MULTI-WAVELENGTH OBSERVATIONS OF COMET C/2011 L4 (PAN-STARRS)
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Received 2013 August 30; accepted 2014 February 16; published 2014 March 12

ABSTRACT
The dynamically new comet C/2011 L4 (PAN-STARRS) is one of the brightest comets observed since the great comet C/1995 O1 (Hale–Bopp). Here, we present our multi-wavelength observations of C/2011 L4 during its in-bound passage to the inner solar system. A strong absorption band of water ice at 2.0 μm was detected in the near-infrared spectra, obtained with the 8 m Gemini-North and 3 m Infrared Telescope Facility Telescopes. The companion 1.5 μm band of water ice, however, was not observed. Spectral modeling shows that the absence of the 1.5 μm feature can be explained by the presence of sub-micron-sized fine ice grains. No gas lines (i.e., CN, HCN, or CO) were observed pre-perihelion in either the optical or the submillimeter. We derived 3σ upper limits for the CN and CO production rates. The comet exhibited a very strong continuum in the optical and its slope seemed to become redder as the comet approached the Sun. Our observations suggest that C/2011 L4 is an unusually dust-rich comet with a dust-to-gas mass ratio >4.

Key words: comets: individual (C/2011 L4) – infrared: planetary systems – Oort Cloud
Online-only material: color figures

1. INTRODUCTION
Comet C/2011 L4 (Pan-STARRS) was discovered at 7.9 AU from the Sun in 2011 June by the 1.8 m Pan-STARRS 1 survey telescope atop Haleakala. The detection was confirmed in follow up observations with the Canada–France–Hawaii Telescope (Wainscoat et al. 2011). The small reciprocal of the original semi-major axis, 1/a = 8.9 × 10^{-5} AU^{-1} (Williams 2013), suggests that this comet is a recent arrival from the Oort Cloud. C/2011 L4 reached an apparent visual magnitude of −1 at 0.301 AU in 2013 March, which made it one of the brightest comets in the past two decades since comet C/1995 O1 (Hale–Bopp). The apparition of C/2011 L4 provided a rare opportunity to monitor a dynamically new comet over a significant time period and a wide range of heliocentric distances, particularly during the in-bound leg.

At the time of discovery, C/2011 L4 showed an extended appearance (Wainscoat et al. 2011), indicating the presence of a substantial coma. The turn-on distance for any appreciable water ice sublimation is around 5–6 AU from the Sun, beyond which the equilibrium surface temperature is too low and H₂O–ice sublimation is not sufficient to lift even the smallest sub-micron-sized dust particles from the surface (Meech & Svoren 2004). It is clear that C/2011 L4 was far beyond the water sublimating zone yet it appeared active. Several possible mechanisms that could power distant comet activity have been proposed, including latent heat release from the amorphous-to-crystalline phase transition of water ice (Prialnik 1992; Notesco et al. 2003; Bar-Nun & Lauffer 2003), sublimation of frozen super-volatiles (Meech & Svoren 2004), and comet fragmentation (Boehnhardt 2004). Among these, the exothermic amorphous-to-crystalline phase transition of water ice is considered to be an important energy source that can trigger distant cometary activity and power a cometary outburst (Enzian et al. 1997). Observationally, crystalline ice differs from its amorphous counterpart by the presence of a sharp narrow feature at 1.65 μm. This feature has been observed in large Kuiper belt objects via near-infrared (NIR) spectroscopy (Jewitt & Luu 2004; Trujillo et al. 2007) and was recently detected in the coma of an outbursting Jupiter-family comet P/2010 H2 (Vales; Yang & Sarid 2010). However, crystalline water ice has never been seen in any Oort Cloud comet (OCC; Davies et al. 1997; Kawakita et al. 2004). Nevertheless, the absence of observational evidence does not exclude the presence of crystalline ice in OCCs. This is because the available OCC spectra have limited signal-to-noise ratios (S/Ns) and spectral resolutions. We conducted a multi-wavelength observational campaign of C/2011 L4, from optical to submillimeter wavelengths. The main goals of this study were three-fold: (1) to search for water ice, in particular, the crystalline feature at 1.65 μm via high S/N and medium-resolution spectroscopy in the NIR, (2) to monitor the onset of volatile species (such as CN, HCN, and CO) in the optical and the radio as the comet approached the Sun, and (3) to monitor the development of the dust and gas coma via optical spectroscopy.

2. OBSERVATIONS AND DATA REDUCTIONS
NIR spectroscopy was conducted using the GNIRS spectrograph on the 8 m Gemini-North (Gemini-N) Telescope and the SpeX spectrograph on the 3 m Infrared Telescope Facility (IRTF) Telescope. The GNIRS observations were taken with the short camera (plate scale: 0′.15 pixel^{-1}). The cross-dispersed mode, 32 1 mm^{-1} grating and 1′.0 slit, provides an averaged resolving power of R ∼ 500 over 0.85–2.5 μm. The SpeX observations were obtained using the high throughput prism mode (0.8–2.5 μm) and a 0′.8 × 15′′ slit that provides a spectral resolution of R ∼ 100 (Rayner et al. 2003). Two nearby G-type stars, used both as the telluric correction standard stars and solar analogs, were observed together with the comet during each run. The GNIRS data were reduced using IRAF software and the Gemini IRAF package. The SpeX data were reduced using the reduction pipeline SpeXtool (Cushing et al. 2004).

Optical spectra were obtained using the Gemini Multi-Object Spectrograph (GMOS) spectrograph on Gemini-N with the long-slit mode (plate scale: 0′.146 pixel^{-1}). We used the B600 grating and set the slit width to 1′.5, which provides a resolving
power of $R \sim 560$. At least one G-type star was observed together with the comet during each observing run. In addition, one spectrophotometric star was observed for flux calibration. The GMOS data were reduced using a combination of the Gemini IRAF package and the XIDL code (J. X. Prochaska 2012, private communication).

Besides, we also obtained submillimeter spectroscopy of C/2011 L4 using the 15 m James Clerk Maxwell Telescope (JCMT) on Mauna Kea, Hawaii. The ACSIS spectrometer was used, providing a total bandwidth of 250 MHz and spectral channel spacing of 30.5 kHz. The comet was observed over three separate observing runs between 2012 August and November. All of our observations were performed with the HARP receiver in position-switching mode (5′ apart in azimuth). The data were reduced using a combination of Starlink and IDL software. A record of the observations is provided in Table 1.

### 3. RESULTS

#### 3.1. Detection of Water Ice

The NIR observations of C/2011 L4 are presented in Figure 1. A strong absorption feature centered at 2.0 $\mu m$ was consistently observed both in the SpeX and the GNIRS spectra. The profile and the center of this absorption feature are consistent with the diagnostic 2.0 $\mu m$ absorption band of water ice. However, water ice, if present, usually exhibits two absorption bands simultaneously, i.e., the 2.0 $\mu m$ band and an accompanying band at 1.5 $\mu m$. The spectra obtained in March and June appear featureless between 1.4 and 1.7 $\mu m$. The July spectrum, however, shows two small absorption features at 1.28 and 1.50 $\mu m$, respectively. The latter feature could be associated with water ice but it is significantly narrower than the 1.5 $\mu m$ band. Comparing the comet spectrum with the standard star spectra taken in July, we conclude that these two minor features are more likely due to incomplete cancellations of telluric absorptions. The apparent absence of the 1.5 $\mu m$ feature in contrast to the presence of the strong 2.0 $\mu m$ band is not unique to C/2011 L4. For instance, the outbursting comet 17P/Holmes exhibited strong absorption bands at 2.0 and 3.0 $\mu m$ without showing any sign of the 1.5 $\mu m$ band (Yang et al. 2009). Attempting to understand the problem of the missing 1.5 $\mu m$ feature, Yang et al. (2009) investigated the effects of impurity and particle size on the synthesized ice spectra. They concluded that neither of the investigated properties could explain the asymmetry between the 1.5 and 2.0 $\mu m$ bands. However, in the study of 17P, the adopted Hapke theory has significant limitations and cannot account for particles smaller than the wavelength being studied (Hapke 1993). In this Letter, we apply Mie theory to synthesize water ice spectra and use the optical constants from Mastrapa et al. (2009). The main reason for choosing Mie over Hapke is that Mie theory is suitable for investigating small particles that have a Rayleigh scattering parameter $X = 2\pi a_g/\lambda$, much less than one, where $a_g$ is the particle radius and $\lambda$ is the wavelength.

Using the new Mie model, we found that the ratio between the depth of the 1.5 and 2.0 $\mu m$ bands is sensitive to grain size. Using sub-micron fine grains, our best-fit areal mixing models can successfully reproduce the observed spectral features, i.e., a strong 2.0 $\mu m$ band and a much weaker 1.5 $\mu m$ band. All the comet spectra can be explained by roughly 30% fine-grained water ice ($a_g \sim 0.2 \mu m$) mixed with spectrally featureless materials (such as amorphous carbon). We note that the strength of the 2.0 $\mu m$ band remained consistent from March to July, indicating that the dust-to-ice ratio of the coma did not change significantly over heliocentric distances from 5.24 to 3.68 AU. The persistence of the ice features suggests that the lifetime of the ice particles must be longer than or comparable to the slit-crossing time. For the July run, the extraction aperture radius is 2′.5 (or \(6700 \text{ km projected in the sky}\)). Assuming the expansion speed of the icy grains is represented by the empirical relation

\[
\nu_{\text{dust}} = 0.535 r_x^{0.6} \text{ km s}^{-1} \quad \text{Bobrovnikoff 1954; Whipple 1978},
\]

the slit-crossing time is at least 7.6 hr. As shown in Lien (1990) and Beer et al. (2006), the lifetime of a sub-micron dirty ice grain at 3.68 AU is less than 2 hr. If dirty icy particles were to survive the slit-crossing, their outflow velocity would have to exceed 1 km s$^{-1}$, which is non-physical for the comet at $r_D > 3.5$ AU. Given the estimates above, the ice particles detected in comet C/2011 L4 it is likely to be pure.

#### 3.2. Optical Spectroscopy

Optical spectroscopy was obtained using Gemini-N in queue mode from 2012 April to July. Specifically, we searched for...
For dust velocity, we adopted an outflow velocity relationship of \(\frac{Q_{\rho}}{f} = 0.04\) for dust particles (Singh et al. 1992), we compute the CN band flux and the CN production rate. The derived upper limits to the gas mass-loss rate is \(\frac{Q_{\rho}}{f} < 3 \times 10^{-26}\) QH\(_2\)O (Sanzovo et al. 1996).

Notes.

- \(\alpha\) 3σ upper limit of the CN band flux
- \(\beta\) CN production rate, upper limit
- \(\gamma\) H\(_2\)O production rate, upper limit, assuming \(Q_{\text{CN}}/Q_{\text{H}_{2}\text{O}} \sim 350\) (A’Hearn et al. 1995)
- \(\delta\) Dust mass-loss rate, assuming a size distribution of \(f(a) \sim a^{-4}\)
- \(\epsilon\) Gas mass-loss rate, assuming \(M_{\delta} = 3.4 \times 10^{-26}\) QH\(_2\)O (Sanzovo et al. 1996)
- \(\zeta\) Dust-to-gas ratio

### Table 2

| UT Date     | \(f_{\text{CN}}\) \(\text{erg cm}^{-2} \text{s}^{-1} \text{Å}^{-1}\) | \(Q_{\text{CN}}\) \(\text{mol s}^{-1}\) | \(Q_{\text{H}_{2}\text{O}}\) \(\text{mol s}^{-1}\) | \(f_{\text{CO}} - f_{\text{HCN}}\) | \(M_{\delta}\) \(\text{kg s}^{-1}\) | \(M_{\delta}\) \(\text{kg s}^{-1}\) |
|-------------|-------------------------------------------------|-----------------|-----------------|-----------------|-----------------|-----------------|
| 2012 Apr 22 | \(<1.68 \times 10^{25}\) | \(<5.9 \times 10^{27}\) | 110.2 ± 8.0 | 670 | \(<200\) | >3.4 |
| 2012 May 15 | \(<1.78 \times 10^{25}\) | \(<6.2 \times 10^{27}\) | 116.9 ± 8.0 | 650 | \(<212\) | >3.1 |
| 2012 Jul 12 | \(<1.41 \times 10^{25}\) | \(<5.0 \times 10^{27}\) | 128.9 ± 9.0 | 730 | \(<168\) | >4.3 |

In the radio, CO and HCN are the most easily detected gaseous species for distant comets \((r > 3\) AU; Senay & Jewitt 1994; Biver et al. 2002). We carried out three observing runs in the submillimeter to search for CO and HCN. No gas emission was detected from August to November. To quantify the upper limits to the production rates of CO and HCN, we calculated the standard errors in two background regions and estimated the upper limits to the production rates of CO and HCN, we calculated the standard errors in two background regions and estimated line area intensities \((f_{\text{CO}}\) and \(f_{\text{HCN}}\)) within a 1.2 km s\(^{-1}\) band. Even at the smallest \(r\) (2.3 AU), where the CO lifetime is the shortest, the expected lifetime against photodestruction for a CO molecule is \(\tau_{\text{CO}} = 3.6 \times 10^{9}\) s (about 1 yr). Similarly, \(\tau_{\text{HCN}} = 4.8 \times 10^{5}\) s (about 4 days). Therefore, we ignored the photodestruction effect for both CO and HCN. We assumed gas molecules escaping from the surface at a constant velocity and adopted an average gas expansion velocity of 0.8 \(\cdot\) \(r^{-0.6}\) km s\(^{-1}\) (Biver et al. 1999). 3σ upper limits to the production rates were computed for two kinetic temperatures, i.e., \(T = 10\) K (higher values) and \(T = 50\) K (lower values). For August, \(f_{\text{CO}} = 0.015\) (K km s\(^{-1}\)), \(Q_{\text{CO}} < 1.5\)–\(4.6\) \(\times 10^{27}\), \(f_{\text{HCN}} = 0.032\) (K km s\(^{-1}\)), \(Q_{\text{HCN}} < 0.5\)–\(3.1\) \(\times 10^{25}\); for October, \(f_{\text{CO}} = 0.024\) (K km s\(^{-1}\)), \(Q_{\text{CO}} < 2.4\)–\(7.4\) \(\times 10^{27}\), \(f_{\text{HCN}} = 0.035\) (K km s\(^{-1}\)), \(Q_{\text{HCN}} < 0.5\)–\(3.3\) \(\times 10^{25}\) and for November, \(f_{\text{CO}} = 0.093\) (K km s\(^{-1}\)), \(Q_{\text{CO}} < 0.9\)–\(2.6\) \(\times 10^{26}\), \(f_{\text{HCN}} = 0.037\) (K km s\(^{-1}\)), \(Q_{\text{HCN}} < 0.6\)–\(3.6\) \(\times 10^{25}\). The much higher upper limit for \(Q_{\text{CO}}\) derived for the November run is due to poor weather conditions.

### 4. DISCUSSION

#### 4.1. Water Ice Features

The critical temperature for amorphous-to-crystalline ice transition is \(T_{c} \sim 140\) K, at which the timescale of crystallization is about 1 hr. The highest possible surface temperature for C/2011L4 should be that at its subsolar point, where \(T_{w}(r_{s}) = T_{0}/\sqrt{r_{s}}\). If we assume C/2011L4 is a slow rotator, then \(T_{0} = 392\) K (Jewitt 2009). At \(r_{s} = 5.2\) AU, C/2011L4 can reach \(T_{w} \sim 170\) K by solar heating alone. Although this is an extreme case, it shows that it is possible that at least part of the surface or near-surface ice could have experienced crystallization within our observation window.

As shown in Figure 2, sub-micron-sized ice grains show a very weak or non-existent absorbing feature at 1.65 \(\mu\)m regardless of...
The model is fitted by minimizing the 1.65 μm band due to Earth’s atmosphere. The absence of the 2.0 μm band does not exclude the presence of very fine crystalline ice grains. When focusing on the 2.0 μm band, our χ² fits show that amorphous ice fits the comet spectra better than crystalline ice for the March and June data, while the crystalline model fits the July data marginally better. However, the small difference between these two ice models is within the noise level of our data. Therefore, we cannot constrain the crystallinity of the icy grains of C/2011 L4, mainly due to their small sizes.

Although the observed asymmetry in absorption strength between the bands at 1.5 μm and 2.0 μm can be successfully explained by sub-micron pure water ice grains, there are other explanations for the observed features. For example, the 2.0 μm absorption feature may not be solely generated by pure water ice grains but could also be due to the superposition of another absorption band of organic materials or hydrated minerals. We explored this possibility by searching for matching materials that exhibit a prominent absorption feature at or near 2.0 μm. We investigated several commonly used spectral libraries such as RELAB (Hiroi et al. 1996), USGS (Clark et al. 2003), and ASTER (Baldridge et al. 2009), which include examined materials from terrestrial minerals to meteorite samples. We find no other material with an NIR signature that matches the shape and position of the 2.0 μm band of C/2011 L4.

4.2 Dust Coma

As shown in Figure 3(b), the slope of the dust continuum became steeper as the comet approached the Sun. Similar color-rh trends have been reported in other comets (Hartmann & Cruikshank 1984). However, later studies (Jewitt & Meech 1988) did not confirm these reports, suggesting instead that the reported trend may have been due to the contamination of cometary emissions. Given that no cometary emissions were observed in our optical data, the observed color trend is not caused by gas contamination. Possible explanations for this correlation, if real, include: (1) increase in the effective size of coma grains, (2) decrease in the ice-to-dust ratio in coma grains, and/or (3) changes in phase angle as the comet approaches the Sun. Our NIR observations suggest that the ice-to-dust ratio remained more or less the same (within uncertainties) and the phase angle of C/2011 L4 did not change much from April to July. Therefore both scenarios (2) and (3) are unlikely and we are left with (1) as the only plausible mechanism: the observed color-rh trend is observed because larger dust particles were released into the coma as the comet moved closer to the Sun.

Given that no gas was detected, what could have been the driving force for the cometary activity? One possibility is that C/2011 L4 underwent a strong outburst which released most of the observed dust and ice grains into the coma. At the time of our observations, the major gas production had ceased and the nucleus was surrounded by a remnant dust cloud. However, the change in the slope of the dust continuum argues for an ongoing mass-loss process. C/2011 L4 is a dynamically new comet, and no other material with an NIR signature that matches the shape and position of the 2.0 μm band of C/2011 L4.

In summary, our multi-wavelength observations yield the following findings: (1) very fine water ice grains were found in the coma of C/2011 L4, (2) no gas emission was detected, (3) C/2011 L4 is unusually dust-rich, and (4) the dust coma seemed to become redder with decreasing rh.

We thank Jason X. Prochaska and Kate Rubin for helping us with the GMOS data reduction and Zahed Wahaj and David Jewitt for valuable discussions and constructive suggestions. We
thank the JCMT staff for their assistance. B.Y. was supported by the NASA Astrobiology Institute under Cooperative Agreement No. NNA08DA77A issued through the Office of Space Science. Work was supported in part by NSF grant AST-1010059.

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Figure 3. (a) Flux calibrated optical spectra of C/2011 L4 are shown in black. Blue lines are the scaled solar analog spectra and red lines are residuals after removing the solar analog continuum. The expected CN, C3, and C2 bands are marked, the bandpasses are taken from Cochran et al. (1992). Small emission-like features in the residual spectra are artifacts due to imperfect removal of the telluric absorptions. (b) Reflectance spectra of C/2011 L4 (black) and linear regression fits (red). The spectral slope seems to be correlated with the heliocentric distance, i.e., the comet spectrum becomes redder as the heliocentric distance decreases. Two gaps at 4700 Å and 5700 Å are caused by ~2″ gaps between the detector chips of GMOS.