THE *NEOWISE*-DISCOVERED COMET POPULATION AND THE CO + CO₂ PRODUCTION RATES

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THE WISE AND NEOWISE TEAMS

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ABSTRACT

The 163 comets observed during the *WISE/NEOWISE* prime mission represent the largest infrared survey to date of comets, providing constraints on dust, nucleus size, and CO + CO₂ production. We present detailed analyses of the *WISE/NEOWISE* comet discoveries, and discuss observations of the active comets showing 4.6 μ m band excess. We find a possible relation between dust and CO + CO₂ production, as well as possible differences in the sizes of long and short period comet nuclei.

Key words: comets: general – infrared: planetary systems

1. INTRODUCTION

When the *Wide-field Infrared Survey Explorer* (*WISE*) mission was launched on 2009 December 14, the complete sky had not been surveyed at thermal infrared (IR) wavelengths since *IRAS*. The primary purpose of the *WISE* mission was to conduct an all-sky survey at 3.4, 4.6, 12, and 22 μ m (referred to as *W1*, *W2*, *W3*, and *W4*) at unprecedented sensitivity and spatial resolution (Wright et al. 2010). An enhancement to the *WISE* mission was funded by NASA’s Planetary Science Division, called *NEOWISE*, to detect moving objects in the data and to develop a searchable archive of moving object photometry and images to facilitate precovery and analysis of subsequent discoveries (Mainzer et al. 2011c, 2012). Both aspects of *NEOWISE* were successful, with over 158,000 small bodies observed including 34000 discoveries. More than 616 NEOs were detected (Mainzer et al. 2012) during the prime mission, from 2010 January 14 through 2011 February 1. *NEOWISE* has provided the largest catalog of thermal-infrared solar-system object data to date. The observations have yielded an unprecedented number of size measurements for a wide array of classes of solar system bodies using radiometric modeling techniques (see Bauer et al. 2011, 2012a, 2012b, 2013; Grav et al. 2011, 2012; Mainzer et al. 2011a, 2011b, 2011c; Masiero et al. 2011, 2012). However, *NEOWISE* also observed the largest number of comets to date in the IR; a total of 163 comets have been identified in the data, a sample that offers a unique set of constraints on cometary physical properties. In addition to measuring the nucleus size distribution of comets, the data are used to quantify dust characteristics and mass loss, as well as gas production of rarely observed species (Bauer et al. 2011, 2012a; Stevenson et al. 2014, 2015).

The *WISE/NEOWISE* survey began regular survey operations on 2010 January 14 (Modified Julian Date [MJD] 55210).

The secondary cryogen reservoir of solid hydrogen was depleted on 2010 August 4 (MJD 55412), resulting soon after in the saturation of the *W4* channel. The survey then continued in *W1-3*, the so-called 3-band cryogenic phase, until the primary reservoir was depleted at the end of 2010 September (MJD 55469). After this, science survey operations were extended for the next 4 months in the *W1* and *W2* until 2011 February 1 (MJD 55593), when the “post-cryogenic” mission phase ended (Mainzer et al. 2012; Masiero et al. 2012). At this point the spacecraft was placed into a hibernation state. The success of *NEOWISE* in this first period, a little more than a year of survey operations referred to as the “prime mission,” led to the decision to restart the *WISE* spacecraft and the survey in 2013 exclusively for the purposes of surveying solar system bodies. The reactivated spacecraft was renamed *NEOWISE*, after the planetary mission, and the survey has been underway since 2013 December 23 (MJD 56649; Mainzer et al. 2014). Since the reactivation, *NEOWISE* has detected >12000 minor planets, including 260 NEOs and 63 comets at 3.4 and 4.6 μ m.

1.1. *WISE/NEOWISE* Cometary Discoveries

During the cryogenic mission, *NEOWISE* was the most prolific discoverer of comets, other than the Sun-grazing comets observed by *Solar and Heliospheric Observatory*. *NEOWISE* discovered 18 comets during the prime mission and discovered activity on an additional three small bodies. Since the beginning of the reactivated mission, *NEOWISE* has discovered four additional comets.¹¹ For the prime mission

¹¹ 2010 KG43 is not included in this tally, since while activity has been reported (Waszczak et al. 2013), it has not been designated as a comet yet. The *NEOWISE* observations of this body are discussed in that reference. On 2015 May 15, the *NEOWISE* reactivated mission discovered its 4th comet, P/2015 J3.

Figure 1. Discovery images of *WISE*/*NEOWISE* comets shown in 3-colors. The prime mission comets have the 22 μm image mapped to the image’s red channel, the 12 μm image mapped to green, and the 4.6 μm image mapped to blue. The comets for which the activity, and not the object, were discovered by *NEOWISE* are shown with blue labels, in the upper left. In the case of the four comets discovered to date by the *NEOWISE* Reactivation (yellow text labels, on the bottom row), the 4.6 μm image is mapped to red, and the 3.4 μm image to both green and blue. The images are 6 arcmin on a side. The comets span a wide range of morphologies and activity levels; over half are LPCs.

discoveries, about half of the comets are designated long-period comets (LPCs; comets with orbital periods >200 years). For the reactivated mission half of the comets discovered are LPCs.

The new *NEOWISE* comets (see Figure 1) form an interesting population that has been discovered based on their thermal emission in the infrared, rather than reflected visible light. This is particularly important as the low albedos of the nuclei (Lamy et al. 2004) and potentially the darker refractory grains (Bauer et al. 2012a) make discovery in reflected light difficult until cometary activity increases the brightness dramatically upon approach to perihelion. The large-grain dust component may be comprised of dark, refractory grains that

facilitate detection and study at IR wavelengths out to greater distances than can be reached by reflected light. Finally, strong gas emission lines of CO (4.67 μm) and CO₂ (4.23 μm) fall within the *NEOWISE* 4.6 μm channel ($\geq 80\%$ peak throughput from 4.13 to 5.14 μm ; Wright et al. 2010), allowing abundance constraints to be set on these species. CO is otherwise only observable from the ground for bright comets, or if the comet’s geocentric velocity is large enough that the comet lines are sufficiently Doppler shifted from their telluric counterparts (see Dello Russo et al. 2009). Emitted CO₂ is only detectable directly from space (Bockelée-Morvan et al. 2004). In this paper, we describe this *NEOWISE*-discovered population in

detail, including analysis of the dust, constraints on the nucleus sizes, and gas production rates of various species. We provide a wider context for the CO + CO₂ analyses by exploring the CO + CO₂ production in the full comet sample from the 163 comets, roughly a quarter of which show 4.6 μ m band excess attributable to CO or CO₂ gas emission. Because the *NEOWISE* W2 band encompasses both CO and CO₂ features, it is difficult to separate their relative contributions; however, CO is generally more than a factor of 11 times weaker than the CO₂ feature (see Section 4.6).

1.2. CO + CO₂ Production Rates

Where H₂O-driven sublimation begins beyond 6 AU and can lift optically detectable sub-micron dust, comets are variable objects that become obviously active typically somewhere inside 4 AU when they cross the point at which water–ice sublimation becomes the dominant driver of activity (Meech & Svøren 2004). However, the exact details of when and how active they will become remains difficult to predict as these events are sensitive to variations in their compositions. In the outer solar system, water–ice is very common, yet other common ices exist as well that can sublimate rapidly at distances greater than 4 AU. For the last several decades, comets have been grouped into dust-rich and gas-rich categories that may not necessarily correlate with their dynamical age or origin (A’Hearn et al. 1995). In most circumstances, water–ice sublimation likely drives their activity near perihelion, but at larger distances other common volatile constituents like CO and CO₂ may be the primary driver. Recent studies have shown that the CO or CO₂ production rate relative to H₂O increases with heliocentric distance (A’Hearn et al. 2012), but these analyses are based on a limited sample. Some in-situ measurements, for example with comet 103P/Hartley 2 (see A’Hearn et al. 2011), suggest different source regions for CO₂ and H₂O on the surface. To date, only 40 comets have had their CO or CO₂ production rates constrained from space-based observations (see Bockelée-Morvan et al. 2004; Pittichova et al. 2008; Bauer et al. 2011, 2012a; Ootsubo et al. 2012; Reach et al. 2013). The *NEOWISE* sample represents a uniform survey of CO + CO₂ production collected with a single space-based instrument with consistent instrumental response. This sample nearly doubles the sample of measured CO + CO₂ production rates in comets reported in the literature. Moreover, the 12 and 22 μ m channel observations set firmer constraints on the nucleus and dust contributions to the signal than do 2-band constraints such as those provided by *Spitzer Space Telescope* (SST; Reach et al. 2013), allowing the gas contribution to be separated.

2. OBSERVATIONS

2.1. WISE Spacecraft Observations

During the fully cryogenic portion of the mission, simultaneous exposures in the four *WISE* wavelength bands were taken once every 11 s, with exposure durations of 8.8 s in W3 and W4, and 7.7 s in W1 and W2 (Wright et al. 2010). The number of exposures acquired for each moving object depends on its rate of motion across the sky, as well as the rate of survey progression. A total of 8 exposures were collected for areas on the sky on the ecliptic on average at each pass, rising to several hundreds of exposures near the ecliptic poles. For most moving objects, this cadence resulted in collecting $\sim$ 12 exposures

uniformly spaced over $\sim$ 36 hr (Mainzer et al. 2011a; Cutri et al. 2012). Note that *WISE* may have observed a subset of its full sample of observations of any particular solar system object while it was in different parts of the sky, i.e., when several weeks or months had passed since the previous exposure (e.g., comet 67P; Bauer et al. 2012a), often providing data at different viewing geometries. Henceforth, we refer to the series of exposures containing the object in the same region of sky as a “visit,” or “epoch.” The spatial resolution in the *WISE* images varies with the wavelength of the band. The FWHM of the mean point-spread function (PSF), in units of arcseconds was 6.1, 6.4, 6.5, and 12.0 arcsec for W1, W2, W3, and W4, respectively (Wright et al. 2010; Cutri et al. 2012).

As with the comets we have previously studied (Bauer et al. 2011, 2012b), some analysis was improved by stacking at the objects’ rates of motion to increase the signal-to-noise ratio (S/N). For each body, the images were identified using the *WISE* image server (<http://irsa.ipac.caltech.edu/applications/wise>), as described by Cutri et al. (2012). Images were stacked using the moving object routine, “A *WISE* Astronomical Image Co-adder” (AWAIC; Masci & Fowler 2009). Figure 1 shows the variation in morphology of the subset of cometary objects discovered by *WISE/NEOWISE*.

During the fully cryogenic prime mission, 163 comets were detected by *WISE/NEOWISE* with an S/N $\geq$ 5 in the stacked image from at least one band. Of these, 94 were detected with an S/N $\geq$ 5 in single-exposure images by the *WISE* moving-object pipeline sub-system (WMOPS). The additional 69 comets were found by co-adding the exposures at each visit. Of the comets detected, 57 were LPCs and 106 were short-period comets (SPCs; comets with orbital periods <200 years), according to present designations.¹²

We report here on the comets discovered by *WISE/NEOWISE*. We also discuss the total sample of comets that show 4.6 μ m excess, likely attributable to CO + CO₂ emission. A summary of their *WISE/NEOWISE* observations are shown in Table 1. Note that LPCs are indicated by a “C/” prefix to their designations.

2.2. Discovery Objects

As of 2015 June, there were a total of 25 cometary body discoveries made by data from the *WISE* spacecraft. These include three distinct categories. Comets 237P, 233P, and P/2009 WX51 (Catalina) were known objects at the time of the discovery of their activity, but were not known to be previously active. *NEOWISE* reported coma and trails for these objects as they were imaged during the prime mission. Additionally, *WISE* discovered 18 new comets during the prime mission, which were named for the spacecraft discovery. These two groups represent a significantly different sample apart from other cometary discoveries, since each comet, or its active nature, was first discovered at thermal IR wavelengths, while comets discovered from ground-based telescopes are selected based on optical observations. Note that this sample could include a further member, 2010 KG43, a body on a centaur-like orbit that was reported to have activity when viewed by the Palomar Transient Survey (Wasczac et al. 2013). The *WISE* discovery observations of this object, taken at a significantly different epoch, showed no coma or extended emission.

¹² JPL’s Horizon’s ephemeris service; <http://ssd.jpl.nasa.gov>

Table 1
Comets Discovered by *NEOWISE* and with Observed 4.6 μ m Excess^a

Comet	Ecc	q (AU)	Incl (degree)	a (AU)	T_J	Earth MOID (AU)	Class	Observation MJDs (Exposure Mid-point Times)
P/2010 K2 (<i>WISE</i>)	0.5894	1.1982	10.642	2.918	2.972	0.204	JFC	55343.1806, 55343.3129, 55343.4452, 55343.5775, 55343.7098, 55343.8421, 55343.9744, 55344.0406, 55344.1067, 55344.1729, 55344.2390, 55344.3052, 55344.3713, 55344.4375, 55344.5036, 55344.5699, 55344.6359, 55344.7022, 55344.8345, 55344.9668, 55345.0991, 55345.2314, 55345.3637, 55345.4960
P/2010 D1 (<i>WISE</i>)	0.3566	2.6691	9.647	4.148	2.899	1.683	JFC	55244.3420, 55244.4742, 55244.6065, 55244.7389, 55244.7390, 55244.8713, 55244.9374, 55245.0036, 55245.1359, 55245.2021, 55245.4667, 55245.5991
P/2010 D2 (<i>WISE</i>)	0.4531	3.6590	57.175	6.691	1.874	2.944	JFC ^a	55252.6899, 55252.8223, 55252.9546, 55253.0869, 55253.2192, 55253.2854, 55253.3515, 55253.3516, 55253.5500, 55253.6823, 55253.7485, 55253.8146, 55253.8147, 55253.8808, 55253.9470, 55254.0131, 55254.2116, 55254.3439
P/2010 B2 (<i>WISE</i>)	0.4803	1.6164	8.931	3.110	3.013	0.630	JFC (ETC)	Epoch 1: 55218.6376, 55218.7699, 55218.9022, 55219.0347, 55219.1670, 55219.2331, 55219.2332, 55219.4316, 55219.4978, 55219.5640, 55219.7625, 55219.8948, 55220.0271, 55220.1594, 55220.1596 Epoch 2: 55412.2406, 55412.3728, 55412.3729, 55412.5051, 55412.5052, 55412.6374, 55412.7697, 55412.8359, 55412.9020, 55412.9682, 55413.0343, 55413.1005, 55413.1666, 55413.2328, 55413.3651, 55413.4973, 55413.4974, 55413.6296, 55413.6297, 55413.7619
245P / <i>WISE</i> (P/2010 L1)	0.4663	2.1410	21.086	4.012	2.747	1.173	JFC	55349.5013, 55349.6336, 55349.7659, 55349.8982, 55349.9643, 55350.0305, 55350.0966, 55350.1628, 55350.2289, 55350.6258, 55350.7581, 55352.9409, 55352.9410, 55353.1394, 55353.2055, 55353.2717, 55353.4040, 55353.5363, 55353.6686, 55353.8009, 55353.9331, 55353.9332
P/2010 N1 (<i>WISE</i>)	0.5338	1.4945	12.876	3.206	2.917	0.491	JFC	55382.4788, 55382.6111, 55382.7434, 55382.8757, 55383.0080, 55383.1403, 55383.2726, 55383.3387, 55383.4710, 55383.5371, 55383.6033, 55383.6694, 55383.7356, 55383.8017, 55383.8679, 55383.9340, 55384.0001, 55384.0002, 55384.1324, 55384.3970, 55384.5293, 55384.6616
233P/La Sagra (P/2009 WJ50)	0.4090	1.7950	11.276	3.037	3.081	0.818	JFC (ETC)	55232.9637, 55233.0960, 55233.2283, 55233.3607, 55233.6253, 55233.6915, 55233.7576, 55233.8238, 55233.9561, 55234.0223, 55234.0886, 55234.3532, 55234.4855, 55234.6179
P/2009 WX51 (Catalina)	0.7403	0.8000	9.593	3.080	2.709	0.009	JFC (NEC)	55288.5082, 55288.6405, 55288.7728, 55288.8389, 55288.8390, 55288.9051, 55288.9713, 55289.0374, 55289.1036, 55289.5005
C/2010 E3(<i>WISE</i>)	1.0	2.2742	96.477	...	...	1.547	LPC (Oort)	55259.9668, 55260.0991, 55260.2314, 55260.2976, 55260.3637, 55260.4299, 55260.4960, 55260.5622, 55260.6284, 55260.6945, 55260.8268
C/2010 J4(<i>WISE</i>)	1.0	1.0855	162.297	...	...	0.307	LPC (Oort)	Epoch 1: 55317.3421, 55317.4082, 55317.4743, 55317.5404, 55317.6065, 55317.6725, 55317.8047, 55317.9370 Epoch 2: 55328.1127, 55328.1788, 55328.2449, 55328.3110, 55328.3771, 55328.4432, 55328.5093, 55328.5754, 55328.7075
C/2010 L4 (<i>WISE</i>)	0.9648	2.8257	102.819	80.28	−0.394	2.530	LPC	55362.4562, 55362.5885, 55362.7207, 55362.7208, 55362.7869, 55362.8530, 55362.9192, 55362.9853, 55363.0515, 55363.1176, 55363.1838, 55363.2499, 55363.3161, 55363.4484, 55363.5806, 55363.5807
C/2010 L5(<i>WISE</i>)	0.9037	0.7908	147.052	8.208	−0.269	0.114	LPC (HTC) ^a	Epoch 1: 55361.2889, 55361.3550, 55361.5535, 55361.5536, 55361.6197

Table 1
(Continued)

Comet	Ecc	q (AU)	Incl (degree)	a (AU)	T_J	Earth MOID (AU)	Class	Observation MJDs (Exposure Mid-point Times)
C/2010 D3 (<i>WISE</i>)	0.9996	4.2476	76.394	10705	0.602	3.585	LPC	Epoch 2: 55391.9946, 55392.1269, 55392.2592, 55392.3254, 55392.3915, 55392.4577, 55392.5238, 55392.5900, 55392.6561, 55392.7223, 55392.8546, 55392.9869, 55393.1192, 55395.9641
								Epoch 1: 55251.0085, 55251.1408, 55251.2731, 55251.5378, 55251.6701, 55252.0670, 55252.0671, 55252.1995, 55252.3318, 55252.8611, 55252.9934, 55253.1257, 55253.2580, 55253.3904, 55253.5227, 55253.6550, 55253.7874, 55254.1844, 55254.7137, 55255.1106, 55255.2430, 55255.2431, 55255.5077, 55255.6400, 55255.7723, 55255.9046, 55255.9047, 55256.0370, 55256.1693, 55256.3016, 55256.4341, 55256.6987
C/2010 DG56 (<i>WISE</i>)	0.9764	1.5915	160.417	67.525	−1.388	0.650	LPC	Epoch 2: 55381.5379, 55381.6702, 55381.8025, 55381.9348, 55382.2655, 55382.3317, 55382.3978, 55382.8609, 55382.9932, 55383.2578, 55383.3239, 55383.3901, 55383.5224, 55383.6547, 55383.7208, 55383.8531, 55383.9854, 55384.2500
								Epoch 1: 55245.0010, 55245.1334, 55245.1996, 55245.2657, 55245.2658, 55245.4642
C/2010 KW7 (<i>WISE</i>)	0.9743	2.5704	147.061	99.85	−1.606	1.626	LPC	Epoch 2: 55403.4776, 55403.6099, 55403.6760, 55403.7422, 55403.8083, 55403.9406, 55404.0729, 55494.1250, 55494.2573, 55494.3895, 55494.3896, 55494.5218, 55494.5880, 55494.6541, 55494.7202, 55494.8525, 55494.9848
								Epoch 1: 55223.9376, 55224.0699, 55224.2022, 55224.2684, 55224.3345, 55224.3346, 55224.4007, 55224.4669, 55224.5330, 55224.5992, 55224.6654, 55224.7977, 55224.9300
P/2010 JC81 (<i>WISE</i>)	0.7773	1.8108	38.690	8.133	1.868	0.827	HTC	Epoch2: 55332.0641, 55332.1964, 55332.2627, 55332.3288, 55332.3950, 55332.5273, 55332.6596
P/2010 P4 (<i>WISE</i>)	0.4987	1.8565	24.102	3.703	2.740	0.854	JFC	55326.6203, 55326.8849, 55327.0172, 55327.2156, 55327.2158, 55327.2819, 55327.3481, 55327.5465, 55327.6127, 55327.6788, 55327.7450, 55327.8773, 55328.0096, 55328.2742
237P/LINEAR (P/ 2002 LN13)	0.3526	2.4193	16.155	3.737	2.916	1.411	JFC	55414.5897, 55414.7221, 55414.8544, 55414.9867, 55415.1190, 55415.1851, 55415.2511, 55415.2513, 55415.3174, 55415.3834, 55415.5157, 55415.5820, 55415.7143, 55415.8464, 55415.9787, 55416.2434
C/2010 G3 (<i>WISE</i>)	0.9981	4.9076	108.268	2597	−0.859	4.492	LPC	55357.3037, 55357.4360, 55357.5684, 55357.7007, 55357.8328, 55357.8330, 55357.8990, 55357.9651, 55358.0314, 55358.0974, 55358.1637, 55358.2297, 55358.2960, 55358.4283, 55358.5606, 55358.6929
C/2010 FB87 (<i>WISE</i> - Garradd)	0.9905	2.8428	107.625	299.3	−0.614	2.538	LPC	Epoch 1: 55300.1382, 55300.2705, 55300.4028, 55300.4690, 55300.5351, 55300.6674, 55300.6676, 55300.7997, 55300.7999, 55300.8659, 55300.9320, 55300.9322, 55301.0643, 55301.0645, 55301.1306, 55301.2629, 55301.3291, 55301.3952, 55301.4614, 55301.5275, 55301.5937, 55301.6598, 55301.7260, 55301.7921, 55301.8583, 55301.9244, 55302.0567, 55302.1890
								Epoch 2: 55380.2411, 55380.3073, 55380.3734, 55380.4396, 55380.5057, 55380.6380, 55380.7041, 55380.7703, 55380.8364
								Epoch 1: 55283.2198, 55283.4846, 55283.6169, 55283.6830, 55283.8154, 55283.9477, 55284.3446

Table 1
(Continued)

Comet	Ecc	q (AU)	Incl (degree)	a (AU)	T_J	Earth MOID (AU)	Class	Observation MJDs (Exposure Mid-point Times)
C/2010 D4 (<i>WISE</i>)	0.8894	7.1482	105.659	64.66	−0.789	6.373	LPC	Epoch 2: 55399.5316, 55399.5976, 55399.6639, 55399.7300, 55399.8623, 55399.9285, 55400.2592
								Epoch 3 (post-cryo): 55573.6618, 55573.7941, 55573.9263, 55573.9264, 55573.9925, 55574.0586, 55574.1909, 55574.2570, 55574.3232, 55574.5877, 55574.8523
								Epoch 1: 55255.0178, 55255.1501, 55255.4809, 55255.5470, 55255.6795, 55255.7456, 55256.4072, 55256.5395, 55256.6719
								Epoch 2: 55381.6953, 55381.8276, 55381.9599, 55382.0261, 55382.1583, 55382.2906, 55382.3568, 55382.4229, 55382.6214, 55382.6875, 55382.7536, 55382.8859, 55383.0182, 55383.0844, 55383.1505, 55383.2167, 55383.2828, 55383.3490, 55383.4151, 55383.4812, 55383.4813, 55383.6135, 55383.7458
2010 KG43 (undesig. periodic comet)	0.4826	2.8894	13.616	5.584	2.695	1.876	JFC	
							(Chiron-type)	55336.4042, 55336.4043, 55336.5365, 55336.5366, 55336.6688, 55336.6689, 55336.8011, 55336.8673, 55336.9334, 55336.9996, 55337.0657, 55337.1319, 55337.1980, 55337.2642, 55337.3965, 55337.5288, 55337.6611
C/2014 C3 (<i>NEOWISE</i>)	0.9828	1.8620	151.783	108.5	−1.437	0.866	LPC	(re-activated) 56702.7097, 56702.8415, 56702.9073, 56702.9731, 56703.0390, 56703.1708, 56703.3024
P/2014 L2 (<i>NEOWISE</i>)	0.6464	2.2344	5.1844	6.32	2.498	1.223	JFC	(re-activated) 56815.4086, 56815.5402, 56815.6718, 56815.8034, 56815.9350, 56816.0007, 56816.0666, 56816.1324, 56816.1982, 56816.2639, 56816.3298, 56816.3956, 56816.4613, 56816.5271, 56816.6588, 56816.7904, 56816.9219, 56816.9220, 56817.0536
C/2014 N3 (<i>NEOWISE</i>)	0.9999	3.8774	61.642	40131.	1.160	2.884	LPC (Oort Cloud comet)	Epoch 1 (re-activated): 56841.6682, 56841.7997, 56841.9314, 56842.2603, 56842.3261, 56842.3918, 56842.4577, 56842.5235, 56842.5892, 56842.6550, 56842.7209, 56842.7866, 56842.9182, 56843.0498, 56843.1813
								Epoch 2(re-activated): 57003.7988, 57003.9302, 57004.0618, 57004.1932, 57004.2589, 57004.3246, 57004.3903, 57004.4562, 57004.5219, 57004.6533, 57004.7847, 57004.9162,
P/2015 J3 (<i>NEOWISE</i>)	0.5538	1.4941	8.125	3.348	2.876	0.499	JFC	(re-activated) 57157.0565, 57157.1877, 57157.1878, 57157.3190, 57157.4502, 57157.5815, 57157.7128, 57157.7784, 57157.8440, 57157.9097, 57157.9753, 57158.0408, 57158.0410, 57158.1065, 57158.1721, 57158.3034, 57158.4347, 57158.5660, 57158.6971, 57158.8284
Additional Comets with Tentative CO + CO ₂ Detections Based on 4.6 μ m Excess								
9P/Tempel 1	0.5116	1.5334	10.503	3.140	2.970	0.519	JFC	55296.0844, 55296.6798, 55296.2167, 55296.3490, 55296.8121, 55296.4813, 55296.6136, 55297.0768, 55296.9444, 55296.4151, 55295.9521, 55295.9520, 55296.6797, 55296.5474
10P/Tempel 2	0.5372	1.4179	12.029	3.064	2.964	0.406	JFC	55313.1161, 55313.2484, 55313.3807, 55313.5130, 55313.5132, 55313.6453, 55313.6455, 55313.7778, 55313.9101, 55314.0424, 55314.1747, 55314.3070, 55314.3731, 55314.4393, 55314.5054, 55314.5716, 55314.6377, 55314.6378, 55314.7039, 55314.7700, 55314.7701, 55314.8362, 55314.9023, 55314.9024, 55314.9685,

Table 1
(Continued)

Comet	Ecc	q (AU)	Incl (degree)	a (AU)	T_J	Earth MOID (AU)	Class	Observation MJDs (Exposure Mid-point Times)
29P/Schwassmann-Wachmann 1	0.0419	5.7580	9.3761	6.009	2.985	4.762	JFC	55315.0347, 55315.1008, 55315.1670, 55315.2331, 55315.2993, 55315.4316, 55315.5640, 55315.6963, 55315.8286, 55315.9609, 55316.0932, 55316.2255, 55316.3578, 55316.4901, 55322.5102, 55322.5763, 55322.5765, 55322.6425, 55322.7086, 55322.7088, 55322.8411, 55322.9734, 55323.1057, 55323.2380, 55323.3703, 55323.5026, 55323.6349, 55323.7672, 55323.8995, 55324.0318 55319.1040, 55319.2363, 55319.3686, 55319.5009, 55319.5672, 55319.6332, 55319.6995, 55319.7655, 55319.8318, 55319.9641, 55320.0964, 55320.2287
30P/Reinmuth 1	0.5012	1.8832	8.1227	3.775	2.838	0.900	JFC	55262.6049, 55262.7372, 55262.8695, 55262.8697, 55263.0020, 55263.1343, 55263.2004, 55263.2666, 55263.3327, 55263.3989, 55263.4651, 55263.5312, 55263.5974, 55263.7297, 55263.8620, 55263.9943, 55264.1266, 55264.1267, 55264.2591
65P/Gunn ^b	0.2607	2.8698	9.2362	3.882	2.987	1.857	JFC	55310.2078, 55310.3401, 55310.4724, 55310.6047, 55310.6709, 55310.8693, 55310.9355, 55311.0016, 55311.3325, 55311.4648, 55311.5971
67P/Churyumov-Gerasimenko	0.6410	1.2432	7.0402	3.4628	2.746	0.257	JFC	see Bauer et al. (2012a)
74P/Smirnova-Chernykh	0.1488	3.5419	6.6513	4.161	3.007	2.558	Encke-type	Epoch 1: 55214.7988, 55214.9311, 55215.0634, 55215.0635, 55215.1958, 55215.2619, 55215.3281, 55215.3943, 55215.5266, 55215.6589, 55215.7913, 55215.7914 Epoch 2: 55384.3289, 55384.4612, 55384.5935, 55384.7258, 55384.8581, 55384.9244
77P/Longmore	0.3579	2.3107	24.399	3.599	2.860	1.316	JFC	55320.9284, 55321.0607, 55321.1930, 55321.3253, 55321.3914, 55321.3915, 55321.4576, 55321.5238, 55321.5899, 55321.6561, 55321.7222, 55321.7884, 55323.8392, 55323.9715, 55324.2361, 55324.3022, 55324.3023, 55324.3684, 55324.8316, 55324.9639
81P/Wild 2	0.5380	1.5931	3.2390	3.449	2.879	0.599	JFC	Epoch 1 (four band): 55414.0950, 55414.2273, 55414.3596 Epoch 2 (three band): 55414.4919, 55414.6242, 55414.6903, 55414.7565, 55414.8226, 55414.8888, 55414.9549, 55415.0211, 55415.0872, 55415.1534, 55415.2195, 55415.3518, 55415.4841, 55415.6164, 55415.7487
94P/Russell 4	0.3643	2.2315	6.1847	3.511	3.003	1.249	Encke-type	55335.1146, 55335.1147, 55335.5115, 55335.5116, 55335.6438, 55335.6439, 55335.7761, 55335.7762, 55335.9084, 55335.9746, 55336.0407, 55336.1069, 55336.2392, 55339.0837, 55339.2821, 55339.3483, 55339.4806, 55339.5467, 55340.0759
100P/Hartley 1	0.4172	1.9909	25.662	3.416	2.851	0.985	JFC	55302.4044, 55302.4045, 55302.5368, 55302.6691, 55302.9337, 55302.9998, 55303.0000, 55303.0660, 55303.1323, 55303.1984, 55303.2646, 55303.3307, 55303.4630, 55303.5292, 55304.0584, 55304.0585, 55304.1908, 55304.3231, 55304.4554
103P/Hartley 2	0.6938	1.0642	13.604	3.475	2.641	0.072	JFC (NEO)	55326.3456, 55326.4779, 55326.6102, 55326.7425, 55326.8748, 55326.9409, 55327.0071, 55327.0732, 55327.1394, 55327.2055, 55327.2717, 55327.3378, 55327.4040, 55327.4701, 55327.6024, 55327.7347, 55327.8670, 55327.9994
107P/Wilson-Harrington	0.6238	0.9938	2.7824	2.642	3.082	0.047	Near-Earth Comet (NEC)	55244.6083, 55244.7408, 55244.8731, 55245.0054, 55245.1377, 55245.2700, 55245.3362, 55245.4024, 55245.4685, 55245.5347, 55245.6008, 55245.6009, 55245.6670, 55245.7332, 55245.7993,

Table 1
(Continued)

Comet	Ecc	q (AU)	Incl (degree)	a (AU)	T_J	Earth MOID (AU)	Class	Observation MJDs (Exposure Mid-point Times)
116P/Wild 4	0.3726	2.1851	3.6077	3.483	3.009	1.184	Encke-type	55245.8655, 55245.9317, 55245.9978, 55246.1301, 55246.2624, 55246.2626, 55246.3949, 55246.5272, 55246.6595, 55249.7692, 55249.8354, 55249.9015, 55249.9016, 55249.9677, 55250.0339, 55250.1000, 55250.1662, 55250.2325, 55250.2985, 55250.3648, 55250.4971, 55250.6294, 55250.7617, 55250.8940, 55250.8941 55302.5333, 55302.6656, 55302.6657, 55302.7980, 55302.9303, 55303.0626, 55303.1287, 55303.1949, 55303.2610, 55303.3272, 55303.3933, 55303.5256, 55303.5257
								55277.0276, 55277.5569, 55277.7553, 55277.7555, 55277.8216, 55277.8878, 55277.9539, 55278.0201, 55280.6003, 55280.7326, 55280.8649, 55280.8651, 55280.9974, 55281.1297, 55281.1958, 55281.2620, 55281.3281, 55281.3282, 55281.3943, 55281.4605, 55281.5266, 55281.5928, 55281.7251, 55281.8574, 55281.9897, 55282.1220
118P/Shoemaker-Levy 4	0.4284	1.9803	8.5131	3.464	2.960	1.011	JFC	55305.5752, 55305.8399, 55305.9722, 55306.0384, 55306.1045, 55306.3030, 55306.4353, 55306.5676, 55306.6999, 55306.8322 55381.6882, 55381.8205, 55381.9528, 55382.0851, 55382.2174, 55382.2835, 55382.3497, 55382.4158, 55382.4820, 55382.5481, 55382.6142, 55382.6143, 55382.6804, 55382.7465, 55383.3418, 55383.3419
143P/Kowal-Mrkos	0.4101	2.5382	4.6897	4.303	2.863	1.538	JFC	55322.4118, 55322.5441, 55322.5442, 55322.6764, 55322.6765, 55322.8087, 55322.8088, 55322.9411, 55323.0072, 55323.0734, 55323.1395, 55323.2057, 55323.2718, 55323.3380, 55323.4041, 55323.5364, 55323.6687, 55323.8010
149P/Mueller 4	0.3884	2.6509	29.734	4.334	2.661	1.728	JFC	55248.9756, 55249.1079, 55249.1742, 55251.6222, 55251.7545, 55251.8868, 55252.0191, 55252.1516, 55252.2177, 55252.2839, 55252.3500, 55252.4162, 55252.4824, 55252.6147, 55252.7470, 55252.8793
169P/NEAT	0.7669	0.6070	11.305	2.604	2.888	0.143	JFC (NEO)	55271.7351, 55271.8674, 55271.9997, 55271.9998, 55272.1982, 55272.2644, 55272.3305, 55272.7275, 55272.8598, 55272.9921, 55273.1244
203P/Korlevic	0.3147	3.1823	2.976	4.6435	2.912	2.1987	JFC	55367.8870, 55367.8872, 55368.0193, 55368.1516, 55368.2839, 55368.4162, 55368.5485, 55368.6809, 55368.7469, 55368.8132, 55368.8792, 55368.9455, 55369.0115, 55369.0778, 55369.1439, 55369.2099, 55369.2101, 55369.2762, 55369.3422, 55369.3424, 55369.4085, 55369.5408, 55369.6731, 55369.8054, 55369.9377, 55370.0699, 55370.0700, 55381.5794
217P/LINEAR	0.6896	1.2235	12.882	3.942	2.549	0.306	JFC (NEO)	55343.3181, 55343.4504, 55343.5827, 55343.7150, 55343.8473, 55343.9135, 55343.9796, 55344.0458, 55344.1119, 55344.1781, 55344.2442, 55344.3104, 55344.4427, 55344.5750, 55344.7072 ^a , 55344.7073, 55344.8395, 55344.8396
236P/LINEAR	0.5088	1.8311	16.334	3.7275	2.794	0.891	JFC	55211.3920, 55211.5244, 55211.6567, 55211.7890, 55211.8552, 55211.9213, 55211.9214, 55211.9875, 55212.0537, 55212.1198, 55212.1200, 55212.1860, 55212.2523, 55212.3846, 55212.5169, 55212.6493
P/2009 Q4 (Boattini)	0.5792	1.3208	10.969	3.139	2.901	0.361	JFC	55217.6080, 55217.7403, 55217.8726, 55218.0049, 55218.0050, 55218.1373, 55218.2034, 55218.2696, 55218.3358, 55218.4019,
P/2010 A3 (Hill)	0.7322	1.6218	15.028	6.057	2.278	0.670	JFC	
P/2009 T2 (La Sagra)	0.7690	1.7548	28.106	7.5960	2.048	0.822	JFC	

Table 1
(Continued)

Comet	Ecc	q (AU)	Incl (degree)	a (AU)	T_J	Earth MOID (AU)	Class	Observation MJDs (Exposure Mid-point Times)
P/2009 Y2	0.6405	2.3392	29.93	6.5071	2.288	1.357	JFC	55218.4681, 55218.5342, 55218.5344, 55218.6004, 55218.6667, 55218.7327, 55218.8652, 55218.9975, 55219.1298, 55220.7839, 55220.7840, 55220.9163, 55221.0486, 55221.1809, 55221.3133, 55221.3134, 55221.3795, 55221.4457, 55221.5118, 55221.5780, 55221.6442, 55221.7103, 55221.7765, 55221.8426, 55221.9088, 55222.0411, 55222.1734, 55222.1735, 55222.3059, 55222.4382
P/2010 A5	0.6643	1.7120	5.784	5.1001	2.493	0.711	JFC	55210.0061, 55210.0721, 55210.0723, 55210.1384, 55210.2707, 55210.4030, 55210.4031, 55210.5354
P/2010 H2 (Vales)	0.1929	3.1077	14.253	3.850	2.988	2.130	JFC	55215.8599, 55215.9922, 55216.1245, 55216.2570, 55216.3893, 55216.4554, 55216.4555, 55216.5216, 55216.5878, 55216.6539, 55216.7201, 55216.7863, 55216.8524, 55216.9848, 55217.1172, 55217.2495, 55217.3818
C/2005 L3 (McNaught)	0.9996	5.5936	139.449	13392.	−2.228	4.712	“Comet”	55383.0064, 55383.0065, 55383.1387, 55383.2710, 55383.4033, 55383.5356, 55383.6018, 55383.6679, 55383.7340, 55383.7341, 55383.8002, 55383.8663, 55383.9986, 55384.1309, 55384.2632, 55384.3955
C/2006 S3 (LONEOS)	1.0030	5.1311	166.033	−1688.7	−2.728	4.131	Hyperbolic Comet	55337.1708, 55340.2798, 55340.2799, 55340.4121, 55340.5444, 55340.6106, 55340.6767, 55340.7429, 55340.8090, 55340.8752, 55340.9413, 55341.0075, 55341.1398, 55341.2721, 55341.4044
C/2006 W3 (Christensen)	0.9998	3.1262	127.075	17989.	−1.321	2.299	“Comet”	55338.7823, 55338.9146, 55339.0469, 55339.1792, 55339.2453, 55339.2454, 55339.3115, 55339.3776, 55339.3777, 55339.4438, 55339.5099, 55339.5100, 55339.6422, 55339.6423, 55339.7745
C/2007 G1 (LINEAR)	1.0015	2.6462	88.359	−1783.0	...	1.843	Hyperbolic Comet	55305.9747, 55306.1070, 55306.2393, 55306.4377, 55306.4378, 55306.5039, 55306.5701, 55306.7024, 55306.8347
C/2007 Q3 (Siding Spring)	1.0002	2.2517	65.650	−9454.1	0.767	1.262	Hyperbolic Comet	55240.4971, 55240.9603, 55241.0264, 55241.0926, 55241.1588, 55241.2249, 55241.2911, 55241.3572, 55241.3573, 55241.4234, 55241.4897, 55241.6220, 55241.7543
C/2007 VO53 (Spacewatch)	0.999603	4.8427	86.995	12194.4	0.143	4.499	“Comet”	Epoch 1: 55206.1909, 55206.2570, 55206.3232, 55206.3894 Epoch 2: 55349.1498, 55349.2821, 55349.4144, 55349.5467, 55349.6790, 55349.7451, 55349.7452, 55349.8113, 55349.8774, 55349.9436, 55350.0097, 55350.0759, 55350.1420, 55350.2082, 55350.2743, 55350.3405, 55350.4066, 55350.4728, 55350.5389, 55350.6051, 55350.6712, 55350.7373, 55350.7374, 55350.8035, 55350.8696, 55350.8697, 55350.9358, 55351.0019, 55351.0681, 55351.1342, 55351.2004, 55351.2665, 55351.3327, 55351.3988, 55351.4650, 55351.5311, 55351.5973, 55351.6634, 55351.7296, 55351.8618, 55351.8619, 55351.9941, 55351.9942, 55352.1264, 55352.2587
C/2008 FK75 (Lemmon-Siding Spring)	1.0027	4.5109	61.175	−1670.3	...	4.056	Hyperbolic Comet	55219.3447, 55219.5433, 55219.6093, 55221.0651, 55221.1974, 55221.3297, 55221.3298, 55221.3959, 55221.5944, 55221.6606, 55221.7267, 55221.7929, 55221.8590, 55221.8592, 55221.9252, 55221.9915, 55222.0575, 55222.1238, 55222.2561, 55222.3223, 55222.3884, 55222.3885, 55222.5869, 55222.7193
C/2008 N1 (Holmes)	0.9971	2.7835	115.521	973.12	−0.885	2.351	“Comet”	55273.5466, 55273.5467, 55273.6790, 55273.8113, 55273.9436, 55274.0097, 55274.0759, 55274.1420, 55274.1421, 55274.2082, 55274.2744, 55274.3405, 55274.4067, 55274.4728, 55274.5390, 55274.6051, 55275.2006

Table 1
(Continued)

Comet	Ecc	q (AU)	Incl (degree)	a (AU)	T_J	Earth MOID (AU)	Class	Observation MJDs (Exposure Mid-point Times)
								Epoch 1: 55228.2909, 55228.7541, 55228.8203, 55228.8864, 55229.0187, 55229.0188, 55229.1511, 55232.9888
								Epoch 2: 55351.5219, 55351.6541, 55351.6542, 55351.7864, 55351.9187, 55351.9849, 55352.0510, 55352.1172, 55352.1833, 55352.2495, 55352.3817, 55352.3818, 55352.5140
C/2008 Q3 (Garradd)	0.9998	1.7982	140.707	8926.0	−1.286	0.814	“Comet”	55307.9318, 55310.8425, 55310.8426, 55310.9087, 55310.9749, 55311.0410, 55311.1072, 55311.2395, 55311.3718, 55311.5041
C/2009 F6	0.9975	1.274	85.765	512.2	0.113	0.505	LPC	55256.2415, 55256.3738, 55256.5061, 55256.5724, 55256.6384, 55256.7047, 55256.7708, 55256.7709, 55256.8370, 55256.9032, 55256.9693, 55257.0355, 55257.1017, 55257.2340, 55257.3001, 55257.3663, 55257.4986, 55257.5648, 55257.6309, 55257.6971, 55257.7633, 55257.8957, 55258.0280
C/2009 K5 (McNaught)	1.0008	1.4224	103.879	−1694.6	...	0.798	Hyperbolic Comet	(post-cryo) 55482.4446, 55482.5768, 55482.7091, 55482.7752, 55482.8414, 55482.9075, 55482.9736, 55482.9737, 55483.0398
C/2009 P1 (Garradd)	1.0002	1.5513	106.168	−6285.8	−0.432	1.255	Hyperbolic Comet	55351.6232, 55354.1369, 55354.2692, 55354.5999, 55354.6661, 55354.7322, 55354.7985, 55354.8645, 55354.9968, 55355.1291, 55355.2615
C/2009 U3 (Hill)	0.9916	1.4144	51.261	167.88	0.952	0.868	“Comet”	55212.1920, 55212.3243, 55212.4568, 55212.5229, 55212.5891, 55212.6553, 55212.7214, 55212.7876, 55212.9199, 55213.0523, 55213.1846
C/2010 J1 (Boattini)	0.9538	1.6957	134.385	36.723	−0.975	0.735	“Comet”	Epoch 1: 55287.9769, 55288.1092, 55288.1093, 55288.2416, 55288.3077, 55288.3738, 55288.3739, 55288.4400, 55288.5723, 55288.7046 Epoch 2: 55378.1164, 55378.2487, 55378.3810, 55378.4471, 55378.5133, 55378.5794, 55378.6456, 55378.7117, 55378.8440, 55378.9763

Note.

^a Orbital properties and observation dates of comets discovered, or with activity discovered, by *WISE/NEOWISE*, and of comets with noted 4.6 μm excess detected during the prime mission. Orbital properties were recorded from JPL’s Small Body Database (<http://ssd.jpl.nasa.gov/sbdb.cgi>) on 2015 May 15. The orbital properties include the comet’s orbital eccentricity (Ecc), perihelion distance (q) in AU, orbital inclination (Incl) in degrees, orbital semimajor axis (a) in AU, Minimum Earth-orbit intersect distance (MOID) in AU, the Jupiter Tisserand parameter, and the comet’s dynamical classification. Comet names are in the IAU-standard format. If an object was observed at multiple epochs these are tabulated separately in the observation dates column, as are the phases of the mission for each epoch if any were not in the fully cryogenic mission phase.

^b Note that the orbit of comet 65P/Gunn has changed significantly since the *WISE* observations in 2010.

In the first year, the reactivated *NEOWISE* mission has discovered three new active comets. These comets (each called *NEOWISE*) were discovered from their $4.6\ \mu\text{m}$ signal, and so may have yet a different set of selection biases apart from those found in the prime mission or ground-based searches. A fourth comet, P/2015 J3 (*NEOWISE*) was discovered on 2015 May 15, after the first submission of this manuscript.

2.3. Comets with Significant $4.6\ \mu\text{m}$ Signal

Throughout the fully cryogenic portion of the *WISE/NEOWISE* mission most comets exhibited their highest S/N in the 12 and $22\ \mu\text{m}$ channels, as the dust, often dark and composed of refractory grains (see Bauer et al. 2011, 2012a), provided strong thermal signal relative to the background. However, a total of 56 comets showed some signal in the $4.6\ \mu\text{m}$ channel, and often also at $3.4\ \mu\text{m}$. While dust thermal emission dominates the 12 and $22\ \mu\text{m}$ bands, the $3.4\ \mu\text{m}$ channel is dominated by the reflected light of the dust. Weak molecular emission lines, primarily from O–H and C–H related species, fall within this channel, but this signal typically is significantly less than that of the dust signal, i.e., $\sim 30\%$ or less of the total signal (see Bockelée-Morvan et al. 1995; Reach et al. 2013). However, strong molecular emission lines of CO ($4.67\ \mu\text{m}$) and CO₂ ($4.23\ \mu\text{m}$) exist within the $4.6\ \mu\text{m}$ bandpass (see Pittichova et al. 2008; Bauer et al. 2011, and Reach et al. 2013). The CO and CO₂ emission bands are strong enough to manifest excess flux within the $4.6\ \mu\text{m}$ channel, apparent when the dust signal contribution is constrained by the $3.4\ \mu\text{m}$ signal and the 12 and $22\ \mu\text{m}$ thermal flux. Often, there are additional morphological differences between the $4.6\ \mu\text{m}$ signal and the other bands. Moreover, the shape of the comets in the $3.4\ \mu\text{m}$ channel often matches better the 12 and $22\ \mu\text{m}$ signal, likely attributable to dust (Figure 2).

A total of 39 comets observed during the prime mission exhibited $4.6\ \mu\text{m}$ band flux excess, attributable to CO to CO₂ emission; two of the comets, C/2009 K5 and C/2010 FB87, exhibited $4.6\ \mu\text{m}$ band excess in the post-cryo mission observations. A quarter of the comets observed during the prime mission, then, exhibited $4.6\ \mu\text{m}$ excess. The rate of occurrence of W2 excess differed for the comets observed thus far during the *NEOWISE*-Reactivation mission, which are about 2/3rds of the total (Bauer et al. 2014). However, the match is nearly identical among the prime and reactivated mission comets observed with any significant W2 signal; both samples have $\sim 2/3$ with $4.6\ \mu\text{m}$ excess. We included in our sample of W2 excess the comets *NEOWISE* from the reactivated mission, three of which show $4.6\ \mu\text{m}$ excess.

3. ANALYSIS

The *WISE* image data were processed using the scan/frame pipeline, which applied instrumental, photometric, and astrometric calibrations (Cutri et al. 2012). Image stacking and photometric analysis was conducted as in previous analyses (Bauer et al. 2011, 2012a, 2012b, 2013; Stevenson et al. 2012, 2015). The images were visually inspected and compared to the *WISE* Atlas (see Cutri et al. 2012) to ensure there were no inertially fixed background sources. Aperture photometry was performed on the stacked images of the 25 discovered comets and the 42 additional comets with $4.6\ \mu\text{m}$ signal. Aperture radii of 9, 11, and 22 arcsec were used, the aperture sizes necessary

to obtain the full signal from W3 and W4, the poorest resolution *WISE* bands.

3.1. Flux Values

The counts were converted to fluxes using the band-appropriate magnitude zeropoints and 0th magnitude flux values provided in Wright et al. (2010). An iterative fitting to a blackbody curve was conducted on the two long-wavelength bands to determine the appropriate color correction as listed in the same. The extracted magnitudes for the 11 arcsec aperture were then converted to fluxes (Wright et al. 2010; Mainzer et al. 2011b) and are listed in Table 2. Proper aperture corrections are required for accurate photometry (Cutri et al. 2012), in addition to the color corrections mentioned above. With these corrections, the derived magnitudes are equivalent to the profile-derived magnitudes providing there are no artifacts, saturation, or confusion with other sources in the apertures of the objects.

3.2. Nucleus Sizes

In order to extract the nucleus signal for the *WISE/NEOWISE* comet discoveries, we used routines developed by our team (Lisse et al. 1999 and Fernandez et al. 2000) to fit the coma as a function of angular distance from the central brightness peak along separate azimuths, as applied in Bauer et al. (2011, 2012a). As per the description in Lisse et al. (1999), the model dust coma was created using the functional form $f(\Theta) \times \rho^{-n}$, where ρ is the projected distance on the sky from the nucleus and Θ is the azimuthal angle. In order to compensate for the *WISE* instrumental effects, the model coma was then convolved with the instrumental PSF appropriate for AWAIC co-added images for the matching phase of the mission (see Cutri et al. 2012). Radial cuts through an image of the comet were made every 3° in azimuth, and the best-fit radial index, n , and scale, f , at each specific azimuth were found by a least-squares minimization fit of the model to the data along that azimuth. The pixels between 5 and 20 arcsec of the brightness peak were used to fit the model coma. For most comets, the coma model fit residuals yielded uncertainty in the photometry of the extracted point-source $\sim 10\%$ for the W3 and W4 images; these uncertainties were similar to the photometric uncertainties in the combined nucleus and coma signals. However, higher residuals $\sim 30\%$ were seen for comets C/2010 L5 and C/2010 J4, and are therefore noted as possible upper limits to the nucleus sizes. We also note below that *WISE* imaged the predicted position of C/2010 L5 in January, before its discovery and did not detect the comet. The detection threshold is less than, but on the order of, the listed nucleus size in Table 3 (E. Kramer et al. 2015, in preparation).

The extracted nucleus signals in W3 and W4 were fit to a NEATM model (Harris 1998; Delbo & Harris 2002; and Mainzer et al. 2011b) with fixed beaming (η) parameters. The fits to only 2 extracted thermal flux points, with increased uncertainties from the raw extractions, were too poorly constrained to leave η as a free parameter to the fit such that it converged to physically realistic values between 0.5 and 3.0. For each comet, fits were used with beaming parameter values fixed to 0.8, 1.2 (Stansberry et al. 2008), and 1.0 (Fernandez et al. 2013). Note that each attempt of a fit requires an interpolation for surface temperature in the *WISE* bands (Wright et al. 2010), so that different flux values are derived

Figure 2. Morphological differences for comet C/2007 Q3 (Siding Spring); see Tables 1 and 2 for observation times and distances. The top three panels (left to right) show $3.4\ \mu\text{m}$ image contours (green) overlaid onto $W1$, $W2$ (blue contours), and $W3$ (red contours) band images. The bottom panels show (from left to right) the peak-normalized difference images of $W2-W1$, $W2-W3$, and $W1-W3$. Note the miss-match between shape of the contours of $W2$ and $W3$ in the top panels, and the better match between the contours of $W1$ and $W3$. Also, note the asymmetries in the difference images for $W2$ that are not present in the $W1-W3$ image. $W1$ and $W3$ trace the dust, while a more spherical component, likely gas emission, is present in the $W2$ flux. Note also the point-spread function’s width is larger in $W3$ than in $W1$ or $W2$. This is the cause of the brightness peak and more extended dark regions when $W3$ is subtracted from $W1$ in the lower right panel.

for each final fit. Table 3 presents the fit results and uncertainties, while it should be noted that, owing to the uncertainty inherent in the thermal models, there is an additional $\sim 10\%$ uncertainty in the derived diameter values (Mainzer et al. 2011b, 2011c). The interpolated corrections for temperature are largest in $W3$. Note that for P/2015 J3 (*NEOWISE*), the size was based on the $W2$ signal assuming no coma contamination for an object with a beaming parameter of 1.

Unlike the asteroids, in most cases the visual band magnitudes of the nuclei were unmeasured. Nuclei were either obscured by activity at shorter wavelengths, or were not measured at distances where they were inactive. Since only the 12 and $22\ \mu\text{m}$ channel images were used (except for P/2015 J3), the albedo was relatively unconstrained. For the thermal fits of the diameters, the geometric visible albedo (p_v) was free, but always converged near the initial condition of a few percent. We used the beaming parameter that provided the smallest fit residuals; those η values are listed in Table 3. An assumed 0.2 uncertainty in h is included in the listed diameter uncertainty. However, the uncertainty in p_v would have negligible effect, and so no uncertainty from that term is included with the diameter values listed in Table 3.

3.3. Dust Photometry, Temperature, and $\text{CO} + \text{CO}_2$ Production Measurements

From the total *NEOWISE*/*WISE* observed sample of comets during the prime mission, 62 comets (or 38%) showed significant signal in $W2$, as shown in Tables 1 and 2. Not all

comets that show significant signal in $W2$ have significant $4.6\ \mu\text{m}$ flux excess. Some of the signal in $W2$ is due to the thermal and reflected light emission of the dust. In order to constrain the dust (and potentially nucleus) thermal and reflected light flux component, it is necessary to extrapolate from the thermal and shorter wavelengths. We fit a Planck function to the $W3$ and $W4$ flux, and a solar spectrum to the $W1$ flux for each comet. Using these two components, we determined the predicted flux at $W2$ (see Figure 3). We consider the flux in excess of the dust (and nucleus) signal when the flux is significantly (at the 3σ level) above the estimated dust and nucleus signal. We use this criterion to be certain of the excess. For those few cases (107P, 169P, and C/2009 F6) where there is weak or no significant $W1$ signal, we calculate the reflected light signal from the dust thermal signal and assume a corresponding emissivity of 0.9, and a surface reflectance of ~ 0.1 to convert this to a reflected light component. For the objects lacking thermal flux measurements (C/2014 C3, P/2014 L2, C/2014 N3, and C/2009 K5), we make the reverse assumptions and extrapolate the thermal component (Stevenson et al. 2015). Using these methods, 42 comets show $W2$ excess. The excess flux is then converted into CO_2 production estimates using the method described in Bauer et al. (2011, 2012a, 2012b).

We noted in Section 2.3 that the $3.4\ \mu\text{m}$ coma signal is likely dominated by dust. However we note here that though that is probably true in most cases when the comet has a moderate to high dust-to-gas ratio, for rare gassy comets it may be that a small but significant component of the signal may be due to

Table 2
Comet Flux Measurements

Comet	W1 Flux (mJy)	W2 Flux (mJy)	W3 Flux (mJy)	W4 Flux (mJy)	Apparent Activity? (Y/N/U)	Image Stack Mid-point (MJDs)
P/2010 K2	0.24 $\pm$ -0.03	2.2 $\pm$ -0.5	41 $\pm$ -8	67 $\pm$ -12	Y	55344.2734
P/2010 D1	...	...	2.7 $\pm$ -0.5	17 $\pm$ -3	Y	55244.9688
P/2010 D2	0.05 $\pm$ -0.01	...	1.9 $\pm$ -0.4	21 $\pm$ -4	Y	55244.9688
P/2010 B2	...	0.24 $\pm$ -0.06	11 $\pm$ -2	26 $\pm$ -5	Y	55219.3984
	...	...	1.6 $\pm$ -0.3	4 $\pm$ -1	U	55413.0013
245P	...	...	5 $\pm$ -1	17 $\pm$ -3	Y	55351.7173
P/2010 N1	0.10 $\pm$ -0.02	0.7 $\pm$ -0.2	20 $\pm$ -4	42 $\pm$ -8	Y	55383.0741
233P	0.10 $\pm$ -0.02	0.15 $\pm$ -0.04	9 $\pm$ -2	24 $\pm$ -5	Y	55233.7908
P/2009 WX51	0.16 $\pm$ -0.03	0.7 $\pm$ -0.2	12 $\pm$ -2	23 $\pm$ -4	Y	55289.0044
C/2010 E3	...	...	5 $\pm$ -1	21 $\pm$ -4	N	55260.4630
C/2010 J4	0.5 $\pm$ -0.1	1.5 $\pm$ -0.4	55 $\pm$ -11	92 $\pm$ -22	Y	55317.6396
	0.4 $\pm$ -0.05	2.3 $\pm$ -0.5	99 $\pm$ -18	140 $\pm$ -25	Y	55328.4101
C/2010 L4	...	...	7 $\pm$ -1	38 $\pm$ -7	Y	55363.0185
C/2010 L5	0.04 $\pm$ -0.01	0.4 $\pm$ -0.1	18 $\pm$ -3	52 $\pm$ -10	Y	55361.4543
	0.8 $\pm$ -0.1	6 $\pm$ -1	180 $\pm$ -33	360 $\pm$ -66	Y	55393.9793
C/2010 D3	0.025 $\pm$ -0.08	...	0.8 $\pm$ -0.2	17 $\pm$ -3	Y	55253.8536
	...	...	1.8 $\pm$ -0.3	22 $\pm$ -4	Y	55382.7616
C/2010 DG56	.13 $\pm$ -0.02	.13 $\pm$ -0.04	3.0 $\pm$ -0.6	9 $\pm$ -2	N	55245.2326
	.16 $\pm$ -0.02	.8 $\pm$ -0.2	74 $\pm$ 13	145 $\pm$ -27	Y	55403.7753
C/2010 KW7	...	...	1.5 $\pm$ -0.3	7 $\pm$ -2	N	55224.4338
	...	...	5.0 $\pm$ -0.9	17 $\pm$ -3	N	55332.3477
P/2010 JC81	0.1 $\pm$ -0.02	0.14 $\pm$ -0.04	12 $\pm$ -2	52 $\pm$ -10	N	55327.4473
P/2010 P4	...	...	4 $\pm$ -0.7	13 $\pm$ -3	Y	55414.9204
237P	...	...	4.7 $\pm$ -0.9	21 $\pm$ -4	Y	55357.9983
C/2010 G3	...	...	0.9 $\pm$ -0.2	23 $\pm$ -5	Y	55301.1636
	...	...	2.6 $\pm$ -0.5	26 $\pm$ -5	Y	55381.0017
C/2010 FB87	...	...	2.9 $\pm$ -0.5	26 $\pm$ -5	Y	55283.7822
	0.9 $\pm$ -0.1	0.6 $\pm$ -0.1	12 $\pm$ -2	142 $\pm$ -26	Y	55399.8954
	0.9 $\pm$ -0.2	1.2 $\pm$ -0.3	...	...	Y	55574.2571
C/2010 D4	...	...	0.9 $\pm$ -0.2	16 $\pm$ -3	N	55255.8449
	...	...	0.6 $\pm$ -0.1	18 $\pm$ -4	N	55381.8276
C/2014 C3	0.28 $\pm$ -0.03	1.0 $\pm$ -0.2	...	...	Y	56703.0061
P/2014 L2	1.0 $\pm$ -0.2	10 $\pm$ -2	...	...	Y	56816.2311
C/2014 N3	0.24 $\pm$ -0.06	.37 $\pm$ -0.09	...	...	Y	56842.4248
	0.86 $\pm$ -0.19	1.2 $\pm$ -0.3	...	...	Y	57004.0486
C/2015 J3	0.11 $\pm$ -0.03	.43 $\pm$ -0.11	...	...	U	57157.9097
Short-period Comets						
9P	0.10 $\pm$ -0.02	0.22 $\pm$ -0.06	18.7 $\pm$ -3.4	46 $\pm$ -9	Y	55296.2167
10P	3.1 $\pm$ -0.3	21 $\pm$ -5	924 $\pm$ -170	1109 $\pm$ -203	Y	55314.7701
29P	1.39 $\pm$ -0.14	3.17 $\pm$ -0.72	50 $\pm$ -9	1316 $\pm$ -241	Y	55317.4994
30P	0.91 $\pm$ -0.09	3.04 $\pm$ -0.69	277 $\pm$ -50	678 $\pm$ -124	Y	55263.3989
65P	2.10 $\pm$ -0.20	8.41 $\pm$ -1.89	209 $\pm$ -38	1499 $\pm$ -275	Y	55310.9025
67P	0.01 $\pm$ -0.007	0.18 $\pm$ -0.05	10.2 $\pm$ -0.4	50 $\pm$ -4	Y	55225.130
74P	0.21 $\pm$ -0.03	0.23 $\pm$ -0.06	19.3 $\pm$ -3.5	157 $\pm$ -29	Y	55215.2620
	0.28 $\pm$ -0.04	0.39 $\pm$ -0.10	21.5 $\pm$ -3.9	196.7 $\pm$ -36.3	Y	55384.5936
77P	0.10 $\pm$ -0.02	0.14 $\pm$ -0.04	15.2 $\pm$ -2.8	78.6 $\pm$ -14.7	Y	55321.6562
81P	3.63 $\pm$ -0.34	9.92 $\pm$ -2.22	446 $\pm$ -82	2386 $\pm$ -437	Y	55414.2273
94P	0.20 $\pm$ -0.03	0.54 $\pm$ -0.13	35 $\pm$ -6	171 $\pm$ -32	Y	55337.5953
100P	0.16 $\pm$ -0.02	0.28 $\pm$ -0.07	14 $\pm$ -3	36 $\pm$ -7	Y	55303.1984
103P	0.08 $\pm$ -0.01	0.31 $\pm$ -0.08	11.1 $\pm$ -2.0	34.1 $\pm$ -6.5	Y	55327.1395
107P	...	0.44 $\pm$ -0.10	42.2 $\pm$ -7.7	67 $\pm$ -13	N	55245.9978
116P	0.23 $\pm$ -0.03	0.31 $\pm$ -0.08	24.6 $\pm$ -4.5	206 $\pm$ -38	Y	55303.0296
118P	1.47 $\pm$ -0.14	3.85 $\pm$ -0.87	124 $\pm$ -23	744 $\pm$ -137	Y	55279.5749
143P	...	0.09 $\pm$ -0.03	10.9 $\pm$ -2.0	57 $\pm$ -11	N	55306.2038
149P	0.07 $\pm$ -0.01	0.12 $\pm$ -0.03	5.8 $\pm$ -1.1	42 $\pm$ -8	U	55382.5151
169P	...	0.35 $\pm$ -0.08	16 $\pm$ -3	49 $\pm$ -9	N	55323.1064
203P	0.27 $\pm$ -0.03	0.14 $\pm$ -0.04	20 $\pm$ -4	216 $\pm$ -40	Y	55252.2508
217P	0.21 $\pm$ -0.03	0.54 $\pm$ -0.13	28.4 $\pm$ -5.2	180 $\pm$ -33	Y	55272.4298
236P	0.05 $\pm$ -0.01	0.21 $\pm$ -0.05	13.2 $\pm$ -2.4	25.2 $\pm$ -4.9	Y	55316.6008

Table 2
(Continued)

Comet	W1 Flux (mJy)	W2 Flux (mJy)	W3 Flux (mJy)	W4 Flux (mJy)	Apparent Activity? (Y/N/U)	Image Stack Mid-point (MJDs)
P/2009 Q4	0.05 $\pm$ 0.01	0.11 $\pm$ 0.03	4.0 $\pm$ 0.7	20 $\pm$ 4	Y	55344.0789
P/2009 T2	0.41 $\pm$ 0.05	1.58 $\pm$ 0.36	130 $\pm$ 24	245 $\pm$ 45	Y	55219.1298
P/2009 Y2	0.08 $\pm$ 0.02	0.16 $\pm$ 0.04	10 $\pm$ 2	55.1 $\pm$ 10.4	U	55210.2707
P/2010 A3	0.26 $\pm$ 0.03	0.77 $\pm$ 0.18	35.0 $\pm$ 6.4	143 $\pm$ 26	Y	55212.0207
P/2010 A5	0.26 $\pm$ 0.03	0.97 $\pm$ 0.22	100 $\pm$ 18	229 $\pm$ 42	Y	55216.6539
P/2010 H2	0.30 $\pm$ 0.04	0.34 $\pm$ 0.08	14.1 $\pm$ 2.6	184 $\pm$ 34	Y	55383.7010
Long-period Comets						
C/2005 L3	.16 $\pm$.02	.21 $\pm$.05	1.2 $\pm$ 0.2	79 $\pm$ 15	Y	55340.7430
C/2006 S3	.17 $\pm$.02	.18 $\pm$.05	1.4 $\pm$ 0.2	105 $\pm$ 20	Y	55339.2785
C/2006 W3	5.4 $\pm$ 0.5	10.2 $\pm$ 2.3	239 $\pm$ 44	4679 $\pm$ 856	Y	55306.4048
C/2007 G1	0.04 $\pm$ 0.01	0.11 $\pm$ 0.03	1.1 $\pm$ 0.2	48 $\pm$ 9	Y	55241.1257
C/2007 Q3	14 $\pm$ 1	25 $\pm$ 6	2670 $\pm$ 490	10250 $\pm$ 1880	Y	55206.2567
	1.17 $\pm$ 0.12	1.40 $\pm$ 0.32	84 $\pm$ 15	1039 $\pm$ 190	Y	55350.7043
C/2007 VO53	0.15 $\pm$ 0.02	0.09 $\pm$ 0.03	1.3 $\pm$ 0.2	52 $\pm$ 10	Y	55221.0320
C/2008 FK75	0.25 $\pm$ 0.03	0.19 $\pm$ 0.05	4.7 $\pm$ 0.9	149 $\pm$ 28	Y	55274.3736
C/2008 N1	0.25 $\pm$ 0.03	0.30 $\pm$ 0.07	17.2 $\pm$ 3.2	178 $\pm$ 33	Y	55230.6399
	0.10 $\pm$ 0.02	0.17 $\pm$ 0.04	3.0 $\pm$ 0.6	52 $\pm$ 10	Y	55352.0180
C/2008 Q3	0.08 $\pm$ 0.01	0.37 $\pm$ 0.09	5.9 $\pm$ 1.1	93 $\pm$ 17	Y	55309.7180
C/2009 F6	...	0.02 $\pm$ 0.01	1.0 $\pm$ 0.2	25 $\pm$ 5	Y	55256.9693
C/2009 K5	1.47 $\pm$ 0.33	4.46 $\pm$ 1.14	...	...	Y	55482.7423
C/2009 P1	0.35 $\pm$ 0.04	0.67 $\pm$ 0.16	4.4 $\pm$ 0.8	221 $\pm$ 41	Y	55353.4424
C/2009 T1	0.07 $\pm$ 0.01	0.06 $\pm$ 0.02	0.37 $\pm$ 0.07	27.2 $\pm$ 5.2	Y	55211.2139
C/2009 U3	0.69 $\pm$ 0.07	2.82 $\pm$ 0.64	56 $\pm$ 10	192 $\pm$ 36	Y	55212.6884
C/2010 J1	1.13 $\pm$ 0.12	2.97 $\pm$ 0.67	230 $\pm$ 42	521 $\pm$ 96	Y	55288.3078
	0.06 $\pm$ 0.01	0.45 $\pm$ 0.11	36 $\pm$ 7	85 $\pm$ 16	Y	55378.5134

Note. Fluxes from stacked images of comets observed by *WISE/NEOWISE*. If an object was observed at multiple epochs these are tabulated separately in the observation dates column. Apertures of 11 arcsec in radius were used for the flux values, and the uncertainties were derived from the background noise statistics measured in the stacked images. Whether the comet had apparent coma (Y = Yes, N = No, U = Uncertain), and the mid-point times of each combined image set from each visit are listed in the table's last two columns.

Table 3
Nucleus Sizes of the Cryogenic Mission Cometary Discoveries

Comet	Diameter (km)	η	p_v	Comments
P/2010 D1	2.53 $\pm$ 0.89	1.2	0.04	...
P/2010 D2	4.65 $\pm$ 1.05	1.2	0.04	...
P/2010 B2	0.99 $\pm$ 0.22	1.2	0.04	...
245P	1.50 $\pm$ 0.33	1.2	0.04	...
P/2010 N1	0.86 $\pm$ 0.26	0.8	0.04	...
233P	1.08 $\pm$ 0.22	1.2	0.04	...
P/2009 WX51	0.43 $\pm$ 0.10	1.2	0.04	...
C/2010 E3	1.73 $\pm$ 0.36	1.2	0.04	No coma seen during <i>WISE</i> observations; JPL Horizon's nucleus magnitude yields $p_v = 0.023 \pm 0.01$
C/2010 J4	0.56 $\pm$ 0.2	1.2	0.03	possible upper limit
C/2010 L4	3.4 $\pm$ 0.72	1.2	0.04	...
C/2010 L5	2.2 $\pm$ 0.86	1.0	0.05	possible upper limit
C/2010 D3	4.3 $\pm$ 0.96	1.0	0.04	...
C/2010 DG56	1.51 $\pm$ 0.27	1.2	0.04	No coma seen; JPL Horizon's nucleus visible magnitude yields $p_v = 0.021 \pm 0.005$
C/2010 KW7	5.69 $\pm$ 1.6	1.0	0.04	JPL Horizon's nucleus magnitude yields $p_v = 0.025 \pm 0.005$
P/2010 JC81	15.7 $\pm$ 4.74	0.8	0.03	No coma seen; JPL Horizon's nucleus visible magnitude yields $p_v = 0.03 \pm 0.02$
P/2010 P4	0.94 $\pm$ 0.16	1.2	0.05	...
237P	2.06 $\pm$ 0.34	1.0	0.04	...
C/2010 G3	7.84 $\pm$ 1.44	1.2	0.04	...
C/2010 FB87	4.88 $\pm$ 1.12	1.2	0.04	...
C/2010 D4	25.6 $\pm$ 6.8	0.8	0.05	No coma seen; JPL Horizon's nucleus visible magnitude yields $p_v = 0.05 \pm 0.02$
P/2010 K2	0.74 $\pm$ 0.11	1.0	0.05	...
P/2015 J3	2.3 $\pm$ 0.82	1.0	0.02	No coma seen during <i>NEOWISE</i> observations; JPL Horizon's nucleus magnitude yields $p_v = 0.02 \pm 0.02$

Figure 3. *WISE* 4.6 μm band (W2) contains CO 4.7 μm and CO₂ 4.3 μm emission lines. C/2009 P1 Garradd’s 4.6 μm band excess is not consistent with reflected or thermal contributions of coma or nucleus, but is consistent with CO₂ and CO emission. The flux from the 3.4 μm (left red triangle), 4.6 μm (right orange triangle), 12 μm (left orange diamond) and 22 μm (right orange diamond) channels are shown. Also the reflected light model (dotted line) thermal model (solid line) and combined signal (dashed line) are over-plotted.

weak emission lines, leading to an overall significant contribution to the signal by emissions from organics and OH. Because this is the only reflected light baseline point, the 3.4 μm -based dust reflected light scaling could lead to uncertainties in the baseline fit in some cases. The result would be an underestimate of the CO + CO₂ production. We also note, however, the case of C/2006 W3 (Christiansen), which had a reportedly high gas content (see de Val-Borro et al. 2014), yet for which we had no significant W1 signal, and derived a high CO + CO₂ production.

The CO₂ production rates (Q_{CO_2}) are provided as a proxy for the combine CO + CO₂ production (see Section 4.6), and as a convenience for analysis of the behavior of the comets, with noted limitations regarding the true fraction of the CO and CO₂ species present. The listed uncertainties in the derived CO₂ production rates are the combination of two components. The first component is the uncertainty in the calculated dust contribution as constrained by the W1, W3, and W4 photometry, a comparatively small component owing to the requirement that the flux is significantly (at the 3σ level) above the estimated dust and nucleus signal. The second component in the listed uncertainty is from the uncertainty in the W2 signal photometry, and is added in quadrature with the dust model uncertainty. Possible systematic sources of uncertainties, such as large variations in the fraction of CO relative to CO₂ or contributions to the W1 flux from non-dust signal, are not included in the tabulated uncertainty values.

Lisse et al. (1998) demonstrated how broadband photometry can be applied to determine the quantity and temperature of the coma dust. As in Bauer et al. (2011, 2012a, 2012b), we performed blackbody temperature fits to the dust coma region surrounding the nucleus, extracting the W3 and W4 measured nucleus flux contribution from the thermal signal. We calculate the effective area for the dust using 9, 11, and 22 arcsec radius apertures. For the thermal bands, this derived area has a factor of the emissivity, ϵ , incorporated into the result. Division by the projected length scale of the apertures, i.e., the ρ value, and by the constant π , provides an aperture-independent means of comparison to the quantity of dust visible at particular wavelengths analogous to $A_f\rho$ (A’Hearn et al. 1984). We call

this factor $\epsilon f\rho$, as introduced by Lisse et al. (2002) and used in Kelley et al. (2013), which is listed in Table 4. The value of $\epsilon f\rho$ assumes that the observed flux is attributable primarily to the dust continuum emission and is the product of the emissivity, ϵ , the fractional area within an aperture filled by the dust, f , and the projected length scale of the aperture radius on the sky at the distance of the comet, ρ , expressed in centimeters. We compute our $\epsilon f\rho$ values multiplying the observed surface brightness of the comet, I_λ , by ρ and dividing by the Planck function, $B_\lambda(T_b)$, where T_b is the fitted blackbody temperature of the dust. The effective area is derived from this quantity by multiplying by $\pi\rho/\epsilon$ using an assumed value of $\epsilon \approx 0.9$. Our uncertainties come from the standard deviation between the derived values for 9, 11, and 22 arcsec apertures. Note that we do not correct $\epsilon f\rho$ values for phase angle (the Sun–target–observer angle) effects, and where we are assuming an idealized $1/r$ behavior in our estimates of uncertainty, we do not find strong deviations in most cases.

The derived dust and production rates are listed in Table 4. It should be noted that for the comets without W3 or W4 signal, it is not possible to derive $\epsilon f\rho$ values directly from measurements. Therefore, we estimated these values based on the means of the $(\epsilon f\rho - A_f\rho)$ values (denoted $\Delta_{(\epsilon f\rho - A_f\rho)}$) from our comet sample that had W1 and W3 or W4 signal. We found a mean value of $\Delta_{(\epsilon f\rho - A_f\rho)} = +0.74 \pm 0.29$ from these comets; therefore, listed values for C/2009 K5, C/2010 FB87, C/2014 C3, P/2014 L2, and C/2014 N3 are simply the W1 derived $A_f\rho$ values $+0.74$, with 0.29 added to the $A_f\rho$ uncertainty in quadrature.

4. DISCUSSION

The comets observed by the *WISE*/*NEOWISE* and Reactivated *NEOWISE* missions represent the largest sample of comets observed in the near-infrared, as summarized in Table 5. The data sets, though obtained with the same spacecraft, vary in what they offer in terms of potential measurements, owing to both the different nature of the various missions (e.g., which bands were and remain operational), and the nature of the activity in the comets themselves. For these analyses, we have focused on the initial study of the comets discovered by *WISE*/*NEOWISE* (the 21 confirmed comets), and the three objects whose activity were discovered by the reactivated *NEOWISE* mission in its first year, as well as those active comets that exhibited W2 excess during the prime mission, 39 in total, including the 9 from the cometary discoveries Fluxes have been reported in Section 3.1 for all the cometary discoveries (including 2010 KG43, reported in Wasczac et al. (2013), but not yet officially designated as a comet), and the known comets with significant W2 signal taken during the *WISE*/*NEOWISE* prime mission, for a total of 56 comets, more than a third of the total *WISE*/*NEOWISE* prime mission sample.

4.1. Thermal Dust

The values for $\Delta_{(\epsilon f\rho - A_f\rho)}$ were for active comets. The distributions of $\Delta_{(\epsilon f\rho - A_f\rho)}$ were similar for long and short period comets. The mean offset in the log values corresponds roughly to the a factor of 5.5 difference, which is less than, but within a factor of 1.6 of, what may be expected for a 3.4 μm albedo of ~ 0.1 and emissivity of ~ 0.9 for the same dust particles. The mean for $\Delta_{(\epsilon f\rho - A_f\rho)}$, however, is notably different when

Table 4
Dust and W2 Excess Analysis Results

Visit	R_h (AU)	Delta (AU)	$Q_{\text{CO}_2}^a$ ($\log_{10} \text{ molecules s}^{-1}$)	$\varepsilon f \rho$ ($\log_{10}(\text{cm})$)	$A f \rho$ ($\log_{10}(\text{cm})$)	T_{eff} (K)
P/2009 WX51	1.26	0.76	25.20 $\pm$ 0.12	0.72 $\pm$ 0.07	0.58 $\pm$ 0.08	241 $\pm$ 7
233P	1.80	1.43	25.04 $\pm$ 0.11	1.18 $\pm$ 0.10	0.58 $\pm$ 0.09	213 $\pm$ 1
P/2010 K2	1.29	0.73	25.74 $\pm$ 0.13	1.10 $\pm$ 0.08	0.68 $\pm$ 0.11	257 $\pm$ 2
P/2010 N1	1.55	1.08	25.49 $\pm$ 0.14	1.19 $\pm$ 0.10	0.67 $\pm$ 0.08	233 $\pm$ 1
C/2010 L5 Epoch1	1.21	0.65	26.43 $\pm$ 0.08	2.12 $\pm$ 0.08	1.63 $\pm$ 0.10	240 $\pm$ 1
C/2010 L5 Epoch2	1.60	1.15	25.08 $\pm$ 0.08	1.18 $\pm$ 0.08	0.04 $\pm$ 0.06	213 $\pm$ 3
C/2010 FB87 Epoch3	2.92	2.75	26.48 $\pm$ 0.11	3.4 $\pm$ 0.3	2.64 $\pm$ 0.14	257 $\pm$ 2
C/2014 C3	1.90	1.60	25.82 $\pm$ 0.08	2.2 $\pm$ 0.2	1.45 $\pm$ 0.05	207
P/2014 L2	2.26	1.98	27.38 $\pm$ 0.08	3.1 $\pm$ 0.3	2.35 $\pm$ 0.10	195
C/2014 N3 Epoch1	4.43	4.27	26.43 $\pm$ 0.10	3.2 $\pm$ 0.2	2.51 $\pm$ 0.11	136
C/2014 N3 Epoch2	3.96	3.79	26.51 $\pm$ 0.11	3.6 $\pm$ 0.2	2.78 $\pm$ 0.10	144
SPCs With 4.6 μm Excess						
29P	6.21	6.04	27.84 $\pm$ 0.09	4.61 $\pm$ 0.25	3.79 $\pm$ 0.05	130 $\pm$ 13
30P	1.92	1.56	26.18 $\pm$ 0.17	2.64 $\pm$ 0.08	1.98 $\pm$ 0.05	225 $\pm$ 3
65P	2.46	2.25	27.28 $\pm$ 0.09	3.60 $\pm$ 0.08	2.70 $\pm$ 0.06	164 $\pm$ 1
67P ^b	3.32	3.31	25.87 $\pm$ 0.14	2.16 $\pm$ 0.07	0.94 $\pm$ 0.26	183 $\pm$ 4
74P Epoch 1	3.61	3.44	25.88 $\pm$ 0.10	2.87 $\pm$ 0.09	2.23 $\pm$ 0.08	158 $\pm$ 1
74P Epoch 2	3.74	3.51	26.22 $\pm$ 0.15	3.04 $\pm$ 0.09	2.36 $\pm$ 0.11	153 $\pm$ 1
77P	2.99	2.80	25.45 $\pm$ 0.15	2.29 $\pm$ 0.08	1.68 $\pm$ 0.08	178 $\pm$ 2
81P	2.22	1.87	27.18 $\pm$ 0.14	3.59 $\pm$ 0.08	2.77 $\pm$ 0.05	178 $\pm$ 3
94P	2.27	1.94	25.91 $\pm$ 0.15	2.43 $\pm$ 0.08	1.51 $\pm$ 0.13	180 $\pm$ 1
100P	2.23	1.98	25.44 $\pm$ 0.12	1.49 $\pm$ 0.09	1.46 $\pm$ 0.05	217 $\pm$ 1
103P	2.29	2.04	25.72 $\pm$ 0.10	1.56 $\pm$ 0.09	1.17 $\pm$ 0.05	206 $\pm$ 1
116P	2.82	2.64	25.84 $\pm$ 0.12	2.88 $\pm$ 0.08	1.94 $\pm$ 0.06	157 $\pm$ 1
118P	2.09	1.75	26.71 $\pm$ 0.09	3.13 $\pm$ 0.07	2.30 $\pm$ 0.04	173 $\pm$ 3
143P	3.25	3.08	25.45 $\pm$ 0.32	2.19 $\pm$ 0.10	0.48 $\pm$ 0.05	173 $\pm$ 2
149P	2.80	2.52	25.52 $\pm$ 0.10	2.10 $\pm$ 0.09	1.34 $\pm$ 0.07	162 $\pm$ 2
169P	2.27	1.94	25.75 $\pm$ 0.15	1.69 $\pm$ 0.10	0.68 $\pm$ 0.07	203 $\pm$ 3
217P	2.46	2.15	26.02 $\pm$ 0.10	2.63 $\pm$ 0.07	1.86 $\pm$ 0.27	169 $\pm$ 1
P/2009 Q4	2.32	2.02	25.23 $\pm$ 0.17	1.53 $\pm$ 0.05	0.99 $\pm$ 0.08	182 $\pm$ 4
P/2010 A3	1.85	1.50	25.86 $\pm$ 0.11	2.15 $\pm$ 0.09	1.37 $\pm$ 0.07	191 $\pm$ 1
P/2010 H2	3.15	2.89	25.96 $\pm$ 0.10	3.06 $\pm$ 0.08	2.20 $\pm$ 0.06	143 $\pm$ 3
LPCs with 4.6 μm Excess						
C/2005 L3	8.21	8.08	26.91 $\pm$ 0.10	3.92 $\pm$ 0.08	3.15 $\pm$ 0.09	102 $\pm$ 2
C/2006 S3	7.23	7.16	26.55 $\pm$ 0.14	3.93 $\pm$ 0.07	3.05 $\pm$ 0.05	104 $\pm$ 1
C/2006 W3	4.15	4.02	27.88 $\pm$ 0.09	4.76 $\pm$ 0.07	3.83 $\pm$ 0.01	133 $\pm$ 3
C/2007 Q3 Epoch 1	2.50	2.25	27.55 $\pm$ 0.10	4.18 $\pm$ 0.08	3.53 $\pm$ 0.05	192 $\pm$ 2
C/2007 Q3 Epoch 2	3.45	3.27	26.68 $\pm$ 0.10	3.85 $\pm$ 0.07	2.91 $\pm$ 0.04	144 $\pm$ 1
C/2008 FK75	4.77	4.66	25.97 $\pm$ 0.12	3.53 $\pm$ 0.09	2.65 $\pm$ 0.08	120 $\pm$ 1
C/2008 N1 Epoch 1	3.08	2.93	25.93 $\pm$ 0.10	2.96 $\pm$ 0.08	2.07 $\pm$ 0.08	150 $\pm$ 2
C/2008 N1 Epoch 2	3.76	3.53	25.99 $\pm$ 0.32	2.68 $\pm$ 0.09	2.01 $\pm$ 0.09	136 $\pm$ 2
C/2008 Q3	3.97	3.79	26.47 $\pm$ 0.10	2.95 $\pm$ 0.08	1.98 $\pm$ 0.06	139 $\pm$ 3
C/2009 K5	2.65	2.45	27.06 $\pm$ 0.10	3.35 $\pm$ 0.2	2.63 $\pm$ 0.09	176 $\pm$ 1
C/2009 P1	6.33	6.23	27.16 $\pm$ 0.10	4.03 $\pm$ 0.09	3.17 $\pm$ 0.10	111 $\pm$ 1
C/2009 U3	1.67	1.29	26.34 $\pm$ 0.10	2.15 $\pm$ 0.08	1.64 $\pm$ 0.05	201 $\pm$ 2
C/2010 J1 Epoch 1	1.84	1.56	25.94 $\pm$ 0.37	2.48 $\pm$ 0.08	2.07 $\pm$ 0.07	229 $\pm$ 5
C/2010 J1 Epoch 2	2.49	2.20	25.71 $\pm$ 0.16	1.88 $\pm$ 0.09	1.23 $\pm$ 0.08	222 $\pm$ 3

Notes.^a Q_{CO_2} production rates are a proxy for the combined rates derived from CO + CO₂ emission (Section 3.3).^b from Bauer et al. (2012a).

considering R_h (see Figure 4). The number of SPCs in this sample is too small at large R_h to be statistically significant. Yet, for the LPCs in our sample, for $R_h < 3$ AU, $\langle \Delta_{(\varepsilon f \rho - A f \rho)} \rangle = +0.57 \pm 0.14$, and for $R_h < 3$ AU, $\langle \Delta_{(\varepsilon f \rho - A f \rho)} \rangle = +0.86 \pm 0.10$. This

could be indicative of larger grains being lifted by activity at greater distances rather than shorter, or possibly, and perhaps more likely, the persistence of larger grains that remain in the dust coma after peak activity.

Table 5
Summary of Comets Observed by *WISE/NEOWISE*

Category	Total	<i>WISE/NEOWISE</i> Prime Mission	Reactivated <i>NEOWISE</i> Mission
Detected Comets	226	163	66
Detected LPCs	86	57	29
Detected SPCs	143	106	37
Discovered Comets ^a	22	18 + 1 ^a	4
Known Asteroids with Cometary Activity Discovered by <i>NEOWISE</i>	3	3	...
Comets with Significant W2 signal	118	52	66
Comets with 4.6 mm Excess	39	36	3

Note. *NEOWISE* reactivated mission tally was as of 2015 May 15.

^a 2010 KG43, reported by Waszczak et al. (2013), no cometary designation yet, and so is excluded from the mission total.

Figure 4. Difference between the $\log \epsilon f \rho$ values derived from 11 and 22 μm dust emission and the $\log Af\rho$ values derived from 3.4 μm dust reflectance. LPCs (red symbols), and SPCs (blue) are shown, with the *WISE/NEOWISE* discovered comets represented using triangles, and the remaining sample by filled circles.

4.2. *NEOWISE* Discovered Comets

A total of 21 comets were discovered by *WISE/NEOWISE* during the prime mission, and 4 additional comets have been discovered during the first year of the *NEOWISE* reactivated mission. Of these 25 objects, 12 are designated LPCs, and those 10 observed during the prime mission have yielded constraints on their nucleus size and dust, along with CO_2 production rates. This gives us a good statistical basis to search for differences between SPCs and LPCs that may be attributed to formation conditions. This small set, a subset of the larger set of 163 comets observed, allows for an unprecedented comparison of nucleus sizes between SPCs and LPCs, for example, using the same methods for each comet. The same methodology does not mean there is no variation on the efficacy of the methods, however, as each comet's behavior varies greatly. Constraints on dust and CO_2 production require the comet be active, or recently active in the case of the dust, where the presence of strong activity during the *WISE* observations obviously hampers the derivation of nucleus sizes. We provide a description for each comet's behavior below (see also Figure 1).

237P/LINEAR (2002 LN13): Activity was first seen in this JFC by *WISE* 190 days after its perihelion while at a distance of 2.70 AU from the Sun. No significant signal was observed in *W1* or *W2*. A faint dust tail was apparent, as was a central condensation, easily separable from the dust, which yielded a nucleus size of ~ 2 km.

233P/La Sagra (2009 WJ50): *WISE* viewed this Encke-type comet very close to its perihelion distance, at 1.81 AU from the Sun, just 34 days before perihelion. The comet's faint tail indicated activity, and significant *W2* excess that yielded a CO_2 production rate of 1.1×10^{25} molecules per second. A strong central peak in the stacked image yielded an extracted nucleus flux corresponding to a size ~ 1 km.

P/2009 WX51 (Catalina): *WISE* viewed this NEC 61 days after its perihelion ($q = 0.8$ AU), when it was at a distance of 1.26 AU from the Sun. The comet displayed a tail, and significant *W2* excess yielded a CO_2 production rate of 1.6×10^{25} molecules per second. The *W3* and *W4* signals showed a strong central condensation, and the extracted nucleus flux yielded a size of < 0.5 km.

P/2010 B2 (WISE): The first *WISE*-discovered comet, 2010 B2 (*WISE*), was detected on 2010 January 23, just 32 days after its perihelion, at 1.64 AU, and again on 2010 August 5, at an outbound heliocentric distance of 2.49 AU. With a Jupiter Tisserand invariant (T_J) of > 3 , and a semimajor axis less than Jupiter's, the comet was categorized as an Encke-type JFC. The first visit in January showed obvious activity, and detections in all four bands. The second visit showed significant signal only at 12 and 22 μm . The extracted flux from *W3* and *W4* in the first visit yielded nucleus size estimates, and showed *W2* excess in the total signal. Our size estimate of 0.99 ± 0.15 km implies the nucleus comprises less than a quarter of the total signal in the bands. The strength of the thermal signal in the second visit suggests the comet was still active at a distance of 2.5 AU, or that the dust component was still significant ($\sim 50\%$ of the total signal), but did not have sufficient extended signal to remove the coma as was possible in the images from the first visit.

P/2010 D1 (WISE): This comet, the second discovered by *WISE* on 2010 February 17, was detected only at one visit by *WISE*, 237 days after its perihelion, at a heliocentric distance of 3.02 AU. A faint coma and tail was shown in the stacked *W3* and *W4* images, making it identifiably a comet. However, extracted *W1* and *W2* signals were very faint, near the level of the noise, at or below 3σ . The extracted nucleus signal yielded a diameter of 2.5 km.

P/2010 D2 (WISE): The third comet discovered by *WISE* was also a JFC, and it was detected only at one epoch by *WISE* during the fully cryogenic mission, on 2010 February 26. The images were taken very near to its perihelion, within 8 days, at 3.66 AU. As with P/2010 D1, the coma was faint, but present, yet lacked a distinctly extended tail. Removal of the coma signal yielded a nucleus size estimate of 4.65 km. In addition to strong flux in *W3* and *W4*, the signal in the stacked images

showed faint (5σ) signal in *W1*, but no significant signal in *W2* that may have indicated CO_2 or CO emission down to production limits (1σ) of 3×10^{25} and 3×10^{26} molecules s^{-1} , respectively.

C/2010 D3 (WISE): The first LPC discovered by *WISE* was detected at two separate epochs during the cryogenic survey. The first visit spanned 5 days centered around 2010 February 26 when the comet was 189 days prior to perihelion at a distance of 4.28 AU, and again outbound, 60 days after perihelion, when the comet was at a heliocentric distance of 4.52 AU. No significant *W2* was detected in either visit, although weak *W1* signal was seen during the first visit, allowing for CO_2 and CO production rate limits of 4×10^{25} and 4×10^{26} molecules s^{-1} , respectively. Faint coma is discernable in the stacked images of *W3* and *W4* during both visits, and the extracted nucleus signal yielded an estimated size of 4.3 km.

C/2010 D4 (WISE): This LPC was discovered on 2010 February 28, 335 days after it perihelion, at a rather distant 7.43 AU from the Sun. A second visit occurred over 2010 July 5, when the comet was at a larger heliocentric distance of 7.66 AU. The comet is not very active in the *WISE* images. No significant signal is present in *W1* or *W2*, and the signal in *W3* and *W4* nearly match the *WISE* PSF, and are likely dominated by the nucleus. The 12 and 22 μm flux measurements from both visits yield a diameter of ~ 25 km.

C/2010 DG56 (WISE): When this LPC was discovered, at a distance of 1.95 AU from the Sun, 3 months prior to it perihelion, no signs of significant activity were apparent. The stack of its PSF-like images for this first visit yielded a diameter of 1.5 km. When the comet was imaged again at a heliocentric distance of 1.87 AU on 2010 July 26, the comet was quite active, enough to sufficiently obscure the nucleus, so that its signal could not be extracted from this second visit. However, though a slight *W2* excess was possibly present, it was not above a $3\text{-}\sigma$ uncertainty.

C/2010 E3 (WISE): Imaged when it was only marginally active, this LPC is on a parabolic orbit. The extracted nucleus signal yielded a size of 0.4 km, and no significant *W2* or *W1* signal was present. The comet was at a distance of 2.3 AU from the Sun at the time, very near its perihelion distance of 2.27 AU, which occurred one month after its discovery.

C/2010 FB87 (WISE-Garradd): First observed inbound, the comet's image nearly matched the *WISE* spacecraft's PSF in *W3* and *W4*, and showed no significant signal in *W1* or *W2*. These first observations were made when the comet was at a distance of 3.62 AU from the Sun, 224 days before perihelion. The comet was imaged a second time, still 108 days before its perihelion, while at a heliocentric distance of 3.04 AU. A faint coma and tail were apparent in the images. *WISE* detected *W1* and *W2* signal during its second visit, but no significant *W2* excess. However, when the comet was imaged by *WISE* a third time, in the post-cryogenic portion of the prime mission, *W2* excess was present. The comet was then outbound at a heliocentric distance of 2.92 AU, 66 days following its perihelion at 2.84 AU.

C/2010 G3 (WISE): This LPC was detected on two separate visits, both during the fully cryogenic phase of the *WISE* mission, and both while the comet was outbound. The first was within 4 days of perihelion, and the second 83 days after perihelion. With the furthest perihelion distance (4.9 AU) of the *WISE*/*NEOWISE*-discovered comets, one might expect CO or

CO_2 to have driven the activity. Surprisingly, no significant *W1* or *W2* signal was seen at either visit, yet *W3* and *W4* images revealed both dust coma and tail. However, the dust modeling suggests that the activity occurred more than a year prior to the observations, and that potentially, the dust was composed of large-particles that lingered after the outburst. At such distances it was unlikely that CO_2 , but rather that CO, was a possible driver. If so, the time of outburst, 726 days prior to perihelion, would have sufficiently preceded the *WISE* observations that the CO would have photo-dissociated. The predicted time scales for CO dissociation at 4.9 AU are ~ 370 days or less (Huebner et al. 1992), and ~ 90 days for CO_2 .

C/2010 J4 (WISE): Comet C/2010 J4 was detected on two visits in 2010 May, the first two days before its 2010 May 3 perihelion and the second 9 days after. This parabolic comet had a perihelion distance of 1.09 AU, and came within 0.31 AU of the Earth's orbit. Both sets of observations showed significant coma and dust tails. *W2* signal was significant in the stacked images of both visits; however, no significant excess above the dust thermal contribution was seen. The dust signal heavily dominated the total signal, and the extracted nucleus flux and derived diameter should therefore be taken as an upper limit.

P/2010 JC81 (WISE): This comet was detected twice during the *WISE* prime mission. The first visit was during the 4-band fully cryogenic period, when the comet was at a heliocentric distance of 3.9 AU, and the second was during the post-cryogenic period, when the comet was 2.65 AU from the Sun. The first and second visits were 350 and 180 days, respectively, before the comet reached its perihelion at 1.8 AU from the Sun, and before activity was noted by ground-based observations. The stacked images of both visits show a near-bare PSF-like surface brightness profile. The fitted temperature, about 40 K above the blackbody temperature, was consistent with a nucleus with a beaming parameter ~ 0.8 . No strong indication of *W2* excess was present in the fully cryogenic mission data, and the *W1* and *W2* fluxes in the second visit were also consistent with a bare nucleus with a beaming parameter near 0.8, and a visual-wavelength albedo on the order of a few percent. We note that it is possible for comets to be very active even out to large heliocentric distances, though small comets have been observed without coma as well. P/2010 JC81 should be an interesting candidate for study upon its return in 2034 for signs of a large nucleus.

P/2010 K2 (WISE): This JFC was detected only once during the *WISE* fully cryogenic mission, and it exhibited a faint tail in *W3* and *W4*. The images were taken when the comets was at a distance of 1.29 AU from the Sun, less than a tenth of an AU from its perihelion distance, and within 41 days of its perihelion passage. There was a clear *W2* excess in the flux, which yielded a CO_2 production value of 1.3×10^{25} molecules per second. The extracted nucleus flux was consistent with a sub-kilometer size diameter.

C/2010 KW7 (WISE): This LPC was imaged by *WISE* during the fully cryogenic mission 255 days prior to its perihelion and again 148 days before perihelion, at heliocentric distances of 3.7 and 3.0 AU, respectively. No significant *W1* or *W2* signal was seen in either data set. However, the *W3* and *W4* signals were strong, and the *W3* and *W4* brightness profiles matched *WISE* PSFs for the two band-passes. The data yielded a nucleus size for this body of ~ 6 km. Activity was later identified by

Table 6
WISE/NEOWISE Discovery Comets Dust Model Summary

Name	Approx. β	Approx. Em. (years)	Approx. Em. (days)	Days Since Perihelion	Approx. R_h at Em. (AU)
C/2010 DG56 (B)	0.003	0.2	73	73	1.59
C/2010 FB87 (B)	0.01	0.25	90	−107	3.46
C/2010 G3 (A)	0.001	2	730	4	7.3
C/2010 G3 (B)	0.001	2.25	821.25	84	7.35
C/2010 J4 (A)	0.003	0.1	30	−2	1.21
C/2010 J4 (B)	0.01	0.1	30	9	1.14
C/2010 L4	0.003	1	365	112	3.75
C/2010 L5 (B)	0.001	0.2	60	52	0.81
C/2010 L5 (C)	0.001	0.25	90	84	0.80
245P	0.003	0.25	90	119	2.16
P/2010 D1	^a	^a	^a	238	^a
P/2010 P4	0.001	1	365	32	3.18
P/2009 WX51	^b	^b	^b	...	^b
233P	0.1	0.1	30	−34	1.85
237P	^b	^b	^b	...	^b

Notes.

^a Tail is present, but too short or faint to make even make an estimate.

^b Orbit plane angle separation is too small to separate syndynes and synchrones.

observations taken at Spacewatch (c.f. Scotti & Williams 2010) 17 days following is perihelion at 2.57 AU from the Sun.

245P/WISE (2010 L1): Activity was clearly shown in the first set of images *WISE* obtained of this JFC. The stacked images yielded no significant *W1* or *W2* flux values. The data were taken 120 days after the comet’s perihelion, when it was at a distance of 2.6 AU from the Sun. The nucleus signal extracted from the stacked images yields a diameter of ~ 1.5 km.

C/2010 L4 (WISE): A dust coma and tail were apparent in the individual images of this LPC, taken 112 days before its perihelion while the comet was at a distance of 3 AU. The stacked images showed no significant signal in the two shortest band passes. The extracted nucleus signal corresponded to a diameter of 3.4 km.

C/2010 L5 (WISE): The comet C/2010 L5 was the only *WISE*-discovered Halley type comet (HTC). It was strongly active when it was first detected 52 days after its perihelion, and again 85 days after. *W2* excess was apparent in both of these visits, and yielded CO_2 production rates of 2.7×10^{26} and 1.2×10^{25} molecules per second, respectively. Because the comet was so active, the extracted nucleus signal, yielding a diameter of ~ 2 km, should be regarded as an upper limit. This is further supported by a non-detection at the comet’s predicted location in January (E. Kramer et al. 2015, in preparation). Large-grain dust modeling suggests that the comet’s peak activity was near perihelion (Table 6). However, its worth noting that CO_2 dissociation lifetimes are ~ 5 and 10 days for the comet’s heliocentric distances of 1.2 and 1.6 AU, respectively, while CO_2 and CO lifetimes are ~ 22 and 39 days at these distances. It is unlikely, then, that outgassing had completely ceased very soon after perihelion. This particular case is discussed in detail in E. Kramer et al. (2015, in preparation).

P/2010 N1 (WISE): This inbound JFC was discovered at a heliocentric distance of 1.55 AU, 41 days prior to its perihelion. The comet was moderately active, but showed a strong *W2* excess and yielded CO_2 production rates of 3.1×10^{25}

molecules per second. The extracted nucleus flux was consistent with a solid surface diameter of 0.9 km.

P/2010 P4 (WISE): The final comet *WISE* discovered during the prime mission was a JFC, detected 31 days after its perihelion. The stacked image revealed a faint tail with a morphology consistent with dust particles emitted long before perihelion. No significant *W1* or *W2* signal was detected, and the extracted nucleus signal matched a body with a diameter of 1.2 km.

C/2014 C3 (NEOWISE): As with all three comets discovered during the first year of the *NEOWISE* reactivated mission, no nucleus sizes could be confidently derived from the *W1* and *W2* images, owing to the level of activity and dust signal observed at these bandpasses. However, all three comets discovered by the reactivated *NEOWISE* mission to date showed $4.6 \mu\text{m}$ channel excess. This LPC showed *W2* excess that yielded CO_2 production rates of 6.6×10^{25} molecules per second at a heliocentric distance of 1.9 AU, 29 days after its perihelion.

P/2014 L2 (NEOWISE): The second comet discovered during the reactivated *NEOWISE* mission was a JFC. *NEOWISE* imaged the comet 37 days before it reached perihelion, at a distance of 2.26 AU from the Sun. The stack images revealed a remarkably extended morphology in *W2* relative to the more compact dust coma and tail in *W1*, and yielded a CO_2 production rate of 2.4×10^{27} molecules per second.

C/2014 N3 (NEOWISE): This LFC was discovered by *NEOWISE* at a distance of 4.4 AU, 251 days prior to its perihelion, and it showed a faint tail and coma in the stacked images. The *W2* excess yielded a corresponding CO_2 production rate of 2.7×10^{26} molecules per second, although CO production at a rate of 2.9×10^{27} molecules per second is the more likely driver at the distances the comet was observed. A second visit occurred 90 days before perihelion ($R_h = 3.96$ AU), and apparent *W2* excess yielded CO production rates of 3.9×10^{27} molecules per second.

P/2015 J3 (NEOWISE): The latest *NEOWISE* comet discovery was made on 2015 May 15 at a distance of 1.67 AU from the Sun. The JFC showed no indication of

Figure 5. The cumulative size distribution of the nuclei of comets discovered by *WISE*/*NEOWISE*, including the 3 discoveries of activity (P/2002 LN31, P/2009 WX51, P/2009 WJ50), and P/2015 J3 from the *NEOWISE* reactivated mission, but not including the remaining 3 comets discovered during the reactivated mission since they had no 11 and 22 μm measurements and appeared active.

activity morphologically, but in ground-based follow-up images there was a faint tail. Size estimates for the nucleus are 2.3 ± 0.7 km, and reflectance 0.02 ± 0.02 , based on JPL’s Horizons rough estimate of the visual-band nuclear magnitude at 18.5.

2010 KG43: This body, on a centaur-like orbit, was found to be active by Waszczak et al. (2013), but has not been confirmed as a comet. Significant flux values were observed in *W3* (3.3 ± 0.6 mJy) and *W4* (9 ± 2 mJy) during the prime mission, yielding a preliminary diameter of 4 ± 1 km, and an albedo of 0.2 ± 0.02 for the object, assuming a beaming parameter near 1. This body is not included in the further analyses, since its official cometary status remains undetermined.

4.3. Nucleus Size

The nucleus sizes of the discovery comets listed in Table 3 are shown as cumulative distribution plots in Figure 5. This sample is not large enough to make definitive conclusions as to the size frequency distribution power-law exponents for the total or sub-samples of LPCs and SPCs. Additionally, these samples are not de-biased in any way. However, because they were discovered by the *WISE* spacecraft, neither are they pre-selected by a strong visual reflectance bias. The data also includes two possible upper limits for the LPCs. However, these fall well below sizes that would influence the mean fractional sizes of the samples. An analysis using a minimum-variance unbiased estimator (MVUE) routine based on Feigelson & Babu (2012) was utilized to examine a power-law relation. The results were inconclusive, with the LPC sample yielding a size frequency distribution power-law exponent, α , of 1.4 ± 0.2 , and the SPC sample yielding $\alpha = 1.6 \pm 0.2$.

Figure 5 suggests that the LPC nuclei are, on average, larger than the SPC nuclei, by something like a factor of ~ 2 . This conclusion is consistent with a similarly sized sample of LPCs presented in Lamy et al. (2004) compiled from sizes in the literature. Statistically, however, the sample sizes are small; a Kolmogorov–Smirnov test of the *NEOWISE* discovered LPC and SPC size distributions yields a 94% confidence that the diameters come from different distributions. One of the sources

in the Lamy et al. (2004) compilation of diameters was Meech et al. (2004), which concluded from visual-wavelength data that there was no average size difference between LPCs and SPCs while using an assumed geometric albedo. Note also that our sample contains SPCs with nuclei larger than 10 km in diameter. SPC nuclei on these scales were also measured in the SEPPCoN sample reported by Fernandez et al. (2013).

4.4. Dust Tails

Of the 21 comets discovered by *WISE* during its prime mission, 9 (6 LPCs and 3 SPCs) were found to have extended emission due to dust tails. We employed the well-described Finson–Probst (Finson & Probst 1968) method to model these dust tails in order to constrain the size and age of the particles that comprised those tails. The Finson–Probst method assumes that once a particle leaves the surface of a comet, its motion is only governed by solar radiation pressure and solar gravity, thereby allowing the particle motion to be parameterized using the ratio of these two forces, called β :

$$\beta = F_{\text{rad}}/F_{\text{grav}}$$

where F_{rad} is the force due to solar radiation and F_{grav} is the force due to solar gravity. Putting in the appropriate values for F_{rad} and F_{grav} and collecting the constant terms yields the ratio

$$\beta = \frac{CQ_{pr}}{\rho_d a}$$

where ρ_d is the particle density [g cm^{-3}], a is the particle radius in cm, Q_{pr} is the scattering efficiency due to radiation pressure, and the factor $C = 5.78 \times 10^{-5} \text{ g cm}^{-2}$ comes from collecting all the constants into a single term. Thus, we can see that β is inversely proportional to the size of the particle: larger β values correspond to a smaller particle size, and vice versa.

The β parameter is incorporated into the equation of motion, which is then integrated for a range of β values using a numerical integrator (based on the work of Lisse et al. 1998, with the version used here described in further detail in Kramer 2014). For each comet, we ran the models for 5 years in 1-day increments, with β values ranging from 0.0001 (roughly cm-sized particles) to 3.0 (sub-micron sized particles). This allowed us to fully explore the reasonable parameter space for each comet tail. The software returns a matrix of points that can be plotted as curves of constant emission date (synchroes) or curves of constant β (syndynes). The models were over-plotted on each corresponding *W4* image, allowing the best β and time since emission to be found for each comet.

In order to determine the heliocentric distance at which strong emission occurred, we find the synchro that most closely matches the brightest part of the tail, giving the number of days since the emission occurred. We then step back in the comet’s orbit using the online tool *Horizons* from JPL to find the heliocentric distance of the comet at that time. The β values listed in Table 6 do not mean that there were no small grains released, but more likely that either they have all been swept away already or that they are not optically active at *W3* and *W4* wavelengths. We further emphasize that this is not necessarily the only time that emission occurred for the comet; it is only where strong emission of particles which are still in the image frame occurred. Similarly for the interpretation of the syndynes, we note that the β values listed in Table 6 correspond to the brightest part of the tail, and there are likely particles both

Figure 6. (Left)—example of FP modeling for comet C/2010 L5 (*WISE*). (Right)—Plot of days from perihelion versus best fit (by eye) of ejection time. Note no obvious trend is discernable. Note that the $\beta = 0.1$ for 233P is indicated by the blue arrow near the top of the page.

larger and smaller than suggested by the best β . The results of this method are shown in Table 6, as well as in Figure 6.

4.5. Dust Temperature

Figure 7 shows the distribution of effective dust temperature based on the *W3* and *W4* band thermal fluxes. These may be effected by more than the dust temperature, namely variations in emissivity with silicate emission features (cf. Hanner & Bradley 2004). However, in a gross sense, these values are consistent with isothermal bodies with emissivity ~ 0.9 . The standard deviation of the points from the thermal curve is ± 17 K.

4.6. CO + CO₂

The presence of CO or CO₂ manifests as a flux excess above the dust signal, as well as a difference in the morphology in *W2* (Sections 2.3 and 3.3). *WISE* detected 163 comets during the prime *WISE/NEOWISE* mission. We found significant *W2* flux excess in 40 comets, listed in Table 4. Assuming CO₂ was the dominant source of the *W2* excess for all 40, we have converted the flux excess into CO₂ production rate values (molecules per second), or Q_{CO_2} . Of course, this is not valid for all the 40 comets. We know significant CO was detected for 29P (Senay & Jewitt 1994) and for C/2009 P1 (Garradd; Feaga et al. 2014), observed at 6.2 and 6.3 AU, respectively, in the *NEOWISE* data. However, these values are readily convertible to approximate CO production rates (Q_{CO}) by multiplication of the ratio of CO₂ to CO fluorescence efficiencies ($g_{\text{CO}_2}/g_{\text{CO}} = 11.6$; see Crovisier & Encrenaz 1983). The conversion to hypothetical Q_{CO_2} production rates facilitates possible comparisons between CO₂ and CO dominant behavior, and how it may be related to the quantity of dust present. We note, as discussed in Section 3.3, the listed uncertainties in the derived CO₂ production rates are the combination of the uncertainty in the calculated dust contribution as constrained by the *W1*, *W3*, and *W4* photometry, added to the uncertainty from the *W2* signal. Possible systematic sources of uncertainties, such as large variations in the fraction of CO relative to CO₂ or contributions to the *W1* flux from non-dust signal, are not included in the tabulated values.

Figure 7. T_{eff} is plotted as a function of R_h . As with previous plots, LPCs are indicated by read symbols, and SPCs by blue. The dashed line indicates the temperature of an isothermal body at the same distance from the sun with an emissivity of ~ 0.9 .

The Q_{CO_2} proxy and $\varepsilon f \rho$ values are plotted as a function of heliocentric distance in Figure 8. Except that the 15 LPCs may be more active than 24 SPCs at heliocentric distances greater than 4 AU, no differentiating trend is readily apparent for CO₂ production. To identify correlations, a Kendall- τ test was applied to the LPC and SPC distributions for comet heliocentric distance with CO₂ production and with $\varepsilon f \rho$; high τ values near 1 indicate a correlation between the two parameters, and low values (~ -1) indicate anti-correlations, where values near zero indicate no correlation. A second variable, the two-sided probability parameter, or p -value, is a test for a null hypothesis, such that a low p -value indicates a higher likelihood of the result indicated by the τ value. For example, a well-correlated pair of parameters, but poorly sampled, would have τ and p -value close to 1, and well-sampled correlated pair would have $\tau \sim 1$ and the p -value ~ 0 , but a well-sampled, but random, pair of parameters would have both values close to zero. Inside of 4 AU, the Kendall- τ test yielded τ values near 0 (0.18 and -0.10 for LPCs and SPCs, respectively), with low significance (p -values of 0.39 and 0.57 for LPCs and SPCs, respectively). Both SPCs and LPCs appear to have similar distributions given the limited sample. This find, in and of

Figure 8. (Left) excess flux in 4.6 μm channel converted to CO₂ production plotted WRT heliocentric distance. (Right) $\epsilon\rho$ as a function of heliocentric distance. Note the distributions for LPCs and SPC are similarly scattered.

itself, is a significant constraint on current solar system formation theories. Dones et al. (2004), for example, place the source of Oort cloud comets and KBOs to be near Jupiter and near Neptune, respectively. However, A’Hearn et al. (2012) suggest that volatile abundances are similar for differing dynamical classes of comets, implying a comparable formation environment between the CO and CO₂ sublimation zones. This data set may affirm this notion, which places profound constraints on the various solar system scenarios, specifically regarding planetary migration. Such theories (see Morbidelli et al. 2008; Walsh & Morbidelli 2011) which have previously suggested different formation regions for cometary types, may have to account for the comparable compositional profiles between differing comet dynamical populations.

Unsurprisingly, $\epsilon\rho$ values correlate well with SPCs ($\tau = 0.5$, $p\text{-value} = 0.02$) and LPCs ($\tau = 0.4$, $p\text{-value} = 0.02$) alike, as suggested previously (see Kelley et al. 2013). When the two values are ratio-ed ($\log_{10} Q_{\text{CO}_2} - \log_{10} \epsilon\rho$), as in Figure 9, we find a relation of R_h^{-2} . Inverse proportionality with R_h have been seen with OH and CN (A’Hearn et al. 1995), yet the relationship with CO₂ is particularly clear. Furthermore, where the A’Hearn et al. (1995) gas-to-dust ratio appears to go as $R_h^{-1/2}$, what we find with respect to CO₂ gas is considerably steeper. Such behavior, whereby an increase in CO₂ gas production lacks a corresponding increase in dust production, was noted in 103P (A’Hearn et al. 2011). This relation persists out to 4 AU, where the trend deviates. If CO₂ is expected to drive activity more within these ranges of R_h , this may indicate that the bulk of CO₂ may be endogenic with the dust. Alternatively, or possibly concurrently, it may be that CO reaches its maximum production before 4 AU if it resides at depth and its sublimation is not driven directly by surface insolation of, say, near-surface CO ice, while CO₂ is.

We found limited overlap between the Akari (Ootsubo et al. 2012; hereafter O12) and SST (Reach et al. 2013; hereafter R13) observations. A total of 13 objects shared reported observations that allowed comparisons with the NEOWISE sample’s somewhat larger time intervals. These results are summarized in Figure 10. The fidelity of the comparisons, however, are somewhat limited in several respects. Neither the R13 nor O12 observations provided $\epsilon\rho$ values, so that only gas production rates could be compared. Furthermore, O12 provided spectrally derived relative abundances, information we did not have, so that in order to make

Figure 9. Log ($Q_{\text{CO}_2}/\epsilon\rho$) as a function of R_h [AU]. LPCs are represented by red symbols, SPCs blue. Note the two dissimilar groupings of behavior (orange and green boxes) inside and outside 4 AU. The latter may be CO production driven activity, and includes 29P at 6.2 AU, and C/2009 P1 (Garradd) at 6.3 AU.

Figure 10. Comparative production rates of CO₂ as a function of heliocentric distance in individual comets. SPCs (blue) and LPCs (red) observed by Akari (Ootsubo et al. 2012), Spitzer Space Telescope (Reach et al. 2013), and WISE/NEOWISE are shown with distinguishing symbols, and with their data points connected. The Akari CO and CO₂ production rates were converted to proxy CO₂ rates for comparison with the Spitzer and WISE data sets (see the text).

comparisons with our values, we converted the CO and CO₂ rates into proxy CO₂ production rates by dividing the O12 CO rate by 11.6, the scaling factor between the line strengths, and adding it to the reported CO₂ rate. Also, many of the comets that overlapped nonetheless were observed at similar times and heliocentric distances. Finally, we did not compare the limits of the non-detections in O12 and R13, but only detections. We found that, similar to the behavior for other species as analyzed in A'Hearn et al. (1995), variations in individual comet behavior did not clearly indicate trends with heliocentric distance for our proxy CO₂ values. What we found with the aggregate total sample shown in Figure 8, with dispersed behavior, seemed to match with the stochastic nature of cometary emission seen in Figure 10.

5. CONCLUSIONS

The 25 *NEOWISE* cometary discoveries are a relatively small but important and representative sample of comets detected by *WISE/NEOWISE*. We find the following from our analysis of this smaller sample:

1. Long period comet nuclei may be, on average, larger than small period comet nuclei. Though the evidence from the sample is suggested, it must be confirmed by later efforts to account for the effects of biases as a function of orbital elements and size, as well as using the larger expanded sample from the *WISE* data.
2. Dust detected at longer thermal wavelengths is large, often up to sizes of millimeters. Few comets reach peak activity after perihelion.

A total of 39 comets out of 163 detected by *WISE/NEOWISE* showed W2 excess, comprising nearly a quarter of the total sample detected in the *WISE* prime mission data. Our analysis of the sample of active comets, which have dust temperature constraints and differ morphologically in the 4.6 mm band, suggests:

1. There is little difference between the nature of the dust production of LPCs and SPCs as a function of heliocentric distance.
2. Similarly, the distribution of CO or CO₂ production as a function of heliocentric distance looks comparable for LPCs and SPCs, though fractionally more LPCs may be producing CO or CO₂ at heliocentric distances greater than 4 AU. The appearance of more LPCs exhibiting CO + CO₂ at these greater distances may suggest an evolutionary effect, such that LPCs retain their more volatile CO, while both LPCs and SPCs may have on average similar CO₂ abundances.
3. Temperatures of dust seen at 12 and 22 μ m are to first order well-approximated by an isothermal blackbody with emissivity ~ 0.9 and with a temperature range within ± 17 K (1-s dispersion).
4. The ratio of CO or CO₂ production to the quantity of dust observed ($\epsilon f \rho$) may follow a relation of $\sim R_h^{-2}$ within 4 AU. No similar relation seems to persist for greater distances. This may be attributable to different source regions (surface versus sub-surface) for cometary CO and CO₂ emissions.

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