CO AT OTHER WAVELENGTHS

JOHN H. BLACK
Steward Observatory
University of Arizona
Tucson, AZ 85721 USA

1. Introduction

Although carbon monoxide is most widely observed in interstellar and circumstellar matter through its pure rotational transitions at radio wavelengths, it can be observed in the ultraviolet and infrared regions of the spectrum, too. These observations complement the mm-wave data in important ways. Ultraviolet measurements probe photon-dominated regions where CO co-exists with C, C⁺, and O. Infrared absorption spectroscopy makes possible the direct measurement of the CO abundance both in solid and gaseous form where cold H₂ is now measurable as well. Ultraviolet absorption lines of CO and H₂ probe the amount of molecular gas in QSO absorbers at high redshift (z ≈ 2 – 4).

The first report of mm-wave line emission of interstellar CO (Wilson, Jefferts, & Penzias 1970) was followed rapidly by a detection in ultraviolet absorption toward ζ Oph (Smith & Stecher 1971), which also yielded an estimate of the $^{12}$CO/$^{13}$CO abundance ratio: 105. The initial measurements with rocket-borne spectrometers were supplanted by observations with the orbiting Copernicus (Spitzer & Jenkins 1975) and IUE instruments. Although Hubble Space Telescope (HST) has superior resolution and sensitivity in the ultraviolet, it is virtually blind at wavelengths between the H I Lyman limit (912 Å) and the threshold for absorption lines of ground-state H₂ (near 1110 Å); therefore, Copernicus remains the source of almost all direct measurements of molecular hydrogen in the same regions where CO is seen. Although CO has been observed in the photospheres of the Sun and other stars for a long time (Goldberg et al 1965, Kuiper 1962, Sinton 1962), interstellar studies in the infrared (2 – 4 μm) had to await improvements in the sensitivity and resolution of IR spectrometers (Kleinmann et al. 1978, Hall et al. 1978).
2. Interstellar Absorption Lines

Absorption line spectroscopy at infrared and ultraviolet wavelengths has several important advantages over mm-wave observations of CO. It is often possible to observe lines arising in a number of rotational levels simultaneously, with the same observing conditions. All measurements toward a common background continuum source usually refer to exactly the same absorbing column; therefore, the determination of relative abundances is rather straightforward. This is especially important where cold, interstellar H$_2$ can be observed directly. The strong electronic transitions at ultraviolet wavelengths are sensitive to small amounts of CO: e.g., limits on column density of $N$(CO) < $2 \times 10^{12}$ cm$^{-2}$ have been reached even for absorbers at high redshift, $z \approx 1.7 - 2.3$ (Levshakov et al. 1989). On the other hand, absorption-line measurements will always be fundamentally limited to regions where suitable background sources are available, whereas mm-wave emission-line observations have the advantage in determining the distribution of molecular gas. Because the extinction per unit column density of interstellar matter rises very steeply to shorter wavelengths, hot stars that lie behind chemically interesting amounts of interstellar matter are often too faint for high-resolution spectroscopy in the ultraviolet.

To compare the detectability of small amounts of cold, dilute CO by various techniques, consider a uniform cloud of H$_2$ density $n$(H$_2$) = 300 cm$^{-3}$ at a kinetic temperature $T_k = 15$ K with a CO linewidth of $\Delta V = 1.0$ km s$^{-1}$. When $N$(CO) = $1.75 \times 10^{14}$ cm$^{-2}$, the $J = 0$ and $J = 1$ rotational levels have fractional populations $X_0 = 0.541$ and $X_1 = 0.417$, respectively (i.e. the excitation temperature is $T_{01} = 4.07$ K). In the $J = 1 \rightarrow 0$ rotational transition, the line-center optical depth is $\tau = 0.10$ and the peak Rayleigh-Jeans brightness temperature is $T_R = 0.10$ K, in excess of the 2.726 K cosmic background radiation. Such a column density is detectable at mm wavelengths in emission, and in absorption toward a suitable background source (e.g. Hogerheijde et al. 1995). For high-resolution absorption-line spectroscopy, we can express the minimum detectable column density as

$$N_{\text{min}}$(CO) = $6.26 \times 10^{13} \frac{\lambda f}{R} \left( \frac{0.541}{X_0} \right) \left( \frac{10^5}{100} \right) (S/N) \text{ cm}^{-2}$$

where $\lambda$ is the wavelength in Å, $f$ is the oscillator strength, and $R = \lambda/\delta \lambda$ is the resolving power. The rms signal-to-noise ratio is $S/N$, and the detection level is set at 3 rms. For the indicated scalings, $N_{\text{min}}$(CO) = $1.1 \times 10^{14}$ cm$^{-2}$ for the (1,0) R(0) vibration-rotation line at $\lambda = 46575$ Å ($f = 1.2 \times 10^{-5}$), and $1.1 \times 10^{12}$ cm$^{-2}$ for the A$^1\Pi$-X$^1\Sigma^+$ (2,0) R(0) line at 1477 Å ($f = 0.04$).