CLM-P711

CLM-P711

UKAEA

Preprint

ELECTRON DENSITIES OF SOLAR FLARES FROM INTENSITY RATIOS OF n = 2-2 TRANSITIONS

K. D. LAWSON
N. J. PEACOCK

CULHAM LABORATORY
Abingdon Oxfordshire

1983

CLM-P711

ELECTRON DENSITIES OF SOLAR FLARES FROM INTENSITY RATIOS OF n = 2-2 TRANSITIONS

K D Lawson* and N J Peacock

Culham Laboratory (Euratom/UKAEA Fusion Association)
Abingdon, Oxon, OX14 3DB, UK

ABSTRACT

Electron densities of the high temperature ($\sim 10^7$K) components of solar flare plasmas are calculated from the spectral line intensity ratios of appropriate n = 2-2 transitions. The transitions used are listed in a recent review of solar observations identified with the n = 2-2 transitions of the elements of the fourth period of the periodic table (Lawson and Peacock 1983). The special attention given to spectral line blending in this review and the careful application of the theory in the present calculations so as to minimise errors are expected to result in the most reliable measurements of electron densities using these transitions to date. The results of the calculations suggest electron densities of about 10^{12} - 10^{13}cm^{-3}.

This study illustrates the usefulness of the n = 2-2 transitions for this measurement. It, also, clearly demonstrates the need for observations having the highest possible spectral resolution, especially in the spectral region around a wavelength of 100Å.

Submitted to Astronomy and Astrophysics

*Present address: Department of Applied Physics, University of Hull, Hull, HU6 7RX, England.

November, 1982

1 INTRODUCTION

The n = 2-2 transitions of elements in the fourth period of the periodic table are of particular interest, since their observation enables plasma parameters to be measured in the high temperature coronal and flare plasmas. These parameters include electron densities (Dere et al 1979), differential emission measures (Dere and Cook 1979), ion temperatures and mass motions (Cheng et al 1979).

The present study considers the measurement of electron densities from the spectral line intensity ratios of the n = 2-2 transitions. A recent review of the n = 2-2 transitions of fourth period elements (Lawson and Peacock 1983) listed all solar observations of these transitions, paying special attention to spectral line blending; this listing forms the basis of the study.

The necessary theoretical data is already available in publications such as Mason et al (1979). These publications show that the electron densities for which ratios of the n = 2-2 transitions likely to be observed in solar plasmas are sensitive include those expected in the solar corona and flares. For example, ratios of the n = 2-2 transitions in iron, are generally, dependent on density in the range 10^{10} to $10^{15}cm^{-3}$. They, therefore, provide an excellent means of diagnosing the high temperature components, $\sim 10^7$K, of coronal and flare plasmas.

An advantage of using line intensity ratios to determine the electron density is that the measurement of absolute line intensities is unnecessary. Further, when transitions in the same ionisation stage are used, there is no need to estimate the volume of the emitting plasma. This is especially difficult for structures which are comparable in size to the spatial resolution of the observing instrument. Both absolute intensity measurement and the determination of the plasma volume are sources of error in previous methods, the most frequently used being to obtain the electron density from the volume emission measure (Mariska et al 1979).

In applications which involve the use of spectral line intensities, a knowledge of the blending of the lines is of the utmost importance. It should be emphasised that there is still significant blending, despite most of the lines considered in the present analysis falling in a window of the quiet sun spectrum. The window extends from 145Å to shorter wavelengths; the region where the majority of n = 2-2 transitions of iron are found lies between 90 and 165Å. Those quiet sun lines present, however weak, and particularly active sun lines which appear in this spectral region will be enhanced in solar flare spectra. Consequently, a significant number of the n = 2-2 transitions are blended, both with enhanced lower temperature lines and with other n = 2-2 transitions. This is especially so in photoelectrically recorded spectra, whose spectral resolution is lower than that which can be achieved on photographic records.

The use of the review of Lawson and Peacock (1983), in which special consideration is given to blending, together with a careful application of the theory so as to minimise errors, is expected to result in the most reliable measurements of electron densities made using the n = 2-2 transitions in iron to date.

2 CALCULATION OF ELECTRON DENSITIES

The observations used to calculate the electron densities are given in the review of Lawson and Peacock (1983). Data from only two experiments are found to be appropriate, having accurate intensities given for observations of suitable transitions. The data used are reported by Kastner et al (1974), the only authors to present solar flare spectra in the wavelength range 66 to 171Å, and by Widing (1978), who has made a study of the high temperature lines in the range 320 to 600Å observed with the NRL Apollo Telescope Mount spectroheliograph (S082A) on Skylab. Many of the other authors whose results are reviewed only give intensity estimates.

Only two of the observations given by Widing can be used to calculate densities. These are of nitrogen-like magnetic dipole transitions in iron. Their intensities are derived from a photographic record of the flare on 17 December 1973 and are, therefore, time-integrated.

In contrast, the spectra of Kastner et al were recorded using a photomultiplier. This detector scanned the spectrum from low to high wavelengths, taking 3 minutes to cover the spectral range of interest. It should be noted that, even during the slow decay phase of a flare, the plasma conditions could alter within this time. It might be expected, therefore, that densities derived from widely separated lines in the spectrum will have a greater uncertainty than those from neighbouring lines.

The possibility was considered of obtaining a relative intensity calibration for the spectra of Kastner et al, by using branching ratios of emission from the same upper energy levels. However, there was an insufficient number of unblended transitions to enable this to be done. Providing transitions from a number of different ionisation stages were used, such a calibration would have allowed for the changing plasma conditions and the variation of the efficiency of the spectrometer with wavelength, which is not given.

In the following analysis, data from the two strongest flares observed by Kastner et al are used. These occurred on 25 February and 12 March 1969 and are denoted by the letters B and E, respectively. More limited data for some other flares is given, but no suitable ratios can be determined for these flares.

The line ratios used to calculate electron densities are listed in Tables 1 to 4. The ratios are between transitions in the OI to BI isoelectronic sequences, in all cases in iron. The tables also give the resulting electron densities, together with a mean density where appropriate. All densities, measured in cm^{-3}, are presented both in the tables and in the text in terms of their logarithm to the base 10.

The reasons for the intensity ratios varying with electron density can be understood when the excitation mechanisms are considered. Ions are excited to higher states, mainly, by electron collisions. The level population is determined by the equilibrium between this excitation and de-excitation by both electron collisions and the spontaneous emission of radiation. Clearly, the electron collisional rates are strongly dependent on the electron density and, consequently, at low densities the populations are similarly dependent. At high densities, the collisional processes are so fast, that the populations tend to values determined by the statistical weights of the levels; this happens to the populations in the lower energy levels first. If an intensity ratio is considered between transitions from a higher and a lower energy level, the ratio will usually be a function of density, for a particular range of densities.

Despite the above model's simplicity - it only includes two of the atomic processes governing the level populations - it can give results that are in reasonable agreement with those of more sophisticated models. In addition to the inclusion of the necessary physical processes, another factor affecting the accuracy of the model is the number of configurations considered. Results from a simple model (Feldman et al 1980), including electron collisional excitation and de-excitation and spontaneous radiative decay between levels within the $2s^n2p^k$ configurations, are used in the present analysis of Fe XIX transition ratios. For this ionisation stage, blending makes a reliable determination of density impossible; the model is more than adequate for the illustrative calculation given.

In the other sequences, more sophisticated models are used. The atomic processes included are electron and proton collisional excitation and de-excitation in the ground configuration, electron collisional excitation from the ground to excited configurations and spontaneous radiative decay from all levels. For Fe XXI, photoexcitation between levels of the ground configuration was considered (Mason et al 1979). A 6000K photospheric radiation field, with an appropriate dilution factor, was included in the model; however, this did not affect the level populations in the density regime considered.

The number of configurations included in the calculations varied. The simplest calculation is for Fe XX (Bhatia and Mason 1980). This includes the three configurations $2s^22p^3$, $2s2p^4$ and $2p^5$. In contrast, that for Fe XXII (Mason and Storey 1980) is the most complex, considering three different sets of configurations. Energy levels and radiative data are calculated for all three sets. However, because of the extreme demands placed on the computational facilities by the larger sets, collisional data is found using only the three $2s^n2p^k$ configurations. In addition, electron collisional excitation followed by cascading from a number of configurations was included in the final statistical equilibrium equations to study the effect on the $2s^22p\,^2P_{3/2}$ and $2s2p^2$ level populations.

Both Mason et al (1979) and Mason and Storey (1980) note that there is only a small change in the level populations with temperature over the range for which there is a significant abundance of Fe XXI and Fe XXII ions, respectively. Further details of the calculations can be found in these references and in Mason (1975).

2.1 Ratios of Fe XIX transitions

The theoretical line intensity ratios for Fe XIX are calculated from data given by Feldman et al (1980). These authors list transition probabilities and level populations for three electron densities, 13.2, 13.6 and 14.0. The ratios of the products of the probabilities and populations give the required intensity ratios. Despite the limited range for which the populations are listed, appropriate to tokamaks rather than solar plasmas, the data has proved to be sufficient.

The analysis for this ionisation stage emphasises the need for the correct choice of transition ratios. In the spectra observed by Kastner et al (1974), 6 positive identifications can be made with Fe XIX transitions, all being within the $2s^22p^4\,^3P$ - $2s2p^5\,^3P$ multiplet. However, ratios of transitions from the $2s2p^5\,^3P_{1,2}$ levels are found to be insensitive at densities between 13 and 14, the variation being less than the experimental errors; any significant variation would be expected to occur at lower electron densities.

The transition from the other $2s2p^5\,^3P$ level, the $^3P_1$ - $^3P_0$ transition is observed and all ratios of ^3P - $^3P_{1,2}$ transitions with the former are found to be sensitive, within the range of densities given by Feldman et al. It should be noted that, if ratios had only been considered with the strongest Fe XIX transition, the $^3P_2$ - $^3P_2$ transition, only one density sensitive ratio would have been found, instead of five.

The reason for the density sensitivity of ratios with the $^3P_1$ - $^3P_0$ transition is probably due to the poorer coupling of the $2s2p^5$ $^3P_0$ level, as compared with the other $2s2p^5$ ^3P levels, with the levels in the ground configuration. Transitions from the higher energy $2s2p^5$ $^1P_1$ level also form density sensitive ratios with those from the $2s2p^5$ $^3P_{1,2}$ levels.

A difficulty arises in that the $2s^22p^4\,^3P_1$ - $2s2p^5$ $^3P_0$ transition is blended, in the spectra of Kastner et al, probably with the Ne VII, $2s2p$ $^3P_2$ - $2s3d\,^3D_3$ transition at 106.19Å. The calculated electron densities, listed in the middle columns of table 1, are, consequently, expected to be too high. The results of a second calculation, in which it is arbitrarily assumed that both components of the blend have equal intensities, are given in the final columns of this table. It can be seen that this modification reduces the mean densities for flares E and B from 13.6 and 13.9 to 13.1 and 13.3, respectively.

Widing (1978) lists two solar observations identified with Fe XIX, magnetic dipole transitions. However, he notes that the intensity of the longer wavelength observation is spuriously low, because of image aberrations, and a comparison with theory confirms this. Nevertheless, future observations of these transitions will be useful for density measurements, particularly as they occur in a different wavelength region from the resonance transitions.

2.2 Ratios of Fe XX transitions

The theoretical data for Fe XX is presented by Bhatia and Mason (1980) in the form of intensity ratios. They are given for a wide range of densities, from 11.0 to 15.0.

Six identifications in the $2s^22p^3$ - $2s2p^4$ transition array are made with the solar observations of Kastner et al (1974). Two of these, the $^2D_{5/2}$ - $^2P_{3/2}$ and $^4S_{3/2}$ - $^4P_{5/2}$ transitions cannot be used because of blending with stronger transitions. It should be noted that another three of these observations may be blended. The other components are expected to be weak, although this could be a possible source of error.

An estimate of the likely size of errors can be made by comparing the theoretical and observed intensity ratios that are insensitive to electron density. With the available observations in this ionisation stage, this comparison can be made for only one ratio, the $^4S_{3/2}$ - $^4P_{3/2}$/ $^4S_{3/2}$ - $^4P_{1/2}$ ratio. The logarithms of the observed intensity ratio are 0.0 and 0.14, respectively, for flares E and B, as compared with a theoretical value of 0.27. If a similar error is then assumed in the intensity ratios used to calculate the electron densities, it leads to an error in the densities of about 0.3.

Of the other intensity ratios, those between the $^4S_{3/2}$ - $^4P_{1/2,3/2}$ and $^2D_{5/2}$ - $^2D_{5/2}$ transitions show a significant variation throughout the range of densities for which data is available, whereas the range over which the $^4S_{3/2}$ - $^4P_{1/2,3/2}$ / $^2D_{3/2}$ - $^2D_{3/2}$ intensity ratios are sensitive is more limited. The $^2D_{5/2}$ - $^2D_{5/2}$ / $^2D_{3/2}$ - $^2D_{3/2}$ ratio only varies with density below values of 12.

The electron densities determined from the first four density sensitive ratios are given in table 2 for the two strongest flares E and B which are observed by Kastner et al. The mean electron densities are 13.0 and 12.8, respectively. The standard deviations of the results are both 0.3; this is the same value as the estimated error determined assuming the same error in the intensity ratios as is found for the insensitive intensity ratio.

The variation of the intensity ratio of the $2s^22p^3(^4S_{3/2}$ - $^2D_{3/2})$ and $2s^22p^3(^2D_{3/2}$ - $^2P_{3/2})$, magnetic dipole transitions extends throughout the range of interest. Widing (1978) gives intensities for both transitions and the resulting electron density is 12.1. It should be noted that Widing expects the intensities of lines in this part of the spectrum to be underestimated due to image aberrations, this error increasing with wavelength. This would lead to an overestimation of the density. However, the two lines are adjacent in the spectrum and the effect is not thought to be serious.

2.3 Ratios of Fe XXI transitions

The theoretical intensity ratios of Fe XXI transitions are listed by Mason et al (1979) for densities ranging from 11.0 to 15.0. Despite the number of identifications made with Fe XXI transitions in the spectra of Kastner et al (1974), only five can be used in the present analysis; this is because of line blending. Even two of these five, the $2s^22p^2\,^3P_1$ - $2s2p^3\,^3D_{1,2}$ transitions, are blended with each other. However, these transitions can still be used to calculate densities, since knowledge of the branching ratios allows the relative intensities of the components of this blend to be found as a function of density.

Among the possible ratios of observed transitions, those with a transition from the $2s2p^3\,^3D_1$ level are found to be sensitive throughout the range for which data is available. The $2s2p^3\,^3D_1$ level is the lowest triplet level in this configuration and is strongly coupled to the ground level.

The calculated electron densities are given in table 3. Only one measurement is possible for flare E, this resulting in a density of 12.3. For flare B, a mean logarithmic density of 11.7 is found, the standard deviation being 0.3, the same as for the densities calculated using Fe XX transitions.

A further indication of the likely size of errors can be found by comparing the theoretical and observed intensity ratios that are insensitive to density. This is the case for the $^3P_2$ - $^3P_2$ / $^3P_2$ - $^3D_3$ ratio. The logarithm of the theoretical intensity ratio is 0.22, whereas that for the observations is -0.12. This discrepancy suggests an error of about 0.4 in the electron density, a value, again, comparable to the standard deviations.

2.4 Ratios of Fe XXII transitions

With the available data, only two intensity ratios of Fe XXII transitions are found to be of use in measuring electron densities. This is, partly, because only four Fe XXII transitions within the $2s^22p$ - $2s2p^2$ multiplet can be positively identified with observations made by Kastner et al (1974). Of these, one, the $^2P_{3/2}$ - $^2P_{3/2}$ transition, is thought to be blended, but, in any case, is not of use, and a second, the $^2P_{1/2}$ - $^2S_{1/2}$ transition, might be blended.

The theoretical data is listed by Mason and Storey (1980) for densities within the range 12.0 to 15.0. Among the possible ratios of observed transitions, the $^2P_{1/2}$ - $^2S_{1/2}$ / $^2P_{3/2}$ - $^2D_{5/2}$ and the $^2P_{1/2}$ - $^2D_{3/2}$ / $^2P_{3/2}$ - $^2D_{5/2}$ ratios are found to be sensitive to electron density throughout this range.

Some of the other intensity ratios are dependent on density, but to a lesser extent. Clearly, the most reliable density measurement will be obtained when there is a large variation in the intensity ratio with density. The variation of these other ratios is thought insufficient for them to be used, being only two of three times the estimated error over a density range of three orders of magnitude.

The $^2P_{1/2}$ - $^2S_{1/2}$ / $^2P_{1/2}$ - $^2D_{3/2}$ intensity ratio is insensitive and has, therefore, been used to estimate the likely error. This is 0.15 in the logarithm of the intensity ratio, corresponding to an error of about 0.2 in the electron densities. The calculated electron densities are presented in table 4, the mean densities being 13.2 and 13.1 for, respectively, flares E and B.

3. DISCUSSION

The results given in table 1, obtained using the Fe XIX transitions, are not considered reliable, because of the blending of the $2s^22p^4\ ^3P_1$ - $2s2p^5\ ^3P_0$ transition. They are presented to illustrate the need for the correct choice of ratios and to demonstrate the usefulness of these transitions for measuring electron densities, given a well-resolved spectrum. That the calculated densities are high is shown by arbitrarily choosing the two components of the blend to have equal intensities. It is interesting to note that this sharply modified intensity only reduces the calculated densities by about 0.6, to values similar to those obtained using the nitrogen- and boron-like transitions observed by Kastner et al.

The electron densities calculated using the Fe XX to Fe XXII transitions, listed in tables 2-4, range over more than an order of magnitude. It must be supposed that this range is an indication of differing plasma conditions or is simply due to errors in the measurements and theoretical models.

Two of the nitrogen-like transitions used are observations of a different flare from those observed by Kastner et al (1974). These observations are of the magnetic dipole transitions reported by Widing (1978). Although the resulting density, 12.1, is expected to be of a similar magnitude to those calculated from the observations of Kastner et al, no detailed comparison can be made. The latter observations result in densities of about 13.0, when ratios of nitrogen- and boron-like transitions are taken, and somewhat lower, about 12.0, when carbon-like transitions are considered.

The spectra of Kastner et al were recorded using a scanning spectrometer. A change in the flare conditions during a scan would result in a systematic difference between densities calculated from widely spaced lines in the spectrum and those calculated from neighbouring lines either near the beginning or the end of a scan. No such difference can be found; any change in the plasma conditions must result in a smaller variation than the noted experimental errors. By the same argument, there can be no significant variation in the spectrometer efficiency throughout the wavelength range of interest.

The most significant errors are expected to be in the experimental measurements arising from such factors as additional blended components, scattered light and the intensity calibration and due to inaccuracies in the theoretical models. Two types of inaccuracies in the theoretical models might be supposed. Firstly, individual level populations or transition probabilities may be in error. The standard deviation of the calculated densities would give a measure of these errors, which would be indistinguishable from the random experimental errors. Secondly, all the populations or probabilities for a particular ionisation stage might be over- or underestimated; the theoretical intensities may still form a relatively consistent set of data when compared with observations, but would result in densities which, on an absolute scale, are in error. The latter are more difficult to estimate. Some self-compensation might be expected, since intensity ratios are considered.

The standard deviations are found to be small, typically being 0.3. This is comparable to the errors estimated from insensitive intensity ratios, which, in any case, provide similar information. This value is significantly smaller than the order of magnitude difference between the electron densities calculated from carbon-like transitions and those from nitrogen- and boron-like transitions. A lower density for a plasma region of intermediate temperature to two higher density regions is unexpected, although it should be remembered that the observations of the carbon-like transitions differ markedly from those of the nitrogen- and boron-like transitions. The intensities of the Fe XX and Fe XXII lines were comparable in flares E and B, whereas Fe XXI is almost absent from flare E.

Unfortunately, without more experimental data it is not possible to determine whether the errors are much greater than is indicated by the standard deviations or whether the method, with the presently available theoretical data, is already a very sensitive measure of density. Certainly, the latter possibility would be more acceptable, if the analysis of other sets of observations show a more expected density with temperature behaviour in which the density increases monotonically with temperature, as is illustrated, for example, by Dere and Cook (1979). It is particularly unfortunate that the Harvard experiment planned for the Solar Maximum Mission Satellite had to be cancelled, since this covered the appropriate wavelength range.

In any case, the present analysis suggests electron densities of about 12.0 to 13.0. This is somewhat higher than other measurements of solar plasmas of these temperatures. For example, in plasmas having a logarithmic electron temperature of around 7, typical of the ionisation stages being discussed, Dere and Cook (1979) find the electron density to be between 11.0 and 12.0. The measurements are of the flare observed from Skylab on 9 August 1973. For the same flare, Doschek et al (1977) calculate a density of 11.7 from a density sensitive ratio of Ca XVII transitions.

The present analysis, also, demonstrates the potential of this method for diagnosing the high temperature components of solar flare plasmas. In using the method, the suitability of the observations must be checked, particularly with regard to line blending. All possible intensity ratios should be considered, only those for which there is a large variation in the intensity ratio with density being of interest.

This last criterion limits the usefulness of the Fe XXII ionisation stage, since all but two of the intensity ratios considered had only a weak dependence on electron density or were insensitive. This assumes that the transitions already observed are the most likely ones to be observed with a measurable intensity in future spectra. In contrast, the Fe XX and Fe XXI ionisation stages are of more use, despite the blending of many Fe XXI lines, since ratios of the unblended transitions have a strong density dependence.

The analysis of the Fe XIX ionisation stage highlights the requirements of future experiments designed to measure electron densities and other parameters for which line intensities must be determined. The difficulty in this ionisation stage arises from the blending of the $2s^2 2p^4\ {}^3P_1 - 2s2p^5\ {}^3P_0$ transition. The other component of the blend is thought to be the Ne VII, $2s2p^3P_2 - 2s3d^3D_3$ transition at 106.19Å. If this identification is correct, the wavelength separation of these transitions is 0.13Å. In order to make an accurate measurement of intensity, the spectral resolution must be significantly better than this separation.

This example is not an isolated instance; as is shown in the review, spectral line blending is a serious problem in this spectral region. Consequently, most meaningful information will be obtained from spectra which have the highest spectral resolution. The use of photographic records makes the data retrieval more difficult and the temporal information less accurate than if photodetectors are used. However, in the absence of spectrometers with greatly improved spectral resolution, the most useful spectra for detailed measurements are those recorded photographically.

4. CONCLUSION

Measurements of electron densities from line intensity ratios are presented for the high temperature components of solar flare plasmas. These measurements are thought to be the most reliable available made from observations of the n = 2-2 transitions of iron. They indicate logarithmic electron densities in units of cm^{-3} of 12 to 13. Because of the limited number of solar observations of these transitions made to date, it is not possible to determine to what extent this range of values is an indication of the error in the results or reflects real differences in the emitting plasma.

In either case, the present analysis illustrates the potential of this method when the n = 2-2 transitions of iron are used. It is hoped that it will encourage further observations of the XUV spectrum of solar flares to be made, particularly at wavelengths below 170Å. The study emphatically demonstrates the need for spectra having the highest possible spectral resolution for use in this and other diagnostic applications. For example, a resolution of better than 0.1Å is required at 100Å to allow the Fe XIX, resonance transitions to be used for density measurements.

ACKNOWLEDGEMENTS

We wish to acknowledge the helpful advice given by H E Mason in the early stages of the preparation of this paper.

REFERENCES

Bhatia A K and Mason H E, 1980, Astron Astrophys, 83, pp 380-2.

Cheng C C, Feldman U and Doschek G A, 1979, Astrophys J, 233, pp 736-40.

Dere K P and Cook J W, 1979, Astrophys J, 229, pp 772-87.

Dere K P, Mason H E, Widing K G and Bhatia A K, 1979, Astrophys J Suppl, 40, pp 341-64.

Doschek G A, Feldman U and Dere K P, 1977, Astron Astrophys, 60, pp L11-3.

Feldman U, Doschek G A, Cheng C C and Bhatia A K, 1980, J Appl Phys, 51, pp 190-201.

Kastner S O, Neupert W M and Swartz M, 1974, Astrophys J, 191, pp 261-70.

Lawson K D and Peacock N J, 1983, Submitted to Astron Astrophys.

Mariska J T, Doschek G A and Feldman U, 1979, Astrophys J, 232, pp 929-39

Mason H E, 1975, Mon Not R astr Soc, 170, pp 651-89.

Mason H E, Doschek G A, Feldman U and Bhatia A K, 1979, Astron Astrophys,73, pp 74-81.

Mason H E and Storey P J, 1980, Mon Not R astr Soc, 191, pp 631-9.

Widing K G, 1978, Astrophys J, 222, pp 735-9.

Table 1. Electron densities determined from Fe XIX transitions

Transition	Wavelength	Electron densities flare E	flare B	Modified densities flare E	flare B
$2s^22p^4 - 2s2p^5$					
$^3P_2 - {}^3P_1$	101.55	13.9	14.0	13.3	13.4
$^3P_2 - {}^2P_2$	108.37	13.6	14.2	13.2	13.6
$^3P_0 - {}^3P_1$	110.14	13.6	14.2	13.1	13.5
$^3P_1 - {}^3P_1$	111.80	13.3	13.3	12.9	12.9
$^3P_1 - {}^3P_2$	119.92	13.4	13.7	13.0	13.2
	Mean densities	13.6	13.9	13.1	13.3

The observations are from Kastner et al (1974).
All ratios are with the $2s^22p^4\,{}^3P_1 - 2s2p^5\ {}^3P_0$ transition at 106.28Å.
Wavelengths are in Å.
The logarithms of densities in cm^{-3} are given.
The modified densities allow for the $2s^22p^4\ {}^3P_1 - 2s2p^5\ {}^3P_0$ transition being blended, equal intensities being supposed for the two blended components.

Table 2. Electron densities determined from Fe XX transitions

Transitions	Wavelengths	Electron densities flare E	Electron densities Flare B
$2s^22p^3$ - $2s2p^4$			
$^4S_{3/2}$ - $^4P_{1/2}$ / $^2D_{3/2}$ - $^2D_{3/2}$	118.70 / 110.86	12.7	12.8
$^4S_{3/2}$ - $^4P_{3/2}$ / $^2D_{3/2}$ - $^2D_{3/2}$	121.85 / 110.86	13.1	13.1
$^4S_{3/2}$ - $^4P_{1/2}$ / $^2D_{5/2}$ - $^2D_{5/2}$	118.70 / 113.45	12.8	12.4
$^4S_{3/2}$ - $^4P_{3/2}$ / $^2D_{5/2}$ - $^2D_{5/2}$	121.85 / 113.45	13.3	12.7
	Mean densities	13.0	12.8
	Standard deviations	0.3	0.3
	Estimated error	0.3	0.3

Transitions	Wavelengths	Electron density
$2s^22p^3$ ($^4S_{3/2}$ - $^2D_{5/2}$) / $2s^22p^3$ ($^2D_{3/2}$ - $^2P_{3/2}$)	567.76 / 541.35	12.1

The observations of the resonance transitions are from Kastner et al (1974); those of the forbidden transitions are from Widing (1978).
Wavelengths are in Å.
The logarithms of densities in cm^{-3} are given.
The estimated error is derived using the difference between the observed and theoretical ratios of the density insensitive ratio, $^4S_{3/2}$ - $^4P_{3/2}$ / $^4S_{3/2}$ - $^4P_{1/2}$.

Table 3. Electron densities determined from Fe XXI transitions

Transitions	Wavelengths	Electron densities flare E	Electron densities flare B
$2s^22p^2 - 2s2p^3$			
$^3P_2 - {}^3P_2$ / $^3P_0 - {}^3D_1$	121.17 / 128.74	-	11.5
$^3P_1 - {}^3D_2$ / $^3P_0 - {}^3D_1$	142.18 / 128.74	12.3	12.1
$^3P_2 - {}^3D_3$ / $^3P_0 - {}^3D_1$	145.66 / 128.74	-	11.9
$^3P_2 - {}^3P_2$ / $^3P_1 - {}^3D_1$	121.17 / 142.18	-	11.3
$^3P_2 - {}^3D_3$ / $^3P_1 - {}^3D_1$	145.66 / 142.18	-	11.8
		Mean density	11.7
		Standard deviation	0.3
		Estimated error	0.4

The observations are from Kastner et al (1974).
Wavelengths are in Å.
The logarithms of densities in cm^{-3} are given.
The estimated error is derived using the difference between the observed and theoretical ratios of the density insensitive ratio, $^3P_2 - {}^3P_2 \,/\, {}^3P_2 - {}^3D_3$.

Table 4. Electron densities determined from Fe XXII transitions

Transitions	Wavelengths	Electron densities flare E	Electron densities flare B
$2s^22p - 2s2p^2$			
$^2P_{1/2} - {}^2S_{1/2}$ / $^2P_{3/2} - {}^2D_{5/2}$	117.18 / 155.89	13.1	13.2
$^2P_{1/2} - {}^2D_{3/2}$ / $^2P_{3/2} - {}^2D_{5/2}$	135.73 / 155.89	13.3	13.0
	Mean densities	13.2	13.1
	Estimated errors	0.2	0.2

The observations are from Kastner et al (1974).
Wavelengths are in Å.
The logarithms of densities in cm^{-3} are given.
The estimated error is derived using the difference between the observed and theoretical ratios of the density insensitive ratio, $^2P_{1/2} - {}^2S_{1/2} / {}^2P_{1/2} - {}^3D_{3/2}$.