NEOWISE Observed CO and CO2 Production Rates of 46P/Wirtanen During the 2018–2019 Apparition*

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Received 2020 September 30; revised 2020 December 11; accepted 2020 December 14; published 2021 February 23

Abstract

We present measurements of comet 46P/Wirtanen obtained by the NEOWISE spacecraft in 2017 through 2019. We detected signal in excess of the dust in the 4.6 µm channel attributable to the presence of CO, or more likely, CO2 emission. The excess, when the comet was outbound at a heliocentric distance of 1.9 au, was consistent with a CO2 production rate of 1.3(±0.07) × 1026 molecules per second, which is equivalent to an active area on the order of a percent of the comet nucleus’ total surface.

Unified Astronomy Thesaurus concepts: Infrared photometry (792); Short period comets (1452); Comet volatiles (2162); Comets (280)

1. Introduction

The comet 46P/Wirtanen (hereafter 46P), with a perihelion distance well within 1.3 au (q = 1.05 au, Q = 5.13 au, e = 0.66, i = 11°?), occupies a near-Earth comet (NEC) orbit, presenting frequent opportunities for detailed studies by ground-based observatories, as well as studies by spacecraft. Comet 46P was a possible target of the Rosetta mission. Its long term evolution and activity on the surface of the nucleus was highly studied. Groussin et al. (2007) observed a rapid increase in the active regions near 1.5 au by comparing the water production rate and the size of the nucleus. Comet 46P was categorized as an hyperactive comet, due to its high fraction of surface activity. An hyperactive comet emits more water molecules than can be expected given the size of the nucleus. One possible explanation is the sublimation of water–ice-rich particles within the coma (Lis et al. 2019). Lab experiments have demonstrated that large icy grains are often ejected when there is subsurface sublimation from highly volatile ices such as CO or CO2 (Lauffer et al. 2005). Comet 103P/Hartley 2 is a good example of a known hyperactive comet with icy grains contributing to its activity A’Hearn et al. (2011). Comet 46P reached perihelion in 2018 December, and made a close approach to Earth a few days after, affording observations for in-place assets to study the comet. One such operational asset was the NEOWISE spacecraft.

Launched in 2009 November, the Wide-field Infrared Survey Explorer (WISE) spacecraft underwent its initial in-orbit checkout and began to survey the sky in 2010 January. The WISE mission obtained simultaneous images of the sky in four infrared channels with central wavelengths at 3.4 µm (W1), 4.6 µm (W2), 12 µm (W3), and 22 µm (W4). The spacecraft followed a Sun-synchronous ecliptic pole-to-pole orbit, approximately 95 minutes in duration, looking outward at elongations of ~90° and completing a full sweep of the sky approximately every six months (Wright et al. 2010).

By 2010 October, the spacecraft cryogen was fully depleted, resulting in the 12 and 22 µm channels becoming non-functional. The mission continued to survey the sky in the 3.4 and 4.6 µm channels through 2011 January, when the spacecraft was placed in hibernation. In 2013 September, the spacecraft was reactivated and restarted its W1 and W2 survey of the sky on 2013 December 23, and renamed NEOWISE. Repurposed as a planetary mission asset to characterize and discover Near-Earth objects (NEOs), NEOWISE has been surveying ever since. Even as the spacecraft precesses off of its terminator-following orbit, it continues to obtain infrared flux measurements of NEOs. Including the data from the WISE prime mission, NEOWISE has collected more than a decade of observations of solar system bodies.

The data contains signal from solar system objects within the images. These detections were serendipitous survey detections, not targeted, observations with fixed exposure times of 7.7 s for the W1 and W2 bands and 8.8 s for the W3 and W4 bands (Cutri et al. 2012). Most detected solar system objects exhibited apparent motion on the sky between orbits. Hence, NEOWISE, originally the planetary component of the WISE prime mission, had as its goal the detection of the moving objects within the WISE data for discovery and characterization, as well as the development of a known solar system object search capability within the image archive to facilitate precovery activity (Mainzer et al. 2011). The thermal signals of the moving objects facilitated derivation of their diameters, out to Main Belt (Masiero et al. 2011), Trojan (Grav et al. 2011), and Centaur distances for those detected in the longest wavelength channels (Bauer et al. 2013).

The analysis of the thermal flux component of the asteroid fluxes has proven an effective means of obtaining measurements of asteroid diameters (see Mainzer et al. 2019). Coma removal techniques have also rendered the effective measurements of comet diameters as well for the cryogenic mission data (Bauer et al. 2017). The WISE prime mission did not detect 46P, and provided no estimates of its diameter. However, multiple other estimates of 46P’s diameter were obtained. Boehnhardt et al. (2002) derived a diameter of 1.1 km...
for 46P’s nucleus, and more recent estimates place the size near 1.4 km, similar to the earlier estimate from visual band observations by Boehnhardt et al. (1997); we use a 1.4 km diameter as the effective nucleus size hereafter.

The WISE prime mission sample suggested that about a quarter of the comets detected have measurable CO or CO2 production. Out of the nine NECs within that sample, six exhibited CO or CO2 production, and the only known hyper-volatile NEC that was observed by NEOWISE, 103P/Hartley 2, had measurable CO2, making 46P a valuable second data point. Lis et al. (2019) notes a correlation between Earth-like D/H ratios and hyper-volatile comets, yet the correlation with CO2 production is less explored.

The NEOWISE reactivated mission obtained detections of 46P during its 2018 perihelion approach, allowing for the detection of CO or CO2 emission line signal and characterization of the comet dust production from the W1 channel’s flux measurements, using the techniques applied in Bauer et al. (2015). The W2 channel allows observation of the CO2 ν3 vibrational fundamental band (∼4.3 μm) and the CO rovibrational fundamental bands (∼4.7 μm). Because the two lines are encapsulated in a single broad 4.5 μm band, it is not possible to separate the relative contributions of the two species. However, these observations in combination with those quantifying CO at the same perihelion approach, such as those presented by McKay et al. (2021) can facilitate identification of the particular species.

### 2. Observations

Observations of solar system objects obtained with the NEOWISE spacecraft are not targeted, but rather are obtained when the survey covers the same region of sky where the object resides. The span of exposures from the survey coverage which covers an objects predicted location is called a visit (see Bauer et al. 2013). The survey covered the region of sky where 46P was predicted to be in 2017 September 10, when the comet was 4 au from the Sun. Neither the individual images nor the coadded images from the 2017 September visit showed any significant signal.

The following year, in 2018 June, NEOWISE covered the position of the comet with 18 individual exposures (called visit A; see Table 1). These images were co-aligned with the comet’s motion and coadded yielding a 4σ and 2.7σ detection in W2 and W1, respectively (Figure 1). The visit A coadd had an effective exposure time of 139 s over a region of sky 180′ on a side.

The next NEOWISE survey visit of 46P (visit B; see Table 1) occurred in 2019 April, four months after its perihelion, and produced 20 exposures in each band that contained the comet, which was apparent in individual exposures of both W1 and W2. The coadds, with effective exposures of 154 s, revealed a more extended morphology and stronger signal in the W2 image (Figure 1). Consequently, the coadded region was extended over a region 30′ on a side, about 10 times the size of the visit A coadd.

Table 1

| Visit | Start Date | End Date | Effective Exposure Time | W1 Detection | W2 Detection |
|-------|------------|----------|-------------------------|--------------|--------------|
| A     | 2018-04-26 | 2018-04-27 | 139 s                   | 4σ           | 2.7σ         |
| B     | 2019-04-02 | 2019-04-03 | 154 s                   | 8σ           | 3σ           |

Note. The UTC start date (in bold) and time of each spacecraft exposure is shown. Rh is the heliocentric distance of the comet, Δ is the observer distance, and α is the phase angle in degrees.
Figure 2. NEOWISE observations of comet 46P at 2.3 au (visit A) and 1.9 au (visit B). The flux from the 3.4 μm (red triangle) and 4.6 μm (red cross) are shown. Also the reflected light model (dotted line), thermal model (solid line) and combined signal (dashed line) are overplotted.

### Table 2
Flux Measurements

| Visit | W1 Flux (mJy) | W2 Flux (mJy) |
|-------|---------------|---------------|
| A     | 0.019 ± 0.007 | 0.12 ± 0.03   |
| B     | 0.23 ± 0.05   | 1.34 ± 0.30   |

### 3. Analysis

The coadds from each visit were created using the AWAIC routine developed for the WISE mission (Masci & Fowler 2009), and utilized in the synthesis of the WISE all-sky atlas (see Cutri et al. 2012). The counts were extracted from the coadded W1 and W2 images employing 11″ apertures, nearly 4 times the full-width at half maximum of the image profile. No aperture corrections were necessary. The background was sampled using annuli apertures centered on the comet with inner and outer radii of 40″ and 50″, respectively, for visit A and 250″-280″ for visit B. The counts were converted to flux values in each band using the methodology described in Wright et al. (2010) and employed in Bauer et al. (2015, 2017). The derived fluxes are provided in Table 2, along with the photometric uncertainties derived using photon statistics.

No color corrections were applied in the flux conversions from W1 and W2. Instead, the signal in W1 was used to constrain the dust signal, as the dust signal dominates in the 3.4 μm bandpass, which includes only weak warm-water emission. The photometric fluxes are shown in Figure 2 for both visits, relative to the derived dust signal as fixed to the W1 flux. The thermal signal was extrapolated using a blackbody temperature for dust with visible wavelength albedo \( p_v \sim 0.05 \) and an emissivity (ε) of 0.9. These values for the dust thermal parameters were derived from the cryogenic comet sample in Bauer et al. (2015), and were shown to well-characterize the dust photometric properties across the sample of 39 comets in that work.

### 4. Discussion

#### 4.1. Gas Production

As an active comet moves inward from 2 au, the thermal signal of the dust begins to dominate in W2. However, even at 1.9 au, the dust signal for 46P is well separated from the W2 measured flux. This excess flux is attributable to the presence of strong emission lines from CO or CO2 features which fall within the 4.6 μm bandpass. Assuming a single species dominates, the excess fluxes can be converted to CO and CO2 production rates using the methodology described in Pittichová et al. (2008) and applied by Reach et al. (2013) for Spitzer Space Telescope observations of comets, and adapted by Bauer et al. (2015) in analysis of the NEOWISE prime mission data. The line strength of CO2 is nearly a factor of 11 greater than that of CO for the same production rate, hence CO2 is chosen as the proxy for the species production rates listed in Table 3. With about an 11 times greater production of CO molecules required to produce the same emission, CO2 is a likely candidate species that drives the excess flux in the infrared W2 channel. Analysis of NEOWISE observations of 103P (Bauer et al. 2011, 2012, 2015) at nearly the same heliocentric distance as 46P’s visit A yielded a comparable CO2 production rate of \( 5 \times 10^{25} \) molecules per second. A’Hearn et al. (2011) clearly identified CO2 as the dominant species, with a CO/CO2 ratio of <1/60.

Additional considerations strengthen the likelihood of a CO2 emission dominated W2 flux. Groussin et al. (2007) noted that the dynamical age of the comet is over 10^6 yr. With multiple passages where the comet approaches close \( R_b \sim 1 \) au to the Sun, the CO may become depleted, and is less likely to survive over large timescales near the surface of the comet. For the particular case of 46P, CO2 and CO are significantly volatile well beyond 6 au (see Meech & Swaren 2004), encompassing the aphelion distance of 46P. Alternatively, measurements of CO and CO2 from spacecraft (see A’Hearn et al. 2011; Läuter et al. 2020, and Ootsubo et al. 2012) of near-earth comets also seem to indicate that CO2 is the dominant species for NECs. Coulson et al. (2020) observed 46P from the James Clerk Maxwell Telescope within six days of perihelion passage and did not detect CO. The 3σ upper limit provided for CO production rates, \( 9.2 \times 10^{25} \) molecules per second, would account for less than 7% of the signal we observed at 1.94 au.

Finally, the depleted production of CO relative to H2O measured in 46P during the 2018 perihelion approach (McKay et al. 2021) affirms the dominance of CO2. As mentioned, owing to the relative line strengths of the species (see Crovisier & Encrenaz 1983), CO production rates would have to achieve a level ~11 times greater than those calculated for CO2 to create the observed infrared excess. The CO production rates would have to be on the order of \( \sim 10^{27} \) molecules per second to dominate the signal observed by NEOWISE during visit B, and \( \sim 10^{26} \) molecules per second for visit A, while those found 31 days after the comet’s 2018 perihelion, while 46P was at a heliocentric distance of 1.13 au, were significantly lower than these values (McKay et al. 2021).

#### 4.2. Dust

As mentioned in Section 3, the coma dust likely dominates within the 3.4 μm bandpass. The \( Af_p \) values in Table 3 are notably well-matched by those derived from observations of 46P by the Zwicky Transient Factory (see Kelley et al. 2021) for similar times. No excess gas or thermal emission is required to explain the signal detected at both visual wavelengths and

| Visit | \( R_b \) (au) | \( Δ \) (au) | \( Q_{CO2} \) (molecules s^{-1}) | \( Af_p \) (cm) | \( pf \) (cm) | \( T_{eff} \) (K) |
|-------|---------------|-------------|-------------------------------|---------------|-----------|---------------|
| A     | 2.32          | 0.08        | \( 2.3(\pm0.4) \times 10^{15} \) | 5.0 ± 1.8     | 20 ± 7    | 188           |
| B     | 1.94          | 1.34        | \( 1.3(\pm0.07) \times 10^{26} \) | 22 ± 5        | 88 ± 20   | 205           |

Note. \( Q_{CO2} \) production rates are a proxy for the combined rates derived from CO + CO2. Values of \( pf \) are extrapolated from the listed \( Af_p \) values with a multiplicative factor derived from Bauer et al. (2015).

Table 3
Gas and Dust Production
within the W1 bandpass. That the dust grains are neutrally colored across wavelength regimes may suggest that the majority of the grains may be several microns in size (see Bauer et al., 2011), and consequently, that the comet has a larger dust mass-production rate. The possibility of such a size distribution is further supported by the presence of mm-sized dust observed in the coma of 67P Kramer et al. (2018). Furthermore, the submillimeter observations of Coulson et al. (2020) near 46P’s perihelion support the presence of dust as large as ~1 mm.

4.3. Other Comets

In Bauer et al. (2015), Figure 3 shows the relation between values of $f_{\text{CO}}$ and $A_{\text{F}}$ (as here, uncorrected for phase) for comets in the WISE prime mission sample, which can be expressed as multiplicative factor of $\sim 4 \pm 2$ when $R_{\text{h}} \sim 2 \text{ au}$. Using this conversion factor, we find a gas-to-dust ratio, expressed as $Q_{\text{CO}/\text{dust}}$, of 24.06 and 24.17 for visit A and visit B, respectively. Figure 3 shows the gas-to-dust ratio for 46P from these measurements relative to the full sample of 39 CO+CO$_2$ active comets in Bauer et al. (2015). The $1/R_{\text{h}}^2$ trend relative to distance seems persistent, but not unexpectedly for the hyperactive comet, 46P appears near the top of the distribution. According to A’Hearn et al. (1995), the surface area required to produce the measured H$_2$O production was 0.89 km$^2$, or about 15% of the comet’s surface. For the species CO$_2$, production rates derived for visit B imply a more modest $\sim 0.3\%$ fraction of the comet’s total surface area, using the model of Cowan & A’Hearn (1979) and assuming nucleus surface properties of $p_{\text{v}} \sim 0.04$ and $\epsilon \sim 0.9$, and a slowly rotating nucleus. For visit A, the fraction falls to $\sim 0.07\%$ of the surface area. For comparison, using the same model, 103P’s CO$_2$ production rate at a similar heliocentric distance as visit A (see Section 4.1) corresponds to an active area of $\sim 0.2\%$.

The presence of highly volatile species can serve as markers of longevity, or the time particular comets have resided in near-Sun orbits, because they are rapidly depleted from the surface under those circumstances. Of particular interest are the instances of the persistence of such species in NECs, which should lose their surface volatiles even more quickly. 46P is such an example, and a better understanding of how the comets evolve while still retaining their highly volatile species would provide a constraint on the comet’s age. Future missions with the ability to detect CO and CO$_2$ emissions for large samples of comets inclusive of the NECs, such as the Near-Earth Object Surveillance Mission, may more firmly establish the relationship between CO$_2$ and hyperactivity in NECs.

This publication makes use of data products from NEOWISE, which is a project of JPL/Caltech, funded by the Planetary Science Division of NASA. K.J.M. acknowledges support through an award from the National Aeronautics and Space Administration (NASA) under grant NASA-80NSSC18K0853.

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Figure 3. $Q_{\text{CO}_2}/d_{\text{dust}}$, a proxy for gas-to-dust ratio, derived from NEOWISE observations of comet 46P at 2.3 au (visit A) and 1.9 au (visit B) and overlapped on the WISE prime mission sample of CO+CO$_2$ producing comets (Bauer et al. 2015). The dashed line indicates a $R_{\text{h}}^{-2}$ for heliocentric distances <4 au. The value is in the overall grouping of comets, but among the higher end of the distribution.