CO AT OTHER WAVELENGTHS

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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 H_2 is now measurable as well. Ultraviolet absorption lines of CO and H_2 probe the amount of molecular gas in QSO absorbers at high redshift ($z \approx 2 - 4$).

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 H_2 (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 $N(\mathrm{CO}) < 2 \times 10^{12}$ 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 $n(\mathrm{H_2}) = 300$ cm^{-3} at a kinetic temperature $T_k = 15$ K with a CO linewidth of $\Delta V = 1.0$ km s^{-1}. When $N(\mathrm{CO}) = 1.75\times10^{14}$ 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

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

where λ 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, $N_{\min}(\mathrm{CO}) = 1.1\times10^{14}$ cm^{-2} for the (1,0) R(0) vibration-rotation line at $\lambda = 46575$ Å ($f = 1.2 \times 10^{-5}$), and 1.1×10^{12} cm^{-2} for the $\mathrm{A}^1\Pi$-$\mathrm{X}^1\Sigma^+$ (2,0) R(0) line at 1477 Å ($f = 0.04$).

2.1. ULTRAVIOLET OBSERVATIONS OF CO

The ultraviolet spectrum of CO longward of the H I Lyman limit ($\lambda > 912$ Å) consists of many electronic transitions, each with vibrational and rotational fine structure. The transitions of interstellar interest (Morton & Noreau 1994) that arise in the ground vibronic state, X $^1\Sigma^+(v=0)$, include the 4th-positive system, A $^1\Pi$ – X $^1\Sigma^+$, which extends to $\lambda = 1544$ Å with bands that span a large range in oscillator strength: from $f_{14,0} = 1.5 \times 10^{-5}$ at $\lambda 1214$ Å to $f_{2,0} = 4.0 \times 10^{-2}$ at 1478 Å. Absorption in the predissociated transitions at $\lambda < 1100$ Å destroys CO and determines its lifetime against photodissociation (van Dishoeck & Black 1988).

In translucent molecular clouds, ^{12}CO, ^{13}CO, C, C$^+$, H, and H$_2$ are all measurable in the same absorbing gas, along with a variety of other simple molecules such as CH, CH$^+$, C$_2$, CN, and OH. Thus it is possible to investigate the chemistry and fractionation of CO exactly where it is just beginning to dominate the gas-phase abundances of carbon and oxygen. The rotational structure is extremely compact in all ultraviolet bands of CO, so that a resolving power $R > 50,000$ is required to disentangle the individual lines and to yield accurate column densities (Black & van Dishoeck 1988).

Although earlier studies of interstellar CO with the *Copernicus* and *IUE* satellites (e.g. Federman et al. 1980; Black 1980; Wannier et al. 1982) were hampered by insufficient resolution, observations with the Goddard High-Resolution Spectrograph on *HST* have recently advanced the state of this art. *HST* observations of the obsessively well studied diffuse clouds toward ζ Oph have provided a variety of recent values for the column density $N(\mathrm{CO}) = (1.8\pm0.2)\times10^{15}$ cm^{-2} (Lyu et al. 1994), 2.2×10^{15} cm^{-2} (Sheffer et al. 1992), and 2.5×10^{15} cm^{-2} (Lambert et al. 1994). More significant is the disagreement over the abundance ratio of isotopomers, ^{12}CO/^{13}CO $= 82 \pm 25$, 150 ± 27, and 167, in the same three studies, respectively: the smallest value is in harmony with no fractionation, while the larger values suggest fractionation controlled by isotope-selective photodissociation. Federman et al. (1994) have identified 7 weak intersystem (singlet-triplet) transitions of CO in the spectrum of ζ Oph, and their assessment of the oscillator strengths for all observed features favors the interpretation of Lambert et al. (1994): $N(\mathrm{CO}) = 2.5 \times 10^{15}$ cm^{-2} with an uncertainty of 20%. The case for the oscillator strengths preferred by Federman et al. has received considerable support from the recent laboratory measurements of Smith et al. (1994). The ζ Oph clouds are a pathological case with two narrow velocity components separated by only ≈ 1 km s^{-1}; therefore, the analysis is extremely sensitive to uncertainties in the oscillator strengths and to the (unresolved) line broadening.

The visual extinction toward ζ Oph is $A_V = 1.0$ mag. With *HST* it is now possible to observe thicker foreground clouds. For example, toward HD 154368, where $A_V = 2.5$ mag, the CO column density is a factor of 10 higher, $N(\mathrm{CO}) \approx 2.5 \times 10^{16}$ cm^{-2} (Snow et al. 1996; Black et al. 1996). Comparison of the fine-structure excitation of atomic coolants like C and C^+ with the rotational excitation of CO shows that CO accounts for only a small fraction, 1–2%, of the total cooling.

2.2. INFRARED OBSERVATIONS OF CO

Both the (1,0) and (2,0) vibration-rotation bands of CO are observable in absorption in the interstellar medium, at 4.67 and 2.34 μm, respectively. The line positions and oscillator strengths are accurately determined (Goorvitch & Chackerian 1994a,b; Goorvitch 1994). The infrared technique is also valuable as a means of observing non-polar molecules that have no allowed rotational transitions at radio wavelengths, such as CH_4 (Knacke et al. 1985, Lacy et al. 1991), C_2H_2 (Lacy et al. 1989), H_3^+ (Oka 1981, Geballe & Oka 1989, Black et al. 1990), and potentially CO_2. The first direct detection of cold H_2 toward NGC 2024 IRS2 and possibly NGC 2264 IRS by Lacy et al. (1994) is a great triumph. In these lines of sight, the CO is also well observed, so that direct determinations of the CO/H_2 abundance ratio can be made. Toward NGC 2024 IRS2, the CO is thermalized at $T = 44$ K and has a total column density of $N(\mathrm{CO}) = 7 \times 10^{18}$ cm^{-2} (Black & Willner 1984, corrected for improved oscillator strengths), while the column density of H_2 is $N(\mathrm{H_2}) = 3.5 \times 10^{22}$ cm^{-2}, including an allowance for the undetected molecules in the $J = 1$ level at the CO temperature (Lacy et al. 1994). This yields $N(\mathrm{CO})/N(\mathrm{H_2}) = 2 \times 10^{-4}$ in the gas phase. The total column density of CO in the solid phase is 2×10^{17} cm^{-2}, based on the results of Tielens et al. (1991) corrected for an improved absorption strength (see §3). The carbon monoxide accounts for 25% of a solar abundance of carbon, the remainder probably residing in atoms (C and C^+), other molecules, and the cores of dust grains. The detection of H_2 is difficult because its vibration-rotation lines are weak, electric quadrupole transitions: the product of population fraction and oscillator strength for the (1,0) S(0) line at 2.2 μm is $X_0 f = 7.2 \times 10^{-14}$ for gas at $T_k = 50$ K and $n(\mathrm{H_2}) = 10^4$ cm^{-3}. The corresponding factor for the *permitted* CO (2,0) R(2) line at 2.3 μm is $X_2 f = 1.1 \times 10^{-8}$; therefore, the strongest 2-μm CO lines are only 15 times stronger than the H_2 line for $CO/H_2 \approx 10^{-4}$. Furthermore, where the H_2 is barely measurable and the ^{12}CO lines are barely saturated in the (2,0) band, $\tau \leq 1$, the ^{13}CO lines of the (1,0) band will have modest line-center optical depths ($\tau \leq 5$) for ^{12}CO/^{13}CO = 60. This means that all three species can often be measured in weak or mildly saturated lines, as demonstrated by Scoville et al. (1983) toward

Orion BN where $^{12}CO/^{13}CO = 96 \pm 5$. Similarly, Mitchell & Maillard (1993) measured the ^{13}CO (1,0) lines toward NGC 2264 IRS and determined an abundance ratio $^{12}CO/^{13}CO = 94 \pm 13$ through comparison with the ^{12}CO (2,0) measurements of Black et al. (1990).

The light sources used in the IR absorption spectroscopy are often luminous young stellar objects that are deeply embedded in molecular clouds. The foreground column densities are usually large enough to make the CO (1,0) lines highly saturated. However, Mitchell et al. (1989, 1990) found, in addition to the thick absorbing column of CO at low temperature ($T \approx 15 - 70$ K), a second thin component at very high temperature ($T \approx 100 - 1000$ K) in several cases. The hot molecules evidently probe the molecular environment very close to the embedded star. In one case, AFGL 2591, the infrared and radio observations of molecules have been combined to make a comprehensive picture of the star-forming cloud core (Carr et al. 1995). The CO absorption toward Orion BN also shows interesting complexity (Scoville et al. 1983). Mitchell, Maillard & Hasegawa (1991) have observed multiple velocity components in absorption toward luminous embedded stars, which they interpret in terms of episodic molecular outflows: blue-shifted features in foreground absorption are unambiguous kinematical signatures of outflow.

3. Solid CO in the Interstellar Medium

Solid CO in the interstellar medium can be observed by means of an absorption feature at $\lambda 4.67\ \mu$m (Lacy et al. 1984, Geballe 1986). The study of interstellar ices has been reviewed recently by Whittet (1993). Laboratory investigations have determined the absorption coefficient and have shown how the band shapes are related to the chemical structure of the ice matrix (Sandford et al. 1988, Schmitt, Greenberg, & Grim 1989, Tielens et al. 1991, Gerakines et al. 1995). Solid CO in a polar H_2O-ice matrix produces a broad, shallow component, while CO in a non-polar matrix produces a narrow component. The integrated absorption strength of the CO 4.67 μm feature is measured to be $\int(\sigma/c)d\nu = 1.1 \times 10^{-17}$ cm molecule^{-1} at $T = 14$ K, independent of the dominant ice constituent but slightly dependent on temperature (Gerakines et al. 1995). This value is approximately 70% smaller than in earlier studies (Sandford et al. 1988, Tielens et al. 1991); therefore, published abundances of solid CO may need to be increased accordingly. The corresponding integrated absorption strength of the $v = 1 \leftarrow 0$ band of gaseous CO is $\frac{\pi e^2}{mc^2} f = 1.1 \times 10^{-17}$ cm molecule^{-1}.

The signatures of both polar and non-polar ices are observed (e.g., Eiroa & Hodapp 1989, Tielens et al. 1991). Because these two components probably have quite different volatilities, their amounts (in relation to each other and to the amount of H_2O ice) can be used as probes of the photochemical and thermal processing that has occurred in interstellar dust mantles. For example, lines of sight toward field stars behind the Taurus dark cloud show a non-polar component appropriate for a CO-dominated, H_2O-deficient mixture at $T = 10$ K; while lines of sight toward embedded stars in the same cloud exhibit a non-polar component consistent with a CO_2:CO mixture at $T = 10$ K, suggestive of efficient production of CO_2 ice by radiative processing in environments near young stars (Chiar et al. 1995). The relative amounts of gaseous and solid CO in the same cloud indicate the extent to which gas has frozen out onto grain surfaces and thus probe the evolutionary state of the cloud (Léger, Jura, & Omont 1985; Whittet & Duley 1991; Sandford & Allamandola 1993; Willacy & Williams 1993; Caselli et al. 1994). There remain interesting questions about the mechanisms of desorption that prevent all heavy molecules from freezing out in quiescent, dark clouds (e.g., Willacy, Williams, & Duley 1994; Hasegawa & Herbst 1993; Dzegilenko & Herbst 1995).

In regions where CO can be observed in both solid and gaseous forms, the column-averaged fraction of all CO in solid form shows an interesting dependence on environment. Observations in cold, dark clouds like Taurus show a solid fraction $\delta(\mathrm{CO}) = 7 - 39\%$ (e.g., data from Chiar et al. 1995), while measurements toward luminous "protostellar" sources in hot cores show $\delta(\mathrm{CO}) = 1 - 10\%$ (data from Tielens et al. 1991).

4. Stellar and Circumstellar Spectroscopy

In stellar studies, the infrared lines of CO can be used to make accurate determinations of the abundances of the isotopes of carbon and oxygen, which are probes of nucleosynthesis and mixing in stars. The shapes of CO line profiles in spectra of young stellar objects yield valuable information about the kinematics of disks around them (e.g., Calvet et al. 1991, Carr et al. 1993). In the environments surrounding young stellar objects, the gas is sometimes so highly disturbed that intense far-infrared rotational line emission (Watson et al. 1985, Boreiko & Betz 1989) and even emission in vibration-rotation lines (Thompson 1985, Geballe & Garden 1990) are excited. Infrared spectroscopy of CO in evolved stars with circumstellar envelopes can reveal radial variations of density and temperature (e.g., Keady et al. 1988). Carbon monoxide is observed in the infrared spectra of novae (cf. Gehrz 1988) and supernovae (e.g., Liu, Dalgarno, & Lepp 1992; Bouchet & Danziger 1993).

Individual giant and supergiant stars can be identified at 2.3 μm in the Galactic Center region (e.g., Eckart et al. 1995; Sellgren et al. 1990); the sharp CO band edges in the spectra of the late-type stars can be used to determine their radial velocities and hence to map the stellar kinematics of the Galactic Center. In this way the mass distribution can be determined from the inner bulge at 100–300 pc (Rieke & Rieke 1988, Blum et al. 1995) into the central 0.5 pc (Krabbe et al. 1995). Such observations have strengthened the arguments for the presence of a possible black hole of $\approx 3 \times 10^6$ $M_\odot$ in the Center, which have relied in the past on kinematical studies of the gas (Genzel, Hollenbach, & Townes 1994). In external galaxies where late-type giants and supergiants dominate the K-band light, the CO bands in the unresolved spectra can be used both to assess the evolved supergiant segment of a starburst population and to determine stellar velocity dispersions (Shier et al. 1994, Doyon et al. 1994, Goldader et al. 1995). The derived dynamical masses in the centers of luminous starburst galaxies are an important complement to gas masses that have been estimated from the intensity of mm-wave CO emission.

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