D. CALIBRATION

https://doi.org/10.1017/S007418090010381X Published online by Cambridge University Press

REVIEW OF METHODS OF INTENSITY CALIBRATION IN THE SPECTRAL RANGE 10–4000 Å

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1. Introduction

In this paper the bases of the various methods of intensity calibration in the vacuum ultraviolet will be examined. The remarks will be directed primarily at the problem of the measurement of spectral intensities from the sun from above the Earth's atmosphere. It is here that the requirements for intensity calibration are most demanding because of the greater sophistication and because the available range of the spectrum is more extensive. For the stars and other distant astronomical objects, hydrogen absorption limits the spectrum to wavelengths longer than about 900 Å although it transmits again in the soft X-ray region. Some reference will also be made to the problem of intensity calibration as it applies to laboratory spectroscopy, particularly where the object of the laboratory work is to measure astrophysically interesting rate coefficients or cross sections.

The wavelength range of this review will be taken as 10–4000 Å, somewhat arbitrarily. This range provides some overlap, with the region where Bragg crystal spectrometers are used and where soft X-ray calibration methods are relatively well established, and also with ground based observations in the visible and near ultraviolet regions. It is in this region where grating spectrometers, either normal, or grazing-incidence are most commonly used as the method of dispersing the radiation.

Before discussing the methods of calibration it is as well to recognize that there are two sides to this problem.

(a) It is necessary to make good measurements of spectral intensities.

(b) It is then necessary to interpret them in terms of one or other of the more fundamental parameters of the solar (or stellar) atmosphere.

Thus the measurements must be made with sufficient accuracy that meaningful interpretation can be carried out, but on the other hand, it is likely to be wasteful of effort to make observations with greater accuracy than the limit set by the accuracy of the theoretical data used in the interpretation. It is also worth noting that in interpreting the relative intensity ratio between two lines, higher accuracy is required than in measuring the absolute intensity. The intensity of a spectral line emitted from a low density plasma, such as the sun's atmosphere is given by the following expression

$$I = \int n_e n_i x \, \mathrm{d}h \,,$$

where n_e is the electron density; n_i is the population density of ground states of the

Labuhn and Lüst (eds.), New Techniques in Space Astronomy, 369–385.

ion responsible for the spectral line; x is the excitation rate coefficient, and the integration is taken through the height h of the atmosphere.

Thus, in principle at least, if one knows the electron density and electron temperature which determines the value of x it is possible to derive values for the abundances of the various ions and elements present. By observing ratios between certain lines, it is possible to derive values for the electron temperature of the appropriate region of the atmosphere. Other line ratios, for ions having a metastable level, can be interpreted in terms of the electron density. It is desirable to derive values for all these quantities with good accuracy but it should be noted that all these interpretations depend upon having good values for the excitation rate coefficient x. The accuracy with which this quantity is known can limit the accuracy with which the parameters are determined. Quantum mechanical calculations and some experimental determinations give values that are considered reliable to between 10% and 20% in a few of the best cases. It would seem therefore that at this stage in time it would be sensible to set $\pm 10\%$ as the accuracy to be aimed at in any rocket or satellite intensity calibration. The accuracy of calibration procedures should therefore be examined with these considerations in mind.

In order to measure a spectral intensity from an astronomical object in the vacuum ultraviolet, it is necessary to (a) calibrate the equipment in the laboratory (b) assemble it on the nose cone of a rocket and propel it into space (c) point it at the appropriate part of the sun or other source (d) measure the signal at the appropriate wavelength and (e) prove that the calibration factor has not changed in the meantime. At each stage care has to be taken. For example, it may be necessary to correct the readings for the absorption due to residual atmosphere. This will be particularly applicable to rockets and in order to make the correction properly, it is desirable to monitor the intensities of selected lines over a fairly large portion of the rocket's trajectory. In recording the signal from the astronomical object, it is important that sufficient photons be detected such that there is no important deterioration in the accuracy of the measurement due to the statistical uncertainty in this number. Most important for satellites is the need to show that the detector sensitivity has not changed between the time of calibration and the time of observation. It is here that rocket-borne equipment has a clear advantage over a satellite in that, given successful recovery of the payload, it may be recalibrated after flight and account taken of any change. For satellites this problem of stability of calibration is most serious with drifts by quite large factors having been recorded. The drifts appear to be associated with detectors which operate in the same vacuum as the spectrometer and are without windows. Progress is being made in this area but a comprehensive review of this work lies outside the scope of this paper. On-board calibration is, of course, one possible way of overcoming difficulties associated with drift of sensitivity. The use of Cerenkov radiation and transition radiation has been suggested in this connection. I should also like to suggest that it may be possible to use the branching ratios method of relative intensity calibration by using the corona of the Sun as the source. Such a calibration method would have a number of advantages but particularly if the object of study was the Sun.

Finally, in this introductory part of the paper, it is of interest to look at the existing measurements and to see how they compare with each other. Claims of between 20% and 30% accuracy have been made for some of the published data but it appears that discrepancies of anything up to a factor of five exist in some spectral regions where agreement is to be expected (some lines vary strongly with solar activity so that it is necessary to take care in making such comparisons). Thus it is not simply a matter of making new measurements with a claimed accuracy of 10% or so but of resolving very much larger discrepancies between existing measurements. One obvious first step in resolving this issue would be to make intercomparisons in the laboratory of the intensity calibrations used by the various observers.

Figure 1 summarizes the ranges of applicability of the calibration methods to be discussed below. In the lower part it indicates the wavelength limits that are relevant to vacuum ultraviolet observations of astronomical objects.

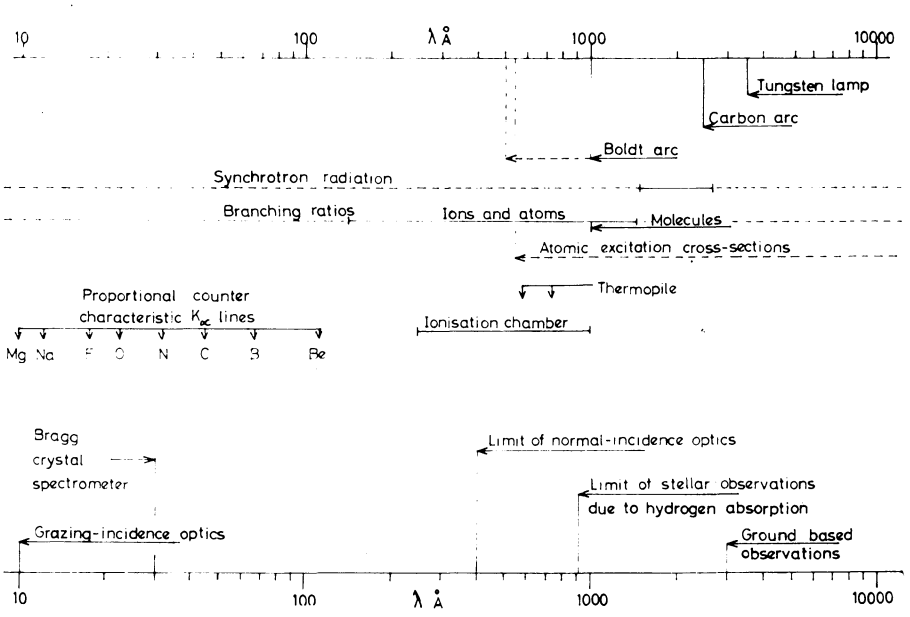

Fig. 1. This diagram indicates the ranges of applicability of the various calibration methods discussed. It also shows some relevant instrumental limitations.

2. Standard Black Body Source, Tungsten Filament Lamp and Carbon Arc

Calibration in the visible and near ultraviolet is done by reference to one or other of these sources. The accuracy of these calibrations falls steeply below 3500 Å because of the small amount of radiation emitted at these shorter wavelengths. In Figure 2 the Planck function is plotted and shows how for a temperature just below the melting point of tungsten the intensity falls off with shorter wavelengths. In order to use this principle at wavelengths below about 3000 Å a source at higher temperature is

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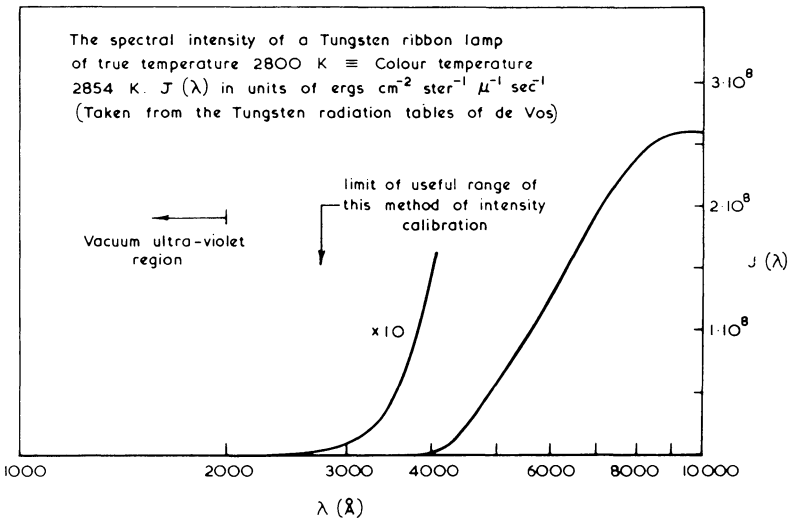

Fig. 2. The 'black body' spectrum of a standard lamp.

required and since materials are no longer solid at these high temperatures the source must be in the plasma state.

3. The Optically Thick Arc

The principle of the Black Body Source has been extended to higher temperatures by Boldt who has built a spectroscopic arc running at a temperature of about 14000 K and close to atmospheric pressure. In this source the particle density and especially the electron density is sufficiently high that the population densities of the atomic and ionic levels present in the plasma are accurately described by the Saha and Boltzmann equations. At the same time the plasma size and density of ground levels is sufficient to ensure that the resonance lines emitted by the plasma are optically thick. Special precautions are taken to ensure that the central dip which often appears on profiles of optically thick lines due to self-reversal does not happen in this case.

A schematic diagram of the optically thick arc is shown in Figure 3. The arc burns predominantly in argon which flows in at the points shown. Once the arc has been established the gas from which the required calibration lines are emitted is introduced at the right hand side and the flow adjusted so that all this gas passes out again from the central part of the arc. Thus the left hand half of the arc burns in pure argon which is thus not able to absorb the resonance lines of the calibration gas. The differential pumping system to the left of the diagram allows the arc to be coupled to a vacuum spectrometer for calibration purposes. The valve at the extreme left is pulsed open for short periods in order to admit the radiation and at the same time avoid having too much gas enter the spectrometer region.

In order to calculate the spectral output of the arc in the optically thick lines it is

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necessary to have an accurate measure of the electron temperature of the region emitting the calibration wavelengths. This has been done by four independent methods whose results agree to within 2%. The four methods are as follows: (a) Stark width of hydrogen Balmer β; (b) Relative intensity of argon I and argon II lines; (c) Absolute intensity of argon I lines; and (b) Absolute intensity of argon I continuum.

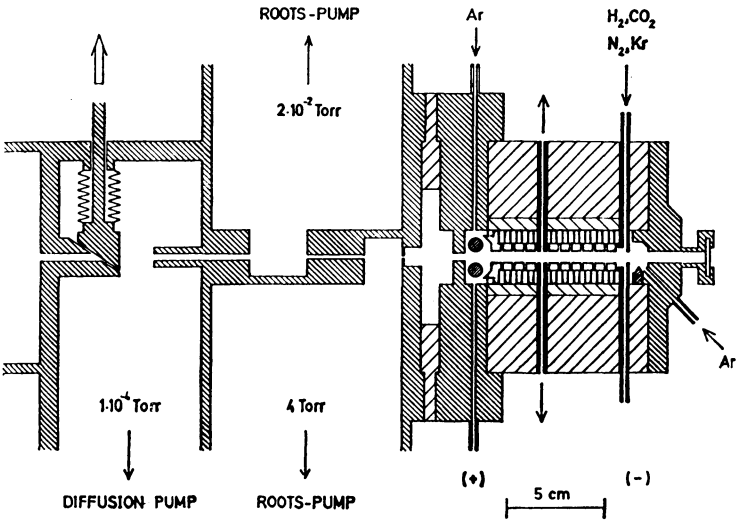

Fig. 3. Schematic diagram of Boldt's optically thick arc.

The fact that such good agreement is found between these methods means that the assumption of the applicability of the Saha and Boltzmann equations is well founded. The uncertainty of 2% in the measurement of the temperature does mean however that the accuracy of the calculated intensities of the calibration line in the region of 1000 Å is about 20%. This is because of the steep variation of the Planck function with temperature at shorter wavelengths. It will be remembered that the temperature appears in the Planck function through the exponential factor.

By making radial observations of the temperature the variation along the axis of the arc has been determined. At the same time by observing one of the characteristic lines of the seed gas the concentration of this has also been determined as a function of position along the arc axis. This is illustrated in Figure 4 which shows that the temperature remains constant up to the point where the concentration (K) of the seed gas falls to a low value. Thus there is no cool gas capable of reabsorbing the resonance line of the seed gas in the region of cooler temperature and hence producing the self-reversal effect which is so important to avoid.

The wavelength of the lines for which calibration has been done are given in Figure 5 which also indicates the uncertainty associated with the calibration at each of these wavelengths. Using this source, calibration is possible in principle down to about 800 Å where argon starts to absorb strongly. In principle, it may be possible to extend

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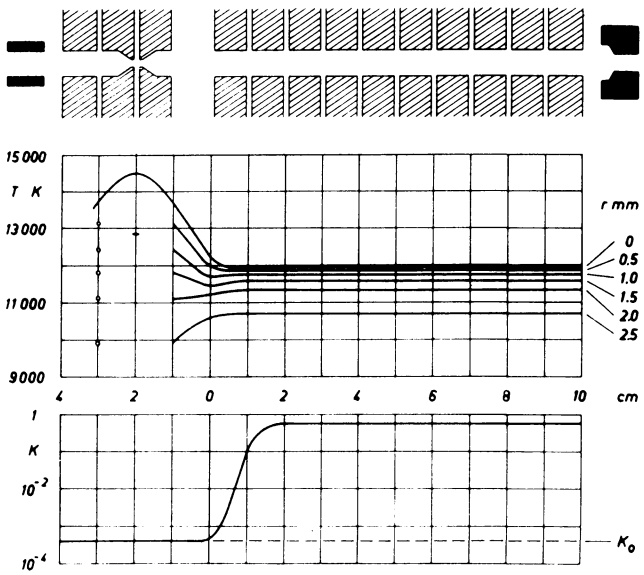

Fig. 4. The measured axial distribution of the temperature and concentration of seed gas in Boldt's optically thick arc.

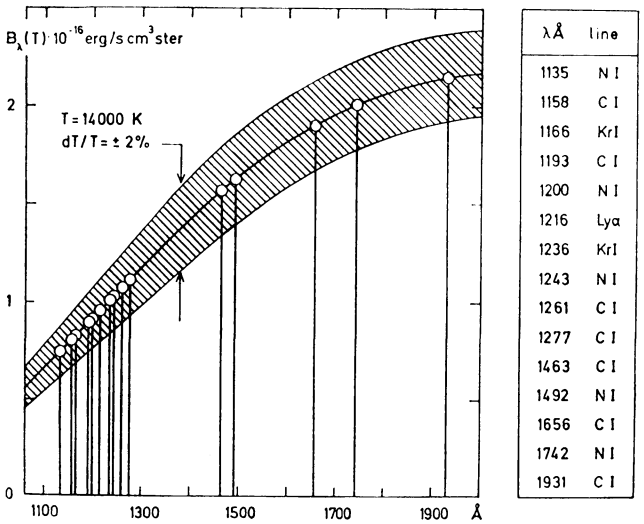

Fig. 5. Wavelengths and intensities of optically thick lines emitted by Boldt's optically thick arc.

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the method down to the ionization limit of Helium I at about 500 Å but the errors in the Planck function curve at these short wavelengths will be even greater.

4. Synchrotron Radiation

The electrons circulating in a synchrotron by virtue of their interaction with the magnetic field radiate a continuum of light that in practise and depending on the characteristics of the machine can extend from the visible down to X-ray wavelengths. The intensity and spectral distribution of this continuum can be calculated exactly from knowledge of the magnetic field and radius of curvature of the electron trajectories. Since these can generally be measured with an accuracy of a fraction of 1%, synchrotron radiation provides an accurate intensity standard over a very wide range of wavelengths. The radiation is strongly polarized and the polar diagram is strongly peaked in the direction of the instantaneous electron velocities. These characteristics coupled with the large cumbersome nature of synchrotron machines introduce a number of practical difficulties in the application of this method. Nevertheless, its unique characteristics make it probable that increasing use will be made of this method in the future.

Figure 6 shows schematically how a synchrotron and a grazing incidence spectro-

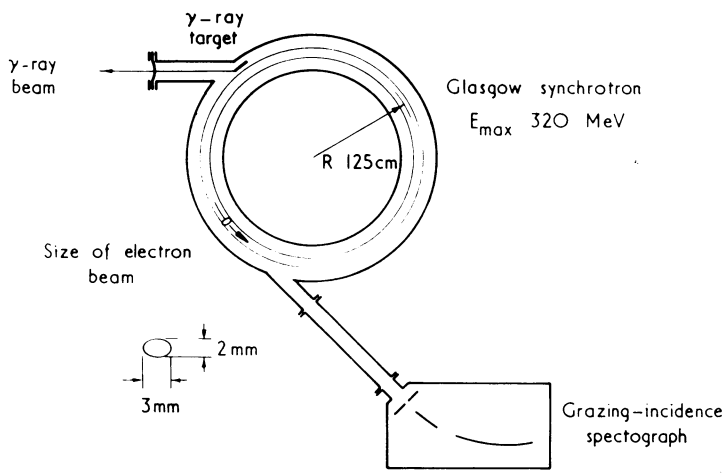

Fig. 6. Schematic arrangements for observing synchrotron radiation.

meter may be set up for calibration purposes. The work can be done without interfering with the gamma-ray beam used for high energy physics experiments. Figure 7 shows the spectral distribution of synchrotron radiation for a machine having a radius of curvature of the electron trajectory of 1.25 m. It may be seen from this figure that the intensity does not depend critically on the electron energy at wavelengths longer than the peak wavelength. Thus the accuracy with which the spectral output may be calculated depends only on the accuracy with which the current of

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circulating electrons can be determined. The best way of measuring this is to measure the intensity of the visible light. By using the same optical arrangements for both the visible and vacuum ultraviolet measurements account can be taken in the calibration procedure of the geometry of the system and the errors from this cause kept to a

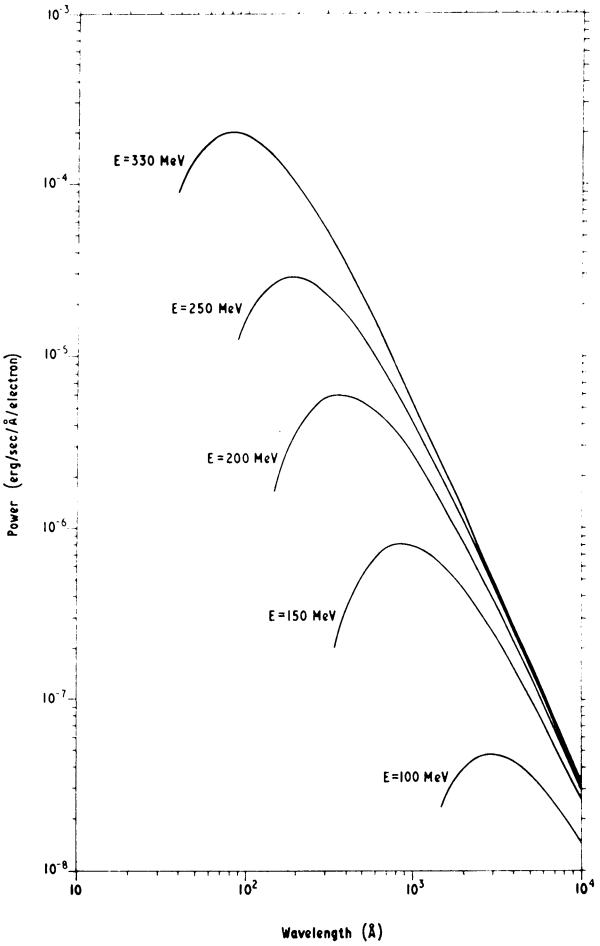

Fig. 7. The spectral distribution of synchrotron radiation from a machine of radius 125 cm.

minimum. With continuum radiation used for calibration purposes difficulties arise because of the effect of higher orders diffracted in grating instruments. This is particularly important with the synchrotron where the spectral distribution shows an increase towards shorter wavelengths and where the wavelength span is so great. To overcome this it is necessary to vary the electron energy in order to suppress unwanted wavelengths. The Figure shows how the spectrum varies with the electron energy. Figure 8 shows how the radiation flux is peaked in the direction of the in-

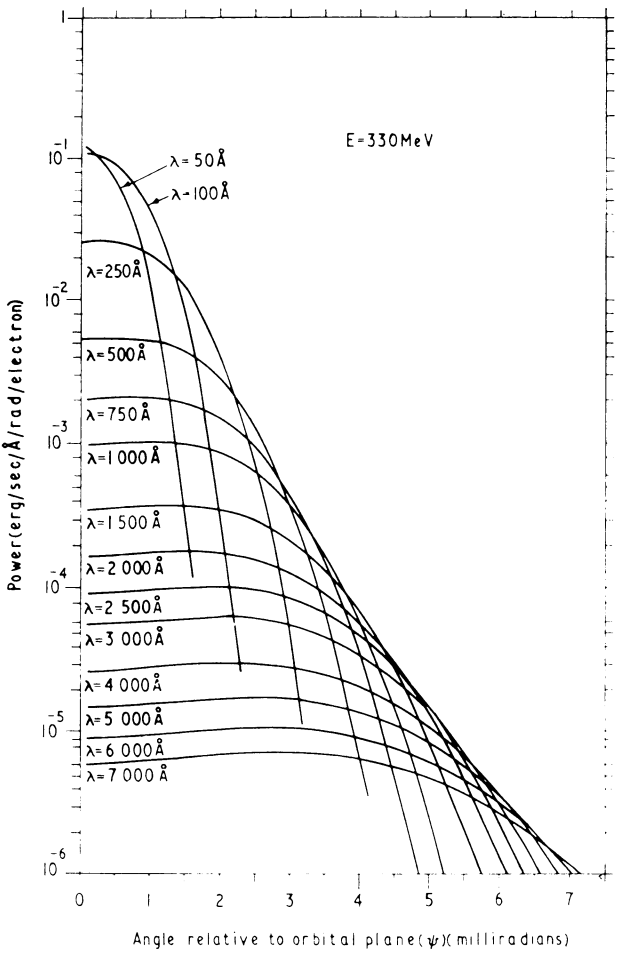

Fig. 8. The angular distribution of synchrotron radiation from a machine of radius 125 cm.

stantaneous electron velocity. It also shows that this distribution is wavelength dependent. Figure 9 shows the polarization characteristics of the radiation and again this distribution is wavelength dependent. In order to take account of the polarization of the radiation in the calibration procedure, the simplest way is probably to rotate the detecting instrument through 90° and in this way measure a mean sensitivity. All these complications coupled with the fact that the source is generally pulsed mean that a tedious amount of computing has to be done to carry out the calibration. To ease this aspect of the problem a computer has been used.

It may be added that the commissioning of the synchrotron storage rings offer some important advantages for the calibration of spectrometers. The first advantage is that the source is steady and the electron energy constant. It seems also that it will be possible with these machines to determine exactly the number of electrons circulating

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in the orbit. This arises because it has been found possible to detect the radiation due to one single electron. Thus these sources could become absolute standards of intensity in a very fundamental sense.

5. Branching Ratios and Excitation Cross Sections

These methods depend fundamentally on the ability to calculate atomic data theoretically. The methods are most readily applicable to laboratory plasma measurements but as these measurements are often carried out to provide fundamental atomic data for the analysis of astronomical spectra it is important to include them in the present review and assess their fundamental accuracy. The branching ratios method has formed the basis of the intensity measurements of the solar lines in the grazing incidence region made by the Culham Group. It has also been suggested in the introduction to this review that this method might be adapted for in-flight calibration of a

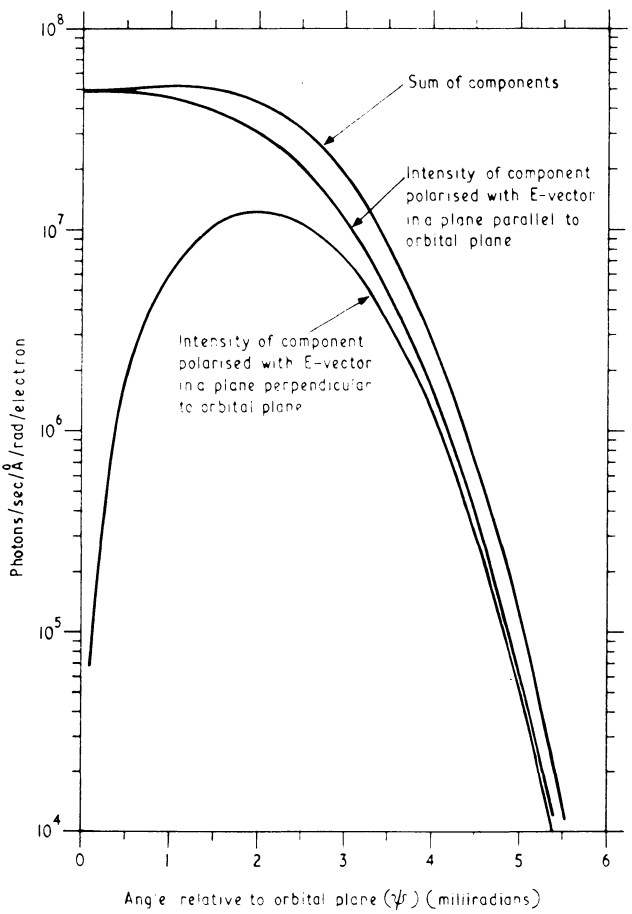

Fig. 9. The polarization of synchrotron radiation for a machine of radius 125 cm.

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solar instrument where the Sun itself is used as the calibration source. In these circumstances it would provide a relative calibration only.

The principle of the branching ratios method is illustrated in Figure 10. It depends on observing two spectral lines arising from the same upper level of some ion of which the transition probabilities may be calculated with good accuracy. For hydrogen and hydrogen-like ions these calculations can be done precisely but for other ions approximations must be adopted. The errors introduced may be quite small and in some cases experimental values are available of sufficient accuracy to be useful. A reasonable

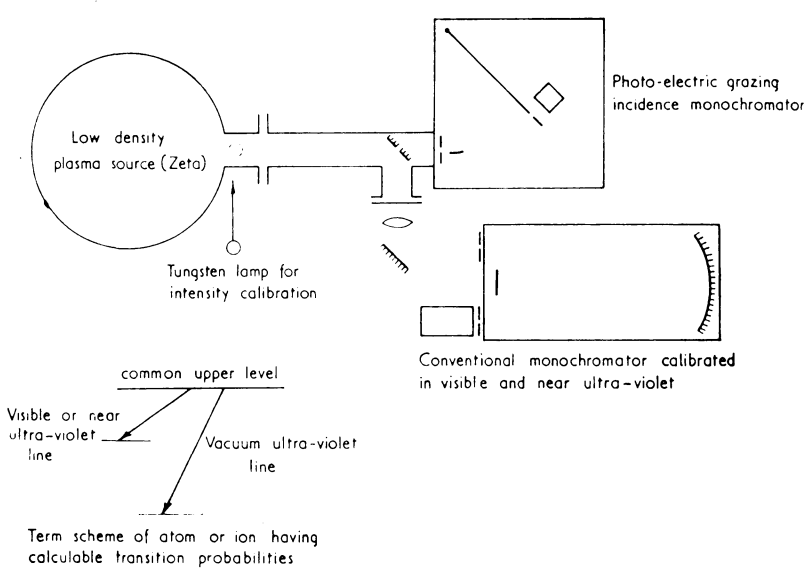

Fig. 10. Diagram illustrating the principle of the branching ratios method of intensity calibration.

number of values are available with an accuracy of 5% or better, particularly for lithium-like ions, whose spectra have turned out to be particularly useful for this calibration purpose. From the transition probabilities, the intensity ratio between the lines may be calculated without any need for assumptions about the mechanism of excitation. In this way the relative calibration between these two wavelengths may be established. If now the absolute intensity of one of the lines can be measured (for example, against a tungsten filament lamp in the visible or X-ray tube in the soft X-ray region) the absolute calibration is established at the other wavelength. By selecting suitable line pairs at various wavelengths a complete calibration may be built up.

Difficulties arise with this method of calibration if the lines are optically thick. This can be tested for experimentally by varying the concentration of the element responsible for the lines and showing there is no change in the ratio. Another problem is the possibility that the fine structure levels are not statistically populated. In order

to establish this point it is necessary to have adequate spectral resolution to be able to measure separately the components of at least one of the line pairs.

An actual calibration which is based on hydrogen-like and lithium-like ions has experimental error associated with the relative calibration of about $\pm 10\%$. This method is particularly suitable for laboratory plasmas, especially if it can be used with the same plasmas as is being studied because in this case many of the geometrical factors cancel out.

The same basic principle has been used for calibration in the region between 1000–3000 Å using molecular lines. Bands of carbon monoxide, nitrogen molecules and hydrogen molecules have been used and the errors arising because of the accuracy of transition probabilities have been estimated to be about $\pm 30\%$.

The transfer of this calibration to other sources has been done but in this case the uncertainties rise to about $\pm 50\%$. This happens mainly because of the difficulty of taking account of the geometry of the optical arrangement including for the very short wavelength lines the grazing incidence optics.

The second calibration method that depends on the calculation of atomic data, is that which relies on theoretical excitation cross-section calculations. In this case the calculations are less reliable and there is none that can be done precisely. However, for electron energies that are very much greater than threshold for the process the Born approximation has been shown to yield results that are reliable to 10% or 20% for a few of the simplest ions and atoms. This method has been used in crossbeam experiments to measure excitation cross sections.

6. Calibration Methods Depending on the Use of Standard Detectors

The most direct way of measuring a spectral intensity from an unknown source is by using a standard source which may be substituted for the unknown source. In the vacuum ultraviolet and especially when making astronomical observations this procedure is never straightforward and it becomes worthwhile to consider the alternative of basing the calibration upon standard detectors. Most of the measurements of solar intensities by the Naval Research Laboratory in Washington and the Air Force Cambridge Research Laboratory have been based on such calibration methods. There are two such detectors (a) thermal detectors and (b) detectors depending upon the ionization of gases. These will now be considered.

7. Thermal Detectors

These are devices like the thermopile which absorb all the radiation falling upon them and as a result are heated. A measure of their temperature rise gives a measure of the amount of radiation absorbed. The relationship between the temperature rise and the energy absorbed may be determined by heating the detector with a measured amount of energy under controlled conditions. This energy may be supplied either electrically with the help of a little heater coil or by using a standard lamp in the visible region of

the spectrum. It is essential for the success of this method that all the radiant energy falling on it must be absorbed by the detector. In general in the vacuum ultraviolet materials are less reflecting than in the visible and little trouble arises because of reflectivity. However a new difficulty arises in this spectral region because of the possibility of photoelectric emission at wavelengths shorter than the work function of material. This problem has been studied by Madden who has measured the energy loss from the detector by photoelectric emission. The results of his measurements are shown in Figure 11. He has also shown that by the proper application of electrostatic or magnetic fields, it is possible to return the photoelectrons to the surface and in this way to eliminate the energy loss.

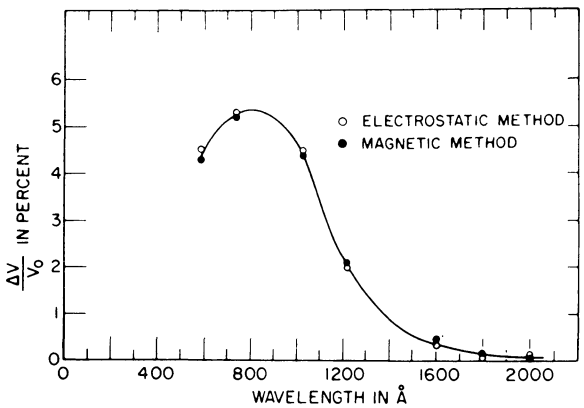

Fig. 11. The percent increase in thermopile signal achieved by returning the photoejected electrons to the detector, as a function of wavelength in the far ultraviolet. The results of the electrostatic method and the magnetic method are compared. The solid line merely connects the experimental points.

The major difficulty with this calibration method is the poor sensitivity of the detector system. It has been possible to make measurements with good accuracy at only a few ultraviolet wavelengths. However, it has been used to make comparison with the ionization chamber in a measurement which is of great importance in establishing the validity of this other calibration method. This comparison measurement is referred to again in the next section of this paper.

8. Methods Depending on the Ionization of Gases

When a photon enters a gas it causes photoionization if it has more energy than the ionization potential of the atoms. By measuring the ionization current a measure of the incident photon flux is obtained. For this to be an absolute method the relation between the flux and the current must be known. The consideration of the possible atomic processes leads to the conclusion that in the relevant range of the spectrum photoionization is the only important process for the monoatomic gases. Madden has confirmed this by measuring the photoionization current at the two wavelengths

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of 584 Å and 735 Å and at the same time determining the flux with a thermopile. He found that photoionization accounted for the whole of the absorption in the gas to within his experimental accuracy of 3%. Samson has compared the photoionization currents for different rare gases but the same radiation flux and over a wide range of wavelengths. His results are shown in Figure 12 and it will be seen that to within 5% the currents are the same. These two measurements prove that the methods of calibration depend upon the ionization of gases and are trustworthy at least over the wavelength range of Samson's observations. There appears to be no reason why one should not draw similar conclusions for a much wider spectral range. However, direct experimental evidence does not appear to exist.

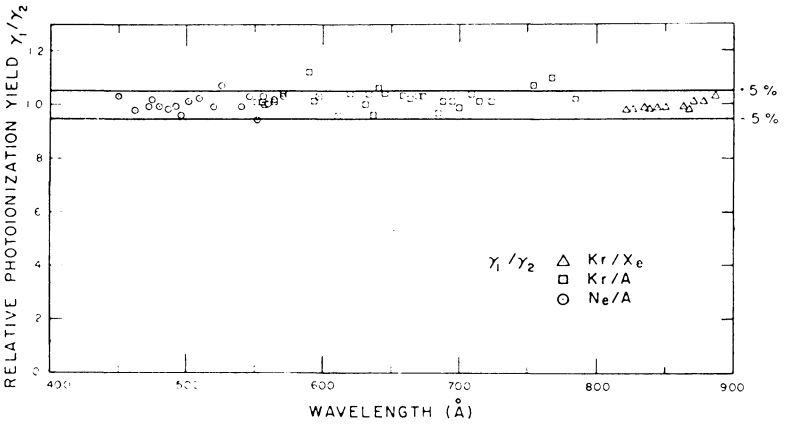

Fig. 12. The relative photoionization yield of the rare gases in the region 400–900 Å. Kr/Xe represents the yield of Krypton relative to Xenon, etc.

These considerations show that ionization chambers may be used as absolute standards of detection to well within 10% over the wavelength range extending from the ionization potential of the chamber gas to twice this value. The reason for this latter limit is that it is important to avoid the possibility of there being two photoelectrons being produced for each photon. This sets the practical limits for the monoatomic gases extending from 250–1000 Å when ionization chambers are used.

At shorter wavelengths a proportional counter has been used as an absolute detector. With this detector a sufficient number of electrons are produced that it is possible to resolve the energy of the incident photon. The basic process is that the first electron is produced by photoionization with sufficient energy to cause subsequent ionizations by electron collision. On average each electron requires about thirty electron volts to be released. Thus this method can only be used meaningfully at wavelengths less than about 100 Å (i.e. where three or more electrons are released). This is the basis of the soft X-ray calibrations adopted when observations are made with Bragg crystal spectrometers. However, it is also applicable in principle to grazing incidence instruments and has in fact been the basis of a number of calibrations of such

equipment. Figure 13 shows a schematic diagram of apparatus set up to intensity calibrate a grazing incidence spectrometer using a proportional counter as the absolute standard. The X-ray tube target is made of some low atomic number material such that the radiation emitted is predominantly the Kα band of the target element. These bands can be resolved by the proportional counter for elements of sufficiently large atomic number (beryllium and heavier) so that the total flux of radiation within these bands may be measured. The need is to know the size of the aperture into the proportional counter and the transmission of the window at the appropriate wavelength. In this way the calibration of grazing incidence spectrometer with its photoelectric detector has been carried out. The accuracy of an actual calibration by this method has been estimated to be 20% at wavelengths from 40 Å downwards.

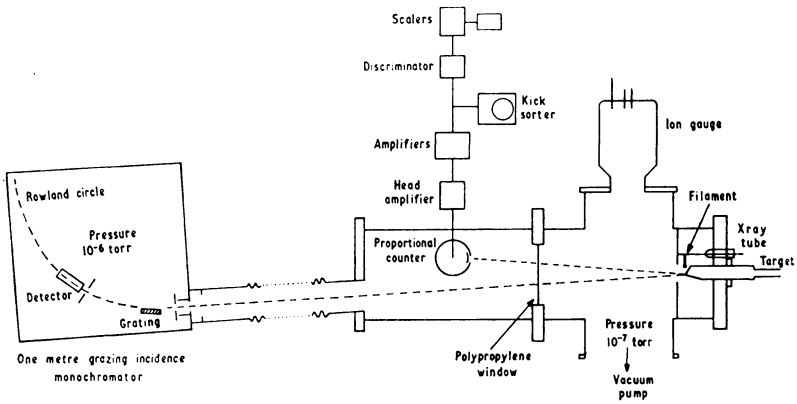

Fig. 13. Diagram illustrating the method of intensity calibrating a grazing-incidence spectrometer in the soft X-ray region against a proportional counter.

A comparison has been made between a calibration based on the proportional counter and the branching ratios calibration of the same instrument. This is shown in Figure 14 where unfortunately there is no overlap of the two calibrations. However it does indicate that there are no gross errors between these calibration methods.

9. Conclusion

On the basis of this review of the calibration methods available in the vacuum ultraviolet it appears to be reasonable to conclude that it should be possible to achieve calibration accuracies approaching 10%. It was shown at the beginning of the paper that such an accuracy is consistent with the needs of the theoretical analysis. To achieve this however a number of technical problems will have to be solved and probably the most important of these is the need for a sensitive detector such as a photomultiplier whose sensitivity can be relied upon to remain constant between the time of calibration and the time of observation in space. Another area where work is

urgently required is the intercomparison of calibrations between different laboratories working in this field and including laboratory measurements of atomic data.

It is clear that intensity calibration in the vacuum ultraviolet is an important area for work to be concentrated now that the initial surveys of the solar spectrum have been largely completed and the need is for more sophisticated experiments, many of which will be aiming at making accurate determinations of solar spectral intensities. The surveys have shown that there is a wealth of data waiting for measurement in this area and there can be little doubt that its interpretation will lead to important advances in the understanding of solar physics in the next few years.

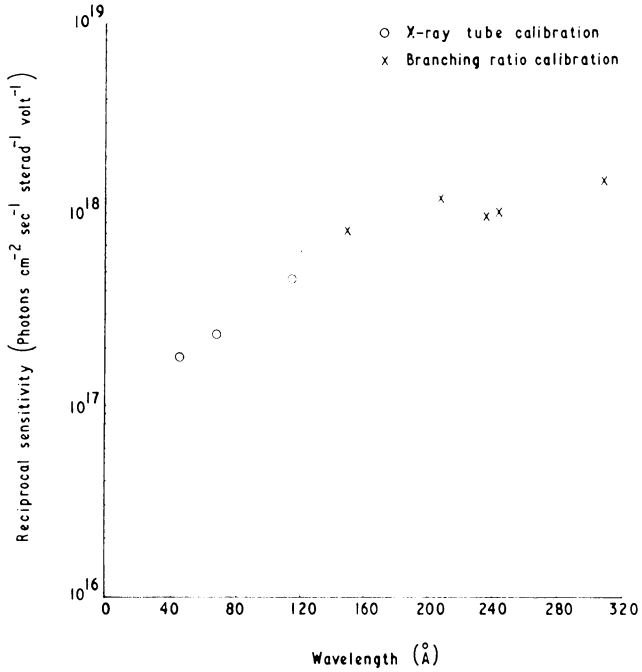

Fig. 14. Intercomparison of calibrations by the branching ratios and proportional counter with X-ray tube methods.

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