THE UNUSUAL SPECTRUM OF COMET 96P/MACHHOLZ

LAURA E. LANGLAND-SHULA AND GRAEML H. SMITH
Department of Astronomy and Astrophysics, University of California, Santa Cruz, 1156 High Street, Santa Cruz, CA 95064; laura@ucolick.org, graeme@ucolick.org
Received 2007 May 24; accepted 2007 June 13; published 2007 July 19

ABSTRACT

We report spectra from 3000 to 5900 Å for comet 96P/Machholz, obtained on 2007 April 27 UT with the 3 m Shane telescope at Lick Observatory. The spectra are extremely carbon-poor, and they show a prominent NH$_2$ series but no CN emission. NH, NH$_2$, and C$_2$ gas production rates are $(8.36 \pm 2.18) \times 10^{25}$, $(29.88 \pm 3.66) \times 10^{25}$, and $(4.52 \pm 0.61) \times 10^{23}$ molecules s$^{-1}$, respectively, as determined from Haser model fits to the data. Upper limits to the gas production rates for CN and C$_3$ are $7.5 \times 10^{23}$ and $2.0 \times 10^{23}$, respectively. Although 96P is depleted in C$_2$ and C$_3$ relative to NH, it is even more depleted in CN than other so-called carbon chain–depleted comets.

Subject headings: comets: general — comets: individual (96P/Machholz) — cosmic rays — Oort Cloud — solar system: formation

1. INTRODUCTION

In recent decades, a rapidly growing number of periodic comets have been discovered, including new members of the low-inclination short-period Jupiter family and the high-inclination medium-period Halley family. A subclass of Jupiter family comets has been shown by many authors (Newburn & Spinrad 1984; A’Hearn et al. 1995; Fink & Hicks 1996) to be depleted in the “carbon chain” molecules C$_2$ and C$_3$ relative to CN. A few comets with more abnormal production rate ratios have been reported, including notably C/1998 Y2 (Yangka) (1988r; Fink 1992). Schleicher (2007, hereafter S07) recently reported unusual gas production rate ratios for 96P, determined from narrowband photometry performed on 2007 May 12 and 24 when the comet was at $e_s = 1.07$ and 1.30 AU, respectively, which we now confirm.

Comet 96P/Machholz was discovered in 1986 May (Machholz et al. 1986). Surprisingly short-period (5.2 yr) orbital elements were calculated from the initial magnitudes and positions reported in the IAU circulars (Table 1). Sekanina (1990a) noted a major outburst several weeks after perihelion and suggested that the comet remained undiscovered in spite of its short period because it is inactive for much of the time. Its small perihelion (0.12 AU) leads to a high erosion rate (Sekanina 1990b), so it may have a mostly dormant iceless surface.

It is in 9/4 resonance with Jupiter, and their orbit evolution calculations show that their perihelion is steadily decreasing to a minimum of 0.03 AU in about the year 2450. 96P has also been suggested as the parent body for several meteor streams (Sekanina 1990a; McIntosh 1990; Babadzhanov & Obrubov 1993). All other references to 96P discuss its meteor stream connection (Jenniskens et al. 1997; Williams & Cullender-Brown 1998) and the possibility that some sunskirting comets are fragments of it that were thrust onto their current parabolic orbits after encounters with Jupiter (Ohtsuka et al. 2003; Sekanina & Chodas 2005).

2. OBSERVATIONS

Comet 96P/Machholz was observed postperihelion on 2007 April 27 UT with the Kast Spectrometer at the Lick Observatory 3 m Shane telescope. The blue side was used with a 1.5" × 128" slit and a 452/3306 grism, giving a dispersion of 2.49 Å pixel$^{-1}$. A Reticon CCD recorded the two-dimensional (2D) spectra (1199 pixels along the dispersion direction and 164 pixels along the slit at a scale of 0.78" pixel$^{-1}$). The comet’s orbital parameters and observational circumstances are given in Table 1.

The data reduction used standard IRAF$^1$ techniques and custom IDL routines. In IRAF, the spectra were trimmed to encompass the length of the slit, flat-field–corrected, median-filtered to remove cosmic rays, and wavelength-calibrated using HeHgCd lamp reference spectra.

Because 96P rose shortly before morning astronomical twilight, there was time for one dark-sky comet frame to be taken starting at 11:38 UT but not enough time to obtain a separate sky spectrum for background subtraction. The second comet spectrum was taken mostly between astronomical and nautical twilight and contained a large scattered sky continuum component. Fortunately, both 2D spectra contain sky information at the ends of the slit, with only a small amount of flux contribution from the NH band at 3360 Å. In IDL, we constructed a virtual 2D sky frame for each comet exposure, by fitting a line under the NH flux at both the top and the bottom of the slit to remove it, and linearly interpolating the sky values from the top and bottom rows of the CCD frame across the entire slit length. Back in IRAF, each virtual sky frame was subtracted from its comet frame.

The final flux calibration was done with a custom IDL code that applies an extinction curve measured for that night and utilizes standard fluxes blueward of 3200 Å not available with IRAF. The spectrograph range was set this blue to observe the OH 3085 Å band in other target comets. The extinction curve was constructed from observations of the standard star BD +33 2642 over the air-mass range 2.52–1.12, using a wide (9") slit to capture all of the starlight. The extinction versus wavelength relation that was derived is shown in Figure 1.

The IDL flux-calibration code does several things: integrates a spectrum of the standard star (taken with the same 1.5" slit as

$^1$ See http://iraf.noao.edu/.
TABLE 1
COMET 96P/MACHHOLZ: OBSERVATIONS AND ORBIT PARAMETERS

| Parameter     | Value         |
|---------------|---------------|
| Date (UT)     | 2007 Apr 27 (11:38) |
| $r_h$ (AU)    | 0.754         |
| $\Delta$ (AU) | 0.747         |
| Air mass      | 2.5–1.87      |
| Exp. (s)      | 2 × 1200      |
| $q$ (AU)      | 0.12          |
| $e$           | 0.96          |
| $i$ (deg)     | 60.18         |

the comet) along the slit, corrects the integrated standard star spectrum to zero air mass, and creates a flux-per-count “sensitivity function” by dividing the standard fluxes by the integrated standard star counts for each pixel along the dispersion direction. The standard fluxes were taken from two sources: the magnitudes per unit frequency distributed with IRAF redward of 3200 Å and the flux per unit wavelength from Bohlin (1986) blueward of 3200 Å. This sensitivity function takes into account total system throughput, including wavelength-dependent light losses from using a narrower slit. The last IDL task is to calculate the appropriate extinction correction for each comet frame, and fold the comet extinction correction into the sensitivity function to create a set of final flux-calibration masks. Finally, back in IRAF, each 2D comet spectrum is multiplied by its flux-calibration mask.

The average of our two flux-calibrated 1200 s spectra of comet 96P, integrated along the slit, is shown in Figure 2. The NH emission band at 3360 Å is clearly visible in Figure 2a. Various NH$_2$ emission bands are identified in Figure 2b. Most of the identified lines are NH$_2$ and NH, presumed to be photodissociation daughter species of ammonia. Notable is the faint C$_2$ emission, and the questionable CN and C$_3$ emission. Some flux was apparent in the region of the C$_3$ band for one spectrum, but the other spectrum only showed noise in this location.

3. MOLECULE PRODUCTION RATES
Molecule production rates were calculated from a Haser (1957) model. For a detailed explanation of how this model was applied to Kast data, please see Turner & Smith (1996).

Fig. 1.—Atmospheric extinction in magnitudes per air mass vs. wavelength at Lick Observatory on 2007 April 27 UT. The solid line is the measured extinction. The long-dashed line is the ozone component. The short-dashed line is the Rayleigh scattering component. The dot-dashed line is the aerosol component. The asterisks show extinction values tabulated previously for Lick Observatory.

Fluorescence efficiencies are from Kim et al. (1989) for NH, Newburn & Spinrad (1989) for C$_2$ and C$_3$, and Tatum (1984) for CN. For NH$_2$, we used the blue-band fluorescence efficiencies of Tegler & Wyckoff (1989) scaled to the newer red-band efficiencies of Kawakita & Watanabe (2002). We assume a gas outflow velocity at 1 AU of 1 km s$^{-1}$ (consistent with A’Hearn et al. 1995) and a scaling with heliocentric distance of $r_h^{-0.5}$ (where $r_h$ is in AU). Sets of scale lengths were determined for the NH, NH$_2$, and C$_2$ bands in each spectrum by experimenting with a range of possible values. Where the best-fit scale lengths for NH$_2$ bands blueward of (0, 12, 0) were most uncertain and exceeded 100 $\times$ 10$^3$ km, the mean of the other scale lengths was used instead. Scale lengths for the CN and C$_3$ bands followed from Turner & Smith (1996).

The scale lengths (applicable at the comet’s heliocentric distance $r_h = 0.754$ AU) and the resulting gas production rates ($\dot{Q}$) with 1 $\sigma$ error bars are given in Table 2. “NA” in Table 2 refers to an undefined production rate where the net flux in a
nondetected emission band was less than the adjacent continuum. S07 report log \(Q(\text{OH}) = 27.33\), while we did not detect OH. Our production rate for NH is a factor of 3 higher than S07, consistent with the smaller \(r_c\) of 96P during our observations, but our production rate for \(C_2\) is 90% of S07’s. Our observation of 96P covers a spatial area of about 820 × 70,570 km. Our slit length is comparable to the larger spatial observations in Fink (1992). Cochran (1985) reviews Haser-model decay scale lengths for the parent molecules of CN [(1.2–2.2) \(\times 10^3\) km], \(N\text{H}_2\) [(1.7–3.5) \(\times 10^3\) km], and \(C_2\) [(1.0–2.5) \(\times 10^3\) km], which are all shorter than our slit length. If cosmic-ray gluing increased the parent decay scale length of \(C_2\) by an order of magnitude, we still expect to see \(C_2\) production. Brightness and polarization measurements of dust in the coma of 96P (Grynko et al. 2004) show grain sizes consistent with in situ measurements of Halley dust, also pointing to limited cosmic-ray gluing.

Greenberg et al. (1993) admit that other dynamically new comets do not display extreme carbon depletions. Likewise, other short-period comets (\(P < 7\) yr), presumably with surfaces similarly processed by solar radiation as 96P, display measurable carbon production: 2P/Encke and 6P/d’Arrest (A’Hearn et al. 1979), 9P/Tempel 1 (Lara et al. 2006), 19P/Borrell (Hamane et al. 2002), 26P/Grigg-Skjellerup (Jockers et al. 1993), 46P/Wirtanen (Jockers et al. 1998), and 67P/Churyumov-Gerasimenko (Schulz et al. 2004). In old dusty comets, or comets moving outbound from perihelion, the CN and \(C_2\) emission bands are the last to be observable as global gas production turns off.

4. Discussion

The only other comet in the literature noted to be this deficient in CN and \(C_2\) is Yanaka (1998r or C/1998 Y1; Kosai et al. 1988). Yanaka was observed postperihelion in 1989 with the f/1.2 spectrograph at the University of Arizona 1.54 m Mount Bigelow telescope (Fink 1991, 1992). The observational parameters are listed in Table 3; those not given in Fink (1992) were obtained from the Minor Planet & Comet Ephemeris Service 2 provided by the IAU.

Comet Yanaka displays a series of \(N\text{H}_2\) emission bands from 5300 to 8500 Å. Fink’s spectrum of it and our spectrum of 96P/Machholz overlap from 5300 to 5800 Å, in the region of the \(N\text{H}_2\) (0, 10, 0) and (0, 11, 0) bands. Noticeably absent in the Yanaka spectrum are the CN 1–0, 2–0, 2–1, and 3–1 bands and the \(C_2\) \(\Delta v = -1\) band.

Greenberg et al. (1993) proposed that three effects could combine nonlinearly to inhibit the detection of CN and \(C_2\) in comet Yanaka. First, cosmic-ray exposure could “glue together” or “carbonize” the comet (deplete H, N, and O relative to C), with two effects: trapping carbon-bearing gas molecules between dust grains and producing larger dust grains more resistant to heating and fragmentation. Finally, since comet Yanaka was observed over a smaller spatial dimension (660 × 16,470 km) than the other comets in Fink (1992; 3420 × 84,200 km and 2400 × 145,600 km), there may be less time for molecule production to occur within the spectrograph slit aperture.

Our observation of 96P covers a spatial area of about 820 × 70,570 km. Our slit length is comparable to the larger spatial observations in Fink (1992). Cochran (1985) reviews Haser-model decay scale lengths for the parent molecules of CN [(1.2–2.2) \(\times 10^3\) km], \(N\text{H}_2\) [(1.7–3.5) \(\times 10^3\) km], and \(C_2\) [(1.0–2.5) \(\times 10^3\) km], which are all shorter than our slit length. If cosmic-ray gluing increased the parent decay scale length of \(C_2\) by an order of magnitude, we still expect to see \(C_2\) production. Brightness and polarization measurements of dust in the coma of 96P (Grynko et al. 2004) show grain sizes consistent with in situ measurements of Halley dust, also pointing to limited cosmic-ray gluing.

Greenberg et al. (1993) admit that other dynamically new comets do not display extreme carbon depletions. Likewise, other short-period comets (\(P < 7\) yr), presumably with surfaces similarly processed by solar radiation as 96P, display measurable carbon production: 2P/Encke and 6P/d’Arrest (A’Hearn et al. 1979), 9P/Tempel 1 (Lara et al. 2006), 19P/Borrell (Hamane et al. 2002), 26P/Grigg-Skjellerup (Jockers et al. 1993), 46P/Wirtanen (Jockers et al. 1998), and 67P/Churyumov-Gerasimenko (Schulz et al. 2004). In old “dusty” comets, or comets moving outbound from perihelion, the CN and \(C_2\) emission bands are the last to be observable as global gas production turns off (i.e., A’Hearn et al. 1995; Fink & Hicks 1996), such that CN is used as a gas-to-dust indicator (i.e., Storrs et al. 1992). However, CN is not detected in the Kast spectra of 96P.

Other dormant comets may perhaps show mostly ices, and not carbon-bearing gas, when they have an outburst. However, CN was detected in 95P/Chiron by Bus et al. (1991). Comet 4P/Faye was observed in outburst by Grothues (1996) and has measurable CN, \(C_2\), and \(C_2\) production rates (Gil-Hutton & Licandro 1994). Chamberlin et al. (1996) detected no CN in three candidate comet-asteroid transition objects, although their signal-to-noise ratio deteriorates in the region of the CN band. Unfortunately, none of these observations were programmed to look for the NH 3360 Å band.

Having exhausted several explanations for the odd spectrum of 96P, we can compare it to other comets with extreme production rate ratios. The values in square brackets in Table 4 refer to logarithmic ratios between the production rates of various species. Where there are discrepancies between the [X/OH] ratios and the [X/CN] ratios for the A’Hearn et al. (1995) comets, the [X/CN] ratios are more reliable and are the basis for the listed [X/NH] ratios. In 96P, we confirm the S07 report that the carbon chain molecules are depleted compared to NH. Even compared

### Table 2

| Molecule | Parent (10^3 km) | Daughter (10^3 km) | Q (10^35 molecules s⁻¹) | Parent (10^3 km) | Daughter (10^3 km) | Q (10^35 molecules s⁻¹) | Mean Q (10^35 molecules s⁻¹) |
|----------|-----------------|-------------------|-------------------------|-----------------|-------------------|-------------------------|-----------------------------|
| NH       | 70              | 200               | 10.54                   | 40              | 120               | 6.18                    | 8.36 ± 2.18                 |
| NH, mean | 3.4             | 42                | 26.22                   | 4.2             | 25                | 33.54                   | 29.88 ± 3.66                |
| (0, 10, 0) | 3.0             | 50                | 17.07                   | 6.0             | 25                | 23.25                   | 20.16 ± 3.09                |
| (0, 11, 0) | 3.0             | 40                | 20.30                   | 4.0             | 25                | 21.65                   | 20.98 ± 0.68                |
| (0, 12, 0) | 5.0             | 35                | 13.03                   | 5.0             | >300              | 29.15                   | 21.09 ± 8.06                |
| (0, 13, 0) | 2.0             | 160               | 47.14                   | 3.0             | 150               | 64.47                   | 55.81 ± 8.67                |
| (0, 14, 0) | 4.0             | >300              | 33.56                   | 3.0             | 210               | 29.19                   | 31.38 ± 2.18                |
| CN       | 7.5             | 240               | NA                      | 7.5             | 240               | <0.0075                 | <0.0075                     |
| C₂       | 7.0             | 20                | 0.039                   | 7.0             | 30                | 0.051                   | 0.0452 ± 0.0061             |
| C₁       | 1.3             | 57                | <0.020                  | 1.3             | 57                | NA                      | <0.020                      |

### Table 3

| Parameter             | Value             |
|-----------------------|-------------------|
| Date (UT)             | 1989 Jan 15 (13:26) |
| \(r_c\) (AU)          | 0.932             |
| \(\Delta\) (AU)       | 0.367             |
| Air mass              | 1.84              |
| Exp. (s)              | 3 × 300           |
| \(q\) (AU)            | 0.43              |
| \(e\)                 | 1.00              |
| \(i\) (deg)           | 71.01             |

2 See http://www.cfa.harvard.edu/iau/MPEph/MPEph.html.
to other “C chain–depleted” comets, 96P is unusual because we detect C2 emission but not CN. A distinctive property of 96P is the very high [C2/CN] ratio, for which we only obtain a lower limit. Rather than being carbon–chain–depleted relative to CN, 96P is the comet with the least amount of CN to also display a C3 band and is by far the comet most depleted in CN relative to NH, C2, and C3 than either “typical” or “C chain–depleted” comets.

5. CONCLUSIONS

Comet 96P/Machholz has extremely depleted C2 and C3 relative to NH and NH2, with CN more extremely depleted. The dimensions of our spectrograph slit were sufficient to see any possible decay of the parents of these carbon molecules. The extreme carbon depletion of 96P is unlikely to be due to cosmic-ray “gluing” in the comet’s past and is unlikely to be due to surface processing by the Sun over repeated short orbits (since this effect is not seen in many other short-period comets). Although 96P was observed to have an outburst shortly after its discovery, other confirmed outbursting comets show carbon emission features. Thus, it appears that 96P/Machholz belongs to a small class of comets with genuinely unusual molecule production rates.

This research is supported by NASA grant NNG05GG59G through the Planetary Astronomy program.

REFERENCES

A’Hearn, M. F., Millis, R. L., & Birch, P. V. 1979, AJ, 84, 570
A’Hearn, M. F., Millis, R. L., Schleicher, D. G., Ospj, D. J., & Birch, P. V. 1995, Icarus, 118, 223
Bahadzhanov, B. P., & Obrubov, V. Yu. 1993, in Meteoroids and Their Parent Bodies, ed. J. Stohl & I. P. Williams (Bratislava: Astron. Inst., Slovak Acad. Sci.), 49
Bohnin, R. C. 1986, ApJ, 308, 1001
Brown, M. E., Bouchez, A. H., Spinrad, A. H., & Johns-Krull, C. M. 1996, AJ, 112, 1197
Bus, S. J., A’Hearn, M. F., Schleicher, D. G., & Bowell, E. B. 1991, Science, 251, 774
Chamberlin, A. B., McFadden, L., Schulz, R., Schleicher, D. G., & Bus, S. J. 1996, Icarus, 119, 173
Cochran, A. L. 1985, AJ, 90, 2609
Cochran, A. L., & Cochran, W. D. 2002, Icarus, 157, 297
Fink, U. 1991, BAA, 23, 1160
———. 1992, Science, 257, 1926
Fink, U., & Hicks, M. D. 1996, ApJ, 459, 729
Gil-Hutton, R., & Licandro, J. 1994, RevMexAA, 28, 3
Green, D. W. E., Rickman, H., Porter, A. C., & Meech, K. J. 1990, Science, 247, 1063
Greenberg, J. M., Singh, P. D., & de Almeida 1993, ApJ, 414, L45
Grothues, H.-G. 1996, Planet. Space Sci., 44, 625
Gryko, Y., Jockers, K., & Schwenn, R. 2004, A&A, 427, 755
Hamane, T., Kawakita, H., Kinugasas, K., Yamamura, T., & Takeyama, N. 2002, PASJ, 54, L35
Hasler, L. 1957, Bull. Acad. R. Sci. Liege, 43, 740
Jenniskens, P., Bertlem, H., de Lignie, M., Langbroek, M., & van Vliet, M. 1997, A&A, 327, 1242
Jockers, K., Credner, T., & Bonev, T. 1998, A&A, 335, L56
Jockers, K., Kiselev, N. N., Boehnhardt, H., & Thomas, N. 1993, A&A, 268, L9
Kawakita, H., & Watanabe, J. 2002, ApJ, 572, L177
Kim, S. J., A’Hearn, M. F., & Cochran, W. D. 1989, Icarus, 77, 98
Kossai, H., Yanaka, T., & Levy, D. 1988, IAU Circ. 4696
Lara, L. M., Boehnhardt, H., Gredel, R., Gutierrez, P. J., Ortiz, J. L., Rodrigo, R., & Vidal-Nunez, M. J. 2006, A&A, 445, 1151
Lisse, C. M., Fernandez, Y. R., & Biesemeier, D. A. 2002, AAS DPS Meeting, 34, 12,06
Machholz, D. E., Morris, C. S., & Hale, A. 1986, IAU Circ. 4214
Mcintosh, B. A. 1990, Icarus, 86, 299
Meech, K. J., Hainaut, O. R., Bauer, J. M., Williams, G. V., St. Cyr, O. C., & Stezelsberger, S. T. 1997, IAU Circ. 6669
Newburn, R. L., & Spinrad, H. 1984, AJ, 89, 289
———. 1989, AJ, 97, 552
Ohtsuka, K., Nakano, S., & Yoshikawa, M. 2003, PASJ, 55, 321
Schleicher, D. 2007, IAU Circ. 8842 (S07)
Schulz, R., Stuwe, J. A., & Boehnhardt, H. 2004, A&A, 422, L19
Sekanina, Z. 1990a, AJ, 99, 1268
Sekanina, Z., & Chodas, P. W. 2005, ApJS, 161, 551
Storrs, A. D., Cochran, A. L., & Barker, E. S. 1992, Icarus, 98, 163
Tatum, J. B. 1984, A&A, 135, 183
Tegler, S., & Wyckoff, S. 1989, ApJ, 343, 445
Turner, N. J. J., & Smith, G. H. 1996, Earth Moon Planets, 73, 33
Williams, I. P., & Collander-Brown, S. J. 1998, MNras, 294, 127

TABLE 4

Comets with Extreme Production Rate Ratios

| Comet                  | Type       | [CN/OH] | [C2/OH] | [NH/OH] | [C2/CN] | [CN/NH] | [C2/NH] | [C3/NH] | Ref.     |
|-----------------------|------------|----------|---------|---------|---------|---------|---------|---------|----------|
| Typical mean          | T          | −2.50    | −2.44   | −2.37   | +0.06   | −0.13   | −0.07   | −1.22   | 1        |
| C chain–depleted mean | D          | −2.69    | −3.30   | −2.48   | −0.61   | −0.21   | −0.82   | −1.70   | 1        |
| P/Howell              | JF, T      | −2.47    | −2.55   | −1.14   | −0.09   | −1.33   | −1.42   | −2.68   | 1        |
| Bowell (1980)          | DN, D      | −3.33    | −3.43   | −2.06   | −0.39   | −0.58   | −0.97   | −2.26   | 1        |
| P/IRAS                 | HF, D      | −2.57    | −3.48   | −2.03   | −0.93   | −0.45   | −1.38   | −2.28   | 1        |
| P/Wolf-Harrington      | JF, D      | −2.53    | −3.75   | −2.78   | −1.20   | +0.30   | −0.90   | −1.75   | 1        |
| Yanaka (1988r)         | DN, D      | −3.97    | −4.34   | −3.14   | ...     | −0.83   | −1.20   | ...     | 2        |
| 96P/Machholz           | HF, E      | −4.93    | −3.63   | −1.86   | +1.30   | −3.07   | −1.77   | −3.17   | 3        |
| 96P (this work)        | HF, E      | ...      | ...     | ...     | ...     | +0.78   | <−3.04  | <−2.26  | <−2.61   |

Note.—Comet families: JF = Jupiter, HF = Halley, DN = dynamically new. “Carbon chain depletion” relative to CN: T = typical, D = depleted, E = enhanced. Very unusual ratios are highlighted in boldface.

References.—(1) A’Hearn et al. 1995; (2) Fink 1992; (3) S07.