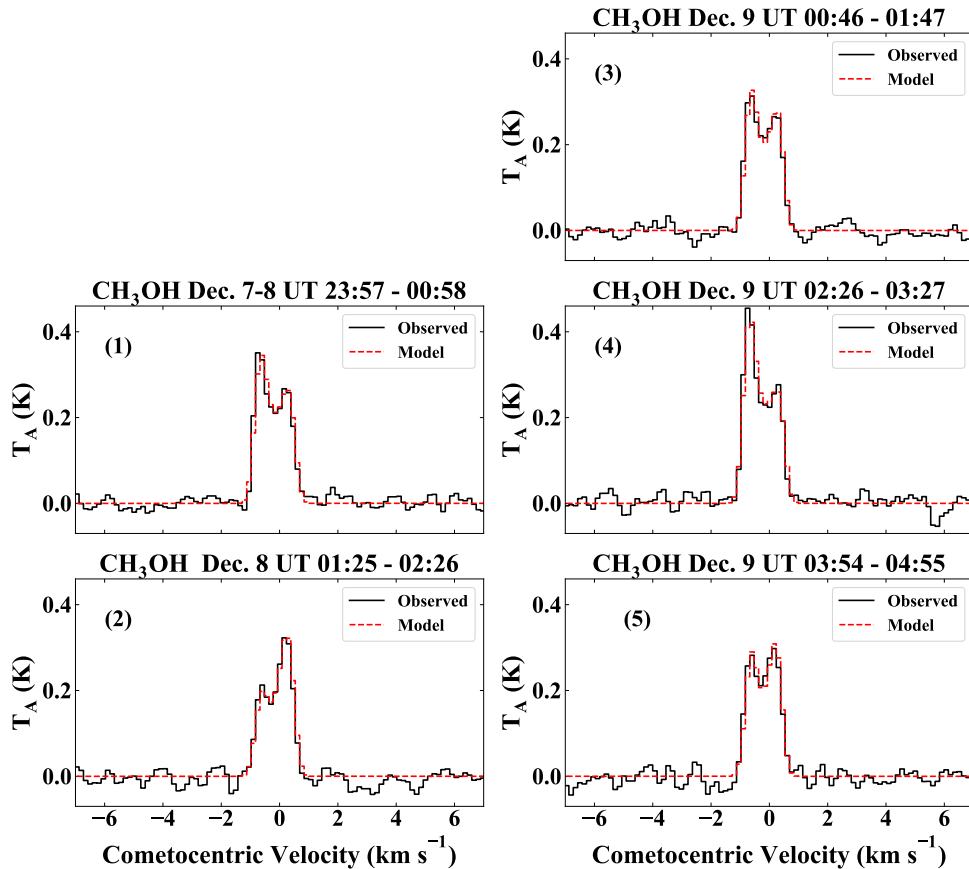
We tested this by running full non-LTE models for all six detected  $\text{CH}_3\text{OH}$  transitions in Execution 4 (the execution with the strongest transitions and highest S/N), setting the model kinetic temperature equal to the best-fit rotational temperature for the execution ( $T_{\text{rot}} = 60 \pm 5$  K; Table 2). We then performed a rotational diagram analysis on the model-generated lines. We find  $T_{\text{rot}}(\text{model}) = 55$  K, in formal agreement with the rotational temperature calculated from the observed spectra (Figure 4). Thus, the use of LTE models (i.e., setting the kinetic temperature of the model to the derived rotational temperature for each execution) is justified and results in negligible changes in production rate (8% difference for  $\pm 5$  K changes in  $T$ ). Given that these conditions were satisfied for Execution 4, it is reasonable to assume that they were satisfied for the other executions. These results are in excellent agreement with data obtained with the IRAM 30-m (Biver et al. 2020).

### 3.3. Expansion Velocities and Anisotropic Outgassing

We derived expansion velocities and outgassing asymmetry factors for the  $\text{CH}_3\text{OH } 5_0-4_0 A^+$  transition in each execution by performing nonlinear least-squares fits of our radiative transfer models to extracted spectral line profiles. Hemispheric asymmetry in outgassing along the Sun-comet vector was considered when fitting the observations for each execution. Consistent with previous ALMA studies of comets, we modeled  $\text{CH}_3\text{OH}$  as a parent species (Cordiner



**Figure 2. Executions 3–5.** Spectrally integrated flux maps for the  $\text{CH}_3\text{OH } 5_0-4_0 A^+$  transition in Wirtanen on UT 2018 December 9, with traces and labels as in Figure 1. Contour intervals are 10% of the projected peak of the gas emission in each map. The rms noise ( $\sigma$ ,  $\text{mJy beam}^{-1} \text{ km s}^{-1}$ ) and contour spacing,  $\delta$ , for each map are (A):  $\sigma = 16$ ,  $\delta = 3.3\sigma$ , (B):  $\sigma = 18$ ,  $\delta = 3.3\sigma$ , and (C):  $\sigma = 21$ ,  $\delta = 2.7\sigma$ . Continuum emission is shown as a color map behind the contours. **Each execution is numbered in the upper left as denoted in Table 1.**



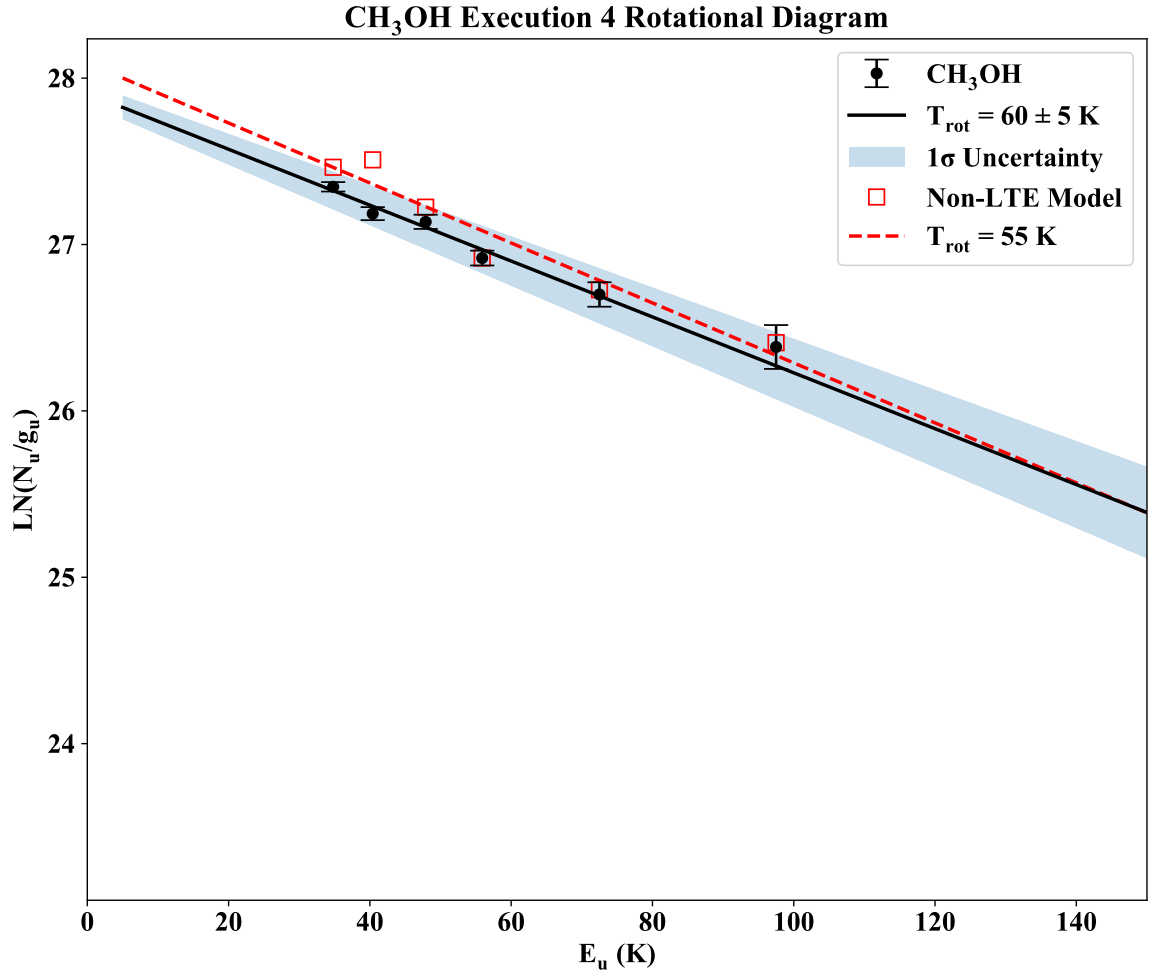
**Figure 3.** Extracted spectra of the  $\text{CH}_3\text{OH } 5_0\text{-}4_0 A^+$  transition in Wirtanen during each ACA execution with best-fit models overlaid. Best-fit model parameters are given in Table 3. Each execution is numbered as denoted in Table 1.

et al. 2017a, 2019b). These models produced excellent fits to the data (reduced chi-square,  $\chi^2_{\text{red}} = 0.97\text{--}1.35$ ) (see Figure 3), **allowing the spectral line asymmetry to be fully reproduced**. Table 3 lists our results, and Figure 3 shows our extracted spectra with best-fit models overlain.

#### 4. VARIATION IN METHANOL OUTGASSING AND PRODUCTION RATES

Table 3 and Figure 3 show that the line velocity profile for  $\text{CH}_3\text{OH}$  emission in Wirtanen varied over the course of our observations. As Table 1 and the timestamps in Figure 3 show, Executions 1 and 4, as well as Executions 2 and 5, were separated by  $\sim 26.5$  hours. The nucleus rotation period of Wirtanen is well-constrained from measurements at optical and millimeter wavelengths during the 2018 perihelion passage: Farnham et al. (2018), Jehin et al. (2018), Handzlik et al. (2019), and Farnham et al. (2020) reported  $P = 8.91 \pm 0.03$  hours,  $P = 9.19$  hours,  $P = 9$  hours, and  $P = 9.13$  hours, respectively. Coupled with this  $\sim 9$  hour rotational period, the line morphologies in Figure 3 and the production rates in Table 3 suggest that these effects could be periodic and related to the rotation of Wirtanen’s nucleus, as Executions 1 and 4 as well as Executions 2 and 5 would be separated by approximately three complete rotations. These variations may be consistent with changes in coma outgassing as active regions rotated from the day side to the night side of Wirtanen’s nucleus. **Examining trends in integrated flux (Table 2) and  $Q(\text{CH}_3\text{OH})$  (Table 3) compared to trends in weather conditions (Table 1) reveals no discernible link between the weather and the observed variability.** We examine potential mechanisms for variability further below.

##### 4.1. Variation on Timescales of Minutes



**Figure 4.** Rotational diagram of the CH<sub>3</sub>OH  $5_{0-4_0} A^+$ ,  $5_{-1-4_{-1}} E$ ,  $5_{0-4_0} E$ ,  $5_{1-4_1} E$ ,  $5_{2-4_2} A^+$ , and  $5_{-3-4_{-3}} E$  transitions in Wirtanen on UT 2018 December 9 during Execution 4 (black circles, Tables 1 and 2), along with the best-fit line (black, solid), corresponding to  $T_{\text{rot}} = 60 \pm 5$  K, and the  $1\sigma$  uncertainty in the fit (blue shaded area). Also shown is the rotational diagram for a non-LTE model with  $T_{\text{kin}} = 60$  K (red squares) and the best-fit line (red, dashed) corresponding to  $T_{\text{rot}} = 55$  K, illustrating formal agreement between the observations and the model.

To further address these potential rotational effects, we searched for changes in outgassing on smaller timescales. Each ACA execution consisted of six scans, with each scan lasting  $\sim 8$  minutes. The S/N in the CH<sub>3</sub>OH  $5_{0-4_0} A^+$  transitions in individual scans was not high enough to draw definitive conclusions, so we averaged the line profiles of the three strongest transitions in each scan (namely the  $5_{0-4_0} E$ ,  $5_{-1-4_{-1}} E$ , and  $5_{0-4_0} A^+$  transitions) to improve S/N. Figure 5 shows our results for December 8, and Figure 6 shows the same for December 9.

Figure 5 shows a clear progression from an asymmetric profile with a blueshifted peak (Figure 3A) to a redshifted peak (Figure 3B) on December 8. The progression from scan-to-scan in Figure 6 on December 9 is less dramatic than on December 8, perhaps owing to the poorer weather (zenith PWV was higher overall on December 9 compared to December 8, and increased over the course of our observations on December 9; see Table 1). Regardless, the progression from a roughly symmetric profile in Execution 3, to an asymmetric profile with a blueshifted peak and higher amplitude in Execution 4, followed by a decrease in amplitude and return to a more symmetric profile in Execution 5, is clearly visible.

To investigate potential periodicity of the variation in line asymmetry, we examined the mean Doppler shift (velocity first moment; i.e., the average velocity weighted by the emission intensity in each channel) as well as the maximum amplitude of the blueward peak (taken as the maximum value for  $v < 0$  km s<sup>-1</sup>) in each scan on both dates and plotted them as a function of time (Figure 7). We calculated least squares fits for sine waves



**Table 3.** Expansion Velocities, Asymmetry Factors, and Molecular Production Rates in Wirtanen for a Hemispheric Model

Execution	UT Date (2018)	$T_{\text{rot}}^{\text{a}}$ (K)	$v_{\text{exp}}(1)^{\text{b}}$ (km s <sup>-1</sup> )	$v_{\text{exp}}(2)^{\text{c}}$ (km s <sup>-1</sup> )	$Q_1/Q_2^{\text{d}}$	$\chi^2_{\text{red}}^{\text{e}}$	$Q^{\text{f}}$ (10 <sup>26</sup> s <sup>-1</sup> )
1	12/7-8, 23:57–00:58	(69)	0.76 ± 0.01	0.45 ± 0.02	3.6 ± 0.2	1.35	3.6 ± 0.4
2	12/8, 01:25–02:26	(86)	0.72 ± 0.03	0.39 ± 0.03	1.5 ± 0.1	1.04	2.0 ± 0.2
3	12/9, 00:46–01:47	(55)	0.74 ± 0.01	0.41 ± 0.02	3.4 ± 0.2	1.11	2.0 ± 0.2
4	12/9, 02:26–03:27	(68)	0.80 ± 0.01	0.45 ± 0.03	5.4 ± 0.3	1.28	3.1 ± 0.3
5	12/9, 03:54–04:55	(67)	0.73 ± 0.02	0.34 ± 0.02	3.4 ± 0.3	0.97	2.0 ± 0.2

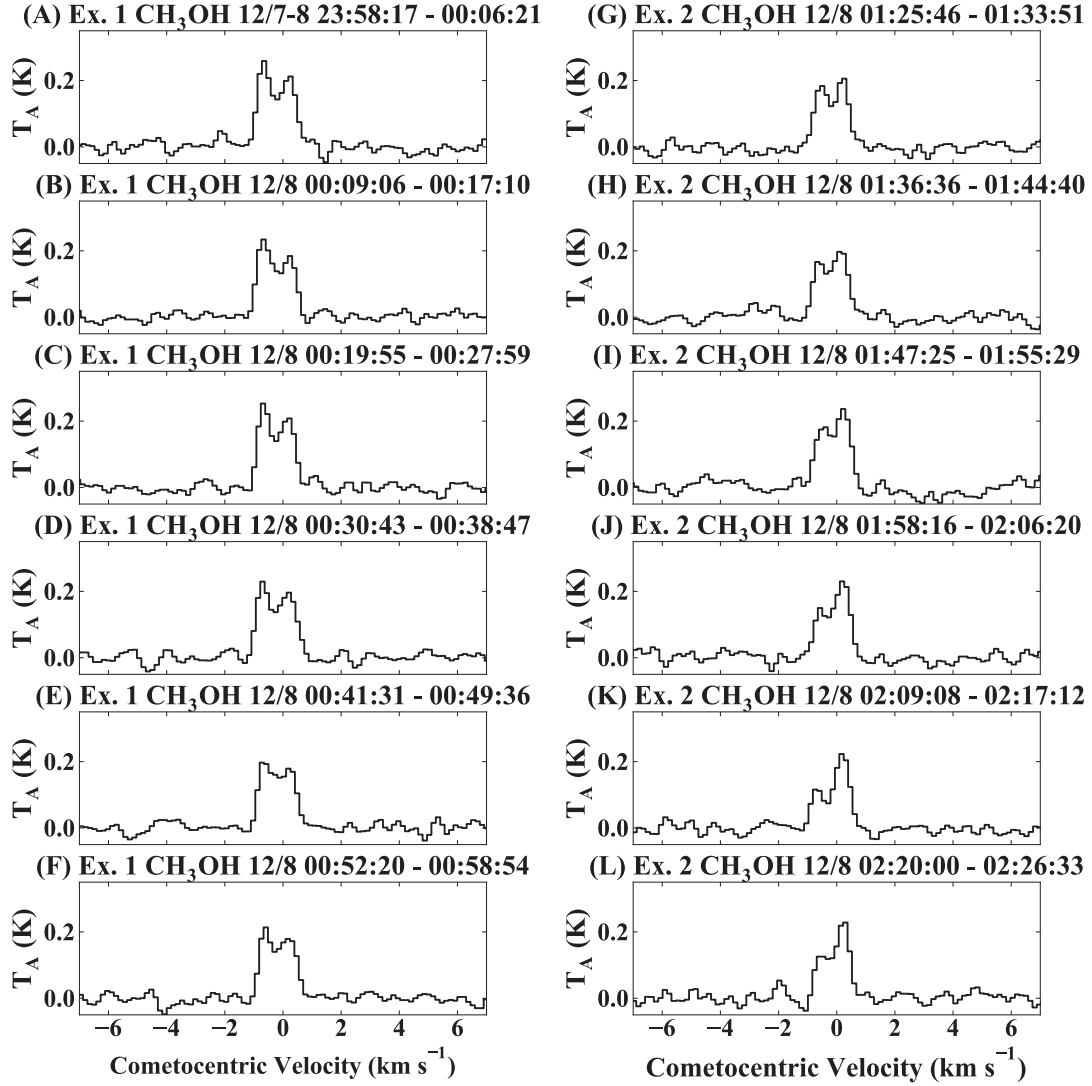
NOTE—Best-fit parameters for the hemispheric outgassing model. <sup>a</sup> We set the model kinetic temperature to the derived rotational temperature for each execution (see Section 3.2). <sup>b</sup> Expansion velocity in the sunward hemisphere. <sup>c</sup> Expansion velocity in the anti-sunward hemisphere. <sup>d</sup> Asymmetry factor: ratio of production rates in the sunward vs. anti-sunward hemisphere. <sup>e</sup> Reduced  $\chi^2$  of the model fit. <sup>f</sup> CH<sub>3</sub>OH production rate.

with periods near 3, 6, 9, 12, and 27 hours for both plots, and calculated the goodness-of-fit (reduced  $\chi^2$ ). The constraint  $\text{Max}[T_{\text{A}}] \text{ (K)} \geq 0$  excludes  $P = 13.6$  hours and 27.15 hours. Based on the reduced  $\chi^2$ , the amplitude of the blue peaks is best-fit by a sine wave with  $P = 6.83 \pm 0.04$  hours, amplitude  $A = -0.07 \pm 0.01$  K, and  $A_0 = 0.20 \pm 0.01$  K. Similarly, the mean Doppler shifts are best-fit by a sine wave with  $P = 9.16 \pm 0.08$  hours,  $A = -0.15 \pm 0.02$  km s<sup>-1</sup>, and  $v_0 = -0.16 \pm 0.01$  km s<sup>-1</sup> (when excluding  $P = 13$  or 27 hours). Thus, within the limitations of the data, our results suggest  $P \sim 7\text{-}9$  hours, consistent with measurements from optical and millimeter wavelengths ( $P \sim 9$  hours; Farnham et al. 2018; Jehin et al. 2018; Handzlik et al. 2019; Farnham et al. 2020). The consistent periodicity between our observations and those from optical and millimeter wavelengths suggests that the variation in CH<sub>3</sub>OH outgassing in Wirtanen reported here is indeed tied to rotational effects. The rotational variation in the velocity structure in Wirtanen is also clearly evident in position-velocity diagrams for each scan (Figure 8 and Figure 9).

In addition to its measured period, the nucleus of Wirtanen is well-studied due to its status as the original target for the Rosetta mission. It is a small ( $r_{\text{eff}} \sim 0.5$  km) prolate ellipsoid (axial ratio  $> 1.4$ ) (Boehnhardt et al. 2002). **Although previous observations were unable to discern whether Wirtanen is in a state of non-principal axis rotation (Samarasinha et al. 1996), measurements during the 2018 perihelion passage demonstrated that Wirtanen is in a state of simple rotation (Farnham et al. 2020, this issue).** Given Wirtanen’s prolate elliptical nucleus shape and rotational period, coupled with the periodicity measured in our observations, it is possible that the variations in CH<sub>3</sub>OH outgassing are due to differences in illumination on the nucleus, along with active sites rotating from the day side to the night side. Such rotational effects have been observed in a comet with a prolate elliptical nucleus before, namely 103P/Hartley 2. At 103P, the EPOXI mission, coupled with ground-based observations with IRAM and CSO, found that varying illumination of the small lobe of the nucleus due to rotation (along with the nucleus shape) caused significant changes in volatile release (A’Hearn et al. 2011; Drahus et al. 2012; Boissier et al. 2014). Furthermore, at comet 67P, the Rosetta mission found diurnal variations in CH<sub>4</sub>, CO, and C<sub>2</sub>H<sub>6</sub> outgassing (Luspay-Kuti et al. 2015; Fink et al. 2016) tied to rotation of the comet’s bi-lobed nucleus. Finally, in comet C/1995 O1 (Hale-Bopp), Bockelée-Morvan et al. (2009) reported strong variations in the spectral line profile of CO consistent with a rotating jet. This rotating jet spiraled along with the rotating nucleus and was active during both the day and night. Clearly, nucleus rotation and complex outgassing are strongly linked in multiple comets.

#### 4.2. Asymmetric Line Center and Hyperactivity

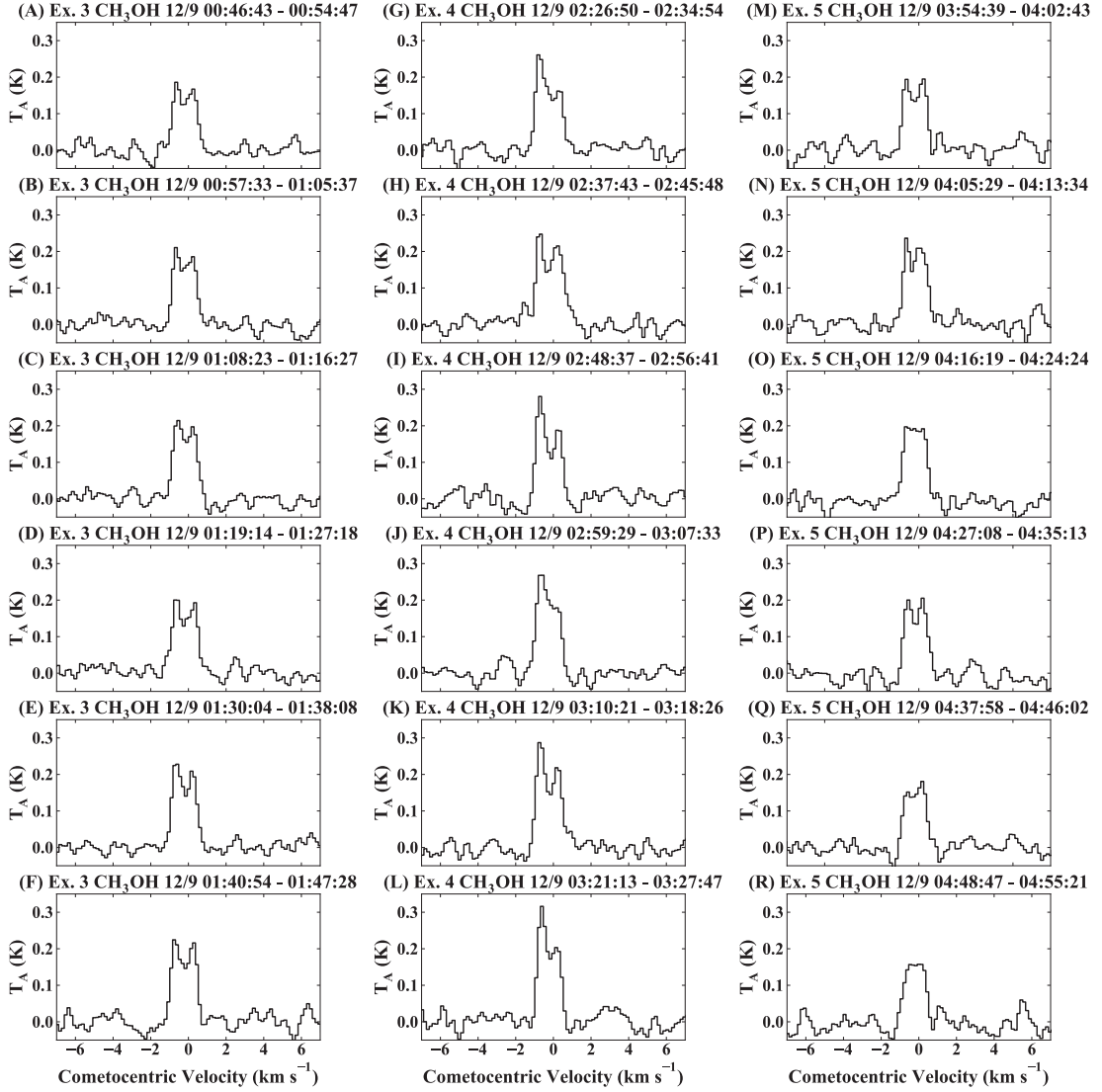
In light of the rapidly varying asymmetry in Wirtanen’s CH<sub>3</sub>OH spectral line profile, an equally striking feature is the consistent blueward offset of the line center observed in *every* spectrum across the two dates of our measurements, including in individual 8 minute scans. Coupled with the higher expansion velocity in the sunward hemisphere compared to the anti-sunward hemisphere (Table 3), this suggests that there is an excess of CH<sub>3</sub>OH outflow on the sunward side of the nucleus. Furthermore, the redward side of the profile is remarkably stable across all of our



**Figure 5.** Averaged spectra of the CH<sub>3</sub>OH  $5_{0-4_0} E$ ,  $5_{-1-4_{-1}} E$ , and  $5_{0-4_0} A^+$  transitions in each scan for Execution 1 (Ex. 1, left column) and Execution 2 (Ex. 2, right column) on December 8 (see Table 1), showing the evolution in the velocity profile of CH<sub>3</sub>OH outgassing over each  $\sim 8$  minute scan.

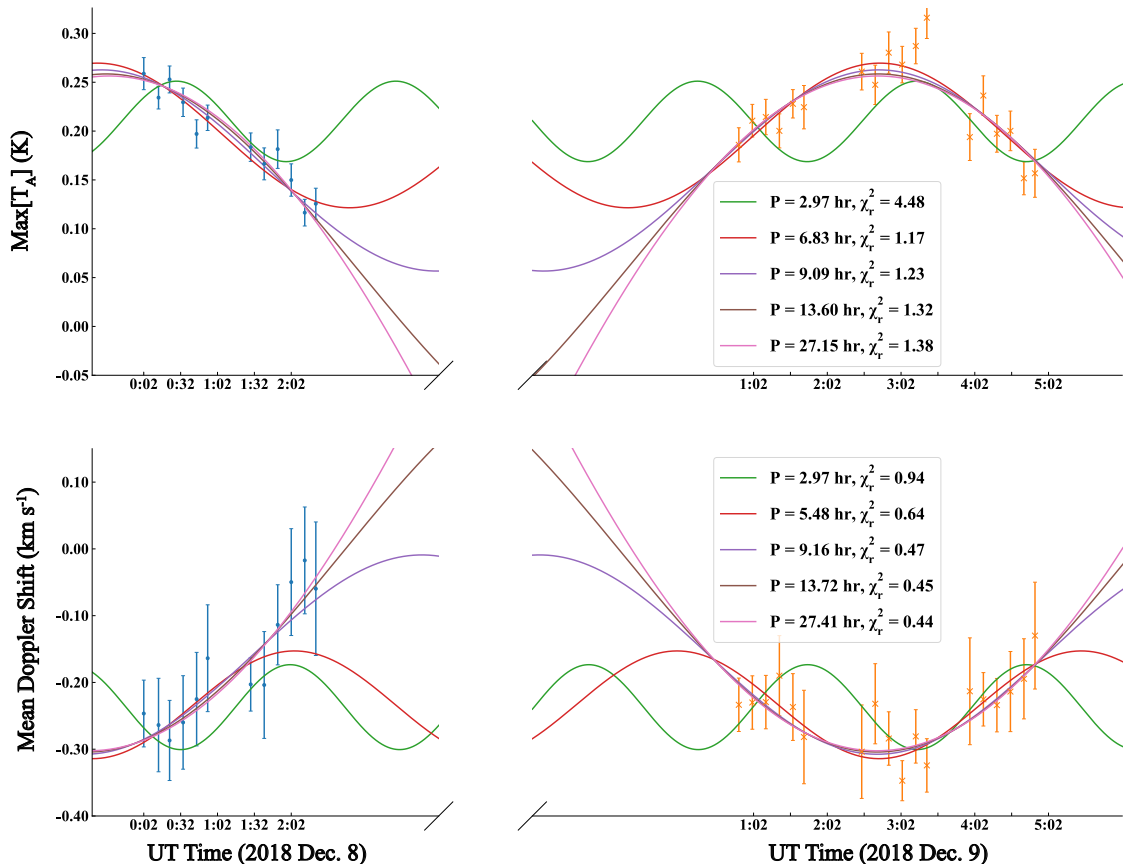
observations, even during Execution 2 on December 8 (Figure 5), where it retains a relatively constant amplitude even as the blueward peak continually diminishes. This implies that the overall variability in CH<sub>3</sub>OH production may be largely due to activity occurring on the dayward side. **This is consistent with optical observations of CN in Wirtanen that indicated two sources of CN production: one which remained active throughout a rotation, and a second which turned on and off as the nucleus rotated (Farnham et al. 2020, this issue).**

Wirtanen is considered a hyperactive comet (e.g., Lis et al. 2019, and references therein), with unusually high  $Q(\text{H}_2\text{O})$  for its small nucleus size attributed to significant release of H<sub>2</sub>O from icy grains in the coma. Observations of H<sub>2</sub>O hot bands near  $2.9 \mu\text{m}$  with NIRSPEC-2 at the W. M. Keck Observatory (Martin et al. 2016, 2018) on December 17 and 18 (Bonev et al. 2020, this issue) and iSHELL at the NASA-IRTF (Rayner et al. 2012, 2016) on December 6, December 18 (Roth et al. 2020, this issue), and December 21 (Khan et al. 2020, this issue) found significant enhancements in the spatial profiles of H<sub>2</sub>O emission, supporting the icy grain contribution to Wirtanen’s H<sub>2</sub>O production (as much as 40% from extended sources; Bonev et al. (2020)).



**Figure 6.** Averaged spectra of the  $\text{CH}_3\text{OH } 5_0-4_0 E$ ,  $5_{-1}-4_{-1} E$ , and  $5_0-4_0 A^+$  transitions in each scan for Execution 3 (Ex. 3, left column), Execution 4 (Ex. 4, middle column), and Execution 5 (Ex. 5, right column) on December 9 (see Table 1), showing the evolution in the velocity profile of  $\text{CH}_3\text{OH}$  outgassing over each  $\sim 8$  minute scan.

Given its hyperactivity, an intriguing possible explanation for the **consistent** blueward offset in the  $\text{CH}_3\text{OH}$  line center is enhanced sublimation on the sunward side of the nucleus, perhaps from icy grains **in the coma**. **Although the presence of icy grains would change the absolute  $Q(\text{CH}_3\text{OH})$  for each execution (compared to the parent species models used here), the trends in production rate and line morphology would remain the same.** This is consistent with measurements of Wirtanen at other wavelengths during its 2018 perihelion passage. **Cordiner et al. (2019b) reported extended  $\text{CH}_3\text{OH}$  release in Wirtanen on UT 2018 December 7, most likely from an icy grain source, based on ALMA observations with the main 12-m array.** Wang et al. (2020) found that the  $\text{HCN } (J = 1-0)$  transition near 3.4 mm displayed a strong blueward offset in its line center on December 14 and 15, consistent with anisotropic outgassing on its sunward side. Furthermore, simultaneous iSHELL measurements of  $\text{CH}_3\text{OH}$ ,  $\text{OH}^*$  (prompt emission, a direct tracer of  $\text{H}_2\text{O}$  production; see Bonev et al. 2006), and dust continuum taken on December 6 found that  $\text{CH}_3\text{OH}$  and  $\text{H}_2\text{O}$  displayed significant peaks in emission in the sunward-facing hemisphere (Figure 10). Post-perihelion measurements with NIRSPEC-2 (Bonev et al. 2020) and iSHELL (Roth et al. 2020; Khan et al. 2020) showed that the enhancements in  $\text{CH}_3\text{OH}$  and  $\text{H}_2\text{O}$  persisted, although

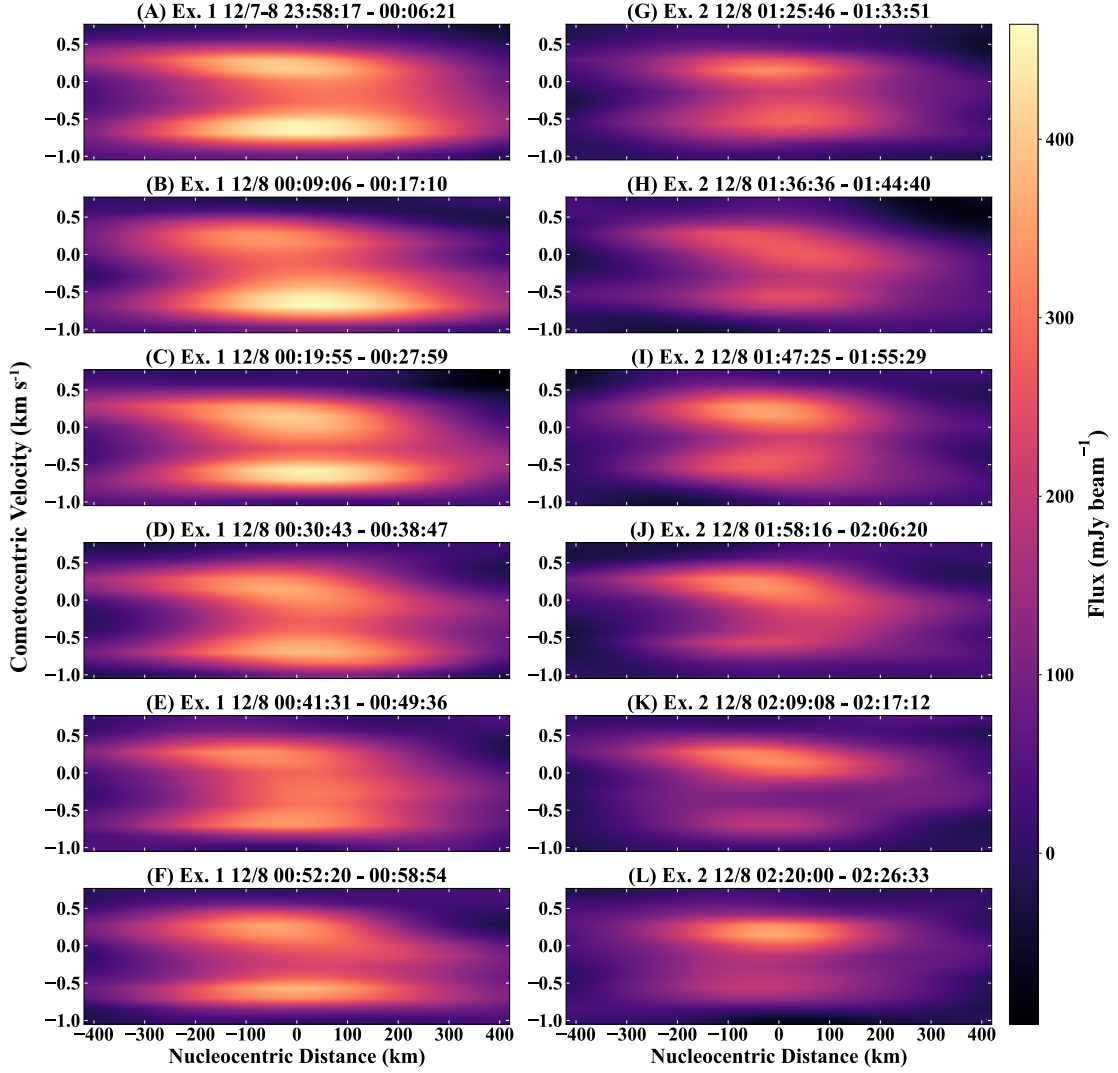


**Figure 7. Top.** Maximum amplitude of the blueward peaks (Figure 5) in each scan on December 8 and 9 as a function of UT time. **Overlaid are best-fit sine waves with periods near 3, 6, 9, 12, and 27 hours, as well as the reduced  $\chi^2$  for each fit.** **Bottom.** Mean doppler shift (velocity first moment) in each scan on December 8 and 9 as a function of UT time. **Overlaid are best-fit sine waves with periods near 3, 6, 9, 12, and 27 hours, as well as the reduced  $\chi^2$  for each fit.**

now in the projected anti-sunward direction (**but at a considerably smaller phase angle,  $\phi \sim 18^\circ$** ). If the  $\text{CH}_3\text{OH}$  enhancement in Wirtanen is indeed owing to icy grain sublimation, it is not the first time that icy grain contributions to multiple species have been found in a hyperactive comet. In comet 103P/Hartley 2, [Drahus et al. \(2012\)](#) found that HCN displayed a varying blueshifted peak corresponding to production from a jet, while the remaining HCN production was attributed to icy grains. In contrast,  $\text{CH}_3\text{OH}$  did not display a blueshifted peak, suggesting the  $\text{CH}_3\text{OH}$  was produced solely from icy grains. Measurements by [Boissier et al. \(2014\)](#) also indicated production of HCN and  $\text{CH}_3\text{OH}$  from icy grains in 103P/Hartley 2, implied by the phase offset between the  $\text{CO}_2$  production curve (produced purely from nucleus sources) and the HCN,  $\text{CH}_3\text{OH}$ , and  $\text{H}_2\text{O}$  production curves. The similarities between these two comets suggest that their outgassing behaviors and sources may have been similar, and emphasize the complex comae of hyperactive comets. Future work analyzing our full ALMA data set of observations towards Wirtanen will enable us to clarify the extent to which icy grain sublimation contributed to  $\text{CH}_3\text{OH}$  production in its coma.

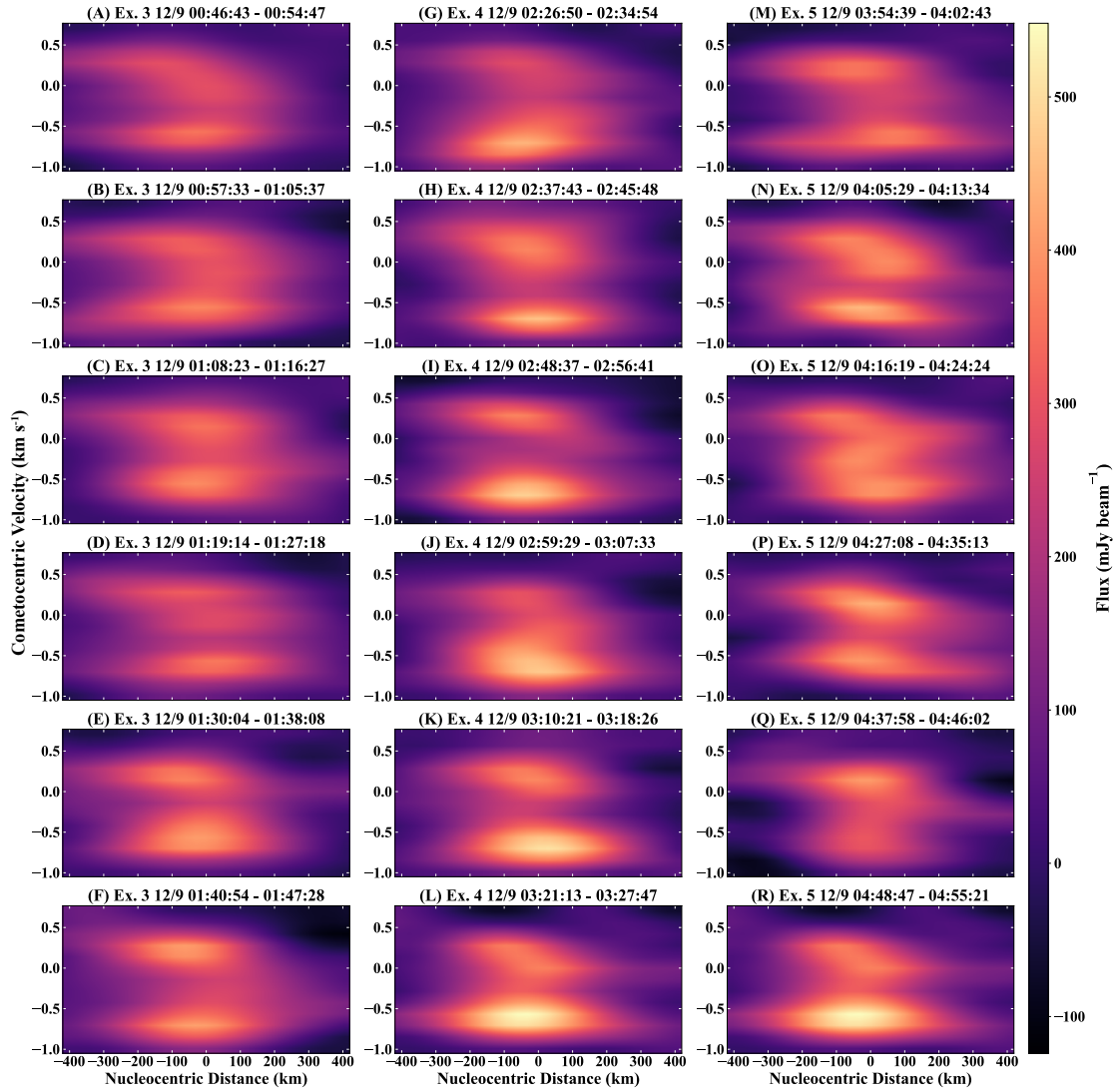
## 5. CONCLUSION

The historic 2018 perihelion passage of Wirtanen together with the capabilities of ALMA enabled us to measure its inner coma with high spatial, spectral, and temporal resolution. Our ALMA ACA observations presented here reveal rapidly varying and anisotropic  $\text{CH}_3\text{OH}$  production in the inner coma of Wirtanen on two pre-perihelion dates shortly before its closest approach to Earth, with the evolution of the spectral line asymmetry clearly visible on a **timescale** of minutes. We found that the variations in  $\text{CH}_3\text{OH}$  were periodic, in good agreement with the nucleus rotational period derived from optical and millimeter wavelength measurements ( $P \sim 9$  hours), and consistent with

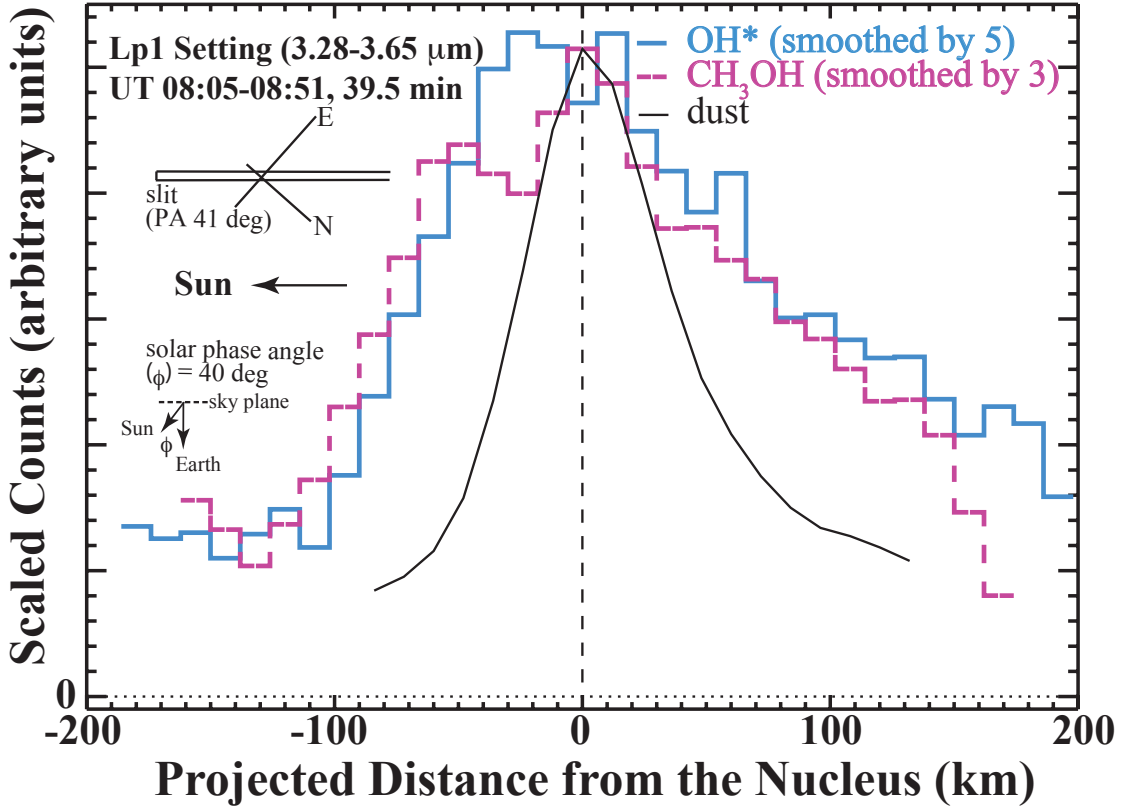


**Figure 8.** Position-velocity diagrams of  $\text{CH}_3\text{OH}$  in Wirtanen for each scan on December 8, taken **parallel** to the solar vector and with the spatial origin at the peak emission position for each scan. Each diagram shows the cometocentric velocity as a function of distance from the image center, with each pixel color-coded by the line flux, thereby showing the evolution in velocity structure across each scan. Scans are labeled and ordered as in Figure 5. **Negative offsets are in the anti-sunward direction.**

hemispheric outgassing along the Sun-comet vector, suggesting variations in outgassing owing to changing illumination of active sites on the nucleus. Furthermore, the consistent blueward offset of the  $\text{CH}_3\text{OH}$  line center, coupled with the higher expansion velocity in the sunward hemisphere, suggested enhanced  $\text{CH}_3\text{OH}$  sublimation in this direction, perhaps from icy grains. The work presented here demonstrates that time-resolved studies of the composition, spatial extent, and outgassing profiles of coma species are possible with the high sensitivity of ALMA on timescales as small as minutes, and lays the groundwork for future **detailed cometary coma studies using ALMA.**



**Figure 9.** Position-velocity diagrams of CH<sub>3</sub>OH in Wirtanen for each scan on December 9, taken **parallel** to the solar vector and with the spatial origin at the peak emission position for each scan. Each diagram shows the cometocentric velocity as a function of distance from the image center, with each pixel color-coded by the line flux, thereby showing the evolution in velocity structure across each scan. Scans are labeled and ordered as in Figure 6. **Negative offsets are in the anti-sunward direction.**



**Figure 10.** Spatial profiles of emission for  $\text{CH}_3\text{OH}$ ,  $\text{H}_2\text{O}$  ( $\text{OH}^*$ ), and dust continuum in 46P/Wirtanen measured with iSHELL on UT 2018 December 6. The slit was oriented along the Sun-comet line (PA  $41^\circ$ ), with the direction of the Sun indicated. Also shown is the Sun-comet-Earth angle (phase angle,  $\phi = 39^\circ$ ). **From observations obtained through NASA-IRTF Director’s Discretionary Time, in support of the 46P ALMA campaign.**

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