Monitoring Comet 12P/Pons-Brooks: Spectral Analysis and Outburst Phenomenology

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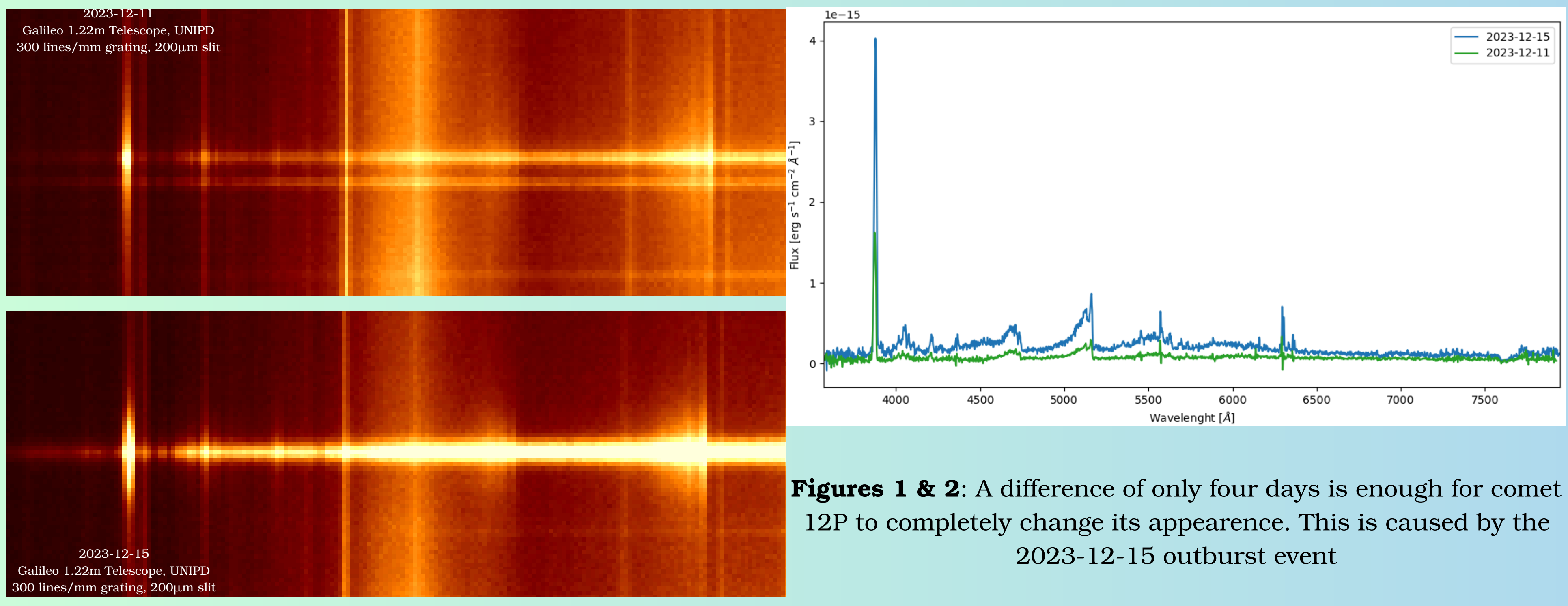
Cometary nuclei are small bodies within the Solar System, believed to be remnants of the original agglomerates of dust grains formed approximately 4.6 billion years ago during the birth of the Solar System.
Halley-type comet 12P/Pons-Brooks is notable for its recurrent outbursts, which have been observed during each of its recent perihelion passages, occurring approximately every 71 years. This behaviour is not unique to 12P/Pons-Brooks; other comets such as 9P/Tempel 1 and 29P/Schwassmann-Wachmann 1 display similar phenomena. Outbursts in comets are characterized by a sudden increase in the comet's brightness, typically ranging from 2 to 5 magnitudes, with a higher likelihood of occurring around heliocentric distances of 1 AU. Despite these observations, the mechanisms driving these outbursts remain poorly understood. From July to December 2023, a detailed follow-up study of comet 12P/Pons-Brooks was conducted using the 1.22m Galileo Telescope at the Asiago Astrophysical Observatory.
Using the Haser coma distribution model, the production rates (Q) of the CN radical was calculated from its emission band. This method effectively monitors the changes in overall cometary activity during an outburst. Preliminary analysis revealed a rapid change in the production rate of the CN molecule as a direct consequence of the outburst. During the observation period, the comet was on its inbound orbit from 3.8 AU to 2.2 AU, covering several significant outbursts. This study highlights significant variations in the production rates of main molecular species within a few days before and after the onset of the outburst. The rapid nature of cometary outbursts, which can last from hours to several days, emphasizes the importance of continuous monitoring.

	Telescope Setup and Observing Conditions						Observation Geometry				
Date yyyy-mm-dd	Grating lines/mm	Slit μm	Exp-Time s[# frame]	Airmass	RA hh:mm:ss	DEC deg:min:sec	r AU	$\dot{r}$ km/s	Δ AU	Solar Elongation deg	ϕ deg
2023-07-23	300	200, 600	600[5], 600[1]	1.016-1.032	18:13:16	+55:47:07	3.850	−17.829	3.539	100.15	14.68
2023-08-11	300	200,600	2100[3], 900[1]	1.115-1.195	17:44:48	+54:46:19	3.652	−18.239	3.404	96.71	15.61
2023-08-21	300	200	5400[3]	1.096-1.197	17:33:17	+53:36:13	3.546	−18.467	3.341	93.87	16.12
2023-08-22	1200(R)	200	5400[3]	1.055-1.195	17:32:31	+53:27:50	3.536	−18.490	3.335	93.58	16.17
2023-10-01	300	150	3000[5]	1.097-1.174	17:20:22	+46:42:22	3.098	−19.494	3.099	80.74	18.03
2023-10-06	600	150	1200[1]	1.208	17:22:26	+45:49:01	3.042	−19.631	3.068	79.18	18.25
2023-10-07	1200(B)	150	2400[8]	1.081-1.17	17:22:45	+45:38:53	3.030	−19.658	3.061	78.88	18.29
2023-11-12	300	150,300	600[1],600[1]	1.413-1.463	17:56:48	+40:20:17	2.623	−20.688	2.790	69.42	19.98
2023-11-17	1200(B)	200,400	1560[5],600[2]	1.221-1.474	18:04:00	+39:47:15	2.551	−20.877	2.735	68.38	20.28
2023-11-18	1200(B)	200	840[8]	1.34-1.413	18:05:27	+39:41:20	2.539	−20.908	2.725	68.19	20.34
2023-11-22	300	150,300	150[5],100[5]	1.304-1.333	18:11:48	+39:18:29	2.491	−21.036	2.687	67.43	20.59
2023-11-25	300	150,300	300[5],300[5]	1.463-1.530	18:16:50	+39:02:38	2.454	−21.132	2.657	66.87	20.80
2023-11-26	300	150,300	2100[13],150[8]	1.256-1.615	18:18:30	+38:57:53	2.442	−21.164	2.647	66.70	20.87
2023-11-28	300	150	300[5]	1.378-1.400	18:21:57	+38:49:04	2.417	−21.229	2.627	66.35	21.01
2023-12-03	300	150,300	1020[11],750[6]	1.287-1.423	18:31:10	+38:28:35	2.356	−21.391	2.575	65.53	21.39
2023-12-06	300	200,400	1650[11],1350[10]	1.333-1.615	18:37:02	+38:18:10	2.319	−21.489	2.543	65.05	21.64
2023-12-07	300	200,400	990[11],1200[10]	1.292-1.987	18:39:00	+38:15:06	2.306	−21.521	2.532	64.90	21.72
2023-12-11	300	200,400	450[5],450[5]	1.557-1.700	18:47:22	+38:03:49	2.256	−21.652	2.489	64.30	22.07
2023-12-14	300	200,400	450[5],300[5]	1.672-1.797	18:53:54	+37:56:54	2.219	−21.749	2.456	63.87	22.35
2023-12-15	300	200	240[4]	1.497-1.518	18:56:03	+37:55:37	2.206	−21.782	2.445	63.73	22.44

Table 1: Main observational and geometrical parameters of comet 12P/Pons-Brooks.



Figures 1 & 2: A difference of only four days is enough for comet 12P to completely change its appearence. This is caused by the 2023-12-15 outburst event

Methods

All the cometary spectra here analyzed are taken at the 1.22m Galileo telescope (DFA-Unipd) in Asiago. The telescope Cassegrain focus is equipped with a Boller & Chievens spectrograph, having a long-slit aperture with fixed length (28 mm) and a variable width. The set of available gratings guarantees a spectral coverage from 3300 Å to beyond 7800 Å with a dispersion reaching 0.6 Å/px. The dispersed light is focused on two combined cameras, the ANDOR iDus 440A Sensor E2V 42-10BU Back Illuminated CCD and the Dioptric Blue Galileo Camera.
The raw spectra have been reduced with a combination of IRAF standard routines and self-provided Python scripts, The frames have been bias subtracted, flatfield corrected and Laplacian Cosmic Ray Identification (L.A. Cosmic)(1) routine for cosmic rays was used. Wavelenght calibration has been performed with the aid of He-Fe-Ar hollow cathode comparison lamps, while the flux calibration was made by comparison with ESO standard spectrophotometric reference stars.
The entire database analyzed here was collected as part of the *Asiago Atlas of Comets* project. Initially launched as an outreach program, the project has produced high-quality spectra of various comets, offering a wide range of potential applications, namely for the ESA Comet Interceptor mission.
Observational data and main geometry parameters of the comet are reported in **Table 1**.

(1) L.A. Cosmic website: http://www.astro.yale.edu/dokkum/lacosmic/

Analysis

The analysis of the spectra includes the computation of molecular CN production rates by using the Haser coma outflow model (Haser, 1957). In particular, the approach used here involves converting the total CN flux collected within a specific aperture into the molecule's production rate. This conversion is achieved by applying the Haser correction, as discussed in Fink and Hicks (1996), which assumes the total flux is collected by an ideal infinite aperture. The expression is the following:

$$Q = \frac{4\pi\Delta^2}{g\tau} \times F \times HC$$

where Q ($mol\, s^{-1}$) is the molecular production rate, Δ (km) is the Geocentric distance, g ($erg\, s^{-1} mol^{-1}$) is the fluorescence efficiency (Schleicher, 2010), τ is the daughter molecule lifetime, F ($erg\, cm^{-2}\, s^{-1}$) is the total integrated flux and HC is the Haser Correction. The scale length set used was the one published by Randall et al. (1992). The CN fluorescence efficiency are those computed by Schleicher (2010). Finally the Haser Correction was computed with the aid of Schleicher's software, available on the Lowell Observatory website(2).
When an outburst event occurs, a steep increment in the flux appears in the spectra. The latest one happenend in December 14, 2023 and the difference with the spectrum outside the ourtburst is clear (**Figure 1 & 2**). Not only the flux of the strongest molecular bands (CN, C2 and C3) increased, but also the continuum produced by the dust visibly brightens. The errors are computed by propagating the errors on flux measurement. **Figure 3** shows the decline of the CN flux with increasing nucleocentric distance.

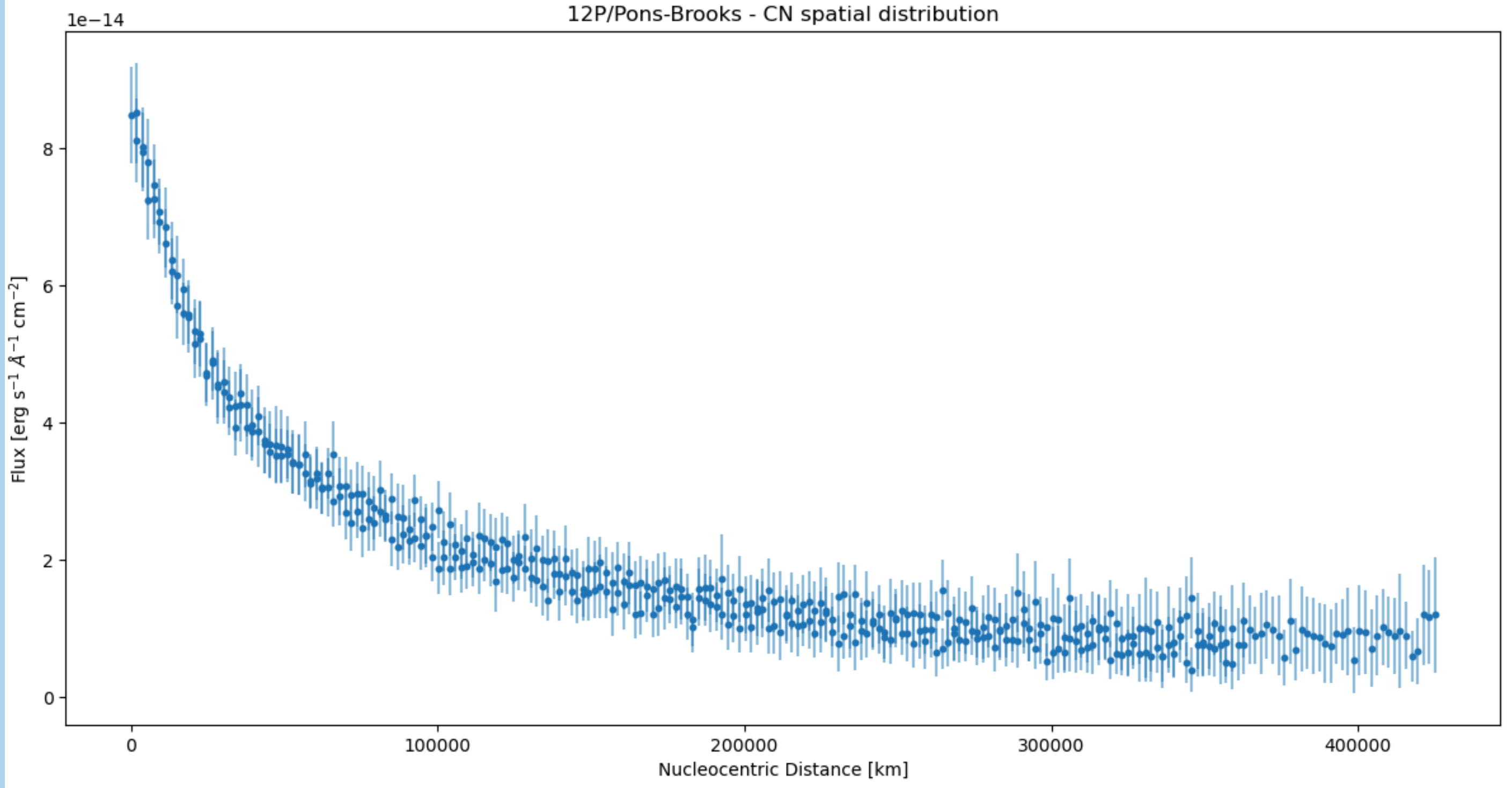


Figure 3: CN spatial distribution of the 2023-12-11 spectrum.

(2)https://asteroid.lowell.edu

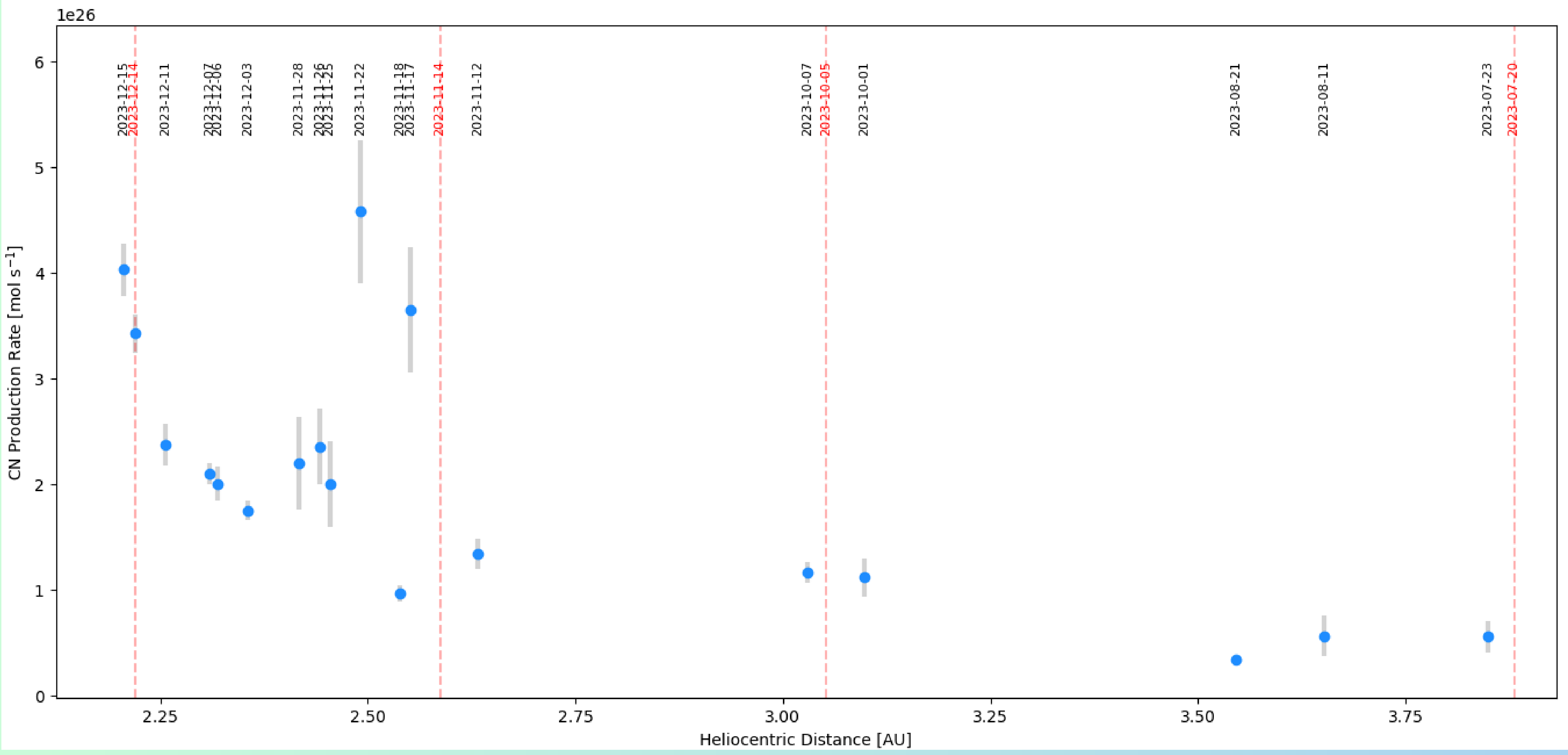


Figure 4: CN production rates (Q) as a function of the heliocentric distance. Color red indicates the occuring of an outburst. The extreme variability of the source is clear. High Q(CN) values are reached in corrispondence of outburst events in October, November and December.

Results & Conclusions

Figure 4 shows how the production rate of CN changes with heliocentric distance with the dates of the observations provided for clarity. What emerges from the plot is the comet's unusual activity in early October, mid- and late-November and mid-December. These sudden bursts of activity make it challenging to clearly define the comet's evolution as it approaches its perihelion, on April 24, 2024. Unfortunately, comet 12P was no longer observable from Asiago's coordinates at the time of its perihelion. However, we were able to track its orbit until it reached a minimum heliocentric distance of 2.2 AU. As shown in **Table 1**, the entire observation period covered a range of nearly 2 AU, beginning at 3.8 AU and ending at 2.2 AU.
The plot highlights variations in activity primarily driven by periodic outburst events. Different authors report at least four outburst:

- July, 20 (Green, D., 2023)
- October, 5 (Usher et al., 2023)
- November, 14 (Jehin et al., 2023)
- December, 14 (James, 2023)

As shown, the computed production rates for the CN radical effectively capture the observed activity, with peaks occurring on the exact dates of the outbursts and in the days that follow. The November event appears to be the most chaotic, with the possibility of a second outburst occurring on November 22nd. Finally, the December event is notable for the continued rise in Q(CN) the day after the outburst.

12P/Pons-Brooks is an extremely variable object, experiencing multiple outbursts with a periodicity of approximately 15 days. This periodicity becomes more consistent as the comet approaches perihelion. The production rate of the CN radical has proven effective in capturing this variability and appears to be one of the primary gases driving the comet's inbound activity.

The results indicate a strong correlation between outburst events and the production rate of the CN radical. In July, the effects of the July 23rd event can still be observed. In October, although the literature reports an outburst on October 5th, the spectra show an increase in the CN production rate as early as October 1st. In November, the cometary activity becomes highly irregular, and our data suggests that a second event may have occurred on November 22nd. Finally, the December event is consistent with the literature, and as seen in the spectra (**Figure 1**), it also involved a significant contribution of dust

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