Analysis of CN Coma Morphology Features of Comet 21P/Giacobini–Zinner

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Abstract

We analyze jet features found in the coma of comet 21P/Giacobini–Zinner (21P/GZ) during its 2018 perihelion passage using narrowband CN photometric imaging in order to determine the comet’s rotational period, and we constrain the CN gas outflow velocity and rotational state through the analysis of azimuthally enhanced morphological features. We find that 21P/GZ has a period of either 7.39 ± 0.01 hr or 10.66 ± 0.01 hr. We measure a lower limit to the outflow velocity for the northern jet of 730 ± 30 m s⁻¹ and for the southern jet of 740 ± 30 m s⁻¹. We analyze the morphologies of the jet features and determine that the northern jet possesses a corkscrew pattern, and we utilize that knowledge to determine a rotational pole position at an R.A. of 169.7 ± 0.3 deg and a decl. of 73.4 ± 0.5 deg, with an undetermined sense of rotation.

Unified Astronomy Thesaurus concepts: Period determination (1211); Lomb-Scargle periodogram (1959); Short period comets (1452); Comets (280); Comet dynamics (2213)

1. Introduction

Since its discovery in 1900 by Michel Giacobini and rediscovery by Ernst Zinner in 1913, Jupiter-family comet 21P/Giacobini–Zinner (21P/GZ) has been monitored over its many apparitions, including throughout its 2018 perihelion passage. During the 2018 apparition, we obtained four nights of photometric imaging data spanning from 2018 August 18 to 2018 September 12. Utilizing narrowband cyanogen (CN) photometric imaging to highlight 21P/GZ’s jet features, we are able to constrain the comet’s gas outflow velocity and spin properties and then compare to previously obtained rotational periods to confirm standard torque effects.

The rotation period of a cometary nucleus can provide clues to the understanding of the comet’s structure, evolution, and formation. There are multiple methods for determining the rotation period of cometary nuclei, including obtaining a light curve of the bare nucleus when it is far away from the Sun and minimal outgassing is present, or by obtaining a light curve of the coma itself when it is active and assuming that variations in the coma are representative of the nucleus’s rotational state. These methods have been used for many comets in the past, including comet 1P/Halley (e.g., Leibowitz & Brosch 1986a; Millis & Schleicher 1986), or even more recently for a variety of comets (e.g., Kokotanekova et al. 2017; Bodewits et al. 2018). Other methods of determining the period of cometary nuclei include the cross-correlation of jet features (e.g., Ivanova et al. 2012), the image cross-correlation of CN shells (e.g., Waniak et al. 2009), repeatability of jet features (e.g., Knight & Schleicher 2011; Bodewits et al. 2018), and even radar observations (e.g., Howell et al. 2017).

For the 1985 apparition of 21P/GZ, the light-curve method was used on the 1.0 m reflector of the Wise Observatory to obtain a rotation period of 9.5 ± 0.2 hr from 1985 July 21 to 1985 August 11 (Leibowitz & Brosch 1986b). In contrast, we utilize a novel method, which measures the radial location of the peak flux of a jet feature as a function of time. This method is particularly effective for corkscrew-like features or morphological features that fluctuate with time. The measured peak flux locations versus time are transformed by a Lomb–Scargle periodogram to find possible periodicities within the data. This method relies on the assumption that there is a repeatable brightness fluctuation present. Evidence that this assumption is justified, as well as a more in-depth explanation of the method, can be found in Section 2.4.

The velocity at which gas is ejected from the nucleus is essential to predict molecular production rates and torques, among other cometary parameters. Cochran & Schleicher (1993) showed that the outflow velocity of gases can be estimated by the relationship \( v \approx 0.85 n_0^{-0.3} \) km s⁻¹, which for typical distances at which outflow velocities are measured produces outflow velocities from a few hundred meters per second to greater than a kilometer per second. Such estimates have been proven accurate over the years through different outflow velocity measuring techniques, such as modeling submillimeter cometary emission lines (Cordiner et al. 2022), or from the OH 18 cm emission line (e.g., Tseng et al. 2007). To measure the CN outflow velocity, we assume that the CN features are moving radially outward.

The pole vector of cometary nuclei can help interpret the rotational features seen and help better understand activity patterns on the surface. There are several methods to constrain the pole vector of a comet. One such method is analyzing a polar jet over time (e.g., Farnham & Cochran 2002; Samarasinha & Mueller 2002). We use a similar method, constraining the pole position with regard to the jet features after a deep understanding of the jet features has been acquired (see Section 4.2).

Sublimating gases, whether in hemispherical outgassing or jet-like features, create torques on nuclei that slowly change comets’ rotational periods over time. Samarasinha & Mueller (2013) introduced a parameter, \( X \) (described in Section 4.3), that relates the change in a comet’s rotational period per orbit to the rotational period itself, its nucleus size, and its water production per orbit per unit area of the nucleus. Samarasinha & Mueller (2013) claim that such a parameter should be fairly...
constant for all comets within a factor of a few unity. Jewitt (2021) empirically shows that the $X$ parameter’s approximate constancy is due to the approximately opposing trends in the dependence of the active fraction and the moment arms of torques on the size of the nucleus. We use the rotational period we have found, in correlation with the previously found period from Leibowitz & Brosch (1986b), to determine the $X$ parameter of 21P/GZ.

2. Data

We observed 21P/GZ over four nights spanning from 2018 August 28 to September 12. Comet 21P/GZ’s closest approach to Earth occurred on 2018 September 10 at 14:16 UT at a geocentric distance of 0.39 au, and its perihelion occurred on the same day at 6:43 UT at a heliocentric distance of 1.01 au (HORIZONS-JPL 2021). Table 1 includes the date and time of each image frame utilized, the peak brightness distances measured for both the northern and southern jets, the heliocentric ($r_h$) and geometric ($\Delta$) distances, the solar position angles (the sky-plane-projected position angle of the Sun with respect to the comet; position angle is measured from north through east), the solar phase angles, and the rotational phases based on our two derived periods. Our images were obtained using the 1.54 m Kuiper Telescope, located on Mount Bigelow, just north of Tucson, Arizona. The telescope has a focal length of 9.6 m, and the imaging system has a pixel scale of 0.42/" pixel$^{-1}$ (in our $3 \times 3$ binning setup) with a field of view of $9.7 \times 9.7$ arcmin$^2$ (Smith 2013).

2.1. Image Enhancement

All images underwent a basic data reduction process that included a subtraction of the bias level and a division of the flat field. Dark noise is negligible, as the camera is liquid nitrogen cooled. In our analysis, we utilize enhancement techniques of the coma to highlight coma morphology features and determine their repeatabilities. Samarasinha & Larson (2014) explain the benefits of enhancement through several different methods, including dividing the images by an azimuthal median and dividing or subtracting two temporally close images by one another to reveal temporal variations. We use a combination of these techniques to observe the behavior of CN jet features in the gas coma. Specifically, to first highlight the cometary jet features, we use a division by the azimuthal median profile as explained in Samarasinha et al. (2014) as seen in Figure 2. We create these enhanced images using the online tool provided in Martin et al. (2015) (available at https://www.psi.edu/research/cometimen). Enhancement by azimuthal median division allows us to distinguish two distinct CN jet features from the overarching coma: a northern jet and a southern jet, as visible in Figure 1.

To confirm that an azimuthal median does not affect the shape of the features but simply removes the overarching coma, we analyze the azimuthal median removed from each image. As is visible in Figure 2, there does not appear to be any significant radial structure that could affect the shape of the features, specifically the distance at which the feature peaks in brightness. The azimuthal median division is a proxy for the overlying coma removal without an actual measurement of it. The nature of Figure 2 shows a good correlation between a radially expanding coma and the azimuthal median measurements. For this reason, and because the coma obscures faint jet features, the measurements described in Section 2.2 are taken from azimuthally enhanced images.

2.2. Jet Feature Morphology

The morphology of jet features, made clearer through enhancement, can be studied to constrain the activity of the coma and the nucleus. We characterize each jet’s behavior both radially and azimuthally.

To characterize the projected radial behavior of each jet, we measure the projected radial distance at which the flux of each jet is at a maximum. This is achieved using a wedge centered on each jet where the total flux at each radius is measured and then fitting a parabola to the data as seen in Figure 3 near the brightness peak to determine the location of the maximum flux. A parabola is chosen to fit the data because it closely matches the shape of the measured brightness profile; however, it is unclear why this is. The 1σ error bars quoted in Table 1 result from a combination of the goodness of the fit and the signal-to-noise ratio of the brightness of the feature. Measurements where stars cannot be properly removed are omitted.

To characterize the azimuthal behavior of the jet features, we choose a set of projected radial distances from the nucleus and measure the azimuthal locations of the jets at each distance for each image. This allows us to track the azimuthal motion of the jet features with time. From this, we detect patterns and behaviors within each jet feature. The analysis of these measurements is explained in Section 4.1.

2.3. Obtaining the CN Gas Outflow Velocity

During the course of our investigation, we measured the projected radial distance of the peak brightness of each jet moving away from the nucleus, suggesting that some amount of material was released in that projected radial direction and was moving away from the comet. This behavior allows us to track the material’s movement over time and thus its projected radial outflow velocity. If we assume the outflow velocity of the material to be constant for each jet over the course of a given night, we can fit a straight line to the projected radial distance of the peak brightness versus time, where the slope is the projected outflow velocity of the CN gas for that feature. Figure 4 shows the linear fit for 2018 August 28 for the northern jet. The errors of the outflow velocities are determined using a Gaussian distribution of the errors on the measurements and a Markov Chain Monte Carlo approach. In this method, the data points are randomly placed along their error bars according to a Gaussian distribution centered on the measurement point. For each iteration, the outflow velocity is measured and recorded. After 100,000 iterations, the standard deviation of the recorded velocities is taken as the error of the velocity measurement. Because of the projection effects, our measured outflow velocities are all lower limits on what the actual CN outflow velocities may be provided that the jet widths are narrow (see Samarasinha 2000).

2.4. Determination of the Periodicity

To determine the periodicity, we rely on the assumption that there exist repeatable brightness fluctuations consistent with radial expansion. This could consist, for example, of continuous jet features with rotationally driven variations in outflow, or even line-of-sight enhancements due to the geometry that specific directions of outflow make with the
observer. In any case, we observe radially expanding features that are periodic in nature with brightness fluctuations, where the brightest locations of the features are shown in Figure 4.

To determine the periodicity, we perform a Lomb–Scargle periodogram (which specializes in discrete and uneven intervals of time) with the peak brightness location versus time data for each jet (see Section 2.2) to generate a power density spectrum (PDS) of the Fourier transform of our data for each jet individually. From each PDS, we extract several most probable periodicities (VanderPlas 2018). Once we determine the periodicities, we phase our data by them to find the most probable period. The phasing equation as described in Stellingwerf (1978) is given by

\[
\text{Phase} = \frac{\text{mod} (t, P)}{P},
\]

where \( t = \text{JD} - \text{JD}_{0} \), the Julian date (JD) minus some referenced or starting point date (JD$_0$), and \( P \) is the period in days. In this equation, we divide the time—which is an adjusted day—by the
Figure 1. Left: unenhanced image of 21P/GZ from 2018 August 28 that has undergone the basic data reduction. Right: same image enhanced by an azimuthal median division, where white denotes regions of higher flux. The white streaks are star trails.

Figure 2. Median azimuthal brightness vs. the radius in log–log form for each image from each night showing a consistent and smooth relationship between projected radial distance and median azimuthal brightness. The brightness variations are caused by variable sky conditions.
null
division. Figure 8 shows the best and worst same-phase divisions for each period. All same-phase divisions yielded few residual features, indicating that each period is plausible. Furthermore, Figure 9 shows the half-phase divisions for the four periods, all showing significant residual features. Because the same-phase and half-phase divisions for all four periods show the expected residual features, none can be ruled out by Figures 8 and 9. As a result, the $7.39 \pm 0.01$ hr and $10.66 \pm 0.01$ hr periods are chosen as the most likely periods for 21P/GZ because they result in the strongest phase plots for both jets in Figure 7, although the $6.24 \pm 0.01$ hr and $8.41 \pm 0.01$ hr periods remain plausible.

Full-phase divisions also allow for the reduction of the errors for the four periods tested. This is done using a reference image (called image A) to divide by another image of the same phase (called image B). Images of increasingly different phase (image C) are then divided from the reference image until there is a noticeable increase in residual features. Next, the time elapsed between images B and C is calculated. This time represents the magnitude of the error accrued over the integer number of rotations, \(N\), elapsed between images A and B. To find the error in the period per rotation, the time elapsed between B and C is divided by \(N\). This was rounded to the nearest hundredth for the four periods used and had a rounded value of 0.01 hr per rotation for each.

3.3. Projected Outflow Velocity of CN Gas

Figure 5 shows that both the northern and southern jets are moving radially away from the nucleus as projected onto the

\[ \text{Projected radial distances of peak brightnesses for the northern and southern jets for the four nights of measurements. The blue circles represent the northern jet, and the orange circles represent the southern jet.} \]
plane of the sky for each night. As explained in Section 2.3, we measure the CN projected outflow velocity, summarized in Table 2, for both the northern and southern jets. The velocities measured represent the projected outflow velocities onto the plane of the sky and are thus lower limits on the outflow velocities for each CN jet. However, as explained in Samarasinha (2000), if the CN jets are broad, these may be representing direct outflow measurements.

4. Discussion
As stated in Section 3, we find that 21P/GZ has a rotation period of either 7.39 ± 0.01 hr or 10.66 ± 0.01 hr in the 2018 August–September time frame. Additionally, we find that the maximum projected outflow velocity of the CN gas is 730 ± 30 m s⁻¹ for the northern jet and 740 ± 30 m s⁻¹ for the southern jet. We can further analyze the morphology of the CN features to constrain the rotational state of the nucleus and gain valuable information about the nature of the jet features themselves.

4.1. CN Jet Feature Morphology
We analytically determine the azimuthal location of each jet feature as a function of projected distance for both the northern and southern jets as explained in Section 2.2. Figures 10–13 and 14–17 show the morphology of the northern and southern jets, respectively, spaced over each night for 2018 August 28.
Figure 7. Phase diagrams of the northern and southern jets plotted for 6.24 ± 0.01 hr, 7.39 ± 0.01 hr, 8.41 ± 0.01 hr, and 10.66 ± 0.01 hr, which are the more prominent peaks of the PDSs in Figure 6. From these phase diagrams, the 7.39 hr and 10.66 hr figures have the strongest correlation, as seen by a clear overlap of data from all cycles.
For the northern jet, there is a clear corkscrew pattern shown in several of these figures, while the southern jet does not show as clear a pattern. We measure the behavior of the corkscrew pattern in the northern jet by determining the position angle of its central location and its width. These results are summarized in Table 3. The small width of the corkscrew pattern suggests that the jet originates at a location near the pole ranging from \( \sim 4^\circ \) to \( \sim 6^\circ \) away, indicating a cometocentric latitude of approximately \( \sim 86^\circ \)–\( 84^\circ \). Additionally, considering the center of the corkscrew, we can determine the axis along which the comet must rotate for each night of observations.

### 4.2. Constraining the Pole Vector

On a given night, the sky-plane-projected rotational pole direction coincides with the measured position angle of the corkscrew’s center, as shown in Table 3. This, however, does not provide us with the nonprojected information, which can be obtained by having a sufficient change in observing geometry of the comet. Utilizing similar methods as described in Samarasinha & Mueller (2002) and Farnham & Cochran (2002), we are able to constrain the pole vector using the northern jet.

We can determine the direction, in R.A., \( \alpha \), and decl., \( \delta \), of the pole vector of 21P/GZ as described below. First, we define Earth’s direction from the frame of reference of the comet as \( \alpha_0 \) and \( \delta_0 \) for the R.A. and decl., respectively. Next, using a spherical-to-Cartesian transformation, we can describe the Cartesian coordinates of the pole vector of 21P/GZ, \( x_p \), \( y_p \), and \( z_p \), as

\[
x_p = \cos \delta \cos \alpha \\
y_p = \cos \delta \sin \alpha
\]
The next step is to perform a transformation between the comet’s frame of reference and Earth’s frame of reference. In this step, we are projecting the comet’s frame of reference into the plane of the sky, where the “northern” component (labeled as $x_N$, $y_N$, and $z_N$) will be the component projected on the sky plane’s north direction, while the “eastern” component (labeled as $x_E$, $y_E$, and $z_E$) will be the component projected onto the sky plane’s eastern direction. Thus,

$$z_p = \sin \delta.$$  \hspace{1cm} (4)

$$x_N = -\sin \delta \cos \alpha_E$$ \hspace{1cm} (5)

$$y_N = \sin \delta \sin \alpha_E$$ \hspace{1cm} (6)

Figure 10. Northern jet morphology for 2018 August 28 at five different times spread out across the night, showing outward movement and a clear corkscrew pattern.
The final step is then to project the comet’s pole vector onto the sky plane—Pole$_N$ and Pole$_E$ for the northern and eastern

\[
z_N = \cos \delta_\odot, \quad (7) \quad y_E = -\cos \alpha_\odot \quad (9) \quad z_E = 0. \quad (10)
\]

and

\[
x_E = \sin \alpha_\odot \quad (8)
\]

Figure 11. Northern jet morphology for 2018 September 4 at five different times spread out across the night, showing outward movement and a clear corkscrew pattern.
components of the pole vector, respectively—to be converted to a measurable position angle and compared to our results. The pole vector projected onto the sky plane is given by

\[
Pole = x_p \cdot x_N + y_p \cdot y_N + z_p \cdot z_N
\]  

(11)

with the projected position angle of the pole position, PA, being given by

\[
PA = \text{atan2}(Pole_N, Pole_E),
\]  

(13)

Figure 12. Northern jet morphology for 2018 September 7 at five different times spread out across the night; this night does not clearly exemplify the same corkscrew pattern seen in previous nights, nor does it show as drastic of outward movements.
where \( \text{atan2}(\text{Pole}_N, \text{Pole}_E) \) is the angle between the north direction on the sky plane and the vector created by \( \text{Pole}_N \) and \( \text{Pole}_E \). To determine the possible pole positions that correspond to our measurements in Table 3, we conduct a grid search over all right ascensions and declinations of potential pole vectors and reject all values that are not within the uncertainty of our measured projected pole position angles. Figure 18 shows the acceptable pole positions for all four nights of data.

To find the pole solution, all intersection points between pairs of nights are mapped, with six intersection points in total, as shown in Figure 18. This produces a family of intersections for the pole position. The family of intersections is then fitted with a parabola, which closely matches the distribution of intersection points. The R.A. and decl. at the halfway point of the parabola’s arc length are taken as the center of the family of solutions and the pole position of 21P/GZ. The position of 21P/GZ’s pole vector is found to be at an R.A. of \( 169^{\circ}28^\prime \) deg and a decl. of \( 73^{\circ}11^\prime \) deg. While the R.A. error is large, it is offset by the pole vector’s high decl. The opposite pole vector would logically point to an R.A. of \( 349^{\circ}23^\prime \) deg and a decl. of \( -73^{\circ}11^\prime \) deg. Due to the lack of information surrounding the spin direction, we cannot conclude which pole corresponds to the conventionally defined positive pole. The pole vector of \( 169^\circ \) and \( 73^\circ \) in R.A. and decl., respectively, is equivalent to an orbital longitude of \( 199^\circ \) and obliquity of \( 10^\circ \) in orbital coordinates, where orbital longitude is measured from the Sun–periaphelion direction in a prograde sense in the orbital plane of 21P/GZ.

4.3. Using Our Determined Period to Calculate the X Parameter

When a comet approaches the Sun, it releases gas that creates torques on its nucleus; these torques affect the rotation of the comet over time. Samarasinha & Mueller (2013)

Figure 13. Northern jet morphology for 2018 September 12 at four different times spread out across the night, showing a definite change in the curvature.
introduce the X parameter, calculated by

\[ X = \frac{|\Delta P| R^2}{P^2 \zeta}, \]  

where \( \Delta P \) is the change in rotational period per orbit, \( R \) is the radius of the nucleus, \( P \) is the period of the comet, and \( \zeta \) is the amount of water lost each orbit per unit surface area. The X parameters of comets are expressed as the ratio between their X parameter and that of comet 2P/Encke. Most comets have an
We use our measured period, along with a period of 9.5 hr measured in the 1985 21P/GZ apparition by Leibowitz & Brosch (1986b), to determine the change in period per orbit. Table 4 provides \( \Delta P \) obtained from a combination of our measurements and those of Leibowitz & Brosch (1986b), along with \( R \) and \( \zeta \) values obtained from Mueller & Samarasinha (2018). Using Equation (14), we calculate that \( \Delta P/GZ/\Delta P/Encke \approx 3.4 \pm 0.1 \) for a period of 7.39 ± 0.01 hr or \( \Delta P/GZ/\Delta P/Encke \approx 1.9 \pm 0.1 \) for a period of 10.66 ± 0.01 hr. This further supports the conclusion found in Mueller & Samarasinha (2018) that the \( X \) parameter is a constant to within a factor of a few unity and suggests that 21P/GZ has not undergone abnormal torque effects in the recent past.

Figure 15. Southern jet morphology for 2018 September 4 at five different times spread out across the night, showing a potential corkscrew pattern more visible at less than 20,000 km.

\[ X/\Delta P/Encke \] within a factor of five (Mueller & Samarasinha 2018).
4.4. Unanswered Questions about Jet Morphology

The morphology of the southern jet, as shown in Figures 14–17, does not follow a clear and consistent pattern. However, it is possible to observe that at large cometocentric distances the southern jet appears to be curving away from the sunward direction ($\text{PA}_m \approx 90^\circ$). This can be explained easily through solar radiation pressure. The relativistic momentum of a photon, $p$, is given by

$$p = \frac{E}{c},$$

(15)
where $E$ is the energy of the photon and $c$ is the speed of light in a vacuum. The average energy that the CN molecules will then receive can be calculated using the fluorescence efficiency, $g$, as follows:

$$E = gt,$$

(16)

where $t$ represents the amount of time a molecule spends in the coma. Combining Equations (15) and (16) provides

$$p = \frac{gt}{c}.$$  \hspace{1cm} (17)

Knowing that $F = dp/dt$, we can calculate the force due to radiation pressure using Equation (17) to obtain $F_{\text{rad}} = g/c$. Finally, using Newton’s second law, $a = F/m$, we can solve for the acceleration due to radiation pressure, $a_{\text{rad}}$, in the direction opposite of the solar direction to obtain

$$a_{\text{rad}} = \frac{g}{cm_{\text{CN}}},$$ \hspace{1cm} (18)

where $m_{\text{CN}}$ is the mass of a CN molecule. Using the fluorescence efficiencies from Schleicher (2010) for 21P/GZ on 2018 August 28, we find that the acceleration due to radiation is $\sim 0.25 \text{ cm s}^{-2}$.

Table 3
Measured Position Angle of the Northern Jet’s Corkscrew Center and the Width of the Pattern

| Date     | Position Angle (deg) | Width of Corkscrew (deg) |
|----------|----------------------|--------------------------|
| 2018-08-28 | 20 ± 4               | 11 ± 4                   |
| 2018-09-04 | 29 ± 3               | 11 ± 3                   |
| 2018-09-07 | 26 ± 4               | 8 ± 4                    |
| 2018-09-12 | 15 ± 3               | 9 ± 3                    |

Figure 17. Southern jet morphology for 2018 September 12 at four different times spread out across the night, showing a potential corkscrew pattern more visible at less than 20,000 km and a strong curvature at greater distances most likely due to solar radiation pressure.
This decreases to 0.21 cm s$^{-2}$ by 2018 September 12 owing to a decreased fluorescence efficiency, $g$.

If we assume all the acceleration to be perpendicular to the motion of the jet and we assume a measured outflow velocity, $v = 730 \pm 30$ m s$^{-1}$, at 50,000 km from the nucleus, the jet would have moved 5900 \pm 500 km in the antisunward direction, the equivalent of $6^\circ \pm 1^\circ$. This is consistent with the curvature at higher distances as seen, for example, in Figure 14.

5. Conclusion

We observed 21P/GZ over four nights from 2018 August 28 to 2018 September 12. We azimuthally enhanced our data to reveal the coma morphology of CN jet features. We used a newly developed method that measured the projected radial distance of the peak flux of a jet versus time; then, using a Lomb–Scargle periodogram, we obtained a rotational periodicity of either $7.39 \pm 0.01$ hr or $10.66 \pm 0.01$ hr. From the rotational periodicity of 21P/GZ and previously obtained measurements dating from 1985 (Leibowitz & Brosch 1986b), we were able to measure the $X$ parameter, as defined in Samarasinha & Mueller (2013), and obtain $X_{GZ}/X_{Encke} \approx 3.4 \pm 0.1$ for a periodicity $7.39 \pm 0.01$ hr or $X_{GZ}/X_{Encke} \approx 1.9 \pm 0.1$ for a periodicity $10.66 \pm 0.01$ hr, which is consistent with contemporary literature.

Additionally, we were able to obtain a maximum projected CN gas outflow velocity for the northern jet of $730 \pm 30$ m s$^{-1}$ and for the southern jet of $740 \pm 30$ m s$^{-1}$.

We further analyzed both jets’ morphologies to constrain rotational states. We determined that the northern jet possessed a corkscrew pattern, approximately $10^\circ$ in width, suggesting a proximity to the pole position. From that analysis, we were able...
to constrain a pole position at an R.A. of $169^{\circ}23^\prime28^\prime\prime$ deg and a decl. of $73^{\circ}11^\prime6^\prime\prime$ deg, with an undetermined sense of rotation. From the analysis of the southern jet, we concluded that radiation pressures had a significant effect on the curvature at large cometocentric distances.

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