# The Extremely Anomalous Molecular Abundances of Comet 96P/Machholz 1 from Narrowband Photometry

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## ABSTRACT

Narrowband filter photometry of Comet 96P/Machholz 1 was obtained at Lowell Observatory during the comet's 2007 apparition. Production rates of OH, CN, $C_2$, $C_3$, and NH were derived from these data sets, and the quantity $A(\theta)f\rho$ — a proxy measure of the dust production — was also calculated. Relative abundances, expressed as ratios of production rates with respect to OH (a measure of the water abundance), were compared to those measured in other comets. Comet Machholz 1 is shown to be depleted in CN by about a factor of 72 from average, while $C_2$ and $C_3$ are also low but "only" by factors of 8 and 19 respectively from "typical" composition (based on an update to the classifications by A'Hearn et al., 1995, Icarus 118, 223). In contrast, NH is near the mid-to-upper end of its normal range. This extremely low CN-to-OH ratio for Machholz 1 indicates that it is either compositionally associated with Comet Yanaka (1988r; 1988 Y1) which was strongly depleted in CN and $C_2$ but not $NH_2$ (Fink, 1992, Science 257, 1926), or represents a new compositional class of comets, since Yanaka had a much greater depletion of $C_2$ (>100×) than does Machholz 1 (8×). Evidence is strongly suggestive that the extremely anomalous compositions of these two comets is primordial rather than from recent thermal processing. It remains unclear if these comets formed at a location in our solar system with unusual conditions and a low probability of being gravitationally perturbed into the inner solar system, or if one or both objects are interstellar interlopers.

*Key words:* comets: individual (96P/Machholz 1): techniques: photometric

## 1. INTRODUCTION

### *Background*

Investigations of the chemical composition of comets are important for a variety of reasons. In addition to revealing the characteristics of comets themselves, the composition of comets hold unique clues to conditions in the early solar nebula and the solar system's formation processes, since comets remain the most pristine objects available for detailed study. In particular, knowledge of the bulk chemical composition of comets and how the composition varies among individuals and/or with evolution due to solar radiation can provide strong constraints on the composition and temperature of the outer protoplanetary nebula at the time solid bodies began to form 4.5-4.6 billion years ago (cf. Mumma, Weissman, and Stern 1993).

While most comets show a remarkably uniform composition, as evidenced in studies by Newburn and Spinrad (1984, 1989), Cochran (1987) and Cochran et al. (1992), A'Hearn et al. (1995), and Fink and Hicks (1996), some comets exhibit significant variations from the norm. The first identified exception was Comet 21P/Giacobini-Zinner (Bobrovnikoff 1927), for which later studies (Cochran and Barker 1987; Schleicher et al. 1987) showed that the carbon-chain species $C_2$ and $C_3$ are depleted with respect to CN by about a factor of 5. It was later shown by A'Hearn et al. (1995) that Giacobini-Zinner was the prototype of an entire class of carbon-chain depleted comets, with depletion factors ranging from about 2 to 20, with the most extreme example being Comet 43P/Wolf-Harrington (Schleicher et al. 1993). Moreover, A'Hearn et al. determined that nearly all carbon-chain depleted comets belonged to the Jupiter-family dynamical class, most of which are presumed to originate from the Kuiper Belt, while very few Halley-type or long-period comets (presumed to originate from the Oort Cloud) were depleted in carbon-chain molecules. With this correlation and because several highly evolved comets do not exhibit depletions, A'Hearn et al. concluded that the carbon-chain depleted class represented a primordial condition presumably associated with a region located *within* the Kuiper Belt, since only about one-half of the Jupiter-family comets exhibited the depletion. The Kuiper Belt is now known to consist of several different dynamical groups, including the classical Kuiper Belt, the resonant population, and the scattered disk, and subsequent studies suggest that most Jupiter-family objects arise from the scattered disk (cf. Duncan et al. 2004; Morbidelli and Brown 2004).

In addition to the carbon-chain depleted class, one comet, Yanaka (1988r = 1988 XXIV = 1988 Y1), was observed by Fink (1992) to have an extremely anomalous composition, with upper limits on the depletions of CN and $C_2$ by factors of 25 and 100, respectively. Indeed, only emission from $NH_2$ and O I $^1D$ was clearly detected in the wavelength range of 5200 Å to 1.0 micron and, until now, Yanaka was the only comet to be identified as exhibiting an unusual CN abundance.

*Comet 96P/Machholz 1*

Discovered on 1986 May 12, Comet 96P/Machholz 1 (1986e = 1986 VIII = 1986 J2) made a relatively close passage of Earth (0.40 AU) in early June on its outward leg following a very small perihelion passage of 0.127 AU. Machholz 1 is a short-period comet, with an orbital period of only 5.2 year, and in fact has the smallest perihelion distance of any short-period comet, except for 2 families of "SOHO" comets that are apparently associated with Machholz 1; see Section 5. However, Machholz 1 is not formally considered a Jupiter-family object due to its high inclination of 60.0°, resulting in a value of the Tisserand invariant with respect to Jupiter ($T_J$) of 1.94; comets are generally classified as Jupiter-family if $T_J > 2$.

At its most recent apparition, our first observations were coincidently on its discovery anniversary, 12 May 2007. Following several observational sets for two other comets, we obtained our first set of narrowband aperture photometry for Machholz 1 and immediately noted very odd raw count levels after allowing for sky levels: the count level for the NH band at 3362 Å was about 10× the count level for the CN band at 3870 Å, whereas the usual cometary ratios are about 10× in the opposite direction. We next obtained 2 confirming sets and also checked that one of our previous comets continued to yield the usual CN to NH ratio, eliminating an unseen cloud or an instrumentation problem as the source of the unexpected values. An additional confirming observation was obtained in late May, and we subsequently announced a summary of the resulting production rates and the unusual abundance ratios in an IAU Circular (Schleicher 2007). In mid-June we learned of a separate compositional measurement, performed by Langland-Shula and Smith (2007) based on spectra they obtained on 2007 April 27 shortly after Machholz 1 emerged from conjunction with the Sun. They report extreme depletions in CN, $C_2$, and $C_3$ with respect to both NH and $NH_2$.

In this paper we present our narrowband photometric results, including production rates and abundance ratios, along with associated derived quantities. We also discuss our findings in context with our compositional database for comets (A'Hearn et al. 1995 and ongoing work), and speculate as to the cause of Machholz 1's extremely unusual composition.

## 2. OBSERVATIONS AND REDUCTIONS

A total of 8 photometric sets were obtained on Comet Machholz 1 over 4 nights in 2007 May and June, using a conventional, photoelectric photometer equipped with an EMI 6256 photomultiplier tube and pulse-counting electronics at Lowell Observatory's 42-inch (1.1-m) John S. Hall telescope. Narrowband filters from the HB comet filter set, manufactured for Comet Hale-Bopp (Farnham et al. 2000), were used to isolate molecular emission bands of OH, NH, CN, $C_2$, and $C_3$, along with reflected continuum from dust grains at 3448, 4450 and 5260 Å. Comet standard calibration stars (Farnham et al. 2000) were observed each night, permitting the determination of nightly atmospheric extinction coefficients and absolute instrumental calibrations for each filter. The comet was observed in each filter for between three and five 15-second integrations, and these were either followed by or interspersed with separate sky measurements more than 15 arcmin away from the comet. The photometer entrance aperture diameter ranged between 61 and 199 arcsec; the particular aperture used for each observational set primarily depended on the need to avoid nearby background stars. Observational circumstances, including the heliocentric ($r_H$) and geocentric ($\Delta$) distances, are summarized in Table 1. The mid-time and aperture size for each set, along with the projected aperture radius ($\rho$), are listed in Table 2.

Our standard methodology for data reduction, as detailed in A'Hearn et al. (1995), was followed, with specific procedures and coefficients for the HB filters as given by Farnham et al. (2000). Resulting absolute fluxes, continuum-subtracted in the case of the emission bands, are listed in Table 2. The fluxes for each gas species were then converted to column abundances by application of the appropriate fluorescence efficiencies ($L/N$) that, in the cases of OH, NH, and CN, vary with heliocentric velocity ($\dot{r}_H$) and, in the case of CN, with heliocentric distance due to the Swings effect; the nightly $L/N$ values are given in Table 1. Column abundances were extrapolated to total coma abundances by application of a standard Haser model (Haser 1957), and gas production rates were computed by dividing by the assumed daughter lifetimes. Haser parent and daughter scalelengths and daughter lifetimes are tabulated in A'Hearn et al. (1995), and all values are assumed to scale as $r_H^2$. Final column abundances, $M(\rho)$, and production rates, $Q$, are listed in Table 3. In the case of OH, which has a single, known parent, $H_2O$, we also derive the parent, i.e. water production rate using the empirical relation derived by Cochran and Schleicher (1993) and discussed by Schleicher et al. (1998).

For each continuum filter, we derive the quantity $A(\theta)f\rho$. As defined by A'Hearn et al. (1984), this proxy for dust production requires no assumptions regarding the particle size distribution, and is simply the product of the dust albedo at the given phase function, the filling factor for the aperture, and the projected aperture radius. The value of this product is independent of wavelength and aperture size if the dust grains are gray in color and have a canonical $1/\rho$ radial distribution.

Listed in Table 3, the uncertainties associated with each data point are 1-σ values derived from a propagation of the observational errors based on photon statistics. One-σ upper limits are given for several measurements when, after sky and continuum subtraction, the resulting NH, CN, or $C_3$ emission band flux was negative; in two cases for $C_3$ the 1-σ upper limits themselves have values less than zero. Indeed, the primary sources of error on the measured fluxes of the weak emission features in Machholz 1 are due to the uncertainties associated with sky subtraction and continuum subtraction. For instance, a typical $C_3$ measurement might consist of a 80% component due to sky, a 15% component due to underlying continuum, and only 5% of the signal due to $C_3$. The need to avoid encroaching background stars caused by the comet's motion across the sky unfortunately prevented us from improving the photon statistics by significantly lengthening the integrations times.

## 3. PHOTOMETRIC RESULTS

### *Gas Production Rates*

The derived production rates listed in Table 3 are plotted as circles in Figure 1 as a function of time from perihelion (2007 April 4.62). As might be expected given the values and the uncertainties, the OH and NH exhibit clear downward trends as Machholz 1 receded from the Sun, corresponding to $r_H$-dependencies (in log-log space) of -2.4 and -3.2. Any trend for $C_2$ is more ambiguous, while no useful constraints on the trends for CN and $C_3$ are evident, because both species are dominated by their respective uncertainties. Also plotted on Figure 1 are the production rates (squares) and upper-limits determined by Langland-Shula and Smith (2007) for April 27, which are generally consistent with what one might expect by extrapolating our own values backwards in time.

### *Dust Properties*

Given the very low uncertainties for each of the measurements, it is clear that the green continuum $A(\theta)f\rho$ values are significantly higher in June than in May, most likely associated with the comet's decreasing phase angle. Evidence for this comes with the May observations, for which the phase angle changes from 66° to 49° between May 12 and 24. This region of cometary phase curves is essential flat, and the continuum $A(\theta)f\rho$ values decrease by about the same amount as do the OH and NH production rates, i.e. to first order the dust is tracking the gas. However, by June there is a discrepancy between the dust and the gas (as compared to May) by a factor of between 4 and 6 times. This can be explained in part by the basic phase angle effects, since by June 20 & 21 the phase angle drops to 14° & 13°, with an expected phase effect of about 1.8× as compared to 49°, based on our derived 1P/Halley phase function (Schleicher et al. 1998). The cause of the additional factor of 2-3× is uncertain, but it seems very unlikely that the dust grains in Machholz 1 have the extremely large phase function that would be required to explain the observations, since other properties of the dust (discussed next) are not unusual. We consider it much more likely that either one or both of two other possibilities occurred: First, a sporadic outburst could have taken place between May 24 and June 20, resulting in an excess of lingering grains; such an outburst occurred during the 1986 apparition (cf. Sekanina 1990). Second, the relatively small phase angle at the time of the June observations would place any dust tail that the comet might have sufficiently close to the line of sight, such that a significant portion of a dust tail could be within the projected photometer apertures; such a dust tail was observed in 1986 (cf. Sekanina 1990). Both options, therefore, appear quite viable. In any case, since a nominal phase correction alone would be insufficient to explain the dust results in June, we have elected to not apply any phase angle adjustment to the $A(\theta)f\rho$ values.

To within the uncertainties, no trends with heliocentric distance or time are evident in other basic dust properties such as color or aperture effects; indeed, we see no clear evidence of any trend of $A(\theta)f\rho$ with aperture size, nor do we see any clear evidence of any reddening in the dust color.

### *Dust-to-Gas Ratio*

Due to the apparent phase angle effects described in the previous sub-section, the derived dust-to-gas ratio varies greatly between May and June. Using as a proxy the ratio of $A(\theta)f\rho$-to-$Q$(OH), the log of this varies from a mean value of -25.82 in May to -25.06 in June. Since we consider the May observations as being more representative of the actual dust-to-gas ratio in the coma, we compare the May mean value to those of other comets in our database. This relatively low dust-to-gas ratio for Machholz 1 is consistent with the overall trend of decreasing dust-to-gas ratio as a function of decreasing perihelion distance found by A'Hearn et al. (1995), believed to be associated with thermal processing of nuclei surfaces.

### *Water Production and Active Area*

The water production rates listed in Table 3 are consistent with an effective active area of about 0.4 $km^2$, using a water vaporization model based on the work of Cowan and A'Hearn (1979; also see A'Hearn et al. 1995). This result confirms the estimate of 0.5 $km^2$ of Sekanina (1990), based on his modeling of the post-perihelion lightcurve in 1986. Assuming the limiting case that the entire surface of the nucleus is active, this would imply a lower limit for the effective nucleus radius of ~0.2 km. However, various nucleus brightness measurements (cf. Sekanina 1990; Green et al. 1990; Licandro et al. 2000) imply an effective radius of between about 3 and 5 km, and a summary compilation value of 3.2 km is given by Lamy et al (2004), resulting in an active fraction of less than 0.4%.

### *Production Rates Ratios*

In Figure 2 we show the resulting production rate ratios for each species with respect to OH, and for $C_2$ with respect to CN. For this latter case, the upper limits determinations for the CN production rate directly yield the lower limits for the $C_2$-to-CN ratio as shown. Among the various gas species ratios, we see no clear evidence of a trend in the ratio's value with time from perihelion or with heliocentric distance. Therefore, we have chosen to simply average all of the linearized values to determine an overall production rate ratio, i.e. a relative abundance. For consistency with our database analyses (see next section), we use the unweighted mean values in discussions and in plots for inter-comparisons, but because of the wide range in the propagated uncertainties, we have calculated the means both weighted and unweighted by the individual sigmas, and these results are listed in Table 4. Note that for all of the depleted species, the weighted results for Machholz 1 yield even more extreme values with respect to other comets than the unweighted values presented.

### *Comet Compositional Classifications*

For comparison, we also summarize in Table 4 the results of our primary compositional taxonomy based on well-determined relative abundances of 41 comets in our original database analyses (A'Hearn et al. 1995). In those analyses we determined that the majority of comets had what we classified as "typical" abundances, where the $C_2$-to-CN production rate ratio was nearly constant but where both $C_2$ and CN varied over a range of about 5× with respect to OH. The remaining comets all exhibited significant depletions of $C_2$ (and $C_3$) with respect to CN — by between 2 and 20 times — and were therefore classified as "carbon-chain depleted."

While no clear groupings associated with the NH abundance were evident in the A'Hearn et al. database study, two of the more strongly carbon-chain depleted comets — 21P/Giacobini-Zinner and 43P/Wolf-Harrington — each exhibited depletions in NH but to a lesser degree than the $C_2$ and $C_3$ depletions (cf. Schleicher et al. 1987; Schleicher et al. 1993). The lack of a more general association in the comet database of NH depletion with $C_2$ depletion was presumed to be due to the relatively large uncertainties associated with the NH abundances. These NH uncertainties were due in part to the NH band at 3360 Å being an intrinsically weak spectral feature, but also because of the contamination of the UV continuum filter by the long wing of the $C_3$ emission band resulted in a contaminated continuum value being subtracted from the weak NH emission band.

We recently embarked on a re-reduction and reanalysis of our entire comet photometry database. In addition to improved statistics due a larger number of comets and more observations of many of the short-period comets since the original database was frozen in 1992, this new reduction includes methodologies allowing the decontamination of the near-UV continuum filter by $C_3$ emission, thereby resulting in improved continuum determinations and much more accurate NH emission band fluxes. At the same time, we have also incorporated improved knowledge of the shape of various emission bands and the fraction of the bands transmitted by our narrowband filters, resulting in systematic shifts in the derived molecular abundances for all comets. As recently discussed in somewhat more detail (Schleicher and Osip 2002; Schleicher et al. 2003; Farnham and Schleicher 2005), on average, resulting band fluxes for a given comet decreased by about 7% for CN and increased by about 10% for $C_2$, while $C_3$ values increased by ~2.1× (from much more extensive $C_3$ band wings, ranging from 3300 Å to 4400 Å, but no change in the total $C_3$ band fluorescence efficiency). Given the above changes, and the fact that the Machholz 1 observations must be reduced using the newer methodologies since it was observed using the HB filter set, we have elected to use our new although only preliminary database analyses (Schleicher and Bair 2008) for making direct comparisons with our Machholz 1 results.

In Figure 3 we show our updated version of Figure 10 from A'Hearn et al. (1995). Our preliminary criteria for which comets are included in these taxonomic studies is essentially the same as from A'Hearn et al., where only comets having at least 3 data sets (at least 2 of which are complete, having measurements of all 5 gas species) observed over 2 or more days are considered sufficiently reliable. Also, to avoid possible artifacts due to extrapolating Haser scalelengths to large distances, observations obtained at $r_H$ >3 AU are excluded. These criteria result in a restricted database currently consisting of 93 comets, as compared to 41 comets in the original A'Hearn et al. restricted set. In the new analysis, both log $Q(C_2)/Q(OH)$ and log $Q(C_3)/Q(OH)$ vs. log $Q(CN)/Q(OH)$ again have the majority of comets tightly grouped along the 45° diagonal, i.e. having both $C_2$ and $C_3$ strongly correlated with CN, even though these carbon-bearing species all vary with respect to OH. Consistent with the A'Hearn et al. classification scheme, and for the purposes of this paper, we declare that the 71 comets aligned along the diagonal in the log $Q(C_2)/Q(OH)$ vs. log $Q(CN)/Q(OH)$ plot are members of the "typical" class. The subset of 21 comets located to the lower-right of the diagonal are again considered members of the "carbon-chain depleted" class, even though in a few cases $C_3$ does not directly follow the behavior of $C_2$. Note that the dividing line between the diagonal region and the carbon-chain depleted class remains somewhat ambiguous and could arguably be shifted either slightly higher or lower, with a corresponding small change in resulting statistics. We also note that many comets show intrinsic, coupled variations in all three carbon-bearing species with respect to OH as a function of time or heliocentric distance, effectively moving them along the 45° diagonal but not changing their classification. Finally, turning to the log $Q$(NH)/$Q$(OH) vs. log $Q$(CN)/$Q$(OH) plot, no overall trends are evident regarding the typical or carbon-chain depleted classes, although as noted before, some of the strongest carbon-chain depleted objects also exhibit relatively low NH abundances.

As is immediately evident from the plots in Figure 3, Comet Machholz 1 does not fit in this simple 2-class compositional scheme, and in fact exhibits quite unusual values in several respects. Most obvious is the extremely low CN-to-OH abundance ratio for Machholz 1, about a factor of 72 below the mean value of the other 92 comets, and a factor of 66 below the mean value of the typical group. It also has a quite low $C_2$-to-OH ratio, and the lowest value for $C_3$-to-OH, which would normally place Machholz 1 into the carbon-chain depleted class, but because of its extreme CN-to-OH value, the resulting $C_2$-to-CN ratio is actually in *excess* of the mean typical value by about 8 times. Finally, NH-to-OH is above average, but not by an unusual amount. To better see the relationship of Machholz 1's composition to that of the other comets within the new, preliminary restricted database, we show histograms of abundance ratios for each minor species with respect to OH, and for $C_2$-to-CN in Figure 4. Filled regions correspond to comets classified as "typical" while open regions correspond to the carbon-chain depleted objects; Machholz 1 is shown with diagonal striping. The preliminary mean values for the typical class from the new restricted database analysis are also listed in Table 4.

### *Compositional Uniqueness of Comet 96P/Machholz 1*

As was evident from Figures 3 and 4 and the previous sub-section, no other comet within our restricted database has a chemical composition even remotely similar to that of Comet 96P/Machholz 1. In fact, of all of the various near-UV/visible compositional studies that have and/or are taking place (cf. Newburn and Spinrad 1984; Newburn and Spinrad 1989; Cochran et al. 1992; A'Hearn et al. 1995; Fink and Hicks 1996), we are aware of only one other comet that exhibited a strong depletion of CN: Comet Yanaka (1988r = 1988 XXIV = 1988 Y1), for which Fink (1992) measured a depletion of CN-to-water of more than a factor of 25. Yanaka also exhibited a normal $NH_2$ abundance, consistent with our NH results for Machholz 1. However, Fink measured a depletion of $C_2$-to-water of more than a factor of 100, much greater than the factor of 8 depletion of $C_2$-to-OH with respect to typical we determine for Machholz 1. Unfortunately, with upper limits for both the CN and $C_2$ abundances, no value or even limit can be placed on Yanaka's $C_2$-to-CN ratio. It is therefore somewhat unclear to what degree Machholz 1 and Yanaka are truly compositionally related.

### *The Relation of Composition with Origin or Evolution*

One of the most significant findings from the original photometry database analyses by A'Hearn et al. (1995) was the clear correlation of carbon-chain depleted comets with the Jupiter-family dynamical class. An updated version of this is shown in Figure 5, where the log $Q(C_2)/Q$(CN) values are plotted as a function of the Tisserand invariant with respect to Jupiter ($T_J$). In the A'Hearn et al. analysis, nearly all non-Jupiter-family ($T_J < 2$) comets are members of the typical class, as are about one-half of the Jupiter-family ($T_J > 2$) comets, whereas nearly all of the carbon-chain depleted comets are Jupiter-family members. Based on these facts, and since it is assumed that most Jupiter-family comets originated from the Kuiper Belt while most non-Jupiter family (i.e. Halley-type and long-period comets) arrived from the Oort Cloud, A'Hearn et al. postulated that carbon-chain depleted comets are formed within the Kuiper Belt and that this composition is primordial rather than evolutionary in nature. This latter conclusion was based on the fact that no trends with dynamical age or with subsequent solar heating were observed in the $C_2$-to-CN ratio among comets in the database and, indeed, some of the most highly thermally evolved comets such as 2P/Encke have typical composition. In addition, we note that three comets — Neujmin 1, d'Arrest, and Arend-Rigaux — having some of the smallest active fractions of any known comets (and therefore are believed to have undergone the most surface processing), also all have typical composition (A'Hearn et al. 1995). Thus there is considerable evidence that carbon-chain depletion is not due to recent, evolutionary thermal fractionation, and so must instead be primordial. The fact that the majority of Jupiter-family comets have typical composition was taken by A'Hearn et al. to imply that the change in conditions within the solar nebula leading to typical vs depleted composition is located *within* the Kuiper Belt, rather than between the Kuiper Belt and the Jovian planet regime where Oort Cloud objects are believed to have originated.

While the specific proportions between the two primary compositional classes differ somewhat in our new analysis as compared to the results given by A'Hearn et al., the case for the basic correlation of carbon-chain depleted comets with the Jupiter-family dynamical class, and thus an origin in the Kuiper Belt is strengthened: 15 of the 35 Jupiter-family comets are depleted, while only 6 of the remaining 60 non-Jupiter-family comets are depleted, and 1 of these 6 (P/IRAS; having $T_J$ of 1.96) has been shown to oscillate across the $T_J = 2$ dividing line (Levison, personal communication). Interestingly, Comet Machholz 1 has the next nearest $T_J$ value (1.94) to the dividing line, raising the obvious question of whether its $T_J$ value also oscillates across the $T_J = 2$ line with time and, in fact, orbital integrations indicate that $T_J$ was greater than 2 about 2500 yr ago (Bailey et al. 1992), and that secular resonances have caused the perihelion distance to decrease with time while the inclination increased; Machholz 1 is currently in a 9:4 resonance with Jupiter (Green et al. 1990, Bailey et al. 1992; and Sekanina and Chodas 2005). Further complicating a diagnosis of origin of any individual object is the fact that a small percentage of Oort Cloud comets (~2%) arrive into the inner Solar System having a sufficiently low orbital inclination to mimic having come from the Kuiper Belt with a resulting $T_J > 2$, while some unknown fraction of Kuiper Belt objects will be expelled into the Oort Cloud by an encounter with a Jovian planet and subsequently return to the inner Solar System with a high inclination and thus a $T_J < 2$. As an aside, we hypothesize that the 3 more strongly carbon-chain depleted comets having $T_J$ well below 2 (see Figure 5) are such highly traveled objects having first formed in the Kuiper Belt. In any case, with $T_J$ =1.94, a period of 5.2 yr, and a perihelion distance of 0.13 AU, along with the fact that no individual object's origin can be uniquely determined, the origin of periodic comet Machholz 1 remains more ambiguous than that of most comets.

In contrast to the situation of Machholz 1, Comet Yanaka is more clearly identified as having an orbit consistent with an Oort Cloud origin, having $T_J = 0.26$, a perihelion distance of 0.43 AU, and an inclination of 71°. Moreover, with an eccentricity of 1.000, Yanaka is assumed to be a dynamically new object, and even if it was not its first passage near the Sun, there is a high probability that it has only been into the inner solar system at most a few times. Therefore, we consider it a safe assumption that Yanaka's CN depletion is primordial rather than induced by evolutionary effects.

## 5. DISCUSSION AND SUMMARY

### *Reality of the Machholz 1 Compositional Results*

The derived extremely unusual compositional results for Comet Machholz 1 are assured for a number of reasons: A variety of possible instrumental effects can be eliminated by the fact that other comets observed on the same nights exhibit normal behavior, and that the observational circumstances were not atypical. With observations obtained over more than a month in time and a range of aperture sizes, we can eliminate extreme sporadic activity or aperture effects in causing the measured anomalous abundances. Moreover, other investigators (Langland-Shula and Smith 2007) using different instrumentation also identified Machholz 1 as exhibiting highly unusual composition. Thus, there is no ambiguity regarding the reality of our compositional results.

### *Why Wasn't the Composition of Machholz 1 Measured Sooner?*

One obvious question arose as soon as we saw the raw counts of CN and NH, and was reinforced when we reduced the observations and calculated relative abundances for Machholz 1: Why had this extremely unusual composition not been discovered before? Subsequently, we learned that it had been discovered 2 weeks earlier by Langland-Shula and Smith (2007), but why not at a previous apparition? The simple answer for the 1991, 1996, and 2002 apparitions was relatively poor observational circumstances coupled with a comet having a relatively small active area, i.e. the comet is not intrinsically very bright. Circumstances at the 1986 discovery apparition, however, were significantly better than in 2007. In 1986, the best geometry occurred only a few weeks following the discovery, requiring a relatively rapid response to a new comet. Moreover, this was shortly after the Comet 1P/Halley apparition and, in our own case, our equipment was still in the southern hemisphere. The net result is that even though the comet has an orbital period of only 5.2 yr, the first good opportunity for planned observations did not occur until 2007, explaining the 21-year delay in discovering this comet's interesting composition.

### *Unique Properties of Machholz 1*

As indicated in Section 3, the chemical composition of Comet Machholz 1 is unique among all comets thus far studied. It exhibits the lowest $Q$(CN)/$Q$(OH) value of any comet, but has a $Q$($C_2$)/$Q$(OH) value at least 12× higher than Comet Yanaka, the only other known $Q$(CN)/$Q$($H_2O$) depleted object (Fink 1992). The $C_2$-to-CN ratio of Machholz 1 is the highest known value of any comet, while Yanaka's value is completely unknown, since only upper-limits were determined for both species. However, Machholz 1 and Yanaka are compositionally similar in several respects: both objects have very low abundances of $C_2$ and $C_3$ with respect to water, and both have normal ammonia abundances. With this combination of chemical characteristics, we are inclined to consider Machholz 1 and Yanaka chemical "cousins" rather than true "siblings."

Although perhaps not truly unique, Machholz 1's orbit is certainly highly unusual, having the smallest perihelion distance of any regular short-period comet and a $T_J$ value close to 2 despite having a quite high inclination. These dynamical properties are placed in comparison to most other comets (excluding so called "SOHO" comets; see next paragraph) in Figure 6, where we show plots of $T_J$ vs perihelion distance, and inclination vs eccentricity. Machholz 1 clearly occupies an otherwise empty location in the $T_J$ plot, and is the only regular short period comet having both a high inclination and a large eccentricity.

The term “regular short-period comet” was used in the previous paragraph because there are actually a large number of “SOHO” comets that have even smaller perihelion distances than Machholz 1 and equally short orbital periods. Indeed, Machholz 1 is associated with and is possibly the parent body of 2 families of nearly Sun-grazing comets, the Marsden group and the Kracht group (Ohtsuka et al. 2003). Having apparently had a cascading fragmentation from either Machholz 1 or a common progenitor more than 1000 yr ago, subsequent encounters with Jupiter have accelerated their progressive drop in perihelion distances to ~0.05 AU as compared to Machholz 1’s 0.12 AU (Sekanina and Chodas 2005). We will return to issues associated with Machholz 1’s orbit and origin in the next sub-sections.

### *Primordial Composition or Subsequent Evolution for Machholz 1?*

This near-uniqueness in dynamical properties naturally raises the question of whether or not Machholz 1’s composition is associated with or caused by its orbital characteristics. As noted earlier, A’Hearn et al. (1995) concluded that the basic taxonomic groupings which they identified — “typical” and “carbon-chain depleted” — were not related to dynamical age or thermal effects since arriving into the inner solar system, and therefore most likely reflected the primordial chemistry of their place of origin. A’Hearn et al. arrived at this conclusion from multiple lines of evidence: First, non-Jupiter-family comets in the database showed no trends or correlations with dynamical age; for instance, Comet 1P/Halley and dynamically new comets have essentially identical composition for the gas species measured in our photometric studies. Second, non-Jupiter-family comets show no trends with perihelion distance, so the $C_2$-to-CN ratio was also independent of the maximum surface temperature a comet reaches. Third, and perhaps most importantly, many Jupiter-family comets believed to be highly physically evolved show no evidence of carbon-chain depletion. Specifically, nearly extinct objects, i.e. those having very small fractional active areas believed to be caused by long-term surface evolution, such as Neujmin 1, Arend-Rigaux, and d’Arrest, all have typical composition. Some of the most strongly heated objects (due to their small perihelion distance), such as 2P/Encke, also have typical composition. Finally, new evidence from Comet 73P/Schwassmann-Wachmann 3 shows that its interior composition matches that prior to its fragmentation; multiple components are all strongly carbon-chain depleted (Schleicher et al. 2006), and thus depletion is not just a surface phenomenon.

It is also clear that most carbon-chain depleted comets are members of the Jupiter-family dynamical class (see Figure 5), and that the few non-Jupiter family comets which are carbon-chain depleted can be explained by basic statistics of inter-planetary “billiards” — this small fraction being consistent with what might be expected of comets originating in the Kuiper Belt, then unsuccessfully working their way past the Jovian planets and instead gravitationally perturbed out to the Oort Cloud, and then eventually perturbed back to the inner Solar System with a higher inclination. The combination of these lines of evidence yields the clear result that carbon-chain depletion is a characteristic that is primordial rather than evolutionary in nature.

While the previous discussion answers the question regarding the origin of carbon-chain depletion, it does not necessarily directly relate to strong CN depletion. One might imagine that at the very strong solar heating experienced by Machholz 1 at perihelion (0.12 AU), the CN parent (either HCN and/or CHON particles) might chemically react, effectively removing the CN either rapidly or after numerous perihelion passages. Here, two lines of evidence are strongly suggestive that this is *not* the case, but the possibility cannot be definitively ruled out: First, Comet Yanaka exhibited strong CN depletion, even though it had a more modest perihelion distance of 0.43 AU and was likely on its first passage, directly implying that Yanaka's CN abundance was *not* thermally induced, and that high-temperature chemistry is *not* required to produce strong CN depletion. Second, numerous Sun-grazing comets have been measured, and we are unaware of any of these have been reported as being CN depleted. Therefore, all current evidence points to strong CN depletion as not being caused by evolutionary processes and, as in the case of carbon-chain depletion, this process of elimination strongly implies, but does not prove, that Comet Machholz 1's observed, current composition is a primordial condition.

*The Origin of Machholz 1*

With the conclusion that Machholz 1's composition is very likely primordial, the next question is obvious: Where did Machholz 1 originate? As noted previously, its current orbit is quite unusual, with its combination of very small perihelion distance, high inclination, and short orbital period (see Figure 6). Unfortunately, its orbit does not provide clear evidence of a place of origin. With a $T_J$ very close to 2, both the Oort Cloud and the Kuiper Belt are quite viable even without invoking inter-planetary billiards. An external origin, from beyond our solar system is also possible, but would not be expected to result in an unusual current orbit. In fact, a comet arriving from inter-stellar space would be nearly indistinguishable from a dynamically new, Oort Cloud comet, especially after its first gravitational encounter with a Jovian planet. Thus, while it seems unlikely that it is just a chance coincidence that a comet with unique composition also has an usual orbit, this appears to be the case. As noted above, long-term strong thermal chemistry cannot be conclusively ruled out, and orbital integrations indicate that Machholz 1 has approached to within 0.2 AU of the Sun on at least 40 revolutions (cf. Green et al. 1990), providing ample opportunity for extreme thermal processing to have taken place. We continue to favor the other scenario, in which the composition is primordial, however, for the reasons stated in the previous sub-section, particularly because at least one comet, Yanaka, exhibited very strong CN depletion without experiencing extreme thermal effects.

Since Machholz 1 is the first out of more than 150 comets in our database to have this extreme composition and, if considered a compositional cousin of Comet Yanaka, only the second out of more than 250 comets (among all of the optical databases), we conclude that it originated either in a location of our solar system from which the probability is very low for crossing inside of Neptune's orbit or that it arrived from interstellar space. While neither of these two scenarios would be expected to yield the unusual orbit of Machholz 1, the probabilities associated with the statistics of a single case are not conclusive, and moreover Yanaka's orbit was *not* unusual for a long-period comet. In the former scenario, the classical Kuiper Belt population, in particular the dynamically cold component, might provide an appropriate source region, given recent studies suggesting that the scattered disk population is the primary source of Jupiter-family comets (cf. Morbidelli and Brown 2004; Duncan et al. 2004). However, it is as yet unclear if an appropriate percentage of these objects could reach the inner solar system, nor is it evident that primordial conditions should differ sufficiently between the cold disk and the warm disk and/or scattered disk to explain the extreme depletion of CN in Machholz 1. We, therefore, consider it somewhat more likely that Machholz 1 is an interstellar interloper (along, perhaps, with Yanaka). Such objects are assumed to exist and, even though no conclusive dynamical evidence for such intruders has been discovered, thereby eliminating the possibility of large numbers of these objects passing through the inner solar system, a small proportion of interlopers is not ruled out. In this scenario, the composition of Comet Machholz 1 is truly unique, as it reflects the formation conditions around a different star prior to its ejection from its native solar system.

### *The Future*

Unlike Comet Yanaka, which will never be available for additional study, Comet Machholz 1 returns in 2012 and every 5+ years for the foreseeable future (cf. Green et al. 1990; Bailey et al. 1992). While the observing circumstances are poorer in 2012 than in 2007, with a geocentric distance twice as large, the highly unusual composition clearly warrants effort on the part of observers to extend these findings to other species, including CH in the visible, CS in the UV, and $CH_4$ in the near-IR portions of the spectrum. A more favorable apparition will then occur in 2017, similar in quality to 2007, but useful only to southern hemisphere observers.

Due to Comet Machholz 1's linkage to two "sunskirting" dynamical families of comets, the Marsden and Kracht groups discovered by the SOHO spacecraft (Ohtsuka et al. 2003; Sekanina and Chodas 2005), a very important but difficult goal would be compositional measurements of any members of these two groups. Since several members have now been observed at two apparitions, there is some hope that a few of the larger bodies might be bright enough at sufficiently large solar elongations to permit the acquisition of narrowband photometry or spectrophotometry.

Finally, we suggest that Machholz 1 be seriously considered for a spacecraft flyby mission, given both the very likely possibility that it originated in an unusual location within our solar system or from around another star, and the certainty that its surface has undergone more thermal processing than that of any other short-period (i.e. predictable for mission planning) comet.

## ACKNOWLEDGEMENTS

We particularly thank A. Bair for assisting with the rereduction of our entire comet photometry database and the preliminary taxonomic results used to place the Machholz 1 results into context, and for assisting with the creation of final tables. Orbital elements used in the orbital dynamics discussion were made available in a useable form courtesy of L. Wasserman. This research has been supported by grants from NASA's Planetary Astronomy Program (NNG06GI28G) and Planetary Atmospheres Program (NNG05GO73G).

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# FIGURES:

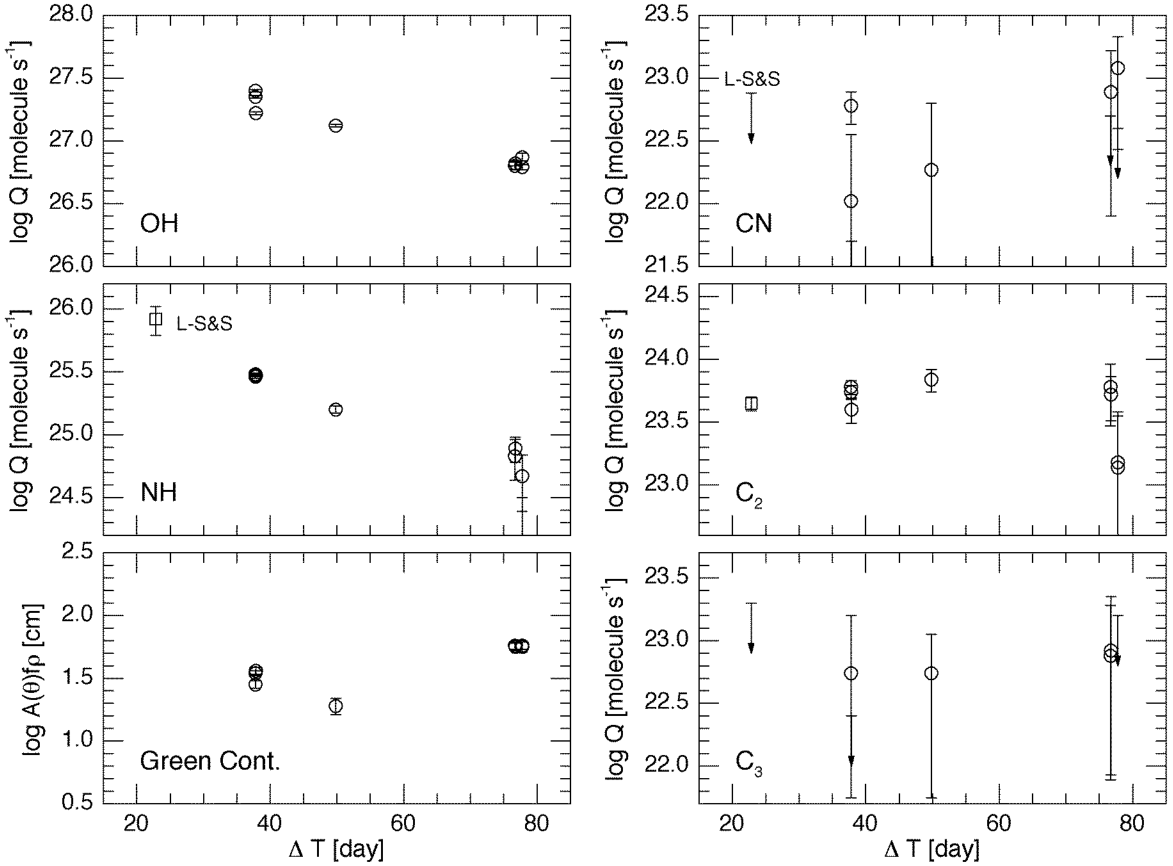

Figure 1. — Logarithmic production rates for Comet 96P/Machholz 1 as a function of time (Δ*T*) from perihelion (2007 April 4.62). Our results (circles) from May and June are plotted for each species, along with the results from the spectraphotometric observation by Langland-Shula and Smith (2007) on April 27 (squares). One-sigma uncertainties or 1-sigma upper limits are also plotted. The observations are generally consistent with declining production rates as the comet recedes from the Sun, with the clear exception of dust. The high *A(θ)fρ* values of the dust at large Δ*T* occur when the phase angle is relatively small, and is presumably due to a combination of phase effects coupled with a possible dust tail within the projected photometer entrance aperture.

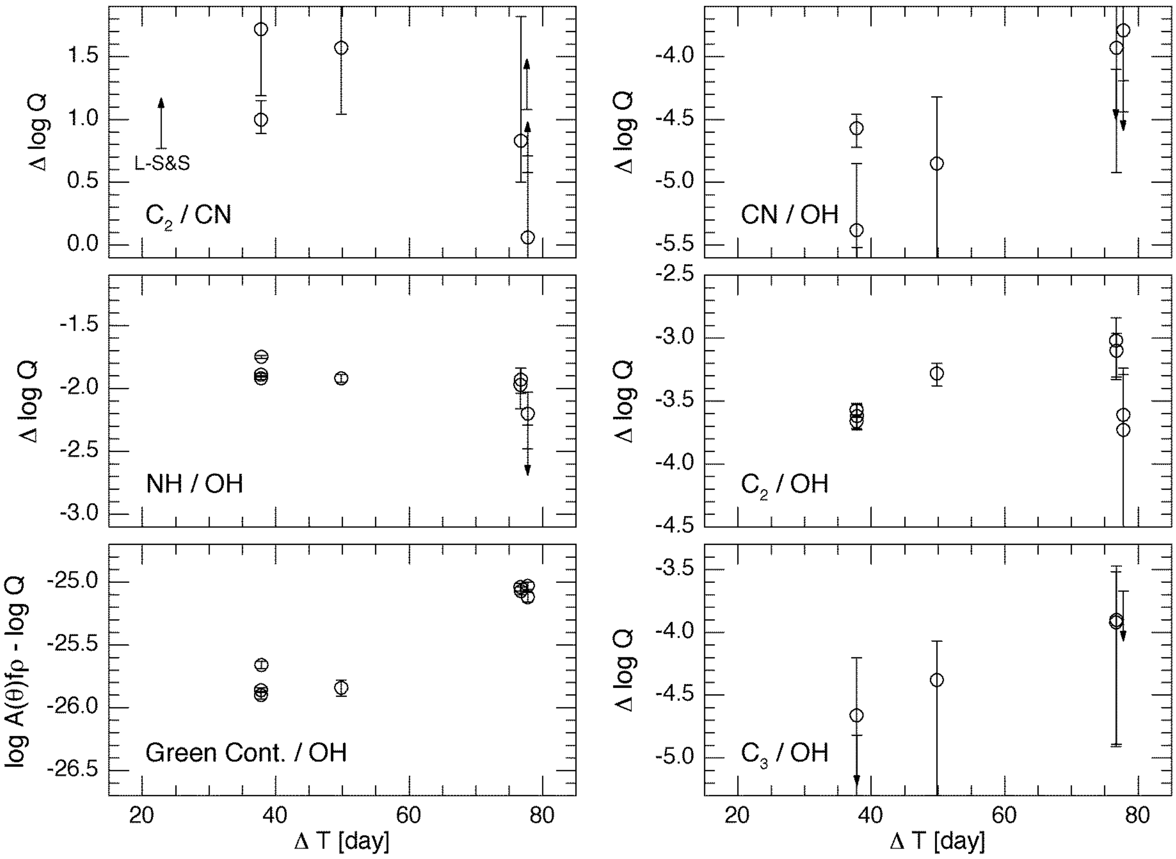

Figure 2. — Logarithmic production rate ratios of each minor species to OH and of $C_2$ to CN (upper-left) as a function of time from perihelion. Symbols are the same as for Figure 1, but upper-limits for CN production rates become lower limits for $C_2$ to CN. These measures of the relative abundances among gas species are all consistent with no systematic variation as a function of time or heliocentric distance. Again, only the small phase angle measurements of dust are unusual.

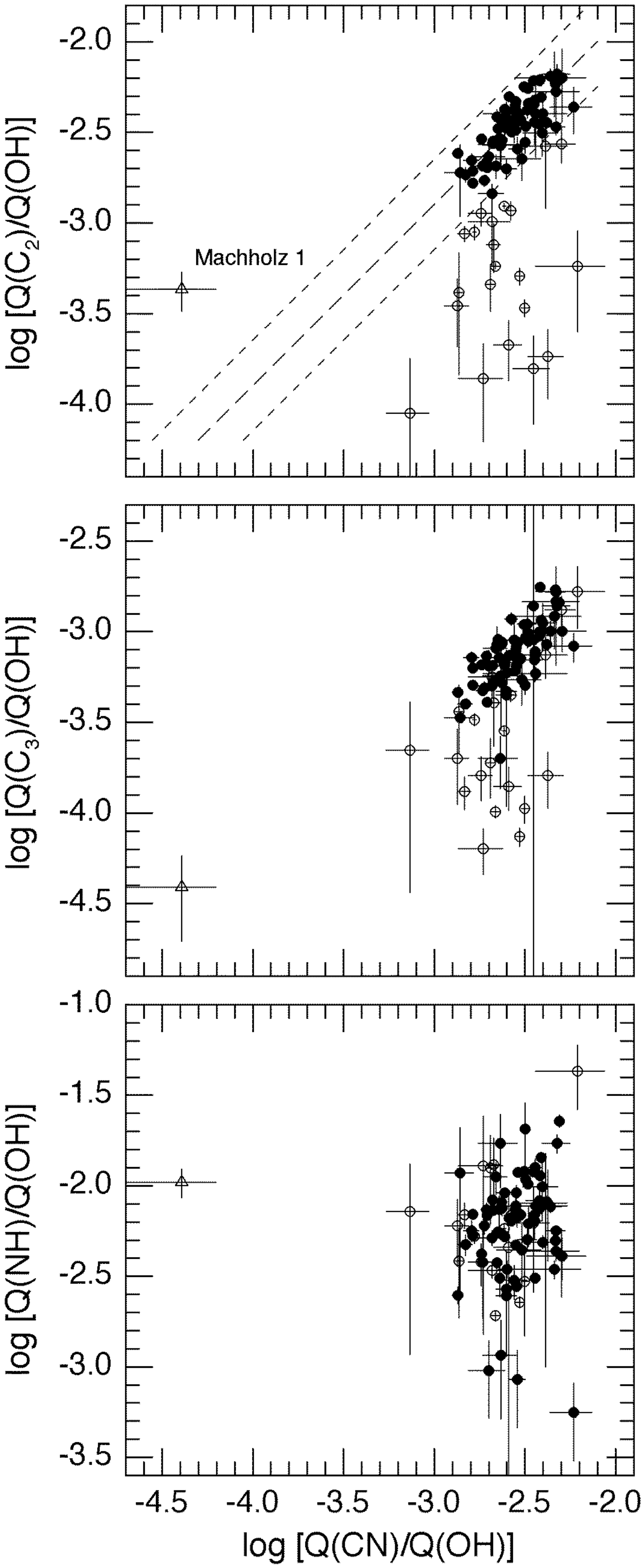

Figure 3. — Abundance ratios plots for comets in our restricted database. Mean production rate ratios for each minor gas species with respect to OH are presented for the 93 comets from our new, preliminary database analysis. These plots are direct analogs to the composition plots shown in Figure 10 by A'Hearn et al. (1995). For most comets, both $C_2$ and $C_3$ are strongly correlated with the CN abundance (the diagonal lines have slopes of unity), even though all three carbon-bearing species vary with respect to OH, i.e. water. There is no obvious corresponding correlation of NH. A subset of comets exhibit depletions in $C_2$ and $C_3$ abundances with respect to CN, i.e. located to the lower-right of the diagonal band. Comet Machholz 1 is the isolated point to the far left on each of these plots, exhibiting very low $C_2$ and $C_3$ abundances along with extreme depletion in CN. In contrast, NH is somewhat on the high side of average composition.

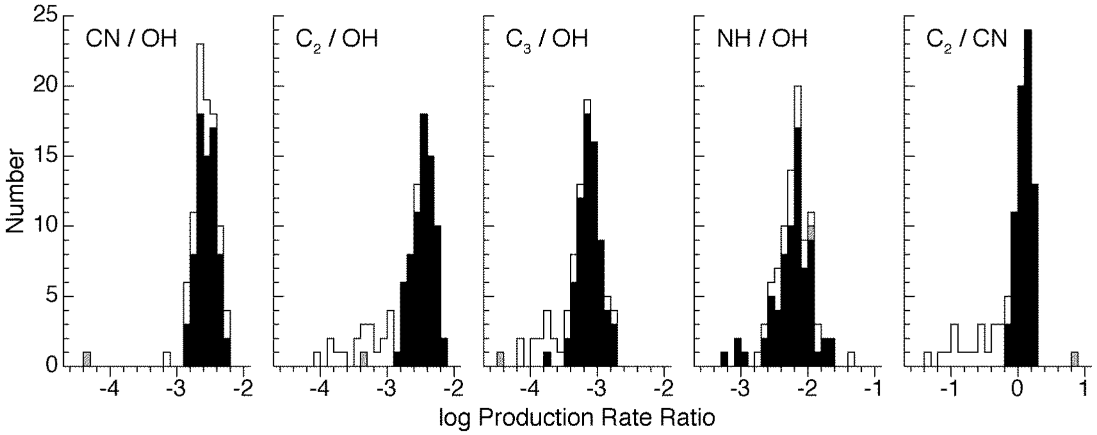

Figure 4. — Histograms of production rate ratios for the preliminary new restricted database. Highlighted regions are comets within the typical class, while open regions correspond to the carbon-chain depleted class. Comet Machholz 1 is shown with diagonal striping.

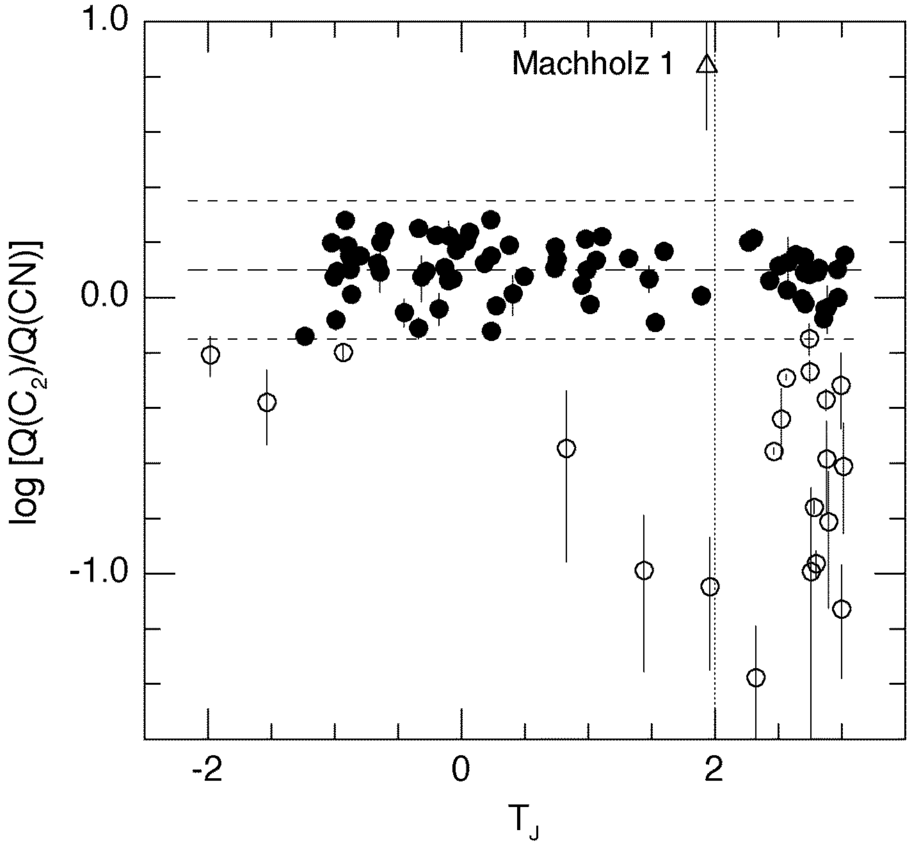

Figure 5. — Primary composition discriminator for our database, the $C_2$-to-CN ratio, as a function of the Tisserand invariant with respect to Jupiter ($T_J$); Jupiter-family comets are commonly defined as having $T_J > 2$. With $T_J = 1.94$, Machholz 1 (the high $C_2$-to-CN object) is formally not considered a member of Jupiter-family comets due to its large inclination; however, orbital integrations show that $T_J$ was slightly greater than 2 in the past. Machholz 1 also has the second smallest perihelion distance for comets within our restricted database, although the orbital integrations indicate that its perihelion distance was also much larger in the past.

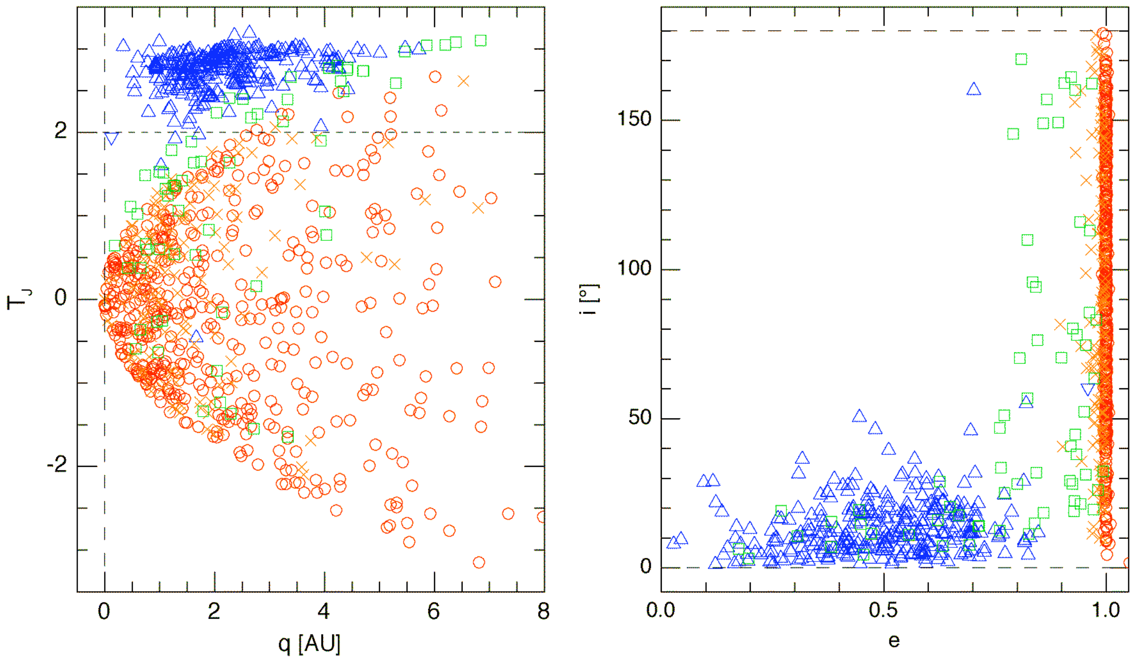

Figure 6. — The Tisserand invariant ($T_J$) for comets vs. perihelion distance (left panel) and the orbital inclination vs. eccentricity (right panel). These orbital parameters are shown for all comets except for the so-called SOHO comets to emphasize the envelopes of differing dynamical classes. In general, comets having $T_J$ greater than 2 are considered members of the Jupiter-family dynamical class. Colors and symbols distinguish orbital periods: <20 yrs (blue; triangles), 20-200 yrs (green; squares), 200-10000 yrs (orange; 'x's); >10000 yrs (red; circles). Comet Machholz 1 (blue; upside-down triangle) is located in an otherwise unpopulated region of this $T_J$ dynamical plot, emphasizing its unusual dynamical nature; in the *i* vs. *e* plot, Machholz 1 has the largest eccentricity of any very short period (blue; upside-down triangle) comet. The only other known CN depleted comet, Yanaka (1988r; red; circle) is located amidst numerous other long period objects.

# TABLE 1

# Photometry Observing Circumstances and Fluorescence Efficiencies for Comet 96P/Machholz 1

| UT Date | $\Delta T$ (day) | $r_H$ (AU) | $\Delta$ (AU) | Phase Angle (°) | $\dot{r}_H$ (km $s^{-1}$) | log $L/N^a$ (erg $s^{-1}$ molecule$^{-1}$) OH | NH | CN |
|---|---|---|---|---|---|---|---|---|
| 2007 May 12.41 | +37.79 | 1.074 | 0.657 | 66.4 | +34.2 | –14.431 | –13.192 | –12.394 |
| 2007 May 24.43 | +49.81 | 1.299 | 0.609 | 49.3 | +30.7 | –14.266 | –13.213 | –12.478 |
| 2007 June 20.31 | +76.69 | 1.733 | 0.754 | 13.7 | +25.6 | –14.141 | –13.198 | –12.475 |
| 2007 June 21.38 | +77.76 | 1.749 | 0.768 | 13.3 | +25.5 | –14.141 | –13.200 | –12.474 |

[a] Fluorescence efficiencies are for $r_H = 1$ AU, and are scaled by $r_H^{-2}$ in the reductions.

# TABLE 2

# Photometry Fluxes and Aperture Abundances for Comet 96P/Machholz 1

| | Aperture | | log Emission Band Flux[a] (erg $cm^{-2}$ $s^{-1}$) | | | | | log Continuum Flux (erg $cm^{-2}$ $s^{-1}$ Å$^{-1}$) | | | log M(ρ)[a] (molecule) | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| UT Date | Size (arcsec) | log ρ (km) | OH | NH | CN | $C_3$ | $C_2$ | UV | Blue | Green | OH | NH | CN | $C_3$ | $C_2$ |
| 2007 May 12.38 | 204.5 | 4.69 | –9.59 | –10.42 | –12.83 | –11.98 | –11.26 | –13.36 | –13.21 | –13.16 | 31.98 | 29.91 | 26.71 | 27.16 | 28.23 |
| 2007 May 12.41 | 97.2 | 4.36 | –10.06 | –10.91 | –12.45 | *und* | –11.59 | –13.59 | –13.55 | –13.57 | 31.52 | 29.43 | 27.09 | *und* | 27.90 |
| 2007 May 12.44 | 97.2 | 4.36 | –10.19 | –10.90 | <–13.5 | <–12.5 | –11.76 | –13.69 | –13.44 | –13.45 | 31.39 | 29.43 | <26.0 | <26.7 | 27.73 |
| 2007 May 24.43 | 62.4 | 4.14 | –10.65 | –11.75 | –13.53 | –12.41 | –12.03 | –14.28 | –13.97 | –14.06 | 30.86 | 28.71 | 26.19 | 26.84 | 27.56 |
| 2007 June 20.27 | 62.4 | 4.23 | –11.28 | –12.55 | <–13.5 | –12.62 | –12.51 | –14.23 | –13.90 | –13.92 | 30.54 | 28.33 | <26.6 | 27.06 | 27.51 |
| 2007 June 20.35 | 126.7 | 4.54 | –10.77 | –11.98 | –12.87 | –12.28 | –12.10 | –14.07 | –13.56 | –13.63 | 31.05 | 28.90 | 27.28 | 27.41 | 27.93 |
| 2007 June 21.37 | 97.2 | 4.43 | –10.92 | –12.41 | –12.86 | <–12.1 | –12.88 | –14.10 | –13.76 | –13.76 | 30.93 | 28.49 | 27.32 | <27.6 | 27.17 |
| 2007 June 21.39 | 155.9 | 4.64 | –10.68 | <–12.2 | <–13.0 | *und* | –12.53 | –13.44 | –13.38 | –13.54 | 31.16 | <28.7 | <27.2 | *und* | 27.52 |

[a] Values preceded by “<” represent the one-sigma upper limit; values which yield a negative production rate at the one-sigma upper limit are undefined and listed as “*und*”.

# TABLE 3

## Photometric Production Rates for Comet 96P/Machholz 1

| UT Date | $\Delta T$ (day) | log $r_H$ (AU) | log ρ (km) | log $Q$[a] (molecule $s^{-1}$) OH | NH | CN | $C_3$ | $C_2$ | log $A(\theta)f\rho$[a] (cm) UV | Blue | Green | log $Q$ $H_2O$ |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 2007 May 12.38 | 37.76 | 0.031 | 4.69 | 27.40 $^{+.01}_{-.01}$ | 25.48 $^{+.01}_{-.01}$ | 22.02 $^{+.53}_{-un}$ | 22.74 $^{+.46}_{-un}$ | 23.74 $^{+.05}_{-.06}$ | 1.64 $^{+.10}_{-.13}$ | 1.47 $^{+.03}_{-.03}$ | 1.54 $^{+.02}_{-.02}$ | 27.51 |
| 2007 May 12.41 | 37.79 | 0.031 | 4.36 | 27.35 $^{+.01}_{-.01}$ | 25.46 $^{+.01}_{-.01}$ | 22.78 $^{+.11}_{-.15}$ | *undef* | 23.78 $^{+.05}_{-.06}$ | 1.74 $^{+.06}_{-.07}$ | 1.45 $^{+.04}_{-.04}$ | 1.45 $^{+.03}_{-.03}$ | 27.47 |
| 2007 May 12.44 | 37.82 | 0.031 | 4.36 | 27.22 $^{+.01}_{-.01}$ | 25.47 $^{+.01}_{-.01}$ | <21.7 | <22.4 | 23.61 $^{+.09}_{-.11}$ | 1.63 $^{+.08}_{-.10}$ | 1.55 $^{+.03}_{-.03}$ | 1.57 $^{+.03}_{-.03}$ | 27.34 |
| 2007 May 24.43 | 49.81 | 0.113 | 4.14 | 27.12 $^{+.01}_{-.01}$ | 25.20 $^{+.03}_{-.03}$ | 22.27 $^{+.53}_{-un}$ | 22.74 $^{+.31}_{-un}$ | 23.84 $^{+.08}_{-.10}$ | 1.37 $^{+.12}_{-.17}$ | 1.35 $^{+.05}_{-.06}$ | 1.28 $^{+.06}_{-.07}$ | 27.20 |
| 2007 June 20.27 | 76.65 | 0.239 | 4.23 | 26.80 $^{+.03}_{-.03}$ | 24.83 $^{+.13}_{-.19}$ | <22.7 | 22.88 $^{+.40}_{-un}$ | 23.78 $^{+.18}_{-.31}$ | 1.76 $^{+.10}_{-.13}$ | 1.76 $^{+.04}_{-.04}$ | 1.76 $^{+.03}_{-.03}$ | 26.81 |
| 2007 June 20.35 | 76.73 | 0.239 | 4.54 | 26.82 $^{+.02}_{-.02}$ | 24.89 $^{+.09}_{-.11}$ | 22.89 $^{+.33}_{-un}$ | 22.92 $^{+.43}_{-un}$ | 23.72 $^{+.14}_{-.21}$ | 1.62 $^{+.14}_{-.21}$ | 1.79 $^{+.03}_{-.03}$ | 1.75 $^{+.03}_{-.03}$ | 26.84 |
| 2007 June 21.37 | 77.75 | 0.243 | 4.43 | 26.87 $^{+.03}_{-.03}$ | 24.67 $^{+.17}_{-.28}$ | 23.08 $^{+.25}_{-.65}$ | <23.2 | 23.14 $^{+.44}_{-un}$ | 1.71 $^{+.13}_{-.19}$ | 1.72 $^{+.04}_{-.04}$ | 1.75 $^{+.04}_{-.04}$ | 26.88 |
| 2007 June 21.39 | 77.77 | 0.243 | 4.64 | 26.79 $^{+.02}_{-.02}$ | <24.5 | <22.6 | *undef* | 23.18 $^{+.37}_{-un}$ | 2.17 $^{+.05}_{-.06}$ | 1.90 $^{+.03}_{-.03}$ | 1.76 $^{+.03}_{-.03}$ | 26.80 |

[a] Production rates, followed by uncertainties. Values preceded by "<" represent the one-sigma upper limit; values which yield a negative production rate at the one-sigma upper limit are undefined and listed as "*undef*". One-sigma lower limits which yield a negative production rate are undefined and listed as "*un*".

# Table 4

## Abundance Ratios

| | log Production Rate Ratio | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | Machholz 1 | | | | | | Typical | |
| | Un-weighted | | | Weighted | | | 2008[a] | 1995[b] |
| Species | mean | $\sigma_{mean}$ | $\sigma_{data}$ | mean | $\sigma_{mean}$ | $\sigma_{data}$ | mean | mean |
| CN/OH | –4.39 | $^{+.19}_{-.35}$ | $^{+.41}_{-un}$ | –4.72 | $^{+.12}_{-.17}$ | $^{+.65}_{-un}$ | –2.55 | –2.50 |
| $C_2$/OH | –3.37 | $^{+.10}_{-.12}$ | $^{+.23}_{-.51}$ | –3.61 | $^{+.03}_{-.03}$ | $^{+.39}_{-un}$ | –2.46 | –2.44 |
| $C_3$/OH | –4.41 | $^{+.17}_{-.30}$ | $^{+.38}_{-un}$ | –4.81 | $^{+.35}_{-un}$ | $^{+.68}_{-un}$ | –3.12 | –3.59 |
| NH/OH | –1.98 | $^{+.07}_{-.09}$ | $^{+.18}_{-.30}$ | –1.87 | $^{+.01}_{-.01}$ | $^{+.16}_{-.27}$ | –2.23 | –2.37 |
| $C_2$/CN[c] | +0.84 | $^{+.56}_{-.23}$ | $^{+un}_{-.48}$ | +1.19 | $^{+.19}_{-.14}$ | $^{+un}_{-.77}$ | +0.10 | +0.06 |

[a] Typical as defined by Schleicher and Bair (2008) and discussed in the text.

[b] Typical as defined by A'Hearn *et al*. (1995) and discussed in the text.

[c] Using log [$Q(C_2)/Q(OH)/Q(CN)/Q(OH)$].