THE 1S-1P/1S-1P EMISSION-LINE RATIOS IN Si XIII AS ELECTRON TEMPERATURE DIAGNOSTICS FOR SOLAR FLARES AND ACTIVE REGIONS

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ABSTRACT

Theoretical Si xiii emission-line ratios $R_1 = I(1s^2 1S-1s3p 1P)/I(1s^2 1S-1s2p 1P)$, $R_2 = I(1s^2 1S-1s4p 1P)/I(1s^2 1S-1s2p 1P)$, and $R_3 = I(1s^2 1S-1s5p 1P)/I(1s^2 1S-1s2p 1P)$ are presented as a function of electron temperature. These ratios are found to be more electron temperature sensitive than the commonly used diagnostic for He-like ions ($G$), with, for example, $R_1$, $R_2$, and $R_3$ varying by factors of approximately 6, 12, and 17 between log $T_e = 6.2$ and 7.2, while $G$ only changes by a factor of 1.8. In addition, $R_1$, $R_2$, and $R_3$ are less dependent on whether or not the Si xiii-emitting plasma is in ionization equilibrium. Electron temperatures deduced using the observed values of $R_1$, $R_2$, and $R_3$ from OY 1-17 and OSO 8 satellite spectra of solar flares and active regions are in good agreement and, in general, compare favorably with those determined from $G$. However, in the case of measurements made with the Flat Crystal Spectrometer on board the Solar Maximum Mission satellite there are large discrepancies between theory and observation. Possible explanations for these are briefly discussed.

Subject headings: atomic processes — Sun: flares — Sun: spectra

I. INTRODUCTION

The three principal lines of helium-like ions, namely the forbidden ($f$) $1s^2 1S-1s2s 3S$, intercombination ($i$) $1s^2 1S-1s2p 3P_{1,2}$, and resonance ($r$) $1s^2 1S-1s2p 1P$ transitions, are frequently observed in the X-ray spectra of laboratory and astrophysical plasmas (Phillips et al. 1982; Kato et al. 1987). They may be used to infer the electron temperature of the emitting region of the plasma through the line ratio $G = (f + i)/r$ (Blumenthal, Drake, and Tucker 1972), although the theoretical values of this ratio are critically dependent on the atomic data adopted in the calculations, especially the electron impact excitation rates between the ground state and $ls^2l$ levels (Gabriel and Jordan 1972). Over the last few years there have been many theoretical determinations of $G$, probably the most accurate currently available being those of Keenan and his coworkers for ions between O vii and S xv (Keenan et al. 1987; Keenan and McCann 1987; McCann and Keenan 1987, 1988; Keenan, Tayal, and Kingston 1984a, b), which are based on excitation rates derived with the $R$-matrix code (Burke and Robb 1975; Berrington et al. 1978).

Recently Keenan, Kingston, and McKenzie (1985, 1986) and Keenan et al. (1987) have extended the above work to derive emission-line ratios in O vii, Ne ix, and Mg xi involving the $1s^2 1S-1snp 1P$, $n = 2, 3$, and 4 transitions, which proved to be more electron temperature sensitive than the normal diagnostic for He-like ions, $G$, and to lead to values of $T_e$ in excellent agreement with those estimated from other methods. In this paper we derive similar ratios for Si xiii and show how these may be used to deduce electron temperatures in solar flares and active regions.

II. THEORETICAL RATIOS

The atomic data adopted in the present emission-line ratio calculations have been described in detail by Keenan et al. (1989). Briefly, the 23 $1snl$ states with $n < 6$ and $l < 3$ were included in the model ion, making a total of 37 levels when the fine-structure splitting in the 3$P$ and 3$D$ terms was included. The only atomic processes considered were collisional excitation and de-excitation by electrons, spontaneous radiative decay, and dielectronic and radiative recombination to the $n = 2$ levels. The plasma was assumed to be optically thin. Further details may be found in Keenan et al. (1989).

In Figures 1–3, the theoretical ratios $R_1 = I(1s^2 1S-1s3p 1P)/I(1s^2 1S-1s2p 1P)$, $R_2 = I(1s^2 1S-1s4p 1P)/I(1s^2 1S-1s2p 1P)$, and $R_3 = I(1s^2 1S-1s5p 1P)/I(1s^2 1S-1s2p 1P)$ are plotted as a function of electron temperature at an electron density of $N_e = 10^{11}$ cm$^{-3}$, although we note that the ratios are insensitive to variations in the latter for $N_e < 10^{15}$ cm$^{-3}$, which is much greater than the densities of the solar features considered here. An inspection of the figures reveals that inclusion of dielectronic and radiative recombination in the calculations has the effect of decreasing the ratios by a few percent for values of $T_e > 6 \times 10^6$ K. This is in contrast to the effect of these atomic processes on $G$, where the ratio is increased by $\sim 11\%$ at $T_e = 6 \times 10^6$ K and $\sim 65\%$ at $1.5 \times 10^7$ K. Therefore the former ratios are less dependent on whether or not the plasma is in ionization equilibrium.

It may also be seen from the present results and Figure 3 of McCann and Keenan (1987) that $R_1$, $R_2$, and $R_3$ are more temperature sensitive than $G$ and hence in principle should be more useful as $T_e$ diagnostics. For example, between log $T_e = 6.2$ and 7.2, the temperature range over which Si xiii has a fractional abundance in ionization equilibrium of $\geq 0.1$ (Arnaud and Rothenflug 1985), $R_1$, $R_2$, and $R_3$ vary by factors of 6.2, 12.0, and 17.3, respectively, while $G$ only changes by a factor of 1.8.

As mentioned by Keenan et al. (1989), there is significant emission due to dielectronic satellites contributing to the inten-
Fig. 1.—The theoretical Si xiii ratio $R_1 = I(1S^2 3S - 1S^2 1P) / I(1S^2 3S - 1S^2 2P)$, where the line intensities $I$ are in photons, plotted as a function of electron temperature at an electron density of $N_e = 10^{11}$ cm$^{-3}$, both excluding dielectronic and radiative recombination (dashed line) and including these atomic processes (solid line).

sity of the Si xiii forbidden line (1S$^2 3S$–1S2$^2$S) which affects the $G$ ratio. There may also be significant emission, at least at comparatively low temperatures ($T_e \leq 5 \times 10^6$ K), as a result of numerous unresolved satellites with $n \geq 3$ spectator electrons to the Si xiii resonance line, which will make a difference to the $R_1$–$R_3$ ratios. We have therefore used the calculations of Nilsen (1988) for satellites up to $n = 4$ to correct the theoretical values of $R_1$–$R_3$. However, we note that these corrections are small—for example, at log $T_e = 6.8$ the ratios are only reduced by ~10%.

III. OBSERVATIONS

The wavelengths of the 1S$^2 3S$–1Snp 1P transitions in Si xiii are summarized in Table 1. These lines are emitted by flares or very hot nonflaring active regions with electron temperatures of at least log $T_e = 6.3$, with the peak of their contribution $[G(T_e)]$ functions being around log $T_e = 6.9$. Their emission during flares is generally much more intense than for active regions, and so photon count statistics are better for spectra taken then. On the other hand, there may be significant variations in the flare emission during the time a scanning crystal spectrometer takes to form a spectrum; there may also be departures from ionization equilibrium if the flare density is low.

The spectral range of the lines has been observed at various levels of solar activity with several spacecraft-borne crystal spectrometers. We will discuss observations from three of these all scanning, flat-crystal spectrometers: that of Walker, Rugge, and Weiss (1974) on the OV 1-17 spacecraft, using an EDDT crystal; that of Parkinson et al. (1978) on the OSO 8 spacecraft, that of Phillips et al. (1982) on the Solar Maximum Mission on 1985 July 2, apart from 1S$^2 3S$–2$^2$P line wavelength, which was not observed for this event (wavelength is from Phillips et al. 1982).
using graphite and PET crystals; and the Flat Crystal Spectrometer (FCS), part of the X-ray polychromator on the Solar Maximum Mission (SMM) satellite, which observed this range with two channels using quartz crystals.

The spectrometer of Walker, Rugge, and Weiss (1974) had a scanning mechanism which rotated the EDDT crystal continuously (the spectrometer always pointed at the Sun), and the 5.285–6.648 Å range of all the Si xiii lines of interest (i.e., \( n = 2\)–5) was covered in a time of \( \sim 48 \) s; this is short compared with typical flare variations. The spectral resolution was determined by the crystal rocking curve, sampling time, and (because the instrument was uncollimated) the spatial distribution of X-ray emission on the Sun: for the observations we discuss, the resolution (FWHM) was \( \sim 5' \) (0.008 Å at the \( r \) line). Walker et al. list intensities of lines in four spectra, from which it is possible to obtain the \( G \), \( R_1 \), \( R_2 \), and \( R_3 \) ratios; three spectra were taken some time after flares or subflares, and the fourth (the weakest) for a nonflaring but hot active region. The intensities are based on prelaunch and in-flight calibration, the relative value of which is of the order of 10% over the appropriate range.

The observations of the OSO 8 instrument discussed by Parkinson et al. (1978) were made with uncollimated graphite and PET crystal spectrometers located in the wheel part of the spacecraft, with scanning achieved by the wheel's rotation (once every 10 s). The spectral resolution of the graphite spectrometer is much worse than the PET, but the intensity calibration is much better known (\(<10\%)\). From details given of three spectra, it is possible to derive the \( R_1 \), \( R_2 \), and \( R_3 \) ratios from the graphite spectrometers (two spectra) and with less certainty the \( G \) ratio from the single PET spectrum. Only one of the spectra (from the graphite spectrometer) is outside of flare conditions and so has line ratios probably unaffected by time variations of emission.

The SMM FCS is a finely collimated (FWHM = 14") scanning crystal spectrometer, which on command can spatially raster with its seven crystals all set at an intense X-ray line or can scan in wavelength at a preprogrammed rate with the collimator directed at some chosen location on the Sun. It has observed numerous flares since SMM was launched in 1980, but comparatively few of these have Si xiii line spectra with ratios accurate enough for comparison with the calculated values. The FCS channel (No. 4) with quartz 1010 crystal (2d = 8.51 Å) includes all the Si xiii lines of interest, while that with quartz 1011 crystal (2d = 6.69 Å, No. 5) includes only the \( n \geq 3 \) lines. Channel 4 would thus normally be the preferred one, but remarkably only two flares were found in which the Si xiii \( n = 2 \) and 3 lines only were visible, and then only weakly. Moreover, an anomaly in the crystal reflectivity prevents a reliable estimate of the \( G \) ratio for the \( n = 2 \) lines. A total of six spectra from channel 5 during the decay phase of five flares were found in the data, but only for one of these—an intense flare on 1985 July 2—was it possible to obtain intensities for the \( n \geq 3 \) lines. The commanded crystal scans in the remaining spectra all excluded the \( n = 3 \) line. Thus, for the 1985 July 2 flare, it is possible to measure ratios of the form: \( R_4 = R_2/R_3 \) \( = \) \( I(1s^2\ 1S-1s3p\ 1P)/I(1s^2\ 1S-1s4p\ 1P) \) and \( R_5 = R_4/R_3 = I(1s^2\ 1S-1s3p\ 1P)/I(1s^2\ 1S-1s5p\ 1P) \), and for the other spectra, \( R_6 = R_5/R_4 = I(1s^2\ 1S-1s5p\ 1P)/I(1s^2\ 1S-1s4p\ 1P) \) only. We present calculations for these line ratios, also performed at an electron density of \( N_e = 10^{11} \) cm\(^{-3} \), in Figures 4–6, respectively.

Table 1 presents the observed line intensities from the FCS spectrometer on SMM (line intensities from the other instruments may be found in the relevant papers), while in Table 2 we summarize the \( R_4 \), \( R_6 \) line ratios with (where appropriate) electron temperatures derived from these and the calculations of Keenan et al. (1989) for \( G \). The observations of Walker et al. generally agree very well with the calculated ratios corrected for unresolved dielectronic satellites, the derived temperatures being equal to expected values for the source of emission observed. Thus, the first spectrum listed on 1969 March 20 has measured temperature of \( \sim 3 \times 10^6 \) K, a typical value for a nonflaring but hot active region. The 1642 UT spectrum has derived temperatures (6–10 \( \times 10^6 \) K) expected for a flare
shortly after its maximum, and the 1529 and 1706 UT spectra rather lower \((4 \times 10^6 \, K)\), reflecting the fact that these spectra were taken well into the decay of two flares. The \(G\) ratios give rather lower temperatures than the \(R_1 - R_3\) ratios, probably owing to there being a distribution of emission measure with temperature, and the higher excitation energy of the \(\text{Si} \, \text{xiii} \ n \geq 3\) lines.

The measured ratios of the Parkinson et al. (1978) active region spectrum (0908 UT on 1975 November 18) give temperatures \((4-6 \times 10^6 \, K)\) that seem appropriate to an active region shortly after a subflare. The \(R_1 - R_2\) ratios for the subflare spectrum at 0841 UT do not apparently correspond to any reasonable temperature, but may well be affected by time variations during the event.

The conclusion from these spectra alone, then, would seem to be that the calculated \(\text{Si} \, \text{xiii}\) line ratios are generally confirmed by the observations, taking into account the range of excitation conditions. However, results from the \(\text{SMM FCS}\) are mostly rather puzzling and do not show this good agreement.

The most reliable spectrum is that of the 1985 July 2 flare, where the measured \(R_3\) ratios indicate the \(\text{Si} \, \text{xiii} \, n = 4\) line to be too weak compared with the \(n = 3\) line or the very nearby

### Table 2
**Observed \(\text{Si} \, \text{xiii}\) Line Ratios and Derived Temperatures**

<table>
<thead>
<tr>
<th>Time (UT) and Source</th>
<th>(G) (log (T_e))</th>
<th>(R_1) (log (T_e))</th>
<th>(R_2) (log (T_e))</th>
<th>(R_3) (log (T_e))</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>A. Walker et al. 1974: 1969 March 20</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0602</td>
<td>(0.98) (6.4)</td>
<td>(0.055) (6.6)</td>
<td>(0.015) (6.5)</td>
<td>...</td>
</tr>
<tr>
<td>1529</td>
<td>(0.85) (6.6)</td>
<td>(0.071) (6.7)</td>
<td>(0.024) (6.7)</td>
<td>(0.004) (6.5)</td>
</tr>
<tr>
<td>1642</td>
<td>(0.91) (6.5)</td>
<td>(0.093) (6.9)</td>
<td>(0.046) (7.0)</td>
<td>(0.018) (7.0)</td>
</tr>
<tr>
<td>1706</td>
<td>(1.02) (6.4)</td>
<td>(0.074) (6.7)</td>
<td>(0.024) (6.7)</td>
<td>(0.006) (6.55)</td>
</tr>
<tr>
<td><strong>B. Parkinson et al. 1978: 1975 November 18</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0841</td>
<td>(0.15) (&gt; 7.4)</td>
<td>(0.072) (&gt; 7.4)</td>
<td>(0.043) (&gt; 7.4)</td>
<td>...</td>
</tr>
<tr>
<td>0908</td>
<td>(0.071) (6.7)</td>
<td>(0.034) (6.8)</td>
<td>(0.015) (6.9)</td>
<td>...</td>
</tr>
<tr>
<td>1945</td>
<td>(1.03) (6.4)</td>
<td>...</td>
<td>...</td>
<td>...</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Date and UT of Observation</th>
<th>Source</th>
<th>(\text{Si} , \text{xiii}) (R_n) ratio (log (T_e))</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>1985 July 2</strong></td>
<td>Decay of M4.5 flare</td>
<td>(R_1/R_3 = 6.26 \pm 1.0) (6.9)</td>
</tr>
<tr>
<td>(2130)</td>
<td>(R_1/R_2 = 3.29 \pm 0.43) (6.4)</td>
<td></td>
</tr>
<tr>
<td><strong>1988 July 2</strong></td>
<td>Decay of M3 flare</td>
<td>(R_3/R_2 = 0.44 \pm 0.17)</td>
</tr>
<tr>
<td>(0054)</td>
<td>(R_3/R_2 = 0.90 \pm 0.37^*)</td>
<td></td>
</tr>
<tr>
<td>(0657)</td>
<td>(R_3/R_2 = 0.89 \pm 0.37)</td>
<td></td>
</tr>
<tr>
<td><strong>1988 July 24</strong></td>
<td>Decay of M3 flare</td>
<td>(R_3/R_2 = 0.64 \pm 0.27)</td>
</tr>
<tr>
<td>(0646)</td>
<td>(R_3/R_2 = 0.85 \pm 0.37)</td>
<td></td>
</tr>
<tr>
<td><strong>1988 August 29</strong></td>
<td>Decay of M1 flare</td>
<td>(R_3/R_2 = 0.85 \pm 0.37)</td>
</tr>
<tr>
<td>(1549)</td>
<td>(R_3/R_2 = 0.85 \pm 0.37)</td>
<td></td>
</tr>
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</table>

* The spectrum in this case was scanned in direction of decreasing wavelength.
$n = 5$ line: the $R_3$ ratio gives a temperature ($8 \times 10^6$ K) typical of a flare shortly after peak, but the $R_4$ temperature ($3 \times 10^6$ K) is much lower. This does not have a ready explanation. The flare was intense enough that the total counts in the lines have high statistical accuracy. Time variations could have affected the line intensities, but it is unlikely that the $n = 4$ line could be weakened as a result, compared with the $n = 3$ or $n = 5$ lines: the X-ray flux over the interval of 7 minutes that the Si xiii $n = 3$–5 lines were recorded declined smoothly and monotonically, as observed by the companion Bent Crystal Spectrometer (BCS) on SMM. Finally, anomalies in the sensitivity over the small wavelength interval in question (e.g., in the crystal reflectivity) are not predicted for this channel.

The other ratio measured—$R_6$—in the remaining flares suggests, though with much worse photon count statistics, that the $n = 4$ line is too strong compared with the $n = 5$. Undoubtedly, time variations do play a part, as illustrated by forward (i.e., increasing wavelength) and reverse wavelength scans in the 1988 July 2 flare, with widely differing ratios as a result. However, the ratios for these and for all other flames are too large to give reasonable temperatures.

IV. DISCUSSION AND CONCLUSIONS

The results of Table 2 for the observations of Walker, Rugge, and Weiss (1974) and Parkinson et al (1978) show that the calculated $R_1$–$R_3$ and $G$ ratios (corrected for unresolved di-electronic satellite lines) lead to temperatures that are expected for the type of emitting plasma observed, or if not, the discrepancy can be easily explained by time variations. The agreement of calculated $G$ ratios with those observed with fully diagnosed tokamak plasmas has in any case already been established (Keenan et al. 1989). Since the photon count statistics are good and the instrumental relative calibrations (with the exception of the PET spectrometer of Parkinson et al.) are reasonably reliable, one may conclude from this that the calculations of the $R_1$–$R_3$ ratios are confirmed by these observations of solar active regions and flares. The measured ratios from the SMM FCS have good statistical accuracy for only one set of observations, that of the decay of a large flare, and for this the $R_3$ ratio agrees with the calculated ratios, but the $R_4$ ratio does not. This would indicate that the calculated ratios lead to too weak an intensity for the $n = 4$ line, but the opposite is true for the several remaining observations, with much poorer statistical accuracy. No ready explanation can be offered, but in view of the inconsistency of these observed ratios and the agreement of the Walker et al. and Parkinson et al. results, it is thought that the problem must lie with the observations of the FCS and that the calculated ratios are essentially confirmed by the solar observations.

For future observations, we believe that the use of the $R_1$–$R_3$ ratios should lead to better determinations of electron temperature than the more familiar $G$ ratio.

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