HIGH RESOLUTION HST STIS SPECTRA OF C I AND CO IN THE β PICTORIS CIRCUMSTELLAR DISK

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ABSTRACT

High resolution FUV echelle spectra showing absorption features arising from C I and CO gas in the β Pictoris circumstellar (CS) disk were obtained on 1997 December 6 and 19 using the Space Telescope Imaging Spectrograph (STIS). An unsaturated spin-forbidden line of C I at 1613.376 Å not previously seen in spectra of β Pictoris was detected, allowing for an improved determination of the column density of C I at zero velocity relative to the star (the stable component), N(3P) = (2–4)×1016 cm−2. Variable components with multiple velocities, which are the signatures of infalling bodies in the β Pictoris CS disk, are observed in the C I λ1561 and 1657 multiplets. Also seen for the first time were two lines arising from the metastable 1D level of carbon, at 1931 Å and 1463 Å. The results of analysis of the CO A – X (0-0), (1-0), and (2-0) bands are presented, including the bands arising from 13CO, with much better precision than has previously been possible due to the very high resolution provided by the STIS echelle gratings. Only stable CO gas is observed, with a column density N(CO) = (6.3 ± 0.3)×1014 cm−2. An unusual ratio of the column densities of 12CO to 13CO is found (R = 15 ± 2). The large difference between the column densities of C I and CO indicates that photodissociation of CO is not the primary source of C I gas in the disk, contrary to previous suggestion.

Subject headings: circumstellar matter—stars: individual (Beta Pictoris)—planetary systems—comets: general

1. INTRODUCTION

β Pictoris is the most extensively studied of the young planetary systems discovered in the last decade and a half. It is a bright Southern hemisphere star (type A5 V), located about 19.3 pc distant from the Sun, with a systemic radial velocity of 20 km s−1 (for a review of the β Pictoris system, see Vidal-Madjar, Lecavelier des Etangs, & Ferlet (1998)). It was observed in 1983 by the IRAS satellite to have a large excess of emission at infrared wavelengths. This was referred to as the Vega-like phenomenon and was identified as arising from an edge-on circumstellar (hereafter CS) dust disk, presumed to be associated with planetary formation (Smith & Terrile 1984). It was soon determined through absorption spectroscopy that there was CS gas associated with the dust as well.

A large body of evidence has accumulated indicating that there are comet-like bodies present in the β Pictoris CS disk. Collisions between dust particles are expected to produce submicron fragments which should be expelled from the system by radiation pressure on time scales much shorter than any plausible stellar age. Thus there must be a secondary source of particles; one model for the production of dust and gas in the CS disk focusses on evaporating comets and is called the Orbiting Evaporating Bodies model (OEB). In this picture, the comets orbit the star at several tens of AU, and thus, the β Pictoris CS disk is a kind of “gigantic multi-cometary tail with its natural constituents: gas and dust” (Lecavelier des Etangs, Vidal-Madjar, & Ferlet 1996). Spectra of β Pictoris show variable redshifted absorption features arising from gas infalling toward the star at high velocities (and infrequently, blueshifted features as well); these features are best attributed to the evaporation of star-grazing comets, called the Falling Evaporating Bodies scenario (FEB) (Beust et al. 1990). Also, gas at close to 20 km s−1 (zero radial velocity relative to the star) is identified in all observations and is called the stable gas component. This gas is difficult to understand, as modeling indicates that it should be expelled from the system by radiation pressure; a continuous source for this gas is required.

Neutral carbon and carbon monoxide have been observed in HST-GHRS UV absorption spectra of β Pictoris; carbon monoxide is the only molecule detected in the CS disk to date (Vidal-Madjar et al. 1994; Jolly et al. 1998). Since CO and C I can be dissociated and ionized by interstellar UV photons on time scales of the order of 200 years, both must be continuously replenished. Carbon
monoxide, in particular, is difficult to reform after dissociation in the $\beta$ Pictoris environment. Thus, the presence of these species indicates that a secondary source for this gas should exist, just as for the CS dust (Vidal-Madjar et al. 1994), Jolly et al. (1998) found the column densities of C I and CO to be comparable, around $10^{15}$ cm$^{-2}$; since their rates of destruction are also comparable, this was taken as evidence that the C I is produced by photodissociation of CO, which evaporates from comets orbiting at various distances and velocities. However, the C I column density was determined from a heavily saturated multiplet and is therefore quite uncertain. In the hopes of further constraining the characteristics of C I and CO in the $\beta$ Pictoris system, we have reinvestigated the transitions observed in the G HRS data, as well as some that were not seen due to the relatively low spectral resolution of G HRS compared with that of the STIS high resolution echelle.

2. OBSERVATIONS

HST STIS high resolution echelle spectra of $\beta$ Pictoris were obtained on 1997 December 6 and 1997 December 19, covering the wavelength range from 1459 Å to 2888 Å in six exposures each day. Table 1 shows the log of observations. All the absorption features discussed in this paper appear in either the first or second data set listed for each day (o4g001020/o4g002020). The data were initially reduced and calibrated using the STScI IRAF package calstis v1.8. Spectra with a signal-to-noise ratio of around 10 were achieved. Examination of the errors in the flux values showed that the error propagation calculation had not been performed correctly and that the stated errors were too small. Therefore the data were re-calibrated using calstis v1.9a, correcting the underestimate of the measurement errors.

The particular advantage of this data set over previous comparable ones is the very high spectral resolution achieved. The instrumental line spread function using the E140H grating is well described by a Gaussian with a FWHM of 1 pixel, corresponding to FWHM = $\lambda/220,000$ (Sahu et al. 1999). However, since the detector under-samples the line spread function, the effective resolution to separate two adjacent lines with this grating is only $R = 110,000$. Using the E230H grating, the FWHM is about 2 pixels, corresponding to FWHM = $\lambda/110,000$ (Sahu et al. 1999).

3. ANALYSIS

3.1. C I $\lambda 1613$ line

This previously undetected spin-forbidden transition ($^{3}P_{0} \rightarrow ^{1}P_{1}$) at 1613.376 Å was clearly observed on both days. It is unsaturated, which allows for an improved determination of the column density of C I. As there was no change in the line between the two days of observation, the spectra were averaged together to improve the S/N; the result is shown in Figure 1. Unfortunately, the other two fine structure lines in the multiplet were not reliably detected. Atomic data were taken from Morton (1991) and the continuum around the line was fit with a sixth-degree polynomial. Voigt line profiles were used to generate transmission functions, which were then convolved with a Gaussian instrumental line spread function with FWHM = $\lambda/220,000$ to create model spectra. The $\chi^{2}$ statistic between the model and the data was then minimized to determine the best velocity centroid, $v$, column density of C I in the ground level, $N(^{3}P_{0})$, and Doppler broadening parameter, $b$; error bars for these parameters were determined from the contours of $\chi^{2}$. Since the line was unsaturated, the column density was also determined from the equivalent width of the line and $b$ and $v$ were determined from a simple Gaussian fit to the line, as a check on the results of the $\chi^{2}$ minimization.

3.2. C I($^{3}P$) $\lambda\lambda 1561$ and 1657 multiplets

The central portion of the 1561 Å and 1657 Å multiplets, arising from the $^{3}P$ ground term, were heavily saturated in the STIS data. However, this allowed us to examine the smaller variable red and blueshifted features in the spectra which are the signatures of infalling comets in the CS disk. In Figures 2 and 3, one can easily see absorption lying at higher redshift in the December 6 data that is not visible in the December 19 data. A model of the multiplet which contains only one velocity component is unable to reproduce the absorption dip at 1561.5 Å or the absorption at higher redshift in the December 6 data.

Due to the fact that the multiplets were extremely saturated and that the multiple velocity components were blended together, we were not able to perform $\chi^{2}$ minimizations to find unique best values for the model parameters. Fe II absorption features in our data set were analyzed and the velocities of their multiple velocity components found. Models of the C I A1561 multiplet were constructed, containing the same number of components as were found in the Fe II features, with roughly the same velocities. The parameters of the stable component at $v = 20$ km s$^{-1}$ were set to those determined from the analysis of the unsaturated 1613.376 Å line. The remaining parameters were then adjusted to find the best model by eye. This model was compared to the 1657 Å multiplet to confirm that the values found in this way were reasonable. A small constant value ($\approx 2 \times 10^{-13}$ erg s$^{-1}$ cm$^{-2}$ Å$^{-1}$) was subtracted from the 1657 Å data to bring the baselines of the totally saturated features to zero.

3.3. C I($^{3}D$) $\lambda\lambda 1931$ and 1463 lines

These lines arise from the excited, metastable $^{3}D$ state of the ground configuration and have not previously been observed in spectra of $\beta$ Pictoris. The $^{3}D$ level has a lifetime of about 4000 s, lying about 10,000 cm$^{-1}$ above the ground level; C atoms in this state may be produced during the photodissociation of CO in solar system comet comae (Tozzi, Feldman, & Festou 1998). The 1931 Å lines were analyzed using the same model generating and $\chi^{2}$ minimization procedures described in § 3.1; the atomic data used were from Hibbert et al. (1993). Although there may be some reason to suspect that the strong central absorption features near 1931.05 Å contain multiple velocity components, since this behavior is seen in lines arising from excited levels of other atomic species, the $\chi^{2}$ minimizations indicated that stable unique solutions containing more than one component in the central absorption features could not be found. Thus, best models were found using only one velocity component. However, the difficulty involved in modeling a saturated, blended line is such that there may well be other undetected components present.
so models with two components in the central absorption feature were compared to the data by eye. The 1463 Å spectra, shown in Figure 5, were so noisy that they served only to roughly confirm the values found from the 1931 Å line. A small constant flux value ($\approx 1 \times 10^{-13}$ erg s$^{-1}$ cm$^{-2}$ Å$^{-1}$) was subtracted from the 1463 Å data to bring the baselines of the saturated lines to zero.

3.4. CO Fourth Positive band system

The (0-0), (1-0), and (2-0) bands of the Fourth Positive system of CO ($A1\Pi - X1\Sigma^+$) did not vary between the two days of observation. The spectra were therefore averaged together to improve the S/N; the result appears in Figure 6. Only a single velocity component was observed. Note the detection of bands arising from $^{13}$CO, the perturbation band $e^3\Sigma^- - X^1\Sigma^+$ (1-0), not previously observed in spectra of β Pictoris, and the strong perturbation band $d^3\Delta - X^1\Sigma^+$ (5-0).

Models were generated using wavelengths and oscillator strengths from Morton & Noreau (1994). Energies of the ground state levels were calculated using the Dunham coefficients from Farrenq et al. (1991) and LTE assumed in order to determine the population of the rotational levels. The parameters of the model are the rotational excitation temperature, $T$, the Doppler broadening parameter, $b$, the column density of $^{12}$CO in the ground vibrational state, $N(^{12}$CO), the column density of $^{13}$CO in the ground vibrational state, $N(^{13}$CO), and the velocity centroid, $v$. $\chi^2$ minimization was then performed on all three bands simultaneously.

4. RESULTS

4.1. C I($^3P$) stable component

The C I $\lambda$1613.376 line showed only one velocity component at 20 km s$^{-1}$, the systemic velocity of the star; the nominal uncertainty in the absolute wavelength calibration of STIS leads to an error in velocity determinations of about 1 km s$^{-1}$ (Sahu et al. 1999). This velocity and the fact that the line did not change between the two days of observation identifies the line as arising from stable gas. The results of the $\chi^2$ minimizations for all the features analyzed appear in Table 2. The column density for stable carbon in the ground level, $^3P_0$, determined from $\chi^2$ minimization was found to agree with that determined from the equivalent width of the line. Similarly the $v$ and $b$ determined from $\chi^2$ minimization agreed with the values found from fitting a simple Gaussian to the unsaturated line.

Using a 3-σ upper limit on the column density of C I in the $^3P_2$ level (from the non-detection of the fine structure line at 1614.5068 Å) and assuming LTE, a firm upper limit of 100 K on the excitation temperature of $^3P$ carbon in the stable component was found. From analysis of the 1561 Å multiplet, discussed below, it was found that the excitation temperature of the stable component must be greater than about 50 K, or the multiplet could not be reasonably modeled. This range in temperature allows us to determine that the total column density of stable C I in the $^3P$ ground term is $(2 - 4) \times 10^{16}$ cm$^{-2}$.

This column density is more than an order of magnitude larger than the total $^3P$ column density found by Jolly et al. (1998) from GHRS data taken in November 1994, $N(^3P) = 2 \times 10^{15}$ cm$^{-2}$. Either the abundance of stable C I has varied over the three years between observations or, as is more likely, the difficult modeling of the heavily saturated C I 1561 multiplet in the GHRS data led to an inaccurate column density. Models with column densities of $10^{16}$ cm$^{-2}$ in the stable component were compared to the 1994 GHRS spectrum of the 1561 Å multiplet and found to fit the data equally well as models with the lower column density. We found the Doppler broadening parameter of the stable C I($^3P$) to be $1.3 \pm 0.5$ km s$^{-1}$. The previous work on the GHRS data found a Doppler broadening parameter of 4.2 km s$^{-1}$, which was much greater than the parameter found for the other atomic species and CO (Jolly et al. 1998). Our smaller $b$ value is equal to that found for CO in our data; we thus do not see any excess kinetic energy in the motions of the C I atoms.

4.2. C I($^3P$) multiple velocity components

The difficulty in modeling a saturated, blended multiplet is formidable, and the values determined for the multiple velocity components of C I($^3P$) from the 1561 Å multiplet are not reliable. However, this analysis did confirm that models with column densities of $10^{16}$ cm$^{-2}$ in the stable component could reasonably fit the 1561 Å spectra. We can also conclude that the total column density of C I($^3P$) in the variable components is about $10^{14}$ cm$^{-2}$ on December 6 and about $10^{15}$ cm$^{-2}$ on December 19, to within an order of magnitude or so. It is also clear that the variable C I features are generally better fit with higher excitation temperatures and larger $b$ parameters, but these values are very poorly determined.

4.3. C I($^1D$)

Using models with only one velocity component in the strong central absorption features, two components arising from the excited $^1D$ level of C I were found in the December 6 data, only one in the December 19 data. The best models are overplotted on the spectra in Figures 4 and 5. Note that the central absorption features do not appear at the same velocity on the two days, that they also do not appear at the systemic velocity of the star, and that the column density of C I($^1D$) changes significantly between the two days of observation. This would seem to indicate that there is no stable component for C I($^1D$). Models with two velocity components in the central absorption feature, which were compared to the data by eye, indicate that there could be a “stable” component which has the same column density on both days. However, it must be at about 22-23 km s$^{-1}$, which is significantly different from the systemic velocity of β Pictoris. These data are not able to conclusively determine the velocity structure present in the C I($^1D$) gas; observation of unsaturated lines at similarly high resolution will be necessary.

4.4. CO

The CO bands showed no multiple velocity component structure and no change between the two days of observation; the absorbing gas is thus entirely associated with the stable component at the systemic velocity of the star. The best model is shown overplotted on the data in Figure 6. The rotational excitation temperature
and the ratio of $N(^{12}\text{CO})$ to $N(^{13}\text{CO})$ show no significant change from the values found by Jolly et al. (1998). $R(^{12}\text{CO}/^{13}\text{CO}) = 15 \pm 2$ is quite small compared to typical values found in the ISM, e.g. $R = 150 \pm 27$ for the diffuse clouds toward $\zeta$ Ophiuchi (Sheffer et al. 1992). However, chemical fractionation at low kinetic temperatures can explain this unusual ratio, as discussed below. The column densities of both $^{12}\text{CO}$ and $^{13}\text{CO}$ were found to be about 1/3 the values found from the GHR data. Note that the column density of $^{12}\text{CO}$ is about 50 times smaller than the column density of stable C I ($^{3}\text{P}$).

5. DISCUSSION

Although CO in solar system comet comae is photodissociated by solar FUV photons, the CO in the $\beta$ Pictoris CS disk is primarily destroyed by interstellar photons. The dissociation energy for CO is $11.1 \text{ eV}$; thus CO may only be dissociated by photons with wavelengths shortward of $\sim 1100 \text{ Å}$. The type A5 star $\beta$ Pictoris lacks the strong FUV emission lines created in the Sun’s chromosphere; thus it emits very little flux in the FUV. The only source for CO-dissociating photons at $\beta$ Pictoris is therefore the interstellar UV radiation field. Since CO photodissociates primarily through discrete line absorptions, self-shielding can have a strong effect on the abundance of CO in interstellar clouds (Van Dishoeck & Black 1988). However, this is unlikely to occur in the $\beta$ Pictoris CS disk because of the very small transverse dimension of the disk. Thus, the photodissociation rate for $^{12}\text{CO}$ in the $\beta$ Pictoris disk should be equal to the unshielded value and should also be equal to the value for $^{13}\text{CO}$. Since $^{13}\text{CO}$ is not selectively dissociated in this situation, its high abundance was explained by the reaction

$^{13}\text{C}^+ + ^{12}\text{CO} \rightarrow ^{13}\text{CO} + ^{12}\text{C}^+ + 35 \text{ K}$

which favors the production of $^{13}\text{CO}$ at gas kinetic temperatures below 35 K (Jolly et al. 1998). Assuming chemical equilibrium and that isotopic exchange is much more important than photodissociation for both $^{12}\text{CO}$ and $^{13}\text{CO}$ (Sheffer et al. 1992),

$$\frac{n(^{12}\text{CO})}{n(^{13}\text{CO})} = \exp \left( \frac{-35}{T_{\text{kin}}} \right) \left( \frac{^{12}\text{C}}{^{13}\text{C}} \right) = 15 \pm 2.$$ 

The rotational excitation temperature of CO often does not accurately describe the gas kinetic temperature in diffuse environments (Wannier, Penprase, & Andersson 1997). However, assuming a ($^{12}\text{C}/^{13}\text{C}$) ratio, we may use the above expression to estimate the true gas kinetic temperature of the CO.

The average volume density of C, $n(^{12}\text{C}) = N(^{3}\text{P})/r \approx 20 \text{ cm}^{-3}$, assuming that the carbon extends over a distance $r = 100 \text{ AU}$. Further assuming that $n(^{12}\text{C}^+) \geq n(^{12}\text{C})$, as is likely, the right hand side of the above expression is greater than or equal to about $2 \times 10^{-9} \text{ s}^{-1}$, an order of magnitude larger than $\Gamma$. However, a more complete treatment of the relationship between $^{12}\text{CO}/^{13}\text{CO}$ and $^{12}\text{C}/^{13}\text{C}$ takes into account photodissociation but requires exact knowledge of the density of $^{12}\text{C}^+$ in the CS disk (Sheffer et al. 1992).

The much larger column density of C I ($^{3}\text{P}$) compared to that of CO leads us to believe that photodissociation of CO cannot be the only source of stable C I in the $\beta$ Pictoris CS disk. Since there is no evidence that CO is produced by infalling comets (no variability or red and blueshifted features), it has been postulated that the CO gas slowly evaporates from the OEBs at several tens of AU from the star and is photodissociated to produce the stable C I (Lecavelier des Etangs 1998). Obviously, some portion of the C I gas must be produced directly from the FEBs (the portion giving rise to the variable red and blueshifted absorption); perhaps this C I gas is decelerated somehow and accumulates in the stable component before being destroyed by photoionization. In this scenario, the equilibrium column density of C I is

$$N(^{3}\text{P}) = \frac{n \times N_{\text{FEB}}}{\Gamma},$$

where $n$ is the mean number of infalling comets per year, $\sim 10^2$ per year (Vidal-Madjar, Lecavelier des Etangs, & Ferlet 1998), $N_{\text{FEB}}$ is the total column density of C I gas produced by an infalling comet, and $\Gamma$ is the photoionization rate for C I, 0.004 yr$^{-1}$. This expression, which assumes that C I atoms are lost only through photoionization by interstellar UV photons, gives $N_{\text{FEB}} \sim 10^{11}$ cm$^{-2}$, which should easily be produced by infalling comets like the ones giving rise to the variable C I ($^{3}\text{P}$) components in our data. However, this is a rough treatment and the number of infalling comets per year varies significantly over time scales of a few years (Vidal-Madjar, Lecavelier des Etangs, & Ferlet 1998). Also, this treatment does not take into account reformation of C I by radiative recombination; we cannot take this process into account properly without knowledge of the amount of C II in the CS disk and the electron density.

Considering the C II ($^{1}\text{P}$), when such atoms are produced by photodissociation of CO, O I ($^{1}\text{D}$) atoms must be produced also to conserve spin. The minimum total photon energy needed for this dissociation is $14.33\text{ eV}$, corresponding to a threshold wavelength of 865 Å. Since this threshold is below the Lyman limit, there are virtually no interstellar UV photons capable of producing C I ($^{1}\text{D}$) by photodissociation of CO. Thus, the C II ($^{1}\text{D}$) atoms in the $\beta$ Pictoris CS disk cannot be produced by photodissociation of CO by stellar or interstellar photons and must be produced by a collisional process involving ground state carbon atoms. Since the energy of the $^{1}\text{D}$ state relative to the ground state is high, the collisional process must be a very energetic one and therefore is likely to be closely
CO and C I in the β Pictoris CS disk

associated with the infalling bodies. Consequently, with a short C I(1D) lifetime, there would be no stable component in this gas; this behavior has not been previously seen in any constituent of the β Pictoris CS disk. But this result is tentative; examination of an unsaturated line at high resolution is needed to determine the velocity structure of the C I(1D) gas.

6. CONCLUDING REMARKS

The very high resolution, low scattered light contamination, and good order separation of this STIS echelle data set has provided some clear advantages over previous observations of β Pictoris. The rotational lines of CO have been resolved, allowing for a much more precise determination of the physical parameters of the gas. The column density of CO is \( N(\text{CO}) = (6.3 \pm 0.3) \times 10^{14} \text{ cm}^{-2} \) and the ratio \( R(\text{^{12}CO}/\text{^{13}CO}) = 15 \pm 2 \) is found. The absence of transient red or blueshifted components in the high resolution CO spectra supports the suggestion that this gas evaporates from cometary bodies orbiting far (several tens of AU) from the star. But the fact that the column density of CO is only about 2% of the total column density of C I in the \(^3\text{P}\) ground term implies that photodissociation of this CO is not the primary source for C I gas. It could perhaps be produced directly from infalling comets close to the star, but the mechanism by which it comes to zero velocity relative to the star and accumulates before being photoionized is unclear (although see Lagrange et al. (1998)). The C I(1D) gas may not have a stable component at 20 km s\(^{-1}\); this unique species could prove to be a valuable tracer of FEB activity in the β Pictoris CS disk.

Despite the advantages of this data set, our lack of success in modeling the heavily saturated C I multiplets indicates that in order to really determine the characteristics of the variable components of the C I gas, we need to observe an unsaturated line or multiplet, with an oscillator strength between that of the 1561 Å multiplet and that of the spin-forbidden 1613.376 Å line. A number of suitable multiplets and lines lie in the FUV, shortward of ~1300 Å. Also, an unsaturated line arising from the \(^1\text{D}\) level would allow us to confirm the velocity structure in this gas and to determine if the velocities of the \(^1\text{D}\) gas components correspond with any of the velocities of the variable components in the \(^3\text{P}\) gas. Three likely lines lie between 1311 Å and 1359 Å. Measurement of the densities of C II and O I would greatly help to unravel the carbon chemistry of the β Pictoris disk. Again, potentially useful multiplets of these species lie in the FUV below 1340 Å. Thus, although this data set has vastly increased our knowledge about the important species C I and CO in the β Pictoris disk, our understanding would probably benefit greatly from investigation of β Pictoris at shorter ultraviolet wavelengths.

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CONCLUDING REMARKS
| Observation ID # | Grating | Slit (arcsec) | Spectral Range (Å) | Start Time (UT) | Exposure Time (s) |
|-----------------|---------|---------------|-------------------|----------------|------------------|
| 1997 Dec 6      |         |               |                   |                |                  |
| o4g001010       | E140H   | 0.2 × 0.09    | 1461 – 1663       | 07:17:58       | 900.0            |
| o4g001020       | E230H   | 0.1 × 0.03    | 1874 – 2146       | 07:40:26       | 80.0             |
| o4g001030       | E230H   | 0.1 × 0.09    | 1624 – 1896       | 07:48:20       | 678.8            |
| o4g001040       | E230H   | 31 × 0.05     | 2624 – 2895       | 08:48:28       | 360.0            |
| o4g001050       | E230H   | 31 × 0.05     | 2374 – 2646       | 09:02:20       | 360.0            |
| o4g001060       | E230H   | 31 × 0.05     | 2124 – 2396       | 09:16:12       | 288.0            |
| 1997 Dec 19     |         |               |                   |                |                  |
| o4g002010       | E140H   | 0.2 × 0.09    | 1461 – 1663       | 19:51:29       | 900.0            |
| o4g002020       | E230H   | 0.1 × 0.03    | 1874 – 2146       | 20:13:57       | 80.0             |
| o4g002030       | E230H   | 0.1 × 0.09    | 1624 – 1896       | 20:21:51       | 678.8            |
| o4g002040       | E230H   | 31 × 0.05     | 2624 – 2895       | 21:25:45       | 360.0            |
| o4g002050       | E230H   | 31 × 0.05     | 2374 – 2646       | 21:39:37       | 360.0            |
| o4g002060       | E230H   | 31 × 0.05     | 2124 – 2396       | 21:53:29       | 288.0            |
Table 2
Results of Modeling

|                      | Velocity \( v \) (km s\(^{-1} \)) | Column density \( N \) (cm\(^{-2} \)) | Doppler broadening parameter \( b \) (km s\(^{-1} \)) | Temperature \( T \) (K) |
|----------------------|------------------------------------|---------------------------------------|---------------------------------------------------|--------------------------|
| **Stable C I\(^{3}P_0\)** | 20 ± 1                             | \((6 ± 1) \times 10^{15}\)            | 1.3 ± 0.5                                         | · · ·                     |
| **C I\(^{3}P\)**     |                                    |                                       |                                                   |                          |
| December 6           | 20 ± 1                             | \((2 - 4) \times 10^{16}\)            | 1.3 ± 0.5                                         | 50 – 100                 |
|                      | 26                                 | \(10^{14}\)                           | 4                                                 | 10^2                     |
|                      | 41                                 | \(10^{14}\)                           | 10                                                | 10^3                     |
|                      | 57                                 | \(10^{13}\)                           | 12                                                | 10^3                     |
| December 19          | 11                                 | \(10^{13}\)                           | 5                                                 | 10^1                     |
|                      | 20 ± 1                             | \((2 - 4) \times 10^{16}\)            | 1.3 ± 0.5                                         | 50 – 100                 |
|                      | 27                                 | \(10^{15}\)                           | 5                                                 | 10^2                     |
| **C I\(^{1}D\)**     |                                    |                                       |                                                   |                          |
| December 6\(^a\)     | 23 ± 1                             | \((4 ± 3) \times 10^{13}\)            | \((4 ± 1)\)                                       | · · ·                     |
|                      | 49 ± 2                             | \((4 ± 2) \times 10^{12}\)            | \((4 ± 2)\)                                       | · · ·                     |
| December 6\(^b\)     | 22                                 | \(4 \times 10^{13}\)                 | 2                                                 | · · ·                     |
|                      | 28                                 | \(8 \times 10^{12}\)                 | 3                                                 | · · ·                     |
|                      | 48                                 | \(6 \times 10^{12}\)                 | 3                                                 | · · ·                     |
| December 19\(^a\)    | 26 ± 1                             | \((1.2 ± 0.7) \times 10^{14}\)       | 4.4 ± 0.8                                         | · · ·                     |
| December 19\(^b\)    | 23                                 | \(4 \times 10^{13}\)                 | 2                                                 | · · ·                     |
|                      | 29                                 | \(3 \times 10^{13}\)                 | 3                                                 | · · ·                     |
| **\(^{12}\)CO**      |                                    |                                       |                                                   |                          |
|                      | 20 ± 1                             | \((6.3 ± 0.3) \times 10^{14}\)       | 1.3 ± 0.1                                         | 15.8 ± 0.6               |
| **\(^{13}\)CO**      |                                    |                                       |                                                   |                          |
|                      | 20 ± 1                             | \((4.3 ± 0.4) \times 10^{13}\)       | 1.3 ± 0.1                                         | 15.8 ± 0.6               |

\(^a\)Results from \(\chi^2\) minimizations using model with one velocity component in the central absorption features

\(^b\)Results from chi-by-eye using model with two velocity components in the central absorption features.
Fig. 1.— The C II λ1613.376 line, with both days of data averaged together. Positions of the two other non-detected fine structure lines in the multiplet are indicated as well. The spectrum has not been rebinned or smoothed.
The C I λ1561 multiplet, with both days of data shown. The data have not been rebinned or smoothed. The continua around the features were fit with sixth-degree polynomials and the best fitting models based on the C I(3P) parameters in Table 2 are shown overplotted on the data.
Fig. 3.— The C I λ1657 multiplet, with both days of data shown. The data have not been rebinned or smoothed. The continua around the features were fit with sixth-degree polynomials and the best fitting models based on the C I(^3P) parameters in Table 2 are shown overplotted on the data.
Fig. 4.— The C I λ1931 line, with both days of data shown. The data have not been rebinned or smoothed. Heliocentric velocity appears on the upper x-axis. The continua around the features were fit with fourth-degree polynomials and the best fitting models based on the C I(1D) parameters in Table 2 are shown overplotted on the data.
Fig. 5.— The C I λ1463 line, with both days of data shown. The data have not been rebinned or smoothed. Heliocentric velocity appears on the upper x-axis. The continua around the features were fit with fourth-degree polynomials and the best-fitting models based on the C I(1D) parameters in Table 2 are shown overplotted on the data.
Fig. 6.—The CO $A-X$ (0–0), (1–0), and (2–0) bands, with both days of data averaged together. The data have not been rebinned or smoothed. The total model based on the CO parameters in Table 2 is overplotted as a dashed line; the contribution from $^{13}$CO alone is overplotted as a solid line.