THEORETICAL EMISSION LINE RATIOS FOR Si Xll
COMPAARED TO SOLAR OBSERVATIONS

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Abstract. The electron collision excitation rates recently calculated for transitions in Si \textsc{xiii} by Keenan \textit{et al.} (1987) are used to derive the electron temperature sensitive ratio $G = (f + i)/r$ and the density sensitive ratio $R = f/i$, where $i$, $f$, and $r$ are the intercombination ($1s^2 1S - 1s2p 3P_{1,2}$) forbidden ($1s^2 1S - 1s2s 3S$), and resonance ($1s^2 1S - 1s2p 1P$), transitions respectively. Also estimated are the values of $R$ in the low-density limit ($R_0$) as a function of electron temperature. The theoretical $G$ ratio at the temperature of maximum emissivity for Si\textsc{xiii}, $G(T_m) = 0.70$, is in much better agreement with the observed $G$ for the 1985 May 5 flare determined by McKenzie \textit{et al.} ($G = 0.60 \pm 0.07$) than is the earlier calculation of Pradhan, who derived $G(T_m) = 0.85$. The error in the observed $R_0$ ratio is so large that both our result and Pradhan’s fall within the acceptable limits of uncertainty and hence one cannot estimate which of the two is the more accurate.

1. Introduction

The study of spectral lines arising from transitions in helium-like ions plays a very important role in the determination of the characteristics of high temperature laboratory and astrophysical plasmas (McKenzie \textit{et al.}, 1985; Kolk \textit{et al.}, 1986). In general the lines emitted from the lowest excited levels $1s2l$ ($l = s$, $p$) are of the most interest. They can be used to deduce the electron density and temperature of a plasma by means of the well-known intensity ratios $R = f/i$ and $G = (f + i)/r$, respectively, where $f = 1s^2 1S - 1s2s 3S$, $i = 1s^2 1S - 1s2p 3P_{1,2}$, and $r = 1s^2 1S - 1s2p 1P$ (Gabriel and Jordan, 1969; Blumenthal \textit{et al.}, 1972).

The best atomic data available must be used if one is to obtain accurate line ratios. Of special importance are the electron excitation rates from the ground state to the $1s2l$ levels. Pradhan (1985) carried out extensive calculations to determine electron impact excitation rates for Ca\textsc{xix} and Fe\textsc{xxv} using the distorted wave approximation, while Kingston and Tayal (1983a, b) and Tayal and Kingston (1984a, b, 1985) calculated electron excitation rates for transitions in C\textsc{v}, O\textsc{vii}, and Mg\textsc{xii} using the $R$-matrix method (Burke and Robb, 1975) taking into account all the resonances converging to the $n = 2$ and $n = 3$ levels. Using the Pradhan (1985) excitation rates, in conjunction with the O\textsc{vii} and Mg\textsc{xii} atomic data from Tayal and Kingston (1984b, 1985), Keenan \textit{et al.} (1987) have performed an interpolation procedure for other ions in this isoelectronic sequence. In this paper we use the Keenan \textit{et al.} (1987) data to derive emission line ratios for Si\textsc{xiii} and compare these with observational results for a solar flare obtained with the SOLEX A spectrometer on board the P78–1 satellite.
2. Atomic Data

The model ion for Si XIX consisted of the 23 lowest 1s\textit{n}l states with \( n < 6 \) and \( l < 3 \), which made a total of 37 levels when the fine structure splitting of the \( ^3P \) and \( ^3D \) terms was included. Energies of the ionic levels were taken from Bashkin and Stoner (1975) and Lin \textit{et al.} (1977a).

Electron impact excitation rates for transitions from the ground state to the 1s2l and 1s3l levels were taken from Keenan \textit{et al.} (1987), and those amongst the \( n = 2 \) states from Pradhan \textit{et al.} (1981) and Jones (1974). Rates for transitions to or between higher levels were either derived from the above in conjunction with the \( n^{-3} \) scaling law (Gabriel and Heddle, 1960) or taken from Sampson \textit{et al.} (1983). Einstein A-coefficients for radiative decays from the \( n = 2 \) states were taken from Lin \textit{et al.} (1977a) and for transitions for \( n > 2 \), values were taken from Lin \textit{et al.} (1977b) and Cohen and McEachran (1972). The effect of dielectronic and radiative recombination of H-like Si XIV and innershell ionization of Li-like Si XIX on the Si XIX level populations was included by using the recombination coefficients of Mewe and Schrijver (1978) and the ionization balance calculations of Arnaud and Rothenflug (1985).

![Graph](image)

Fig. 1. The theoretical ratio \( R = I(1s^2 1S - 1s2s 3S)/I(1s^2 1S - 1s2p 3P_{1,2}) \) plotted as a function of electron density at the temperature of maximum Si XIX emissivity, \( T_m = 1.1 \times 10^7 \) K (Mewe \textit{et al.}, 1985). The present calculations are shown both including (-----) and excluding (---) dielectronic and radiative recombination and innershell ionization.
3. Results and Discussion

Using the atomic data discussed in Section 2 and the statistical equilibrium code of Dufton (1977), Si Xlll level populations and, hence, emission line strengths were calculated for a range of electron temperatures and densities appropriate to the solar corona. In Figure 1, the density sensitive ratio \( R = I(1s^2 1S - 1s2s^3S)/I(1s^2 1S - 1s2p^3P_{1,2}) \) is plotted at the temperature of maximum Si Xlll emissivity, \( T_m = 1.1 \times 10^7 \) K (Mewe et al., 1985). The effect of dielectronic and radiative recombination as well as innershell ionization on this line ratio is clearly illustrated, with \( R \) being increased by approximately 12\% in the low-density limit. Since \( R \) is only density sensitive for values of Ne > \( 10^{13} \) cm\(^{-3}\), which is much greater than the densities in solar plasmas, one would expect this ratio to be in the low-density limit. This limit \( (R_0) \) is plotted as a function of electron temperature \( (T_e) \) in Figure 2. The inclusion of radiative recombination, dielectronic recombination and innershell ionization clearly cause a dramatic increase in \( R_0 \) at temperatures greater than \( T_m \). In Figure 3, a similar diagram is shown for the temperature sensitive ratio

\[
G = \frac{I(1s^2 1S - 1s2s^3S) + I(1s^2 1S - 1s2p^3P_{1,2})}{I(1s^2 1S - 1s2p^1P)},
\]

where the effects of recombination and ionization processes are seen to increase \( G \) by approximately 30\% at the temperature of maximum emissivity. Also illustrated in the figure are the calculations of Pradhan (1982), which include the above atomic processes as well.

![Graph](image)

Fig. 2. The low-density limit \( (R_0) \) of the theoretical ratio \( R \), plotted as a function of electron temperature. The present calculations are shown both including (- - -) and excluding (-----) dielectronic and radiative recombination and innershell ionization. In addition the results of Pradhan (1982), which also include these atomic processes are given (---).
Fig. 3. The theoretical ratio $G = \frac{I(1s^2 \, 1S - 1s2s \, 3S) + I(1s^2 \, 1S - 1s2p \, 3P_{1,2})}{I(1s^2 \, 1S - 1s2p \, 1P)}$ plotted as a function of electron temperature for the present calculations, both including (---), and excluding (——) dielectronic and radiative recombination and innershell ionization. In addition the results of Pradhan (1982), which also include these atomic processes, are given (---).

Part of the payload on board the P78–1 satellite was an instrument known as SOLEX (McKenzie et al., 1985; Landecker et al., 1979), which was used to obtain X-ray spectra from 3 to 25 Å of the quiet and active solar corona as well as flares. Its basic hardware consisted of two collimated spectrometer systems, namely SOLEX A with a spatial resolution of 20 arc sec and an Ar/CO$_2$ filled proportional counter, and SOLEX B which had a 60 arc sec spatial resolution and a channel electron multiplier Array (CEMA) detector. The CEMA was a high gain, low noise detector needed to detect X-ray lines above 14 Å. Each spectrometer system employed either an ammonium dihydrogen phosphate (ADP) or a rubidium acid phthalate (RAP) crystal. In effect, due to interchangeable crystals, there were four available spectrometers but only two could be used at any one time (see Landecker et al., 1979 for details).

The disadvantage of using the CEMA as the SOLEX B detector was that it had three absorption edges within the range under observation. A sharp change in efficiency at the Si K absorption edge occurred at 6.738 Å which almost coincided with the Si XII forbidden ($f$) line at 6.739 Å. Consequently the line flux corresponding to this transition was underestimated and neither $R$ nor $G$ could be determined with this detector (McKenzie et al., 1985). A similar anomaly in the crystal (Quartz 1010) reflectivity for the Si XII forbidden transition was noted by Phillips et al. (1982) in spectra from the Solar Maximum Mission (SMM) satellite, rendering its intensity uncertain. Hence, the
only suitable observation for determining the $\text{Si XIII}$ $R$ and $G$ ratios was the 1981, May 5 14:10 UT SOLEX A spectrum (McKenzie et al., 1985). The $\text{Si XIII}$ spectrum was corrected for satellite line emission by scaling from the measured strength of two lines using the data from Bhalla et al. (1975). In addition, blending of $f$ with the $\text{Mg XII}$ $1s^2 S - 4p^2 P$ line at 6.740 Å (Garcia and Mack, 1965) was estimated to account for 15% of the apparent forbidden line flux. After all corrections McKenzie et al. (1985) obtained an observed value of $R_0 = 2.59 \pm 0.60$. Pradhan's (1982) theoretical value is $R_0(T_m) = 2.64$, while we deduce $R_0(T_m) = 2.44$. However, the errors in the observed $R_0$ are so large that one cannot determine which of these two is the more accurate calculation. The value of $G$ obtained by McKenzie et al. for the flare was, after correcting for $\text{Mg XII}$ emission, $G = 0.60 \pm 0.07$. Without this correction they would have found $G = 0.67$, but even this was not sufficient to account for the discrepancy between the observed ratio and the theoretical value of $G(T_m) = 0.85$ obtained by Pradhan (1982). Our calculation of $G(T_m) = 0.70$ is, however, in much better agreement with observation.

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References


