Ultraviolet Observations of Comet 96/P Machholz at Perihelion

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Abstract

Ultraviolet spectra of Comet 96/P Machholz were obtained during its 2002 perihelion with the UltraViolet Coronagraph Spectrometer instrument on board the SOHO satellite. Emission from H I, C II, C III, and O I is detected near the nucleus. The outgassing rate is in line with the value extrapolated from rates at larger distances from the Sun, and abundances of C and O are estimated. Reconstructed images show a nearly spherical cloud of H I Lyα emission and an ion tail seen in C III. Radiation pressure on the hydrogen atoms produces a modest distortion of the shape of the Lyα cloud as seen from SOHO and Doppler shifts up to 30 km s⁻¹ in the outer parts of the cloud. We estimate a ratio of C to H₂O similar to what is observed in other comets, so low carbon abundance does not account for the anomalously low C₂ and C₃ ratios to NH₂ observed at optical wavelengths.

Unified Astronomy Thesaurus concepts: Main-belt comets (2131); Comet tails (274); Ultraviolet astronomy (1736); Comet volatiles (2162)

1. Introduction

Comet 96P/Machholz (hereafter Comet Machholz) is remarkable in many ways. It has a very small perihelion distance of 0.124 au and a period of 5.3 yr. Its inclination is high at 58°, but the orbit is changing rapidly. Its eccentricity and inclination oscillate out of phase, with perihelion varying between 0.03 and 1 au on a 4000 yr timescale (Green et al. 1990; McIntosh 1990). Comet Machholz is believed to be the largest surviving piece of a larger body that broke up to produce the Marsden and Kracht groups of sungrazing comets (Ohtsuka et al. 2003) and the Quadrantid (McIntosh 1990) and Na-poor Southern δ Aquarid (Matlović et al. 2019) meteor streams. It shows remarkably low C₂ and C₃ abundances relative to NH₂ (Langland-Shula & Smith 2007; Schleicher 2008).

Eisner et al. (2019) observed Comet Machholz far from perihelion, when there was no detectable dust coma and they could observe the comet’s surface. They found that the colors are unusually blue compared to Jupiter-family comets, its radius is 3.4 km, and it has an axial ratio of 1.6 with a 4.1 hr rotation period. Combi et al. (2011, 2019) reported water production rates of 5 x 10²⁷–5 x 10²⁹ at distances between 0.16 and 0.83 au.

Because Comet Machholz passes close to the Sun, it presents a good example of dust scattering at extreme phase angles. Gryeko et al. (2004). Comet Machholz is expected to be an excellent target for imaging observations at Lyα and white light by the Metis coronagraph on the Solar Orbiter (Bemporad et al. 2015), because from the point of view of the Solar Orbiter, it will transit the Sun in 2023 January (G. Jones & M. Knight 2021, private communication). Thus, it will be seen at an extreme phase angle, and at the same time, it will have a very large outgassing rate.

The UltraViolet Coronagraph Spectrometer (UVCS) on board the SOHO satellite (Kohli et al. 1995) obtained UV spectra of a number of comets, including sungrazing comets (Raymond et al. 1998, 2018; Uzzo et al. 2001; Bemporad et al. 2005; Ciaravella et al. 2010; Giordano et al. 2015; Raymond & Giordano 2019). Those observations were used to determine outgassing rates, dust vaporization rates, and elemental compositions including the products of vaporized dust, along with properties of the solar corona including density, temperature, and outflow speed (Bemporad et al. 2007; Jones et al. 2018). The UVCS also observed the near-Sun comet C/1997/H2 (Mancuso 2015) to determine its outgassing rate and the periodic comets Encke (Raymond et al. 2002) and Kudo–Fujikawa (Povich et al. 2003). These observations were used to study outgassing rates, elemental compositions, and the behavior of the ion tail.

The UVCS observed Comet Machholz during its 2002 perihelion. We analyze those observations to determine the composition of the comet and its outgassing rate and study the ion tail seen in C III λ977. We present the observations, followed by a discussion of the atomic processes and a simple model for the Lyα intensity and velocity distributions. We then reconstruct images from the time series of long-slit spectra, and we derive elemental abundances and outgassing rates. Finally, we discuss the ion tail, and we compare the results with observations of other comets near the Sun.

2. Observations

The UVCS is described by Kohli et al. (1995). Its 41° long entrance slit can be placed at heliocentric distances between 1.4 and 10 R₉ at any selected position angle. For this set of observations, we used the O VI channel and 50 μ, 100 μ, or 150 μ slit widths, which provide 0.2, 0.4, or 0.6 Å spectral resolution and cover 14°, 28°, or 42° spatial elements, respectively. The data were binned by different factors for the different observations, which reduces the spatial and spectral resolution in some cases. The O VI channel of the UVCS spectrograph includes a mirror that provides a redundant means of observing Lyα. Therefore, each spectrum covers two
wavelength ranges, referred to as primary and redundant. The wavelength and radiometric calibrations are carried out for each channel separately in the UVCS data analysis software.

As with other comets observed by UVCS, the slit was placed so that Comet Machholz would drift across it over the course of 2–4 hr. Seven such crossings were observed over 16 hr. Different instrument configurations were used for the various crossings to obtain different spatial and spectral resolutions and ranges, trading those parameters off to stay within the data rate limitations imposed by the telemetry rate. Exposure times were 120 s, and about 10 s were needed for readout between exposures. For the third crossing, the slit was parallel to the comet’s path so that the comet moved along the slit, providing many exposures and a high signal-to-noise ratio spectrum of the coma that is useful for faint lines.

The H I Lyα line is by far the brightest, and even when it does not fall on the detector (as in crossing 3), Lyα photons scattered by the grating generally dominate the noise level and impose the detection limit for faint lines. There are also a number of grating ghosts of the Lyα line that were identified in spectra of coronal mass ejections. Each of them has a fixed apparent wavelength and intensity ratio to Lyα. A noteworthy one at 1033 Å could be confused with an O VI line. We indicate those ghosts in the spectral plots, but we do not include them in tabulated spectra. The Lyα line is bright enough that it approaches the limit of linearity for the microchannel plate crossed delay line detector. We have used the correction given by K. Wilhelm in the SolarSoft package for the SUMER detector, which is virtually identical to that used by UVCS. The correction turned out not to be significant.

The slit positions are shown in Figure 1. Table 1 lists the slit position (apparent heliocentric distance, R, and position angle, PA) and primary and redundant spectral ranges for each slit crossing, along with the true heliocentric distance, r, and phase angle, α, from the ephemeris provided by Brian Marsden. Crossing 7 covered sections of the detector with four separate panels in a trade-off between resolution and spectral coverage. The wavelength ranges for each panel are given in Table 1.

Figure 2 shows the LASCO image taken at the time of the third crossing, with a green bar to represent the UVCS slit. During this exposure sequence, the comet nucleus moved along the slit. We measured the spectrum of the coma by tracking the brightest pixel in Lyβ as the comet moved along the slit during this crossing. The pixel covers an area given by the slit width and the spatial binning of 10 pixels, or 21″ × 70″ on the sky. We averaged the first 30 exposures, which were obtained before the coma drifted to the edge of the slit. The O I lines at 1027.4 and 1028.2 Å are on the wing of the Lyβ line, and we subtracted a scaled Lyβ profile from a region far from the coma before measuring this pair of lines. The spectrum is shown in Figure 3, and the intensities are given in Table 2.

Table 2 also gives intensities for the ion tail. We extracted the spectra of the ion tail from crossing 6 in two ways. First, we tracked the three spatial bins that show C III emission as the comet crossed the slit and averaged 20 exposures to provide the maximum feasible number of counts. However, the averaging dilutes the intensity because the emission is brightest just after the coma passes across the slit. Therefore, we also present the intensities for the single brightest 21″ × 70″ bin.

3. Analysis

3.1. Atomic Processes

Photoionization rates were computed based on extreme-ultraviolet fluxes from the SEE instrument on the TIMED satellite (Woods et al. 2000). Fluxes were not available for the day of our observations, so we used the spectrum from one solar rotation later. The photoionization cross sections were taken from Reilman & Manson (1979). Table 3 gives the rates at perihelion, 0.1241 au, and they can be scaled to the other heliocentric distances. They are compatible with the photoionization rates used in comet studies over many decades, the
Table 1
UVCS Observations of Comet Machholz, 2002 January 8

| Crossing | \( R (R_\odot) \) | PA (deg) | \( r (\text{au}) \) | \( \alpha \) (deg) | No. of Exp. | \( t_{\text{cross}} \) (UT) | Slit Width (\( \mu \)) | \( \lambda_{999} \) (\( \AA \)) | \( \lambda_{\text{RED}} \) (\( \AA \)) |
|----------|----------------|----------|----------------|--------------|-------------|----------------|----------------|----------------|----------------|
| 1        | 7.72           | 88.2     | 0.1267         | 163.6       | 165         | 02:23         | 50             | 970–977        | 1213–1220 |
| 2        | 6.97           | 64.5     | 0.1252         | 166.5       | 54          | 06:47         | 50             | 1018–1120      | 1177–1270 |
| 3        | 6.27           | 55.4     | 0.1247         | 166.7       | 54          |               | 100            | 942–1043       | 1100–1193 |
| 4        | 6.45           | 41.9     | 0.1244         | 166.5       | 54          | 11:12         | 50             | 1018–1119      | 1177–1271 |
| 5        | 6.85           | 30.4     | 0.1242         | 165.5       | 54          | 13:05         | 150            | 940–1041       | 1126–1193 |
| 6        | 7.44           | 20.5     | 0.1241         | 163.8       | 54          | 15:03         | 150            | 987–992        | 1198–1202 |
| 7        | 8.22           | 12.4     | 0.1242         | 162.0       | 54          | 16:58         | 50             | 969–975        | 1213–1219 |

The rate of charge transfer of \( \text{H} \) with solar wind protons is typically higher than the photoionization rate. The solar wind mass flux is fairly constant, near \( 3 \times 10^{8} \text{ cm}^{-2} \text{s}^{-1} \) at 1 au (Wang 2010), so scaling to 0.124 au and multiplying by the cross section of \( 1.1 \times 10^{-15} \text{ cm}^{2} \) (Schultz et al. 2008) gives \( 2.2 \times 10^{-5} \text{ s}^{-1} \). The charge-transfer process produces neutral \( \text{H} \) atoms with the solar wind speed and velocity distribution. While such neutrals produce the Ly\( \alpha \) tails of sungrazing comets in the static corona near the Sun, in the case of Comet Machholz at 0.124 au, they are severely Doppler dimmed and do not contribute significantly to the observed Lyman line intensities. If they did contribute, they would be distinguished by a blueshift and line width determined by the solar Ly\( \alpha \) profile and the velocity distribution of the solar wind protons, or around 100 km s\(^{-1}\). One other charge-transfer process may be important. Because the ionization potentials of \( \text{H} \) and \( \text{O} \) are nearly equal, the charge transfer between neutral \( \text{H} \) and \( \text{O}^{+} \), along with its inverse, is relatively fast. The table gives the rate based on the Kingdon & Ferland (1996) cross section, a temperature of 30,000 K, and a neutral hydrogen density of 1000 cm\(^{-3}\), as would be typical for a distance of 0.1 \( R_\odot \) from the nucleus and an outgassing rate of \( 5 \times 10^{29} \text{ s}^{-1} \). It is slow enough compared to the photoionization rate that it can be neglected.

We note, however, that compression and heating of electrons by the bow shock or plasma waves could increase the collisional ionization and excitation rates. Feldman et al. (2018) discussed signatures of collisional excitation and dissociation in the ALICE spectra of Comet 67P/Churyumov–Gerasimenko, and Cravens et al. (1987) used a three-temperature approximation to the electron distribution measured near Comet Halley by Gringauz et al. (1986) to compute ionization rates. In the case of Comet Machholz, the bow shock standoff distance is of order 10\(^{8}\) cm, which is small compared to the UVCS resolution elements. Nevertheless, the high density in that small region might make collisional processes significant.

Table 4 gives the photoexcitation rates of the lines we observe. The line intensities at 0.124 au are given in \( 10^{9} \text{ ph cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1} \text{ angstrom}^{-1} \) in a wavelength interval corresponding to 30 km s\(^{-1}\) for \( \text{H} \) and 3 km s\(^{-1}\) for the other ions. The scattering cross sections, scaled from total flux to line center spectral flux with the formulae of Lemaire et al. (2015). The profile of Ly\( \gamma \) was not included in Lemaire et al. (2015), so we estimate the line shape from the figure in Curdt et al. (2001). The O \( \Pi \) and C \( \Pi \) values are peak fluxes from the Curdt et al. (2001) SUMER atlas for the quiet Sun, scaled from solar minimum to the time of observation based on the assumption that they scale with Ly\( \beta \). The C \( \Pi \) and N \( \Pi \) lines are formed at higher temperatures. We assume that the increase in Ly\( \beta \) compared to solar minimum results from the presence of active regions, and we use the quiet Sun–to–active region contrast given by Vernazza & Reeves (1978) to estimate the fraction of the Sun covered by active regions. We then use the contrast between the quiet Sun and active regions in the C \( \Pi \) and N \( \Pi \) lines to scale by a factor of 1.6 from the peak SUMER fluxes of Curdt et al. (2001).
proportional to the oscillator strength, $f$, and branching ratios of 0.88 and 0.84 are included for Ly$\alpha$ and Ly$\gamma$, respectively.

Because Comet Machholz was at perihelion, its velocity component toward the Sun was essentially zero, so Doppler dimming (reduction of the scattering rate when an atom is Doppler shifted away from the solar Ly$\alpha$ emission profile, somewhat analogous to the Swings effect) should not be significant. The plasma velocity within the ion tail is not independently known, however. Since the solar disk lines that illuminate the ions are fairly narrow, plasma speeds as low as 40 km s$^{-1}$ could lead to significant Doppler dimming. We will return to this point in discussing the elemental abundances.

Finally, we must consider the opacity in the Ly$\alpha$ line. For an outgassing rate of a few times 10$^{29}$ s$^{-1}$, the optical depths between the nucleus and the Sun and between the nucleus and SOHO are each expected to be on the order of 1. We can assess the optical depth from the crossings that measured both Ly$\alpha$ and Ly$\beta$ intensities, since their ratio is constant for optically thin scattering. Crossings 2, 4, and 5 all showed an increase in the Ly$\beta$/Ly$\alpha$ ratio by a factor of 2.2 close to the nucleus, meaning that Ly$\alpha$ was attenuated by a total optical depth (comet–Sun and comet–SOHO) of $\tau \approx 0.8$. The observations of these three crossings were highly binned in the spatial direction in order to give the broadest possible wavelength coverage, so that 0.8 is the weighted average of $\tau$ over a 14$''$ × 70$''$ spatial bin, or about 8600 × 43,000 km.

### 3.2. Water Production Rate

The H I Ly$\alpha$ radiance profiles of the comet obtained during the first and last crossings (1 and 7 in Table 1) through the UVCS slit were least-squares fitted to a Haser model with H atom velocities of 20 and 8 km s$^{-1}$ (from photodissociation of Figure 3. Spectrum of the coma. This is the average of the brightest 28$''$ × 70$''$ spatial bin over 40 exposures as the comet slid along the UVCS slit between 07:56 and 09:26 UT on January 8. Two grating ghosts are indicated, along with lines of H I, C II, C III, and O I. The continuum is due to Ly$\alpha$ photons scattered by the diffraction grating.

#### Table 2

| Ion | $\lambda$ (Å) | Coma | Tail Average | Tail Peak |
|-----|---------------|------|--------------|-----------|
| H I | 1025.7        | 126  | 4.55         | 16.8      |
| H I | 972.2         | 12.2 | 0.41         | 5.50      |
| C III | 1036.9 | 5.0  | 0.09         | ...       |
| C III | 977.0 | 25.1 | 1.21         | 11.9      |
| N III | 989.99 | <1   | <0.1         | <1        |
| O I | 989.7  | 3.0  | ...          | ...       |
| O I | 991.0 | 1.8  | ...          | ...       |
| O I | 1027.4 | 2.9  | ...          | ...       |

#### Table 3

| Ion | $q_{\text{phot}}$ (s$^{-1}$) | $q_{\text{coll}}$ (s$^{-1}$) | $q_{\text{CT}}$ (s$^{-1}$) |
|-----|-------------------------------|------------------------------|---------------------------|
| H I | 4.47e-6                       | 2.0e-5                       | 2.2e-5                    |
| C I | 7.70e-4                       | 4.3e-7                       | ...                       |
| C II | 9.56e-6                     | 1.1e-9                       | ...                       |
| C III | 1.85e-6                     | ...                          | ...                       |
| N I | 3.23e-5                       | 7.5e-8                       | ...                       |
| N II | 1.63e-6                      | 1.9e-10                      | ...                       |
| N III | 4.03e-6                     | ...                          | ...                       |
| O I | 4.04e-5                       | 5.5e-8                       | 1.16e-6                   |

**Note.** $q_{\text{phot}}$ in 10$^9$ photons cm$^{-2}$ s$^{-1}$.

$^a$ See text for assumed density and temperature.

$^a$ $I_{124}$ in 10$^6$ photons cm$^{-2}$ s$^{-1}$.
H$_2$O and OH, respectively). In the model, described by Mancuso (2015), the value for the lifetime $\tau_H$ of the H atoms was left as a free parameter, together with the unknown outgassing rate, $Q_{H_2O}$, to be solved by comparing the coma model with the Ly$\alpha$ radiance measured along the UVCS slit from the exposures containing the nucleus. The model was applied to the data by imposing the same value of $\tau_H$ for the two crossings. More details on the other assumed parameters can be found in Mancuso (2015). The best-fit $Q_{H_2O}$ values estimated near perihelion for the two UVCS crossings are, respectively, $5.09 \times 10^{23}$ and $4.58 \times 10^{23}$ molecules s$^{-1}$, with a best-fitting $\tau_H = 1.5 \times 10^6$ s. However, that value of $\tau_H$ corresponds to a length scale above $10^{12}$ cm, which is much larger than the extent of the measured radiance profiles, and it is therefore uncertain. In Figure 4, we compare our results for $Q_{H_2O}$ with the ones obtained by Combi et al. (2011, 2019) with SOHO/SWAN at larger heliocentric distances as part of the full-sky imaging program during the apparitions near perihelion of 1996, 2002, 2007, and 2012 (Combi et al. 2011, 2019). An average power-law fit to the same data. The results obtained in this work near perihelion during two crossings of the UVCS slit (orange circles) are shown for comparison.

Figure 4. Water production rates in Comet Machholz plotted as a function of the comet’s heliocentric distance. Shown are results from SOHO/SWAN observations obtained during four apparitions of the comet in 1996, 2002, 2007, and 2012 (Combi et al. 2011, 2019). The dashed line is an average power-law fit to the same data. The results obtained in this work near perihelion during two crossings of the UVCS slit (orange circles) are shown for comparison.

slowly expanding cloud, which we assume to be spherical. The atoms are destroyed by photoionization or collisional ionization at the rates given in Table 3. They also undergo charge transfer with solar wind protons, in which case they have the solar wind velocity and effectively cease to scatter Ly$\alpha$ photons due to Doppler dimming (the Swings effect). Thus, there is an exponential cutoff at a timescale of about $t_{\text{int}} = 2.7 \times 10^4$ s, which corresponds to a spatial scale somewhat below 1 AU. That is similar to the extent of the measured Ly$\alpha$ cloud.

Radiation pressure accelerates the H atoms, and the scattering rate in Table 4 implies an acceleration of 73 cm s$^{-2}$. In fact, the radiation pressure acceleration is comparable to the gravitational acceleration, just as for the micron-sized dust grains that are seen as the optical tail. Of course, the dust grains last much longer, and the range of sizes produces a range of ratios of radiative to gravitational forces. The main difference is that the H atoms are ejected at speeds an order of magnitude faster than the dust grains, so radiation pressure has a correspondingly smaller effect.

Given the initial speed and the acceleration, each atom follows an analytically described path relative to the nucleus. For a given initial speed, we eject particles at 1$^\circ$ intervals in altitude and azimuth about the axis pointing toward the Sun. Each particle scatters Ly$\alpha$ photons at the rate given in Table 4 multiplied by $\exp(-t/t_{\text{int}})$ to account for the destruction of the H atoms. The optical depth in Ly$\alpha$ can be significant, so we use the computed density of H atoms to calculate the optical depth between each point and the Sun and multiply the emissivity by $\exp(-\tau)$. For the optical depth calculation, we approximate the velocity profile as a top hat with a width of twice the initial speed. This is somewhat crude, but the optical depth is only significant close to the nucleus for the outgassing rate of Comet Machholz.

The emission is computed in a 501 $\times$ 501 $\times$ 501 grid of cells of 7$''$ as seen from SOHO, which was 0.86 au from the comet during the first crossing. The 3D model was then rotated to match the SOHO point of view. Because the phase angle was in the range 162$^\circ$–167$^\circ$ during these observations, the line of sight is not far from the vector between the comet and the Sun. Therefore, the radiation pressure accelerates atoms toward SOHO.

We then sum the emission along each line of sight to produce a 2D model of the Ly$\alpha$ intensity, and we average the velocity to predict the velocity centroids as a function of distance from the nucleus. Figure 5 shows the predicted intensity image for an initial speed of 16 km s$^{-1}$. While the contours are approximately circular, the outer contours are displaced somewhat away from the Sun relative to the nucleus.

Though the hydrogen atoms follow different trajectories depending upon their initial velocities, the basic expectation is that they will be accelerated to speeds of order 20–30 km s$^{-1}$ away from the Sun as they travel a distance of order 1 AU from the nucleus. Because our line of sight is not far from the comet–Sun line, most of that velocity will appear as a blueshift that gets stronger with distance from the comet. Figure 6 shows the velocity centroid as a function of distance from the nucleus measured during the first slit crossing. It is compared with the prediction of the model for a cut through the nucleus at an angle of 30$^\circ$, approximately the angle between the comet’s trajectory and the slit. This model assumed that H atoms leave the coma at 16 km s$^{-1}$.

3.3. Emission Models

To aid in interpreting the observations, we constructed models of the Ly$\alpha$ intensity and average velocity as seen from SOHO. Hydrogen atoms produced by photodissociation of H$_2$O and OH receive some kinetic energy, and most have initial speeds of 8–24 km s$^{-1}$. In the frame of the comet, they form a
There are serious limitations to the simple model. In particular, we assume that all of the hydrogen atoms are isotropically ejected at velocities of 16 km s\(^{-1}\), while the speeds range from about 8 to 24 km s\(^{-1}\). In addition, our treatment of optical depth effects is crude, and that will affect the line profile near the nucleus. Nevertheless, Figure 6 does show a zeroth-level agreement in that there is a blueshift of about 30 km s\(^{-1}\) at distances of about 150 pixels or about 1 \(R_c\) from the nucleus. With the help of more sophisticated models, it might be possible to constrain the initial velocity distribution of the H atoms. In particular, if the H atoms lose very much momentum to heavier atoms such as O by collisions during the initial expansion, that would imply longer times to reach 1 \(R_c\) from the nucleus and blueshifts larger than those observed. At the high outgassing rates inferred above, the H atoms are expected to lose a considerable amount of momentum on collisions with oxygen (Combi & Smyth 1988). Perhaps low-velocity H atoms contribute to the region of small Doppler shifts near the nucleus seen in Figure 6.

### 3.4. Reconstructed Images

We reconstruct intensity images with the method used for past UVCS observations of comets (Povich et al. 2003; Bemporad et al. 2005; Giordano et al. 2015), in effect using the motion of the comet across the slit as though we were making a raster scan of the slit across the comet. For each exposure, we measure the intensity of a line in each spatial bin along the slit and place it in a 2D array. The velocities of the comet perpendicular and parallel to the slit are known from the comet’s orbit and the position angle of the slit. We multiply those velocities by the time between exposures (exposure time plus readout time, or about 130 s) and offset the intensities from subsequent exposures accordingly.

Figure 7 shows the composite LASCO images and reconstructed \(\text{Ly}\alpha\) images from UVCS spectra at crossings 1, 2, 5, and 7, when \(\text{Ly}\alpha\) was detected. Those images allow the comparison of the shape and orientation of the comet. The \(\text{Ly}\alpha\) cloud is approximately, but not exactly, spherical, as predicted by the model in the previous section. A similar departure from spherical expansion was seen in reconstructed \(\text{Ly}\alpha\) images of Comet Encke (Raymond et al. 2002). Figure 8 shows a larger version of the \(\text{Ly}\alpha\) image from the first crossing, with contours indicating the intensity.

### 3.5. Ion Tail

A notable feature of the reconstructed images is the ion tail in C\textsc{iii} \(\lambda 977\) emission seen in Figure 9. A similar C\textsc{iii} tail was found in images reconstructed from UVCS spectra in Comet Kudo–Fujikawa (Povich et al. 2003). In that case, the ion tail was interrupted, apparently as a result of a disconnection event caused by interaction with a reversal in the direction of the interplanetary field (Brandt & Snow 2000). The image of the ion tail of Comet Machholz as seen from SOHO is foreshortened by about a factor of 2.4 because our line of sight is not far from the comet–Sun line. The angle between the C\textsc{iii} tail and the comet trajectory is roughly 70°. Assuming that material in the tail moves radially away from the Sun, and correcting for the projection due to the viewing angle, the angle between the tail and the comet’s path implies a velocity of the material in the tail of about 100 km s\(^{-1}\). That is in line with Scherb et al. (1990) and Rauer & Jockers (1993), who
measured Doppler shifts increasing to 70 km s\(^{-1}\) for H\(_2\)O\(^+\) ions along the tails of comets Halley and Levy 1990c, respectively. It is also in line with Jockers et al. (1972), who found that the motions of features along the plasma tail of Comet Tago–Sato–Kosaka 1969 IX increased from 40 km s\(^{-1}\) close to the comet to 300 km s\(^{-1}\) farther away. Unfortunately, we cannot directly measure the velocity by means of the Doppler shift because of the 150\/^\circ\) slit width used for this observation and the uneven filling of the slit, which can shift the line centroid to the red or blue during different exposures.

An important consequence of the acceleration of C III ions to speeds above 50 km s\(^{-1}\) is severe Doppler dimming. The C III line from the disk is only about 50 km s\(^{-1}\) wide FWHM (Feldman et al. 2011). The width of the C III velocity distribution in the tail is difficult to measure because of the large slit width, but FWHM < 120 km s\(^{-1}\) is an upper limit. Acceleration of the plasma along the ion tail could strengthen the Doppler dimming and cause the observed fading with distance from the nucleus. However, the fraction of carbon in the form of C III is very small near the nucleus (see Table 5 below) and apparently much larger in the tail, judging by the C III/C II ratio (Table 2). That offsets some of the effect of Doppler dimming. Some kinetic heating of the C III ions by the process that accelerates the plasma tail could also reduce the Doppler dimming effect.

### 3.6. Elemental Abundances

The elemental abundances are of special interest because of the unusually low C\(_2\) and C\(_3\) abundances relative to NH\(_2\) in Comet Machholz (Langland-Shula & Smith 2007; Schleicher 2008).

Abundance analyses of sungrazing comets observed by UVCS yield total abundances because dust grains rapidly sublimate close to the Sun (Kimura et al. 2002). At 0.124 au, however, the sublimation times are longer, so the spectra of Comet 96/P Machholz reveal the composition of the volatile component. The intensities observed in the coma in Table 2 can be multiplied by 4\(_\pi\) and divided by the photon scattering rates in Table 4 to obtain the column densities of the atoms and ions observed. The line-of-sight depth can be estimated from the size of the spatial element. Dividing that into the column density gives the density. We take the line-of-sight depth to be the average of the long and short dimensions of the 21\("\) × 70\("\) spatial element at a distance of 0.86 au, or 2.8 × 10\(^9\) cm. Finally, multiplying by the outflow speed and 4\(_\pi\) gives the outgoing rate. We present those rates in Table 5 separately for each line to provide a consistency check. We assume outflow speeds of 15 km s\(^{-1}\) for H and 3 km s\(^{-1}\) for the other elements.

The C/O ratio is probably the most reliable because C and O atoms should have similar velocities as they leave the coma. The O/H ratio is more questionable because the O and H velocities are different (Combi & Smyth 1988), and both are uncertain. In addition, the H abundance determined from Ly\(_\alpha\) is subject to optical depth uncertainty, and it may be affected by radiation pressure on the H atoms. The factor of 1.5 discrepancy in the rate of production of O determined from different O I lines may be due to uncertainty in the measured intensity of the lines at 1027 and 1028 \AA, which are on the wing of the much brighter Ly\(\beta\) line. However, one expects a hydrogen-to-oxygen ratio of 2:1, and the derived ratio is twice that. If CO or CO\(_2\) contributes a significant amount of O, the discrepancy is made worse. The easiest explanation would be that the oxygen outflow rate is larger than we assumed.

Close to the nucleus, the carbon is mostly C II because C I is rapidly photoionized, and it takes so long to ionize C II to C III that only about 1% of the carbon in the central region is C III. Overall, we estimate the ratio of the outgassing rates of carbon and nitrogen as \(\dot{N}(C)/\dot{N}(H) \approx 0.02\). For comparison, the sungrazer C/2003 K7 showed \(\dot{N}(C)/\dot{N}(H) = 0.0006–0.018\), even with substantial dust sublimation at 3.37 \(R_\odot\) (Ciavarella et al. 2010). We find that \(\dot{N}(C)/\dot{N}(O) < 1/10\) in Comet Machholz, suggesting that much of the carbon could be locked up in dust.

Unfortunately, \(\dot{N}(N)\) is poorly constrained because we have no N II lines and only an upper limit on N III. There is no obvious enhancement of nitrogen ions, which may be surprising in view of optical indications of strong NH\(_2\) emission compared to C\(_2\) and C\(_3\). That might again indicate that much of the carbon remains locked in grains or is in the form of CO or CO\(_2\).

We do not detect any Si lines, unlike in comets C/2011 W (Lovejoy) and C/2003 K7 (Ciavarella et al. 2010; Raymond et al. 2018). That is probably due to the fact that Comet Machholz was beyond the heliocentric distance where silicate grains can rapidly sublimate, and it is likely that nearly all of the silicon is in grains.

As noted in Section 3.1, collisional excitation and ionization could contribute to a degree not included in our estimates. However, the scale of the bow shock region where such processes will be strong is roughly 1\(^2\) cm, compared with a spatial resolution element of 1400\(^2\) cm for crossing 3.
4. Discussion

As described in Section 3.2, the outgassing rate fits nicely with the extrapolation of the values determined by Combi et al. (2011, 2019) at larger distances.

The UVCS has observed two other short-period comets, Comet 2P/Encke (Raymond et al. 2002) and Comet C/1997 H2 (Mancuso 2015), both near perihelion at 0.34 and 0.137 au, respectively. Comet 2P/Encke showed an outgassing rate of \(1.1 \times 10^{29} \) H atoms s\(^{-1}\), increasing by about 30% over the course of a day. The upper limits on the O I and CII lines were about \(10^{-4}\) times Ly\(\alpha\). That is consistent with the Comet Machholz observations, except for the C III line, which is \(3 \times 10^{-4}\) times as strong as Ly\(\alpha\) in the nucleus but probably consistent with \(10^{-4}\) when averaged over a larger volume. Comet Encke’s Ly\(\alpha\) brightness contours showed a small deviation from spherical, presumably due to radiation pressure as in Comet Machholz. Comet C/1997 H2 also had a similar outgassing rate of \(1.2 \times 10^{29} \) H atoms s\(^{-1}\).

Comet 2002/X5 (Kudo–Fujikawa) was a longer-period object that was observed near perihelion at 0.19 au (Povich et al. 2003). It showed much higher outgassing rates of \(5 \times 10^{30} \) H atoms s\(^{-1}\) and carbon-to-hydrogen ratios of order 20% based on submillimeter observations of carbon-bearing molecules (Biver et al. 2011), as opposed to 2% in Comet Machholz. Comet Kudo–Fujikawa would be an older long-period comet according to the classification of
A’Hearn et al. (1995), so it has probably passed through the inner solar system before. Perhaps the most interesting similarity between Comet Kudo–Fujikawa and Comet Machholz is the ion tail observed in the C III emission line. The two comets were observed close to the Sun, and that is probably necessary for the ionization of C II to C III over a modest length scale. Povich et al. (2003) obtained two reconstructed images of the ion tail of Comet Kudo–Fujikawa. The first image shows a disconnection event that was attributed to the crossing of a field reversal in the solar wind (Brandt & Snow 2000). The second image resembles that seen in Comet Machholz in curvature and length but viewed from a different angle.

Emission from carbon ions has also been detected in the sungrazing comet C/2003 K7 (Ciavarella et al. 2010), which showed a C:H ratio of about 0.004. That comet was observed at a heliocentric distance of 3.4 R_{\odot}, which meant that grains were very rapidly sublimated, and the abundance ratio includes both gaseous and dust components. Nevertheless, Comet Machholz shows a much higher C:H ratio of about 1.8%. Comet C/2003 K7 was a member of the Kreutz family of sungrazing comets, and it was close enough to the Sun that it had been reduced to a gaseous and dust components. Nevertheless, Comet Machholz will transit the Sun from the point of view of the Earth on 2003 January. That will be an excellent opportunity for observations possible, and the UVCS operations team that carried out the observations. We also thank the anonymous referee, who pointed out gaps in our knowledge of comets. This work was supported by NASA grant NAG5-12814 to the Smithsonian Astrophysical Observatory.

5. Summary

Comet Machholz is unusual in many ways, including its orbit (Green et al. 1990; McIntosh 1990), its relationship to the Marsden and Kracht groups of sungrazing comets (Ohtsuka et al. 2003), and its low apparent C:N ratio (Langland-Shula & Smith 2007; Schleicher 2008).

The UVCS observations during the 2002 perihelion show outgassing in agreement with values extrapolated from SWAN measurements at larger radii (Combi et al. 2011). The H I Lyα cloud that expands slowly away from the comet nucleus is affected by radiation pressure on the hydrogen atoms, producing a modest asymmetry and about 30 km s^{-1} Doppler shifts when seen from the point of view of SOHO. The ion tail is seen in C III, and it is similar to that seen in Comet Kudo–Fujikawa (Povich et al. 2003). We do not have useful measurements of the Doppler shift, but the intensity structure is consistent with the gradual acceleration of the ion tail seen in molecular ions in other comets (Jockers et al. 1972; Scherb et al. 1990). The ratio of C to H2O of 1.8% is not anomalously low, but we do not have a good limit on N, so the low C/N ratio seen in molecules (Langland-Shula & Smith 2007; Schleicher 2008) remains mysterious. Perhaps the carbon originated from CO or CO2.

Geraint Jones and Matthew Knight predict that Comet Machholz will transit the Sun from the point of view of the Solar Orbiter in 2023 January. That will be an excellent opportunity for observations with the Metis coronagraph, since the white-light images will show the effects of scattering at extreme phase angles, and the Lyα images will show the Lyα cloud discussed here but projected at different angles. The images can be used to extract both solar wind and comet parameters (Bemporad et al. 2015). Other instruments on the Solar Orbiter should be able to observe the comet in absorption.

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