

FUSE MEASUREMENTS OF RYDBERG BANDS OF INTERSTELLAR CO BETWEEN 925 AND 1150 Å¹

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Received 2003 August 13; accepted 2003 September 11; published 2003 October 13

ABSTRACT

We report the detection of 11 Rydberg bands of CO in *FUSE* spectra of the sight line toward HD 203374A. Eight of these electronic bands are seen in the interstellar medium for the first time. Our simultaneous fit of five non-Rydberg *A–X* bands together with the strongest Rydberg band of CO, *C–X* (0–0), yields a four-component cloud structure toward the stellar target. With this model we synthesize the other Rydberg bands in order to derive their oscillator strengths. We find that the strength of some bands was underestimated in previously published results from laboratory measurements. The implication is important for theoretical calculations of the abundance of interstellar CO, because its dissociation and self-shielding depend on oscillator strengths for these bands.

Subject headings: ISM: abundances — ISM: molecules — molecular data — stars: individual (HD 203374A) — ultraviolet: ISM

1. INTRODUCTION

The second most abundant molecule in interstellar clouds, CO, has a rich and long observational history in the radio, near-infrared, and far-ultraviolet (FUV) regimes. This sequence of spectral windows provides a view of pure-rotational and rotational-vibrational transitions among ground-state ($X^1\Sigma^+$) levels and of electronic transitions between the *X* state and the first excited singlet state, *A* $^1\Pi$ (Morton & Noreau 1994). Deeper into the FUV, additional prominent dipole-allowed bands of CO appear, involving the Rydberg states *B* $^1\Sigma^+$, *C* $^1\Sigma^+$, and *E* $^1\Pi$. The first astronomical observations of the *C–X* (0–0) band at 1088 Å, which has the largest band oscillator strength ($f_{00} = 0.123$) according to Federman et al. (2001, hereafter F01), and of the *E–X* (0–0) band at 1076 Å were conducted with the *Copernicus* satellite with a spectral resolution (R) of 20,000 (Jenkins et al. 1973). Later, Morton (1975) also reported *Copernicus* data on the *B–X* (0–0) band at 1150 Å. This band is the only dipole-allowed band other than the *A–X* bands that has been fully resolved into individual rotational lines—see the Goddard High Resolution Spectrograph spectrum from the *Hubble Space Telescope* (*HST*) in Figure 5 of Sheffer et al. (1992). Another UV space mission following *Copernicus* that detected the *C–X* (0–0) band was the *Orbiting and Retrievable Far and Extreme Ultraviolet Spectrometer* (*ORFEUS*), albeit at the more modest resolution of $R = 3000$ (Lee et al. 2002).

In 1999, *FUSE* was launched, covering the spectral range of 905–1187 Å at the same resolution as that of *Copernicus* (Moos et al. 2000; Sahnou et al. 2000). In addition to covering the *B–X*, *C–X*, and *E–X* bands, *FUSE* should be able to detect a significant number of bluer Rydberg bands below 1075 Å. These are the signatures of high-lying states of CO that converge onto electronic states in CO^+ . The Rydberg states have an important role in the photodissociation of CO, which occurs via line absorption of FUV photons from the ground state, followed by predissociation into atomic C and O. Letzelter et al. (1987) mapped 46 bands between 885 and 1099 Å, i.e., to

the blue of the *B–X* (0–0) and (1–0) bands. Of these, 43 bands are predissociating, a fact that enabled Viala et al. (1988) to revise the rate of CO photodissociation upward by a factor of 20. Not only was CO found to be more readily destroyed when exposed to the UV field, but the nature of line absorption leads to strong self-shielding of this molecule as its column density increases into a molecular cloud (van Dishoeck & Black 1988; Warin, Benayoun, & Viala 1996). Self-shielding limits the effectiveness of photodissociation. Therefore, any revisions to f -values for the Rydberg bands are an important input for theoretical models of the interstellar CO abundance.

These bands have been studied in the laboratory. Line lists and band constants were presented by Eidelsberg & Rostas (1990) and Eidelsberg et al. (1991 [hereafter E91], 1992). Unfortunately, it seems that optical depth effects hindered reliable measurements of f -values for many of these bands, which are invariably strong. Later investigations at high resolution and low temperature (20 K) were reported by Stark, Yoshino, and collaborators (Yoshino et al. 1995, and references therein). In a recent study F01 measured laboratory f -values for five bands involving the B, C, and E states and found that the f -values were larger than those in E91 by factors of between 1.08 (a negligible difference) and 1.99 (a significant one). Clearly, there is a need to extend the reevaluations to other Rydberg bands. *FUSE* spectra turn out to be complementary to the laboratory measurements, since they allow internally self-consistent f -values to be extracted from interstellar CO bands. Here we present the interstellar results for CO toward HD 203374A, including eight Rydberg bands that are detected in the interstellar medium (ISM) for the first time.

2. OBSERVATIONS AND ANALYSIS

FUSE observations of HD 203374A were obtained on 2001 August 2, as part of the *FUSE* Guest Investigator program B030. The target, which is a member of the Cep OB2 Association, is a B0 IV star with a reddening of $E_{B-V} = 0.6$ mag. Thirty-four subexposures were secured in the HIST (spectral image) mode, totaling 18,653 s. All subexposures were co-added and calibrated using the CalFUSE software (ver. 2.4). The data were then rebinned by a factor of 4 to yield 2 pixels per nominal resolution element (0.05 Å). The binned pixels are of higher signal-to-noise ratio (S/N) thanks to the large number of subexposures, which effectively diluted the fixed pattern noise of *FUSE*. Scattered light was successfully corrected in

¹ Based on observations made with the NASA-CNES-CSA *Far Ultraviolet Spectroscopic Explorer* (*FUSE*), which is operated for NASA by the Johns Hopkins University under NASA contract NAS5-32985.

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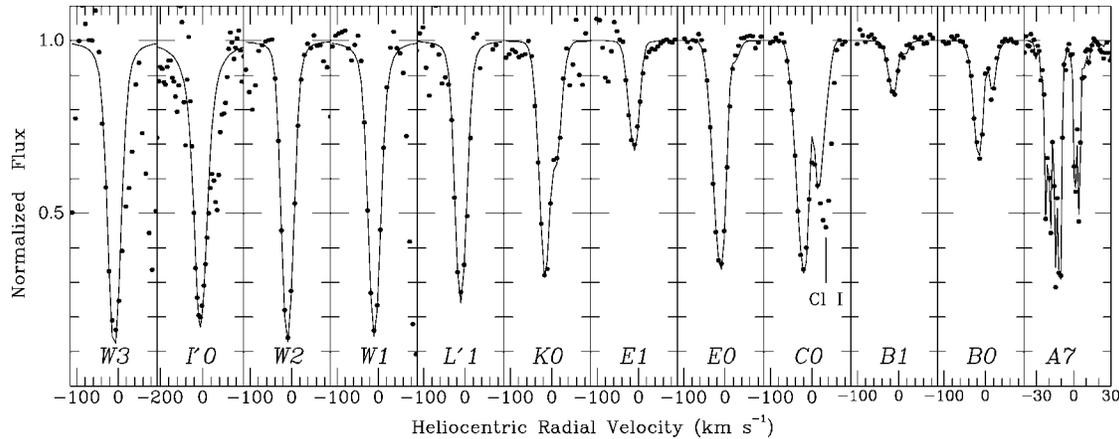


FIG. 1.—Montage of 11 Rydberg bands of CO from *FUSE*, together with a sample fourth positive band, *A-X* (7–0), from *HST*, toward HD 203374A. Band notation has been shortened by deleting the ground state. The sequence of bands follows their wavelength order, with redder bands to the right. The heliocentric radial velocity for the *R*(0) line of all bands has been adopted from the STIS spectra, owing to the uncalibrated *FUSE* radial velocity scale. The scale is expanded for *A7* and is reduced for the broad *I0* band.

the CalFUSE processing, with the opaque flat cores of H_2 lines found to be well below the 1% normalized flux level. Most of the *FUSE* spectral range is covered by two (sometimes three) independent detector segments, except for the 1017–1075 Å region, where four segments are available. Each of the CO bands was modeled in each individual segment, as well as in the final co-added spectrum from all available segments. The spectral resolution varies between detectors: $R = 15,000$ for bands in the SiC channels and 19,000 in the LiF ones. The only band with equal contributions from both types, *E-X* (1–0), was modeled with $R = 17,000$. The final co-added spectra that became input for our synthesis code, ISMOD, have a S/N ratio of 80–100 per pixel. ISMOD fits each rotational line with a Voigt profile whose Gaussian component is based on the Doppler broadening parameter and whose Lorentzian part is controlled by the inverse lifetime as determined by radiative decay and predissociation. Upper level lifetimes, which were treated as fixed input, were gathered from E91, Morton & Noreau (1994), Ubachs et al. (1994), and Cacciani et al. (1998). The code then minimizes the rms residuals between the data and a model that incorporates freely varying parameters, using shrinking step sizes down to 10^{-4} of a parameter's value. Although ISMOD was first used to synthesize CO bands in *HST* spectra, we recently modified it to synthesize H_2 bands seen by *FUSE*. This new derivative of ISMOD was essential for the initial step of dividing out the H_2 lines before the blended CO bands could be recovered and then modeled successfully.

3. RESULTS

As a prelude to CO analysis, a model of the H_2 gas toward HD 203374A was derived. It shows a total H_2 column density of $5.10(\pm 0.05) \times 10^{20} \text{ cm}^{-2}$ and a kinetic temperature (or $T_{1,0}$ of H_2) of $74.5 \pm 1.5 \text{ K}$. This model was varied by small steps to account for *FUSE* spectral changes in various wavelength regions and was then divided into CO spectral cuts as a means of deblending the Rydberg bands. Each CO band involves *R*, *P*, and for upper Π states *Q* transitions from four significantly populated rotational levels ($J'' \leq 3$) in the ground state. Bands that involve an upper Σ^+ state, e.g., *B-X* (1–0) and *K-X* (0–0), resemble a blended double absorption profile from their *P* and *R* branches (see Fig. 1). Those that involve

a Π state, such as *E-X* (1–0) and *W-X* (2–0), have a *Q* branch containing a pileup of lines between the *R* and *P* branches, and thus appear as a single feature. While *FUSE* spectra cannot resolve individual rotational lines, a splitting of each transition into four cloud components, as described below, is required to synthesize the bands in an adequate manner.

The derivation of *f*-values for optically thick CO bands requires that both the total CO column density, $N(\text{CO})$, and the cloud structure are known. Five high-resolution ($R = 140,000$ after $\times 2$ binning) spectral cuts from *HST*/STIS data toward HD 203374A were kindly supplied to us by E. Jenkins. These include five consecutive *A-X* bands of CO, from (7–0) at 1344 Å to (11–0) at 1263 Å, for which accurately known *f*-values are available (Chan, Cooper, & Brion 1993; Lambert et al. 1994). Although the weaker bands are adequate for $N(\text{CO})$ derivations, we also incorporated the strong *C-X* (0–0) band from our *FUSE* data as a calibrator of this analysis. Such a strong band is especially sensitive to variables that control the optical depth, i.e., the position, fraction, and width of individual clouds, as well as the excitation temperature (T_{ex}) of ground rotational levels. Together with the *C-X* (0–0) band, the run of bands covers a range of 2.8 orders of magnitude in *f*-value, thereby being able to accommodate any other FUV band as part of a robust model fit. Note that *C-X* (0–0) is a bit problematic, owing to a blending of its *P* branch with the strong interstellar line of Cl I at 1088.06 Å (Federman 1986). However, the important benefit of using this band was realized by limiting model fitting to its *R* branch.

Our synthesis was based on the four-component cloud structure seen in high-resolution ($R = 200,000$) CH spectra at visible wavelengths (Pan et al. 2003). The structure was kept fixed during H_2 synthesis but was allowed to vary for the high-resolution CO fits. The resulting relative velocity (in km s^{-1}), fractional strength, and Doppler width [*b*-value = $\Delta v(\text{FWHM})/1.665$, in km s^{-1}] are (0.0, 0.44, 0.77), (–3.6, 0.51, 0.54), (–7.3, 0.02, 0.59), and (–11.4, 0.03, 0.54). Jointly, these four components give a total $N(\text{CO})$ of $2.41(\pm 0.24) \times 10^{15} \text{ cm}^{-2}$ in front of HD 203374A. The fitted equivalent widths (W_λ) for the *A-X* (7–0) to (11–0) bands are 50.9 ± 0.8 , 36.3 ± 0.5 , 22.6 ± 0.6 , 11.7 ± 0.5 , and $5.6 \pm 0.7 \text{ mÅ}$, respectively. The W_λ for the *C-X* (0–0) band is $139 \pm 13 \text{ mÅ}$.

TABLE 1
COMPARISON OF RYDBERG BAND f -VALUE MEASUREMENTS

Parameter/Band	B1	E1	K0	L'1	W1	W2	I'0	W3
$\lambda_0[R(0)]$ (Å)	1123.57	1051.67	970.33	968.85	956.22	941.15	940.17	925.79
$FUSE W_\lambda$ (mÅ)	19 ± 2	37 ± 6	104 ± 4	95 ± 4	117 ± 5	109 ± 7	259 ± 13	125 ± 5
f -values ($\times 10^{-3}$) ^a :								
E91	0.72 ± 0.07	2.5 ± 0.3	21.0 ± 2.1	12.4 ± 1.2 ^b	13.5 ± 1.4	25.8 ± 2.6	21.3 ± 2.1	16.3 ± 1.6
S91, S92, S93 .....	...	3.0 ± 0.3	26.8 ± 3.8 ^c	7.5 ± 0.8 ^c	14.8 ± 1.5	30.0 ± 3.0	23.6 ± 2.4	14.9 ± 1.5
C93	1.32 ± 0.13	3.53 ± 0.35	...	...	...	...	...	...
Y95 .....	...	...	33.5 ± 5.0 ^c	...	...	20.4 ± 3.1 ^c	...	17.0 ± 2.6 ^c
Z97 .....	...	4.67 ± 0.66	...	...	...	...	...	...
S99	1.1 ± 0.1	...	...	...	...	...	...	...
F01	0.80 ± 0.12	...	...	...	...	...	...	...
HD 203374A	1.06 ± 0.11	3.3 ± 1.1	31 ± 4	10.1 ± 1.1	15.8 ± 2.0	23 ± 5	22.6 ± 2.9	19.8 ± 2.4
ISM/lab ^d	1.47 ± 0.21	1.32 ± 0.46	1.48 ± 0.24	0.81 ± 0.12	1.07 ± 0.17	0.88 ± 0.21	1.06 ± 0.17	1.21 ± 0.19

NOTE.—Band notation has been shortened by deleting the ground state.

^a References: (E91) Eidelsberg et al. 1991; (S91, S92, S93) Stark et al. 1991, 1992, 1993; (C93) Chan et al. 1993; (Y95) Yoshino et al. 1995; (Z97) Zhong et al. 1997; (S99) Stark et al. 1999; (F01) Federman et al. 2001; (HD 203374A) this Letter.

^b Contamination from $L0$ suspected; see text.

^c Laboratory measurement at 20 K.

^d The f -value ratio of this Letter to Eidelsberg et al. 1991.

Modeled values of T_{ex} are 3.2, 3.5, and 5.0 K for the first three rotational levels, relative to $J'' = 0$. As is the case along previously studied lines of sight, CO-bearing cloud components have the narrowest line widths among either atomic or molecular species, as well as some of the lowest T_{ex} values. At first glance it would seem that the last two components, which have fractional strengths of $\leq 3\%$, are too weak to be of significance in the fit. However, for bands with large f -values, the strongest components are very optically thick, allowing the weaker components to determine band profile shapes.

Following the simultaneous fit of the six bands, we refitted each of them separately in order to gauge the associated uncertainties. Using the newly derived cloud structure and T_{ex} , individual $N(\text{CO})$ values were up to 11% away from their average. Therefore, $N(\text{CO})$ toward HD 203347A is uncertain by $\sim 10\%$. Additional testing is available through comparison of three other bands studied by F01. $B-X$ (0–0) has fitted $W_\lambda = 50 \pm 3$ mÅ and f -value = $5.7(\pm 0.9) \times 10^{-3}$, and $E-X$ (0–0) has fitted values of 97 ± 2 mÅ and $63(\pm 7) \times 10^{-3}$, respectively. The values for $B-X$ (1–0), which is a first ISM detection, are presented in Table 1. The corresponding deviations from the f -values of F01 are -15% , -8% , and $+33\%$, respectively, thus averaging about $\pm 2 \sigma$ relative to our uncertainty for $N(\text{CO})$. With uncertainties of 10% for the $A-X$ bands (Chan et al. 1993) and 13% for $C-X$ (0–0) (F01), the absolute 1σ uncertainties on our f -values are close to 15%.

Seven additional Rydberg bands farther into the FUV, which were not studied by F01, are seen in our $FUSE$ spectra (see Fig. 1 and Table 1). Of these, $K-X$ (0–0), $W-X$ (1–0), and $W-X$ (2–0) are least affected by blending with H_2 lines. Indeed, these three bands have appreciable contributions to the photodissociation rate of interstellar CO, as can be seen in Table 2 of van Dishoeck & Black (1988). Since $N(\text{CO})$ is now known, self-consistent f -values for all $FUSE$ bands can be derived. Ratios of the interstellar f -value to that of E91 are 1.27 ± 0.24 and 1.75 ± 0.26 for $B-X$ (0–0) and $E-X$ (0–0), respectively. Together with the f -value ratios given in Table 1, eight bands out of 10 are stronger by factors of between 1.06 and 1.75 relative to E91, although most of these factors are smaller than their 1σ uncertainties. The three bands with the most significant factors are $E-X$ (0–0), $K-X$ (0–0), and $B-X$ (1–0), which have f -value ratios of 1.75 ± 0.26 (deviating by 2.9σ), 1.48 ± 0.24 (2.0σ), and 1.47 ± 0.21 (2.2σ), respectively. For

the weakest of these bands, $E-X$ (1–0), most determinations are consistent with an f -value of $\sim 3.5 \times 10^{-3}$.

The new interstellar band f -values confirm the conclusions of F01, namely, that the older f -values in E91 are too small for moderately strong to strong bands. However, the average correction for the bands to the blue of $E-X$ (0–0) is not as large as the one derived from the redder bands of F01, which was dominated by the strongest bands of CO, $C-X$ (0–0) and $E-X$ (0–0). Therefore, the trend of larger corrections for stronger bands from F01 is also confirmed. Rotational lines of Rydberg bands below ~ 1000 Å tend to have larger natural widths owing to level lifetimes that are predominantly shorter than $\sim 10^{-11}$ s, whereas above ~ 1000 Å longer lifetimes are encountered. The larger natural widths result in smaller optical depths at line centers, thus alleviating the line saturation more readily associated with redder bands of similar oscillator strength. This may explain why interstellar f -values agree better with synchrotron absorption results for bands below 970 Å.

There is one exception to this trend. The band $L'-X$ (1–0) has a ratio of 0.81 ± 0.12 (1.6σ) relative to Eidelsberg et al.'s (1991) result. As shown in Table 1, the 20 K result from Stark et al. (1993) is somewhat smaller than ours. Two earlier studies found that $L'-X$ (1–0) is weaker than $L-X$ (0–0), a band only 0.6 Å to the blue of $L'-X$ (1–0), and blended with it at room temperature (Letzelter et al. 1987; Stark et al. 1991). The roles are reversed in E91, with $L'-X$ (1–0) being the stronger band, thus prompting us to suspect some contamination from $L-X$ (0–0). Note that the continuum under this interstellar band had to be corrected by 10% owing to unidentified (probably stellar) absorption. Without this correction, the f -value would be 1.16 ± 0.16 relative to E91.

The band $I'-X$ (0–0) is a special case. Initial inspection showed that only a weak feature in the $FUSE$ spectra coincided with the E91 position of the band, while a much larger feature to the blue could not be identified. In the laboratory, this band is very diffuse and shows at least three intensity peaks in its room-temperature profile (Stark et al. 1991, their Fig. 1). Such a structure is in conflict with the E91 tabulation that provides two branches (R and P) and the assignment $\Sigma^+ - \Sigma^+$ for this band. We suspected that $I'-X$ (0–0) suffers from strong perturbations or that it may be blended with another, hitherto unaccounted for, CO band. A laboratory spectrum acquired at 80 K (M. Eidelsberg 2003, private communication) more clearly

defines the *R* and *P* branches of *I'*-*X* (0-0), leading to a shift of -0.243 \AA in line positions relative to E91. Since this shift leads to excellent agreement with the larger feature in the *FUSE* spectra, we adopted this shift in our synthesis of the band, yielding the *f*-value given in Table 1. The agreement with laboratory results is excellent. This is the only case in which we did allow the natural width of the lines to vary, owing to the extremely diffuse nature of the band. Our fit of its wings resulted in a lifetime change from 10^{-12} s (E91) to $4.2(\pm 0.8) \times 10^{-13} \text{ s}$. For a complementary confirmation it would be highly desirable to obtain a new laboratory recording of this region at a very low T_{ex} .

4. CONCLUDING REMARKS

In this Letter we showed that *FUSE* spectra can be used to measure the Rydberg bands of CO by isolating them from the strong presence of H_2 . Indeed, the bands not totally obscured are precisely those that play the major role in CO photodissociation. Thus observations via *FUSE* have a direct impact on detailed modeling of the CO distribution in the ISM. *FUSE* can be turned into a reliable estimator of CO abundance and conditions, provided that the number of velocity components is available from high-resolution ground-based spectra of CH or from *HST*/*STIS* data of CO itself, i.e., its *A*-*X* bands.

Most of the interstellar results confirm the larger *f*-values of relatively strong Rydberg bands of CO reported in recent laboratory studies (see F01). Interestingly, this is especially true for the *B*-*X* (0-0), *E*-*X* (0-0), and the first three bands in Table

1, but much less obvious for all bands below 970 \AA , the result of diminishing lifetimes for bluer bands. Overall, interstellar values show good agreement with laboratory *f*-values obtained at 20 K (Stark et al. 1993; Yoshino et al. 1995) and with laser absorption spectroscopy at very high resolution (Stark et al. 1999). Otherwise, room-temperature spectroscopy suffers from serious blending of bands, especially below $\sim 1000 \text{ \AA}$.

In an earlier Letter (Sheffer, Lambert, & Federman 2002) we showed that the older theoretical models of van Dishoeck & Black (1988) and Warin et al. (1996) reproduced either the observed isotopomeric ratios or the observed column densities of four CO isotopomers, but a given model could not reproduce both quantities. The new results from CO toward HD 203374A and the recent laboratory determinations of band *f*-values provide evidence that CO is more resilient to destruction by enhanced self-shielding because larger *f*-values cause higher optical depths for individual lines. Theoretical models of molecular clouds that explore kinematic aspects of the CO photodissociation rate, e.g., Röllig, Hegmann, & Kegel (2002), will also be affected. The new *f*-values of Rydberg bands in the FUV should be incorporated into the next generation of models to yield improved predictions of CO abundance.

We thank NASA for grants NAG5-8961, NAG5-10305, and NAG5-11440. We are grateful to Dr. E. Jenkins for sharing *STIS* data, to Dr. M. Eidelsberg for an update of the laboratory view of *I'*0, to Dr. K. Pan for providing us with the cloud structure from CH spectra, and to an anonymous referee for helpful comments.

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