Dust Production of Comet 21P/Giacobini Zinner using Broadband Photometry

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Introduction

Comet 21P/Giacobini-Zinner is a Jupiter family comet that was discovered in December of 1900 by the French astronomer Michel Giacobini, and rediscovered two orbits later by German astronomer Ernst Zinner in 1913 [3]. 21P is approximately 2 km in diameter, and is the parent of the Draconids, a meteor shower known to undergo dramatic outbursts. In 1933 and 1946 ,up to 10,000 meteors per hour were reported for the Draconids [1]; and 2011 saw a minor Draconid outburst. As meteor stream modeling/ forecasting is a primary focus for the NASA Meteoroid Environment Office, it was decided to monitor 21P for three purposes: firstly to find the apparent and absolute magnitude with respect to heliocentric distance; second to calculate *Afρ* [2], a quantity that describes the dust production rate and is used in models to predict the activity of the Draconids; thirdly to detect possible increases in cometary activity, which could correspond to future Draconid meteor outbursts.

Giacobini-Zinner is unique in several ways. It was the first comet to have measurements made *in situ.* Comet 21P was visited by ICE (International Cometary Explorer) in 1985 to study the interaction of the cometary atmosphere with the flowing solar-wind plasma [10]. It is a carbon-depleted comet [8], and most studies show that it peaks in gas and dust production pre-perihelion, specifically in two very studied passages; 1985 and 1998 [9],[8].

A prior study was conducted by Pittichova et al (2008) for 21P during its 2004-2006 close approach to the Sun. Apparent and absolute magnitudes were measured at various heliocentric distances as well as the dust production [3]. At 2.32 AU from the Sun, 21P exhibited an apparent magnitude of 17.05 and *Afρ* of 83 cm, and an apparent magnitude of 15.91/*Afρ* of 130.66 cm at 1.76 AU. Another such study performed by Lara et al [8] on 21P's 1998 apparition found values of *Afρ* of 1010 cm when 1.05 AU from the Sun, two weeks before perihelion, and 669 cm at perihelion, when 1.03 AU from the Sun [8].

Theory (*Afρ*)

Afρ is a quantity indicative of the dust production of a comet, typically expressed in centimeters. Derived from measured magnitudes, it permits the determination of the heliocentric dependence of the dust production of a given comet. It lets observers compare data obtained at different sites, telescopes, and geometrical arrangements. Often comet outbursts exhibit a sharp increase in *Afρ,* and it has been shown that results obtained from both CCD filter photometry and spectrophotometry agree [7]. Typical values of *Afρ* are anywhere from 5 cm to 5000 cm and are majorly affected by the size of the comet and its distance from the Sun.

Afρ is explicitly the albedo *(A),* multiplied by the filling factor of the grains *(f),* and the nucleocentric distance *(ρ).* It is calculated using the Earth-comet distance, (*Δ*), nucleocentric distance (the distance from the comet's nucleus to the edge of the aperture being used for photometry), the flux of the Sun at 1 AU in the same filter used to image the comet, F_{SOL}, and the observed flux from the comet found using the apparent magnitude, F_{COM}. Explicitly the filling factor (*f*) is $N\rho\sigma/\pi\rho^2$ where σ is the cross second of a single grain.

$$Af\rho = \frac{(2\Delta R)^2}{\rho}\frac{F_{com}}{F_{sol}}$$

$$F_{COM} = 10^{\frac{M_{app}}{-2.512}}$$

Δ and *ρ* are in cm, but *R* is in AU. M_{APP} is -27.15 when finding F_{SOL}.

$$\rho = \tan(1.12838 * \frac{5}{206,265})\Delta$$

In the equation above, 5 accounts for the radius of a 10x10 arcseconds aperture, which is converted to radians (1 arcsecond =1/206,265 radian), and 1.12838 is a correction factor as the true aperture is not a square, but a circle whose area is equivalent to that square.

FoCAs (FOtometria Con AStrometrica or Photometry with Astrometrica) [5], the reduction software used to perform multi-aperture photometry, has set apertures of 10"x10", 20"x20'" 30"x30", 40"x40" and so on. Analysis was performed using the aperture size which gave the largest value of *Afρ*. Since *Afρ* is inversely proportional to *ρ*, when increasing the aperture size, if the amount of dust within that aperture does not increase, *Afρ* will therefore decrease. If the amount of dust within the aperture (F_{COM}) increases proportionally more than the aperture size, the value of *Afρ* at that larger aperture will give higher results. In this case the larger aperture should be used.

The magnitude and *Afρ* graphs presented here were determined with a10x10 arcsecond aperture which corresponds to *ρ* of 9100 +/- 500 km (as 21P's Geocentric distance, Δ, varies).

Method

Images of 21P were were obtained in the Johnson R-filter from May 20, 2011 until October 24, 2011 (3.04 to 1.77 AU heliocentric distance). The equipment used was a 0.5-meteor f/8.1 Ritchey-Cretien telescope on a German equatorial mount with an Apogee 16M CCD camera located in the mountains of southern New Mexico (Mayhill, NM), and operated remotely from Marshall Space Flight Center. Standard bias subtraction and flat-field reduction were performed on all data.

Analysis was done with Astrometrica [4] and FoCAs. Astrometrica produces a log file of the astrometry and photometry of all reference stars as well as the object (which must be manually chosen). This log file is read by FoCAs. FoCAs determines the centroid of the object to perform its photometry. The value of the background of the image is found as the median of the whole image, not with concentric circles around the object itself (as in other photometric software), which minimizes contamination from the tail of the comet. A comparison of results obtained from this process was made with those produced by Wafrho, created by CARA (Cometary ARchieve for *Afρ*) [6] as a verification step.

Phase Dependence

It is important to correct for phase in these reductions; unfortunately a standard procedure does not exist. Phase affects a solar system body in different ways based on the composition/grains, and as comets often do not have consistent out gassing, it is difficult to measure this effect.

Figure 1 is the phase correction used in this report, normalized at a phase angle of 0° (opposition). This specific fit was found through personal communication with D.G. Schleicher and is a splice of two curves, one using data from comet Halley at small phase angles, and the other based on the Henyey-Greenstein function. This correction for the phase angle were applied to all data [7].

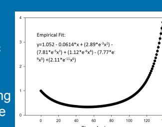


Figure 1: Normalization curve for phase angle correction.

The most standard value to use for normalization, which was used in this report, is opposition (0°). This implies that all data are extrapolated and the values of *Afρ* are higher than those originally measured. Consequently, values of *Afρ* before phase correction (denoted *A(θ)fρ*), and after phase correction are given. As phase correction for comets is an ongoing work, the original data may be revised accordingly in the future.

Results

Over the five months 21P was imaged we saw results that were in rough agreement with Pittichova et al's 2008 results, which covered 21P's previous apparition [3]. The analysis also compares favorably to Lara et al's 2003 results from the 1998 apparition [8]. **21P went from an apparent magnitude of 19.6 to 15.7, corresponding to an absolute magnitude of 15.1 to 12.1. This correlated to an *Afρ* of 16.48 cm to 284.17 cm (Figure 2).** There were no significant outbursts during this time.

Dust production of 21P followed a logarithmic slope (*γ*) of -4.468 with respect to heliocentric distance. The slope permits the extrapolation of the data out to the perihelion (1.038 AU) of 21P, to an *Afρ* of 3824 cm. The *Afρ* and *γ* of a comet are the two of the main descriptors of its dust production.

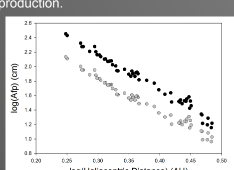
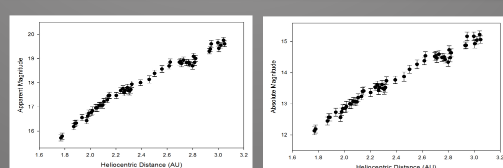


Figure 2(left). Dust production of comet 21P from May 20 to October 24, 2011. Grey data is *Afρ* results before correction for phase, and black data is after phase correction.

There was a slight increase in brightness around 2.8 AU for several nights, which could correspond to a small outburst in 21P. This is seen as an increase in *Afρ.* However, 21P was passing through a dense star-field during this time which could have affected the photometry. As typical comet outbursts have an immediate brightening of several magnitudes, contamination by field stars appears likely.

Date	Δ (AU)	R (AU)	Θ (°)	ρ (Km)	App Mag	Abs Mag	A(θ)fρ (cm)	Afρ (cm)
5-24	3.05	2.16	10.6	8816	19.61	15.06	10.65	16.48
6-26	2.79	2.12	17.9	8675	18.69	14.34	20.38	38.18
7-19	2.62	2.19	22.3	8978	18.54	14.22	21.35	43.40
8-24	2.32	2.33	25.2	9518	17.72	13.52	37.49	78.85
9-24	2.04	2.37	24.9	9689	16.96	12.99	59.73	126.76
10-24	1.77	2.31	23.8	9459	15.05	12.13	136.28	284.17

Table 1: Selected results throughout the entire run of observations of 21P. The six different dates here show the span of phase angle *(θ)* and aperture radius *(ρ)*. The second to last column is *Afρ* before phase angle correction is applied, which we call *A(θ)fρ* because of the phase dependence on the albedo. The last column is *Afρ* after the phase angle correction has been applied.



Figures 3 & 4. Apparent (left) and absolute (right) magnitude of comet 21P from May 20 to October 24, 2011. The magnitudes presented here are averages found from analyzing several images per night. The average is weighted over the night according to the signal to noise ratio of the comet in each image. Errors in the graphs correspond to the average photometric errors after performing a fit to CMC-14 catalog magnitudes.

ρ (km)	9000	18000	27000
Afρ at 3.04 AU (cm)	16.48	11.07 (67%)	7.64 (46%)
Afρ at 2.29 AU (cm)	82.43	63.61 (77%)	49.72 (59%)
Afρ at 1.77 AU (cm)	284.17	262.51 (92%)	211.85 (75%)

Table 2: Dust production of 21P for three aperture sizes and various heliocentric distances.

Dust production was measured with 3 apertures, the quantity ρ describing the radius of the aperture in kilometers. Performing multi-aperture photometry permits the determination of the shape and surface brightness profile of a comet's coma, and how these vary with heliocentric distance. The average profile of the brightness of the comet's coma is described as a power law, represented by the slope of *log(Afρ) vs log (ρ) [8].* The growth of the coma with decreasing heliocentric distance is clearly seen by examination of the surface brightness profile. This is reflected in Table 2 by a greater percentage of *Afρ* seen in larger apertures as 21P approaches the Sun. When 21P is 3.04 AU from the Sun, and nearly a point source, the dust production falls off significantly with increasing aperture size. However by 1.77 AU from the Sun, 21P has grown a pronounced coma, which extends into larger apertures. The values determined using the 9000 km aperture yielded the peak *Afρ* values, and so are presented in this paper.

Future Work

NASA's Meteoroid Environment Office plans to use these *Afρ* measurements to refine its stream modeling and forecasts for future Draconid shower activity.

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The authors would like to thank NASA's Meteoroid Environment Office for support of this project, and to D. Schleicher and M. A'hearn for their helpful correspondence.