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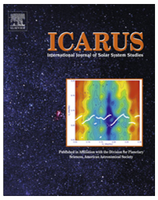

The volatile composition of 81P/Wild 2 from ground-based high-resolution infrared spectroscopy

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ABSTRACT

Volatile abundances in Jupiter-family Comet 81P/Wild 2 were measured on four dates in February and March 2010 using high-dispersion ($\lambda\Delta\lambda \sim 2.5 \times 10^4$) infrared spectroscopy with NIRSPEC at the W.M. Keck Observatory. H_2O was detected on all dates, including measurements on UT March 29 of lines from the $\nu_2 + \nu_3 - \nu_2$ hot-band not previously targeted in comets. C_2H_6 and HCN were detected on three dates, and CH_3OH was detected on one date. Tentative detections or upper-limits are reported for CH_3OH on other dates, as well as for C_2H_2, H_2CO, and NH_3. Abundances of all species relative to H_2O are in the typical range with the exception of CH_3OH, which is depleted compared to other comets. Gas production was significantly higher in late February than in late March. Rotational temperatures were determined for H_2O on UT February 22 and 23 and found to be about 30–40 K. The spatial distributions of H_2O, C_2H_6, and CH_3OH are all symmetric and similar to the spatial distribution of the dust continuum. H_2O abundances from this work are compared to other measurements from both the 1997 and 2010 apparitions. There is no clear evidence of a change in overall gas productivity between the two apparitions within measurement accuracy. Abundances of C_2H_2, C_2H_6, HCN and NH_3 are consistent with these species being the primary parents of C_2, CN, NH and NH_2 as measured at optical wavelengths. Although optically classified as carbon-chain depleted, Wild 2 appears more chemically similar in parent volatile chemistry to carbon-chain typical comets; however, we note that in the small sample of Jupiter-family comets measured to date, each comet is chemically distinct.

1. Background

The large optical photometric and spectroscopic databases, built over more than thirty years of observations, have revealed a notable diversity of comet composition through the comparison of a few daughter species in comets (A'Hearn et al., 1995; Fink and Hicks, 1996; Schleicher et al., 2007; Fink, 2009). This diversity extends to comparisons between dynamical classes of comets; short-period Jupiter-family comets are more likely to be depleted in carbon-chain molecules (C_2 and C_3 relative to CN and OH) than comets from the Oort cloud (A'Hearn et al., 1995; Fink, 2009). In order to put this large database into proper context, it is important to link these daughter species to their sources in the comet nucleus. This can be addressed by determining the composition of parent volatiles in cometary comae.

Although Jupiter-family comets are generally fainter than their Oort cloud counterparts, and thus more difficult to characterize spectroscopically, progress has been made on determining their parent volatile chemistries. About ten Jupiter-family comets have been characterized at radio wavelengths in recent years (e.g., Crovisier et al., 2009a), and improved instrumentation on large telescopes has made the systematic study of the volatile composition of Jupiter-family comets possible at infrared wavelengths (Weaver et al., 1999; Mumma et al., 2000, 2005, 2011; Villanueva et al., 2006; Kobayashi et al., 2007; DiSanti et al., 2007, 2013; Dello Russo et al., 2007, 2008, 2009a, 2011; Paganini et al., 2012a; Kawakita et al., 2013; Radeva et al., 2013). These infrared spectroscopic observations can test the origin of daughter and granddaughter species (e.g., OH, C_2, CN, NH, and NH_2) in the

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coma by comparing relative abundances with likely parents released directly from the nucleus (e.g., H_2O, C_2H_2, C_2H_6, HCN, and NH_3). Although the infrared database of Jupiter-family comets is small compared to the optical database, a comparison of chemistries determined by both optical and IR studies may provide indirect clues about the parent chemistry of comets sampled only at optical wavelengths once the relationship between parent and daughter species becomes better understood. Recent results suggest that it is not always true that abundances of C_2, CN, NH and NH_2 in Jupiter-family comets are consistent with abundances of suspected parents C_2H_2, C_2H_6, HCN, and NH_3 (Dello Russo et al., 2009a). However, such comparisons can only be done coarsely because IR and optical measurements are rarely simultaneous, production rates are determined with different techniques and physical assumptions, and comparisons often span different apparitions.

81P/Wild 2 (hereafter Wild 2) is a Jupiter-family comet based on its short period (6.2 years), low-inclination orbit (3.2°), and Tisserand invariant with respect to Jupiter (2.88). Wild 2, the target of the Stardust mission (Brownlee et al., 2004), is the only comet from which material has been collected *in situ* and returned to Earth for laboratory analysis. Whereas Stardust returned predominantly non-volatile material, we present observations of simple parent volatiles that were stored as ices in the nucleus of Wild 2 before their release into the coma. We report absolute and relative abundances (and upper limits on some dates) of H_2O, C_2H_6, CH_3OH, H_2CO, HCN, C_2H_2, and NH_3 and compare abundances in Wild 2 to other comets. We investigate how the H_2O production rates derived here compare to other measured values during the 2010 and 1997 apparitions. We also compare the abundances of parent volatile species (HCN, C_2H_2, C_2H_6, and NH_3) to potential corresponding daughter species (e.g., CN, C_2, NH, and NH_2) measured at optical wavelengths and discuss how parent volatile abundances in Wild 2 and other Jupiter-family comets compares to optical classifications from the abundances of daughter species.

2. Observations and data analysis

Observations were performed with the NIRSPEC instrument (McLean et al., 1998) at the W. M. Keck Observatory on Mauna Kea, Hawaii. The observing circumstances are summarized in Table 1. The overall volatile production rate based on direct daily measurements of H-Lyα from SOHO/SWAN during the 1997 apparition and light curves measuring comet brightness show Wild 2 reaches maximum brightness and productivity about one month before perihelion (Szutowicz et al., 2008; Combi et al., 2011). However, the optimal geometry for ground-based observations in 2010 was after this time, so our observations were obtained in two time periods, one close to perihelion and one a little over a month after perihelion.

For the Wild 2 observations we used a $24'' \times 0''.432$ slit, resulting in a spectral resolving power ($\lambda\Delta\lambda$ of $\sim$28,000. At each grating setting, comet spectra were acquired using a sequence of four scans with an integration time of 1 min on-source per scan (4 min for the complete sequence). During a sequence of scans the telescope was nodded 12″ between A and B positions in an ABBA pattern, keeping the comet on-slit for all integrations. The position angle of the slit was set in the nominal, physically-fixed position on NIRSPEC and allowed to rotate on the sky during the observations for all dates. Flux calibrations were obtained for each grating setting and were based on observations of infrared standard stars; HR 4689 was used for the February observations and HR 5511 was used for the March observations. The widest NIRSPEC slit is only five pixels ($0''.74$) wide so corrections for slit losses were included in the NIRSPEC flux calibration analysis. The average seeing (FWHM) on these dates was between $0''.5$ and $0''.7$.

The data were processed using algorithms specifically tailored to our comet observations, and application of these for data acquired with NIRSPEC have been described elsewhere (e.g., Bonev, 2005; Dello Russo et al., 2006, 2008). Measured molecular line fluxes determined within 3-pixel (spectral) × 9-pixel (spatial) extracts ($0''.43 \times 1''.72$) centered on the peak gas intensity are given in Table 2, and example spectral extracts are shown in Figs. 1–3.

Production rates and rotational temperatures were derived from the column densities within 3 × 9-pixel nucleus-centered extracts by applying a coma model that assumes spherically symmetric outflow and uniform velocity. Any outflow asymmetries will have an effect on our derived global production rates, but this method has been shown to be a valid approach to first order and is unlikely to be a major source of uncertainty (Xie and Mumma, 1996). Pre-perihelion observations of the 557 GHz H_2O line from the HIFI instrument on the Herschel Space Observatory in early February 2010 yielded an estimated mean gas expansion velocity of $0.6\ \mathrm{km\ s^{-1}}$ at a heliocentric distance of $R_h = 1.6$ AU (de Val-Borro et al., 2010). For Wild 2, we assume a gas outflow velocity of $v = 0.8 \times R_h^{-0.5}\ \mathrm{km\ s^{-1}}$, which is in agreement with the Hershel results and values typically seen in faint comets. The transit time for molecules from the nucleus to the edge of the field of view (in the plane of the sky) is short compared to the lifetime of all measured species, so the derived production rates are proportional to the assumed outflow velocity.

Production rates derived from nucleus-centered extracts are always underestimated owing to slit losses, so a production rate growth curve analysis is performed to determine production rates from regions offset from the nucleus where slit losses due to seeing, comet drift, and suboptimal focus are less important (see Dello Russo et al., 1998 for the origin and full explanation of production rate growth curve analysis). For this analysis, the multiplicative growth factor is the ratio of derived production rates determined from off-nucleus extracts to production rates determined from $0''.43 \times 1''.72$ extracts centered on the peak gas intensity. Multiplicative growth factors are obtained by coadding all lines from a single species within a grating setting to increase the signal-to-noise ratio of molecular emission in offset positions from the nucleus. In cases where multiple strong lines of a single species are present, reliable multiplicative growth factors are derived. For species whose lines are few, weak or not apparent (in cases where only upper limits are derived) multiplicative growth factors are assumed to be the same as for other species detected within the same grating setting. Multiplicative growth factors ranged from 1.4 to 1.7 for all species on these dates.

3. Results

3.1. Rotational temperatures

In order to obtain rotational temperatures and production rates from measured line fluxes, the fluorescence efficiencies (g-factors) for individual ro-vibrational lines are needed as a function of temperature. A description of the fluorescence models used in this analysis for all molecules except CH_3OH is given in Dello Russo et al. (2009a). For CH_3OH, only ν_2 lines were sampled, so individual line g-factors based on an empirical CH_3OH model for the ν_2 band were used (DiSanti et al., 2013).

In general, the rotational temperature of a species in the coma can be determined if multiple strong lines with a range of ground-state rotational energies are measured (e.g. Dello Russo et al., 2004). Because the predicted strengths or g-factors for