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Measurements of electron temperature in the solar chromosphere and corona

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The electron temperatures at which the lithium-like ions O VI, Ne VIII, and Mg X are formed in the solar chromosphere and corona were determined in a rocket experiment by measuring the intensity ratio of pairs of emission lines from the same ion. The ratios compared the intensity of the resonance multiplet 2s–2p with the multiplets 2s–3p, 2p–3s and 2p–3d. The theoretical dependence of the three ratios on electron temperature was determined by assuming that the free electrons have a Maxwellian distribution of velocities and that the electron distribution over the excited levels is given by a coronal-type equation. Collisional excitation cross-sections given by Bely and Burke *et al.* were used in the calculation. The experimental temperatures are in fairly good agreement with the theoretical temperatures of the maximum abundance of the ions obtained by assuming ionization balance.

Introduction

This paper describes the results of a rocket experiment having the objective of measuring the electron temperatures in the regions of the solar atmosphere where the ions O VI, Ne VIII, and Mg X are formed. The purpose of the experiment was to obtain an experimental check on the theoretical temperatures of the maximum abundances of the ions which have been calculated by assuming ionization equilibrium (Jordan 1969; Allen & Dupree 1969).

The method used to determine the electron temperature T_e consists of measuring the intensity ratio of emission lines from the same lithium-like ion (Heroux 1964; Schwob 1964). Figure 1, where the emission lines measured in the present experiment are indicated, illustrates the term diagram for a typical ion in this sequence. In general, the separation in energy between the 2p term and the closely spaced 3s, 3p, and 3d terms is large. Because of this large separation, the intensity ratios between the 2s–2p resonance multiplet and any of the three multiplets originating from the 3s, 3p, and 3d terms will be a sensitive function of electron temperature over the temperature range where the ion is formed with appreciable abundance in the solar atmosphere.

To calculate the intensity ratios, it is assumed that the distribution of electron populations over the bound levels of the ion will be given by a coronal-type equation. For this distribution to be valid, the only important excitation process is electron excitation from the 2s ground term to the excited level q, followed by radiative decay from level q. A coronal-type distribution is expected for the higher stages of ionization of the lithium-like ions produced in the solar atmosphere because the electron density is low and the emission lines are optically thin. In addition, the ions do not have metastable levels which could invalidate the coronal distribution.

For a coronal distribution, the rate of photon emission ($cm^{-3}\,s^{-1}$) for the transition between level q and a lower level l having the transition probability $A_{lq}(s^{-1})$ is

$$I(l\text{–}q) = n_e n_{2s} S_{2s,q} A_{lq}/A_q, \tag{1}$$

where n_e is the electron number density (cm^{-3}), n_{2s} is the ground state ion density, $S_{2s,q}$ is the collisional excitation function ($cm^3\,s^{-1}$) which depends upon T_e, and A_q is the total transition probability for level q. For the multiplets shown in figure 1, the branching fractions A_{lq}/A_q are

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either unity or very close to unity. If one assumes that the two emission lines from the same ion are emitted with the same spatial distribution in the plasma, the intensity ratio is then given simply by the ratio of two excitation functions. This assumption can introduce an error in the intensity ratios when the gradient of the electron density is steep in the region of the plasma where the lithium-like ion is formed. The effect of this error on the measurements of T_e in the solar atmosphere will be discussed in a later section.

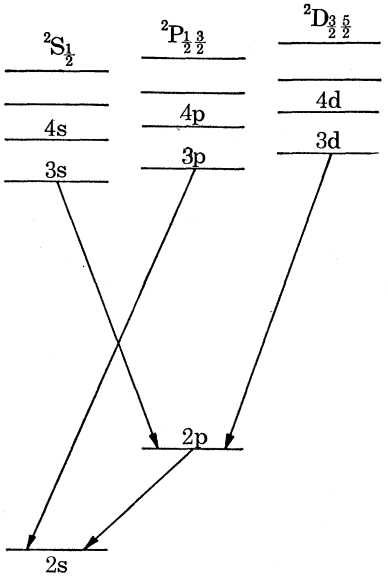

FIGURE 1. Typical term diagram for the lithium-like ion.

The three intensity ratios which are relevant to the present experiment are given by

$$\frac{I(2s\text{–}2p)}{I(l\text{–}q')} = \frac{S_{2s,\,2p}}{S_{2s,\,q'}}, \tag{2}$$

where the transition l–q′ corresponds to one of the optically allowed transitions 2s–3p, 2p–3s, or 2p–3d indicated in figure 1. The ratios are therefore independent of n_e and depend only upon the electron temperature. The collisional excitation function for the transition 2s → q is obtained by evaluating the integral

$$S_{2s,\,q} = \int_{v_{2s,\,q}}^{\infty} Q_{2s,\,q}(v)\, v f(v)\, dv, \tag{3}$$

where $Q_{2s,\,q}$ is the cross-section for excitation by electrons of velocity v, $v_{2s,\,q}$ is the electron velocity corresponding to the threshold energy of the transition, and $f(v)$ is the Maxwell velocity distribution for temperature T_e. The calculations for the particular ratio $I(2s\text{–}2p)/I(2p\text{–}3d)$ are given in figure 2. Similar calculations have been made for the other ratios $I(2s\text{–}2p)/I(2s\text{–}3p)$ and $I(2s\text{–}2p)/I(2p\text{–}3s)$. In the calculations, the cross-sections of Bely (1966*a*, *b*), based upon the Coulomb–Born approximation, were used for the transitions 2s–2p, 2s–3s, and 2s–3d. For the 2s–3p transition, the cross-sections of Bely were modified to make their shapes, close to threshold, conform to the shape of the cross-section of the 2s–3p transition in *NV* calculated by Burke, Tait & Lewis (1966). The latter have shown that the Coulomb–Born approximation grossly underestimates the cross-section of the 2s–3p transition near threshold because of the neglect of the effects of close coupling between the nearly degenerate 3s, 3p, and 3d terms.

The uncertainties in the intensity ratios $I(2s\text{–}2p)/I(2p\text{–}3s)$ and $I(2s\text{–}2p)/I(2p\text{–}3d)$ are estimated

to be 20 % based upon the errors assigned to the theoretical cross-sections. The error for the ratio $I(2s–2p)/I(2s–3p)$ is difficult to establish because of the scaling procedure used for the 2s–3p cross-section near threshold. However, the good agreement between the experimental electron temperatures obtained from the three ratios for both O VI and Mg X (figure 6) would indicate that an estimated error of 20 % for the ratio $I(2s–2p)/I(2s–3p)$ is also reasonable.

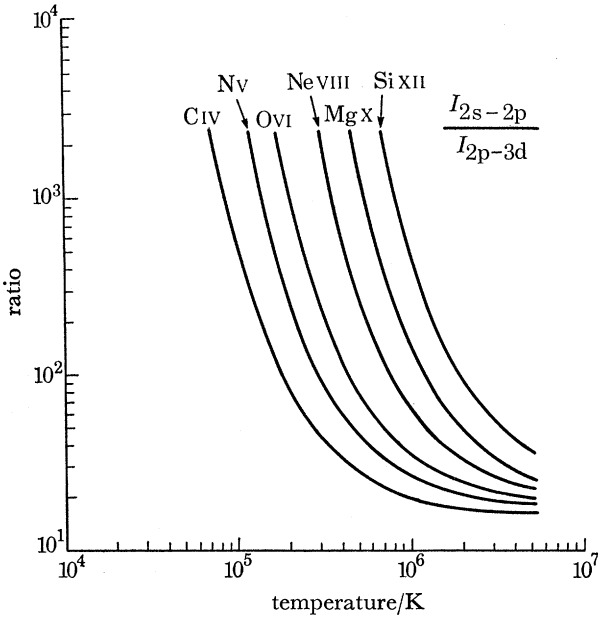

FIGURE 2. Theoretical intensity ratios for the multiplets 2s–2p and 2p–3d.

EXPERIMENTAL TECHNIQUES

(*a*) *The spectrometer*

The present method of measuring electron temperatures introduces the experimental problem of measuring the relative intensities of emission lines widely spaced in wavelength. In planning the experiment, the four ions N V, O VI, Ne VIII, and Mg X were selected for study. The relevant emission lines for these ions are spread over the wavelength region 5 to 125 nm. The 2s–2p resonance multiplets of the ions are strong and at least one component of the multiplet is easily separated in the solar spectrum. The shorter wavelength multiplets from the $n = 3$ level, however, are generally weak and fairly high resolution is required to separate them from neighbouring solar emission lines.

To measure the line ratios during the limited time available in a rocket experiment, a new spectrometer was developed. A schematic of the instrument is given in figure 3. The instrument is similar in many respects to other telemetering monochromators flown by the Air Force Cambridge Research Laboratories (Hinteregger 1961; Manson 1967). The two features of the instrument that are different are the use of two spectrometers in a single casting to cover a wide range of wavelengths and the use of eight exit slits and channeltron multipliers to scan different wavelength regions simultaneously. One deck having a 1200 lines/mm grating covers the wavelength range 5–32.5 nm in which the emission lines from the $n = 3$ levels of the ion fall. Most of this range (5 to 30 nm) was scanned by the four exit slits with some overlap in wavelength between adjacent channels. The entrance slit and four exit slits were matched in width (50 μm) and

produced triangular line profiles having a full width at half maximum intensity (f.w.h.m.) of about 25 pm. The other deck having a 300 lines/mm grating covered the possible wavelength range 20 to 130 nm. The four exit slits on this deck scanned through limited regions of wavelength which bracketed the 2s–2p resonance multiplets. For this deck, the width of the entrance slit was 30 μm and the width of each exit slit 45 μm. The line profiles were 'flat-topped' with a f.w.h.m. of about 80 pm.

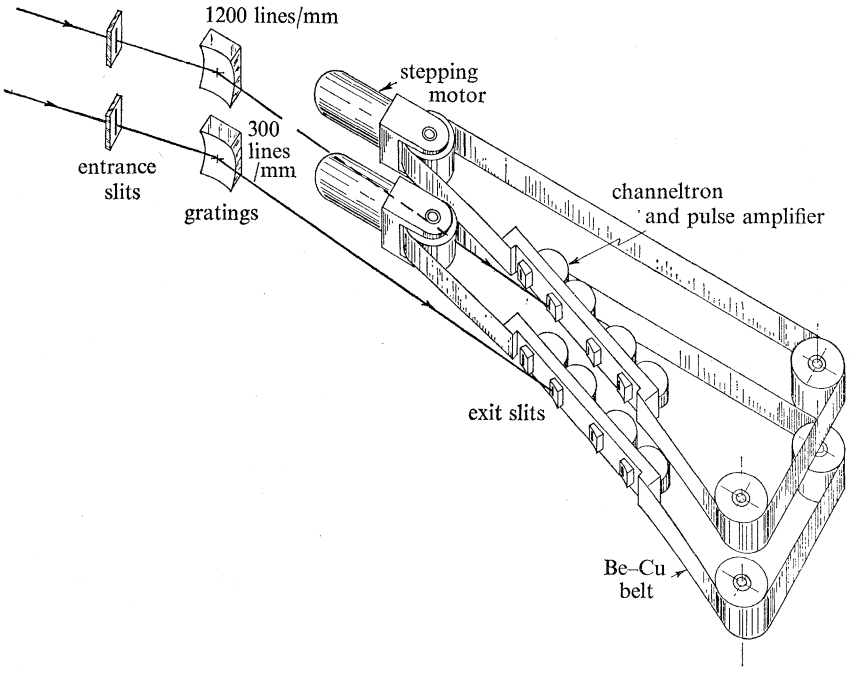

FIGURE 3. Schematic of the rocket spectrometer for measuring the intensity ratios of the lithium-like ions. The possible wavelength range covered by the instrument is approximately 5–125 nm.

Wavelength scanning was accomplished by moving the exit slits and detectors along the Rowland circle in small steps. Counts were accumulated at each position of the slit for 80 ms, the slit moved to its adjacent position, and the cycle repeated. The time required to scan the wavelength range 5 to 30 nm was 128 s. The wavelength drive was programmed before launch to obtain a complete scan in wavelength centred around the peak altitude of the rocket. The time required to scan through the 2s–2p multiplets was 50 s during which one complete scan was obtained very near peak altitude.

The photometric efficiency of the spectrometer was determined in the laboratory at several wavelengths between 4.5 and 123.6 nm by recording the counting rate of the spectrometer when the grating was illuminated with a dispersed photon beam having a known photon rate (Hinteregger 1965). The incident photon beam was measured with a thin-window Geiger–Müller counter (Manson 1967) at four wavelengths between 4.5 and 18 nm, and with a reference tungsten cathode at several wavelengths between 23.7 and 123.6 nm. The calibration was remeasured at 4.5 nm by using undispersed C–K radiation from an X-ray source to illuminate the grating and a proportional counter and multi-channel pulse height analyser to determine the total flux within the emission band (Manson 1967). There was good agreement between the efficiency at 4.5 nm obtained by using dispersed and undispersed radiation. The estimated errors in the photometric calibration were between 15 and 20 % depending upon the wavelength range.

(b) The spectra

Data that are typical for the resonance multiplets of the ions are illustrated in figure 4 which gives a complete spectral scan of the channel that includes the two components $2s\,^2S_{\frac{1}{2}}$–$2p\,^2P_{\frac{1}{2},\frac{3}{2}}$ of Ne VIII. The intensity ratio of the two components of the multiplet would be expected to be 2/1 when the lines are optically thin and when the levels $^2P_{\frac{3}{2}}$ and $^2P_{\frac{1}{2}}$ are populated according to

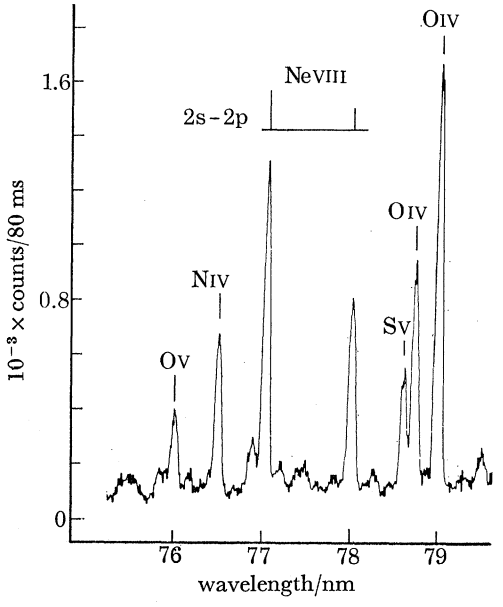

FIGURE 4. A spectral scan through the region of wavelength which includes the 2s–2p multiplet of Ne VIII. The vertical scale gives the counts per 80 ms. The relative intensities of the two components of the multiplet for statistical population of the levels of the upper term are indicated by vertical lines.

their statistical weights. This ratio is observed for O VI and Mg X. The ratio for Ne VIII is somewhat less than 2/1, as can be seen in figure 4, probably because the component Ne VIII 78.032 nm is blended with a fourth-order component of the intense line Fe XII 19.514 nm. Some of the structure apparent in the figure near 76.9, 77.3, and 77.4 nm coincides with the fourth-order components of other intense solar lines of Fe XI and Fe XII. The relatively high background in this channel is due to the hydrogen Lyman continuum.

Spectral scans in the neighbourhood of the multiplets of O VI which originate from the 3s, 3p and 3d terms are illustrated in figure 5. The signals for these same transitions in Ne VIII and Mg X are in general weaker than those for O VI. However, figure 5 illustrates the general features of the short wavelength multiplets. Each plotted point in the figure gives the counts accumulated during an 80 ms interval at one position of the exit slit. The wavelength scale was established by using the grating equation and the positions of two solar lines of known wavelength (not those lines given in figure 5) which fell within the channel. The vertical lines give the wavelength positions of the O VI lines according to Kelly (1968) and the relative intensities of the components of the multiplets for statistical population of the upper terms. The instrumental line widths $\Delta\lambda$ are experimental for a monochromatic emission line which should produce a triangular profile since the entrance and exit slits are matched in width. The unresolved components of the 2s–2p multiplet near 15 nm can be seen to produce a line profile slightly broader than $\Delta\lambda$. The two components of the 2p–3d multiplet are clearly distinguished in the profile near 17.3 nm. The

broad feature near 18.4 nm is assumed to originate from the two relatively widely spaced components of the 2p–3s multiplet. The multiplet is rather weak so that scatter in the data masks the two components of the multiplet. Nevertheless, the observed width for the line profile appears to be correct.

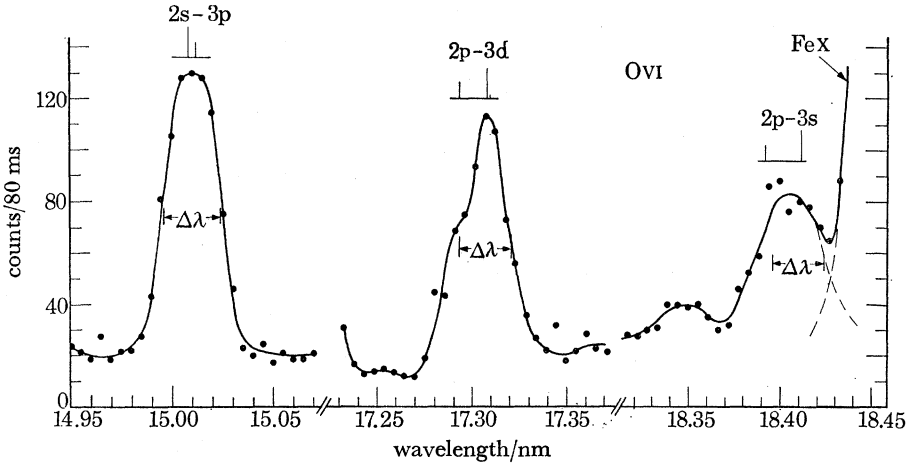

FIGURE 5. Spectral scans through the 2s–3p, 2p–3d, and 2p–3s multiplets of O VI. The instrumental line width (f.w.h.m.) for a monochromatic emission line is indicated by Δλ. The solid lines are used only as a visual aid to connect the measured points.

The data for the 2s–2p resonance multiplets were obtained over an altitude range 246 to 247 km. A correction of 5 and 15 %, respectively, were applied to the data for Ne VIII and Mg X to account for atmospheric absorption of the multiplets (L. A. Hall, private communication). The uncertainties in absolute flux for the resonance multiplets were estimated to be about ± 15 %, this uncertainty being due chiefly to errors in the photometric calibration. The data for the short wavelength multiplets from the $n = 3$ levels of the ions were obtained over an altitude range of 230 to 247 km. The fluxes measured were assumed to correspond to fluxes at the top of the atmosphere. This is probably a safe assumption since atmospheric absorption of the short wavelength multiplets should be negligible at these heights. The uncertainties in the fluxes for the short wavelength multiplets were estimated as about ± 20 % for the intense 2s–3p and 2p–3d multiplets of O VI, shown in figure 5, and about ± 25 % for the remaining multiplets.

THE MEASUREMENTS OF ELECTRON TEMPERATURES

The experimental electron temperatures obtained from the intensity ratios of the ions O VI, Ne VIII and Mg X are given in figure 6. Three ratios were measured for O VI and Mg X and one ratio for Ne VIII. The other two ratios for Ne VIII were not used in the analysis because the 2p–3d multiplet near 9.82 nm is blended with two other emission lines which bracket the multiplet, and the 2s–3p multiplet near 8.81 nm is a possible blend. The errors indicated in the figure do not include possible errors in the theoretical intensity ratios. The latter errors give an additional uncertainty in T_e of about ± 10 % for O VI and ± 20 % for Ne VIII and Mg X. The theoretical calculations of Jordan (1969) for the ionization equilibrium $n(i)/n(E)$ for the ions as a function of electron temperature are also plotted in the figure where $n(i)$ is the ion density in the particular stage of ionization and $n(E) = \Sigma n(i)$ is the total number density of the element. In the calculations for the Sun, dielectronic recombination has been reduced to take account of the variation of

electron density in the solar chromosphere and corona. For the other set of calculations, labelled low density plasma, full dielectronic recombination has been retained. Similar calculations have been made for the low density plasma by Allen & Dupree (1969) and the temperatures T_{max}, corresponding to the maximum abundance of the ion, are nearly the same as those of Jordan.

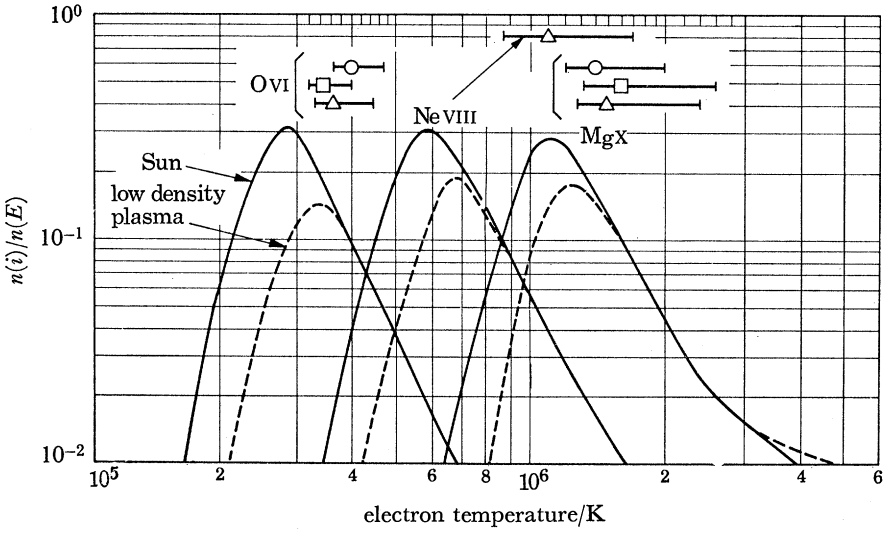

FIGURE 6. The experimental measurements of electron temperature for ions O VI, Ne VIII, and Mg X. The temperatures were obtained from the intensity ratios: ○, I(2s–2p)/I(2s–3p); □, I(2s–2p)/I(2p–3d); and △, I(2s–2p)/I(2p–3s). The indicated errors do not include errors in the calculated intensity ratios. The theoretical values $n(i)/n(E)$ versus T_e of Jordan (1969) are given by the solid and broken lines. For the solid lines, dielectronic recombination has been reduced to take account of the electron density in the solar chromosphere and corona. For the broken lines, full dielectronic recombination has been included in the calculations.

The ratio that is measured in a rocket experiment is an average ratio $\langle R \rangle$ produced by the ions distributed over a range of temperatures. The average ratio is given by

$$\langle R \rangle = \int \frac{n(i)}{n(E)} R(T_e)\, dT_e \Big/ \int \frac{n(i)}{n(E)}\, dT_e, \qquad (4)$$

where $R(T_e)$ is the intensity ratio for the particular ion species. The experimental temperatures plotted in figure 6 were obtained by converting the measured ratio $\langle R \rangle$ to an electron temperature $\langle T_e \rangle$ by using theoretical curves for $R(T_e)$, such as plotted in figure 2, which are assumed to be independent of n_e. To check if the electron temperatures obtained in this manner correspond to the temperatures at which $n(i)/n(E)$ is a maximum, $\langle R \rangle$ can be evaluated for a distribution of ions $n(i)/n(E)$ and converted to $\langle T_e \rangle$ by using the density independent ratios $R(T_e)$. If the distributions of either Jordan or Allen & Dupree are used for $n(i)/n(E)$, it is found that $\langle T_e \rangle$ and T_{max} agree to within about 1 % for the ratios of O VI and to within 3 % for Ne VIII and Mg X. This would indicate that the experimental electron temperatures plotted in figure 6 should correspond to T_{max} for the distribution of ions.

McWhirter, Gabriel & C. Jordan of the Culham Laboratory (private communication) have recently found that if the lithium-like ion is formed in the transition region between the solar chromosphere and corona where the gradient of the electron density is steep, the intensity ratios can depend on n_e. Because of this gradient, the experimental temperatures obtained from the

above procedure may be higher than T_{max}. They investigated this problem by calculating the specific ratio $I(2s–2p)/I(2s–3p)$ for the lithium-like ions produced in the solar atmosphere by using Jordan's values of $n(i)/n(E)$ and a solar model, also by Jordan, which gives the variation of the electron density $\int n_e^2 dh$ with temperature. The model for the electron density was derived from experimental intensity measurements of extreme u.v. emission lines emitted from the entire solar disk on 30 March 1964 during a period of low solar activity. The intensity ratio is given by

$$\frac{I(2s–2p)}{I(2s–3p)} = \int \frac{n(i)}{n(E)} S_{2s,2p} n_e^2 dh \Big/ \int \frac{n(i)}{n(E)} S_{2s,3p} n_e^2 dh, \quad (5)$$

which can be obtained from equation (1) (Pottasch 1964). This ratio of the integrated fluxes of the two emission lines is the quantity that would be measured in a rocket experiment and thus it is similar to $\langle R \rangle$ in equation (4), except that n_e is now retained in the ratio. When this ratio is evaluated and converted to $\langle T_e \rangle$, again by using the temperature independent ratios $R(T_e)$, McWhirter *et al.* find that $\langle T_e \rangle$ is about 30 % greater than T_{max} for O VI, about 10 % greater for Ne VIII, and essentially the same for Mg X. For their solar model, the discrepancy is largest for O VI because that ion is formed in the upper part of the transition region where the gradient of n_e is still appreciable.

The reason for the temperature dependent intensity ratios in the solar atmosphere is that the flux emitted by the higher excitation 2s–3p multiplet may be enhanced relative to the low excitation resonance multiplet at temperatures considerably above T_{max} for the ion species. This enhancement of the short wavelength multiplet is a particularly important effect for the lithium-like ions because of the high temperature tail in $n(i)/n(E)$. The enhancements of the short wavelength multiplets of O VI in the solar atmosphere have been emphasized previously by Zirin (1968) and by Kozlovsky & Zirin (1968).

Discussion

The measurements of T_e given in figure 6 were obtained from data of 4 April 1969. During the rocket flight, an active region in the northwest quadrant of the Sun was evident from images of the Sun in Hα and Ca–K radiation. The emission lines from the ions studied here are known to be enhanced in active regions (Goldberg *et al.* 1968) where the electron density is significantly greater than in regions of low activity (Noyes, Withbroe & Kirshner 1969). The emission lines measured here without spatial resolution are therefore produced in regions having a considerable variation in electron density.

The experimental values of T_e are in general higher than T_{max} given by the calculations for ionization equilibrium. The experimental values, however, should be corrected for electron density variations in the solar atmosphere which will bring them into better agreement with T_{max}. Accurate corrections cannot be applied since this would require detailed knowledge of the electron density in the region of the solar atmosphere where the ion is formed. If the density gradient where O VI is formed is assumed to be similar to that given by the solar model used by McWhirter *et al.* in their calculation, the experimental temperatures for O VI should be reduced by about 30 % which would bring them into good agreement with T_{max}. For low solar activity, the calculations of McWhirter *et al.* indicate that only a small correction is necessary for Ne VIII and a negligible correction for Mg X. Because the flux from these ions is enhanced over active regions where the electron density is known to increase significantly, a correction should probably

also be applied to the experimental temperatures for Ne VIII and Mg X. For Mg X, only a small correction (30 % or so) would be required to bring T_e and T_{max} into fairly good agreement. The experimental value of electron temperature for Ne VIII is a factor of about two greater than T_{max} predicted by ionization balance. This rather large discrepancy may be due to the enhancement of the 2p–3s multiplet of Ne VIII relative to the 2s–2p multiplet. However, this is difficult to say with certainty because the measurement for Ne VIII is based upon a single ratio only in which the 2p–3s multiplet is weak. Any blending of the 2p–3s multiplet with other solar lines would also shift the experimental values of T_e toward a higher temperature.

In summary, the experimental values of electron temperature for O VI and Mg X are in fairly good agreement with the calculated temperatures of maximum abundance of the ions obtained by assuming ionization equilibrium. The difference of about 30 % between the experimental and calculated temperatures can be explained by density gradients in the region of the solar atmosphere where the ion is formed. The agreement between the experimental and theoretical temperatures for Ne VIII is not as good as for the other two ions. Part of the discrepancy, a factor of about two, may be due to a density gradient in the active regions of the Sun and part due to blending of the 2p–3s emission line which was used to form the intensity ratio.

We wish to express our appreciation to R. W. P. McWhirter, A. Gabriel and C. Jordan of the Culham Laboratory for making available their unpublished results concerning the effect of electron density on the intensity ratios of the lithium-like ions. T. J. L. Jones, while on leave of absence from Culham Laboratory, set up the laboratory facilities for the photometric calibration of the instrument and participated in its initial testing. We would also like to thank our co-workers at Air Force Cambridge Research Laboratories for active support of the experiment.

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