

**HIGH-RESOLUTION OSCILLATOR STRENGTH MEASUREMENTS OF THE  $v' = 0,1$  BANDS OF THE B – X, C – X, AND E – X SYSTEMS IN FIVE ISOTOPOLOGUES OF CARBON MONOXIDE.** G. Stark<sup>1</sup>, A. N. Heays<sup>2</sup>, J. R. Lyons<sup>3</sup>, P. L. Smith<sup>4</sup>, M. Eidelsberg<sup>5</sup>, S. R. Federman<sup>6</sup>, J. L. Lemaire<sup>7</sup>, L. Gavilan<sup>7</sup>, N. de Oliveira<sup>8</sup>, D. Joyeux<sup>8</sup>, and L. Nahon<sup>8</sup>, <sup>1</sup>Department of Physics, Wellesley College, Wellesley, MA 02481, USA; [gstark@wellesley.edu](mailto:gstark@wellesley.edu), <sup>2</sup>Leiden Observatory, Leiden University, P. O. Box 9513, 2300 RA Leiden, The Netherlands, <sup>3</sup>School of Earth and Space Exploration, Arizona State University, 781 S. Terrace Rd, Tempe, AZ 85281, USA, <sup>4</sup>93 Pleasant Street, Watertown, MA 02472, USA, <sup>5</sup>Observatoire de Paris, 5 place Jules Janssen, 92195 Meudon, France, <sup>6</sup>Department of Physics and Astronomy, University of Toledo, Toledo, OH 43606, USA, <sup>7</sup>LAMAp/LERMA, Université de Cergy-Pointoise, 95031 Cergy-Pointoise, France, <sup>8</sup>Synchrotron SOLEIL, Orme de Merisiers, St. Aubin, BP 48, 91192 Gif sur Yvette Cedex, France.

**Introduction:** The primary destruction mechanism for interstellar and circumstellar CO and its isotopologues is photodissociation, which is entirely governed by discrete line absorption into predissociating levels in the wavelength range 91.2 to 111.8 nm. Because the CO spectrum consists primarily of resolved line features, self-shielding effects in high-column density environments [1,2,3] can lead to strong isotopic fractionation signatures in both CO and elemental O and C [4,5,6].

CO self-shielding in the solar nebula has been invoked [7,8,9] to explain the unusual oxygen isotope ratios observed in the earliest solar system condensates, *viz.* calcium-aluminum inclusions (CAIs) in primitive meteorites. Analysis of solar wind collected by the NASA Genesis mission [10] showed that the Sun has an oxygen isotope anomaly similar to that of the isotopically lightest CAIs, a result that is consistent with CO self-shielding in the early solar nebula or parent cloud. Astronomical observations of CO isotopologue ratios [3,5] although valuable, are of insufficient precision to quantitatively address the hypothesis that CO self-shielding is responsible for the oxygen isotope ratios seen in CAIs in primitive meteorites. A comprehensive database of line positions, oscillator strengths (*f*-values), and line widths for all relevant CO isotopologues is needed to assess this hypothesis and for the development of models of astrophysical environments.

**Measurements:** Measurements were carried out at the third-generation SOLEIL synchrotron facility in Saint Aubin, France. The vacuum ultraviolet Fourier transform spectrometer on the DESIRS beam line [11] was used to record unprecedented high-resolution spectra ( $0.32 \text{ cm}^{-1}$  and  $0.22 \text{ cm}^{-1}$ ) of the CO isotopologues in a windowless absorption cell. The broad and adjustable continuum bandpass of the DESIRS beamline allowed for the simultaneous recording of room-temperature absorption in *pairs* of CO bands, facilitating the determination of precise ratios of band strengths. We report line and band *f*-values for the six strong vibrational bands between 105.0 and 115.2 nm, associated with transitions from  $X(v''=0)$  to the  $v' = 0$

and 1 levels of the B  $^1\Sigma^+$ , C  $^1\Sigma^+$ , and E  $^1\Pi$  states, in five CO isotopologues. We compute revised dissociation branching ratios for the C( $v'=0,1$ ) and E( $v'=0,1$ ) levels based on these *f*-values.

For a subset of the spectra, absolute column densities were determined by measuring absorption in the B(0) band. The B(0)–X(0) *f*-value has been well-characterized [12,13], and was adopted as a calibration standard with a band *f*-value of 0.0065(5). Our most direct measures of isotopologue dependences in *f*-values come from the analyses of absorption spectra of mixed samples of CO isotopologues.

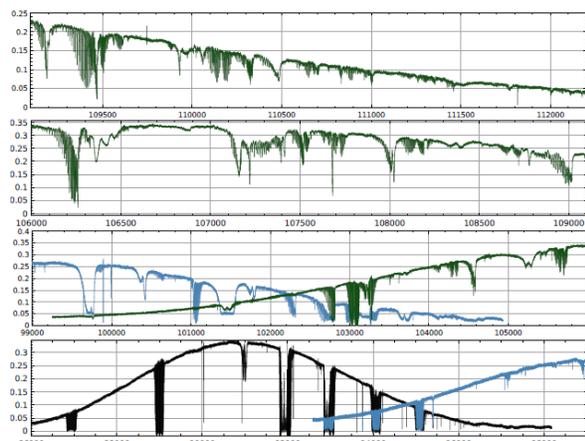
**Results:** The measurements reveal *J*-dependences in the branch intensities of the C( $v=0,1$ )–X(0) and E( $v=0,1$ )–X(0) bands in all isotopologues. The analyses of absorption in mixed gas samples of  $^{12}\text{C}^{16}\text{O}/^{12}\text{C}^{17}\text{O}$  and  $^{12}\text{C}^{16}\text{O}/^{12}\text{C}^{18}\text{O}$  show minimal or no isotopologue-dependence in the C( $v=0,1$ ) – X(0) and E( $v=0,1$ ) – X(0) band *f*-values at the ~5% uncertainty level see Table 1. The absence of measureable isotopologue-dependence in our band *f*-values is an important factor in establishing more reliable photodissociation branching ratios. The isotope dependence of the measured *f*-values (and inferred dissociation probabilities) is too small to account for the high  $\delta^{17}\text{O}/\delta^{18}\text{O}$  slopes (~1.4) measured by [14] in laboratory CO photolysis experiments at 105 (E(1) band) and 107 nm (E(0) band). Additionally, the very weak (to nonexistent) perturbations in the E(0) and E(1) bands also offer no plausible explanation for the measured slopes in [14]. Interpretation of their results is therefore problematic.

TABLE 1

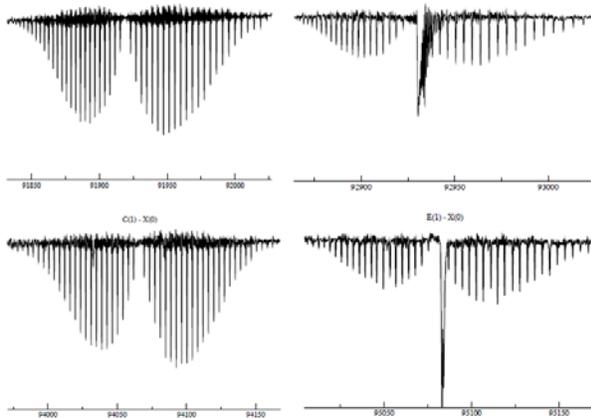
Measured ratios of isotopologue-specific <i>f</i> -values				
BAND:	C(0)	C(1)	E(0)	E(1)
$^{12}\text{C}^{17}\text{O}/^{12}\text{C}^{16}\text{O}$	1.00(4)	1.01(4)	1.01(4)	1.05(4)
$^{12}\text{C}^{18}\text{O}/^{12}\text{C}^{16}\text{O}$		1.01(4)	1.00(4)	

The work presented here is part of a larger effort to establish a reliable high-resolution database for CO isotopologue absorption features in the 91.2 to 111.8 nm region.

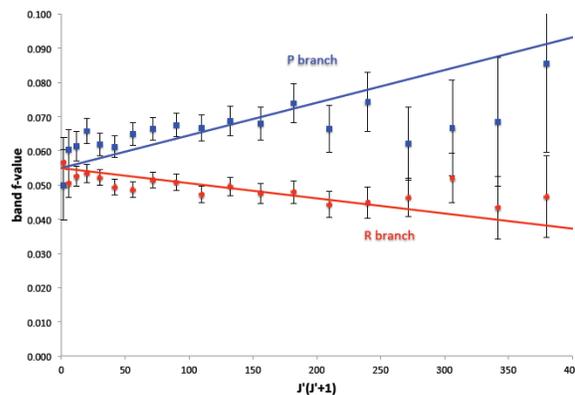
**References:** [1] Federman S. R. et al. (2003) ApJ, 591, 986. [2] Sheffer Y. et al. (2007) ApJ, 667, 1002. [3] Smith R. L. et al. (2009) ApJ, 701, 163. [4] Bally J. & Langer W. D. (1982) ApJ, 255, 143. [5] Sheffer Y. et al. (2002) ApJ, 574, L171. [6] Sonnentrucker P. et al. (2007) ApJS, 168, 58. [7] Clayton R. N. (2002) Nature, 415, 860. [8] Yurimoto H. & Kuramoto K. (2004) Science, 305, 1763. [9] Lyons J. R. & Young E. D. (2005) Nature, 435, 317. [10] McKeegan K. D. et al. (2011) Science, 332, 1528. [11] Nahon et al. (2012) J Synch Rad, 19, 508. [12] Stark et al. (1999) ApJ, 520, 732. [13] Federman S. R. (2001) ApJS, 134, 133. [14] Chakraborty et al. (2012) JCP, 137, 024309.



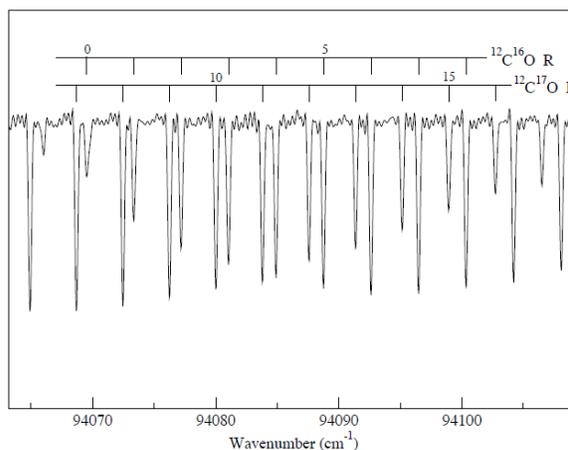
**Fig. 1** High-resolution absorption bands of  $^{12}\text{C}^{16}\text{O}$  taken on the DESIRS beamline at the SOLEIL synchrotron (units are relative intensity vs. wavenumber ( $\text{cm}^{-1}$ )). We focus here on bands in the 86000-92000  $\text{cm}^{-1}$  region.



**Fig. 2** Representative absorption spectra of C(0), C(1), E(0), and E(1) bands in  $^{12}\text{C}^{16}\text{O}$  recorded at a resolution of  $0.32 \text{ cm}^{-1}$ .



**Fig. 3**  $^{12}\text{C}^{16}\text{O}$  band  $f$ -values determined from measured  $P$ -branch (blue squares) and  $R$ -branch (red circles) rotational line  $f$ -values and Hönl-London factors. The  $J$ -dependences of the branch-specific  $f$ -values are represented by linear fits to  $J(J+1)$ .



**Fig. 4** Overlapping portion of the C(1) - X(0) bands in  $^{12}\text{C}^{17}\text{O}$  and  $^{12}\text{C}^{16}\text{O}$  recorded from the mixed  $^{12}\text{C}^{16}\text{O}/^{12}\text{C}^{17}\text{O}$  gas sample at a resolution of  $0.22 \text{ cm}^{-1}$ . Despite the overlapped bands, individual rotational lines in each isotopologue can be easily identified and analyzed.