CO FLUORESCENCE IN THE EXTREME-ULTRAVIOLET SOLAR SPECTRUM

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ABSTRACT

Emission lines in the fourth positive system of CO have been identified in the extreme-ultraviolet solar spectrum 1540-1660 Å. These lines are excited by the C iv transition-zone lines at 1548 and 1551 Å. They are strong in the spectrum of a sunspot and in parts of the adjacent active region. Some of them appear as weak, broad emission features in the quiet Sun.

Subject headings: molecular processes — Sun: chromosphere — Sun: spectra — Sun: sunspots — ultraviolet: spectra

I. INTRODUCTION

Carbon monoxide has been known in absorption in the EUV spectrum of the quiet Sun for some years. Goldberg, Parkinson, and Reeves (1965) suggested its presence in a spectrum photographed by Tousey (1964). Porter, Tilford, and Widing (1967) identified several bands in the wavelength region 1540 to 1970 Å, corresponding to transitions in the fourth positive system A m-x^1S+.

A high spectral (0.06 Å) and spatial (~1") resolution spectrum from 1175 to 1700 Å was obtained during the first rocket flight of the Naval Research Laboratory's high-resolution telescope and spectrograph (HRTS) on 1975 July 21. During the flight the 15" long slit of the spectrograph was placed from the center of the Sun to the limb, crossing a plage and a sunspot. Details of the instrument are described by Brueckner et al. (1978).

Figure 1 (Plate L3) shows portions of the spectrum in the vicinity of the 0-0 (1544.44 Å), the 0-1 (1597.16 Å), and the 0-2 (1653.02 Å) bands of the A 'II-X ^3Σ^+ system. The following areas of the solar disk are shown from top to bottom: (1) the solar limb; (2) a quiet region at cos θ ~ 0.9; (3) a plage and a sunspot. Details of the instrument are described by Brueckner et al. (1978).

II. THE CO EMISSION LINES

The lines identified as due to CO are indicated in Figure 1 and are listed in Table 1. It can be seen that the lines are not only strong over the sunspot but that lines from J' = 28 also exist in emission in regions of the adjacent plage where the continuum is low. There is some indication that weak emission features also exist in the quiet Sun spectrum.

As for H2, only a few strong emission lines are seen, not the complete band, which in CO would consist of closely spaced lines. By study of the observed separation of lines near the 0-1 band head, it was found that there are three consistent with the ΔJ spacing for J = 27, 28, and 29 in the X ^1Σ^+ ν^0 = 1 state of CO.

These lines therefore fit the P(29), Q(28), and R(27) transitions in the 0-1 band. Simmons, Bass, and Tilford (1969) have made an extensive study of the fourth positive system, but did not observe transitions to such high J levels. The energies have been calculated from the constants given in their paper. The corresponding transitions can be seen in the 0-2 band around 1660 Å. The presence of lines from a common upper level strongly suggests selective photoexcitation, and this is confirmed by the position of the Q(28) and R(27) lines in the 0-1 band. Simmons, Bass, and Tilford (1969) have made an extensive study of the fourth positive system, but did not observe transitions to such high J levels. The energies have been calculated from the constants given in their paper. The corresponding transitions can be seen in the 0-2 band around 1660 Å. The presence of lines from a common upper level strongly suggests selective photoexcitation, and this is confirmed by the position of the Q(28) and R(27) lines in the 0-1 band. Simmons, Bass, and Tilford (1969) have made an extensive study of the fourth positive system, but did not observe transitions to such high J levels. The energies have been calculated from the constants given in their paper. The corresponding transitions can be seen in the 0-2 band around 1660 Å. The presence of lines from a common upper level strongly suggests selective photoexcitation, and this is confirmed by the position of the Q(28) and R(27) lines in the 0-1 band. Simmons, Bass, and Tilford (1969) have made an extensive study of the fourth positive system, but did not observe transitions to such high J levels. The energies have been calculated from the constants given in their paper. The corresponding transitions can be seen in the 0-2 band around 1660 Å. The presence of lines from a common upper level strongly suggests selective photoexcitation, and this is confirmed by the position of the Q(28) and R(27) lines in the 0-1 band. Simmons, Bass, and Tilford (1969) have made an extensive study of the fourth positive system, but did not observe transitions to such high J levels. The energies have been calculated from the constants given in their paper. The corresponding transitions can be seen in the 0-2 band around 1660 Å.
Fig. 1.—Selected portions of a high-resolution ultraviolet solar spectrum in the vicinity of the $0-0$, $0-1$, and $0-2$ bands of the fourth positive system of CO.

Barzee et al. (see page 145).
Simmons et al. In the 0–1 band the lines again are close in wavelength to Si i lines in the disk spectrum, but over the spot are far too strong to be accounted for by Si i. In the 0–2 band only the R(17) line is masked by C i at 1654.37 Å. Since the P(17) line is masked by C i at 1657.37 Å, the two alternative excitation routes to the upper \( J' = 16 \) level must be considered. Given the half-width of the C iv line (0.11 Å, FWHM), the coincidence with C iv should be close enough to give effective excitation. Evidence that C iv rather than C i is the source of excitation is provided by the weakness of the P(18) line at 1601.38 Å. If photoexcitation from C i 1657.37 Å occurred, then the P(18) line should be stronger than the P(17) line, since in the 0–2 band the P(18) line lies at 1657.41 Å. The high opacity in the C i lines may be the cause of the less effective excitation at the depth of the CO molecules.

The corresponding Q(16) lines are not observed. This can be accounted for by the \( \Lambda \)-type doubling of the CO \( ^1 \Pi \) state (Herzberg 1950). Excitation in a \( P \) or \( R \) branch line [in this case P(17) in the 0–0 band] will populate only the \( \Pi^+ \) component of the \( J' = 16 \) level. There is no excitation route to the \( \Pi^- \) component; thus only decays in the P(17) and R(15) transitions are observed. In the case of the excitation to the \( J' = 28 \) level, both \( \Pi^+ \) and \( \Pi^- \) components are populated by the R(27) line at 1548.15 Å and the Q(28) line at 1550.72 Å.

Other, weaker emission lines of CO probably exist from the 0–0, 0–1, and 0–2 bands, but the absence of further strong lines and alternative excitation routes supports our conclusion that the excitation of the lines observed is by the C iv lines.

The intensities of the CO lines will depend on the details of the C iv line profiles, on their absorption oscillator strengths and branching ratios, but over the temperature range ~4000 to 7000 K will be insensitive to temperature. Kurucz (1976) gives the oscillator strengths for the transition identified, and the relative intensities of lines from the same branch in the different bands are consistent with the theoretical branching ratios. Similarly, for the lines from \( J' = 28 \), the relative intensities of the \( P, Q, \) and \( R \) branches are approximately as expected.

The extension of the CO lines into the penumbra and cool regions of the adjacent plage compared with the restriction of the H\( \alpha \) lines to the sunspot umbra shows that the CO excitation is taking place at a higher temperature than that of the H\( \alpha \) lines.

It seems that there is little opacity over the sunspot between the CO molecules and the C iv radiation. In their discussion of the CO absorption bands, Goldberg et al. and Porter et al. point out that above the Si i edge at 1525 Å the quiet chromosphere is sufficiently transparent to see through to the photospheric layers which produce CO. In the sunspot the presence of strong CO emission cannot therefore be due only to the lower opacity over the spot; rather, a more extended region at low temperatures is suggested.

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REFERENCES


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