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AN INTERPRETATION OF THE TOTAL INTENSITIES OF THE LYMAN α AND β LINES OF HYDROGEN EMITTED BY THE SUN

A. G. HEARN

Culham Laboratory,
Culham, Abingdon, Berkshire
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AN INTERPRETATION OF THE TOTAL INTENSITIES OF THE LYMAN α and β LINES OF HYDROGEN EMITTED BY THE SUN

by

A.G. HEARN

ABSTRACT

Measurements of the absolute intensities of the Lyman α and β lines of hydrogen emitted by the sun are used in an interpretation of the mean electron temperature and density of the layers emitting these lines. Calculations of the line intensities emitted by a finite, uniform, plane parallel atmosphere were used where the coupled equations of statistical equilibrium and radiative transfer in the lines were solved explicitly for the first nineteen levels including the effect of the radiation from the photosphere. To obtain a unique interpretation for the electron temperature a third measurement is required and the calculations show that the geometrical thickness of the layers emitting the two lines is very sensitive to the electron temperature. No measurement of this thickness has been made, but an upper limit is obtained which corresponds to a maximum electron temperature of 30,000°K. There is a lower limit to the electron temperature of a little under 16,000°K. The limits of electron density corresponding to these temperatures are 10^{9} to 10^{11} cm^{-3}.

U.K.A.E.A. Research Group,
Culham Laboratory,
Nr. Abingdon,
Berks.

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CONTENTS

1. INTRODUCTION

The total intensities of the Lyman α and β lines of hydrogen emitted by the sun have been measured several times by Hinteregger and his colleagues with similar results each time. In this paper the interpretation of one of these measurements (Hall, Damon and Hinteregger 1962) is discussed. Fluxes were measured which correspond to specific intensities emitted by the sun, assuming that it is emitting uniformly, of 7.42×10^4 ergs cm^{-2} sec^{-1} $sterad^{-1}$ for Lyman α and 7.10×10^2 ergs cm^{-2} sec^{-1} $sterad^{-1}$ for Lyman β. The ratio of the intensity of the Lyman β line to the Lyman α line is 9.6×10^{-3}. This is an important parameter in the interpretation.

In the calculation of the line intensities the coupled equations of statistical equilibrium and radiative transfer in the lines were solved explicitly for the first nineteen levels. The interpretation is made in terms of the equivalent uniform finite plane parallel atmosphere which emits the observed total intensities. The advantages of the simplicity of interpreting the intensities of the lines without considering the profiles have also been used by Athay (1965 a,b,c). The radiation from the photosphere has an important effect on the line intensities by means of the photoexcitation of the Balmer lines and those of the higher series and this is included in the calculation.

The calculations show that for any assumed electron temperature the optical thickness of the atmosphere at the centre of the Lyman α line and the electron density may be determined from the ratio of the intensity of Lyman β to Lyman α and from the absolute intensity of the Lyman α line, but to obtain a unique interpretation for the electron temperature a third measurement is required. One that is very sensitive to the electron temperature is the geometrical thickness of the layers emitting the lines. Unfortunately no direct measurement has been made, but measurements of the intensity of Lyman α made during a total solar eclipse show that the thickness cannot exceed 19,000 km and from this the calculations show that the electron temperature of the layers emitting the Lyman α and β lines cannot exceed $30{,}000^{\circ}$K. This contrasts sharply with the temperature of 70,000 to $90{,}000^{\circ}$K obtained from the Doppler width by Morton and Widing (1961) in their interpretation of the Lyman α profile. A maximum electron temperature of $30{,}000^{\circ}$K corresponds to a minimum electron density of 10^9 cm^{-3} and a maximum optical thickness at the centre of Lyman α of 480.

The processes which populate the levels emitting the Lyman α and β lines through the higher bound levels from the continuum become important as the electron density increases and they place an upper limit on the electron density of about 10^{11} cm^{-3} for the range for which the observed ratio of the intensity of

Lyman β to Lyman α may be obtained from the calculation. There is a corresponding lower limit to the electron temperature of a little less than 16,000°K.

Over the whole range of possible solutions to this interpretation, the optical thickness at the centre of the Balmer α line of the layers emitting the Lyman α and β lines is less than 0.01, and the intensity emitted at the centre of the Balmer α line is 10% or less of the intensity of the Balmer α Fraunhofer line emitted by the photosphere. The broad conclusions of this interpretation are not altered by changing the geometry from a finite plane parallel atmosphere to a long cylinder, and they would appear to be inconsistent with the suggestion that the Lyman lines are emitted by spicules.

2. THE CALCULATIONS

Previously the analysis of the emission of the hydrogen lines from the sun, for example by Morton and Widing (1961) following the work of Thomas and Athay (1961), has been done in terms of a semi-infinite atmosphere. These authors argue that if one looks into the sun in Lyman α or Balmer α radiation the optical depth of the sun is effectively infinite and they solve the equation of transfer in a semi-infinite atmosphere with increasing optical depth corresponding to increasing distance inside the sun.

The observations of the line profiles of Lyman α (Tousey 1964, Purcell and Tousey 1961, Tousey et al 1964) show no clear sign of a background continuum, and it is certainly less than 1% of the peak intensity of the line. Clearly one can choose a level in the sun such that all layers below it make only a small contribution to the total intensity of the Lyman α line and this may be neglected. The region above this level is a layer of finite optical thickness which contributes effectively all the Lyman α radiation, and the problem is then changed from a semi-infinite atmosphere to a finite atmosphere. The rest of the sun is included by means of the boundary conditions at the lower edge of the atmosphere. These are that no Lyman α radiation is incident on the boundary from below, that radiation leaving the lower boundary never returns, and that in the Balmer and higher series for which the atmosphere is optically thin, there is black body radiation at 4,000°K incident on the lower boundary from all directions. This radiation has a significant effect on the population density of levels 3 and above.

This approach is valid only because the black body intensity of the photosphere is much less than the peak intensity of the line. This approach is not valid for the Balmer lines for example.

The steady state population densities of levels 1 to 19 in a finite, uniform, plane parallel atmosphere were calculated from the coupled equations of statistical equilibrium and radiative transfer in the lines. It was assumed that the population densities of levels 20 and above were in a Saha-Boltzmann distribution relative to the free electrons which were assumed to have a Maxwellian distribution and that the sub-states of the levels were populated according to their statistical weights. The processes included in the calculation were excitation and de-excitation, ionization and three-body recombination due to inelastic electron collisions, spontaneous and stimulated emission and photo-excitation between the bound levels and radiative recombination.

Photo-ionization by the Lyman continuum is quite negligible for finite atmospheres whose optical thickness at the centre of the Lyman α line is only several hundred; photo-ionization by the radiation of the photosphere in the Balmer and higher continua is small and was included using the Kramers photo-ionization cross section with a Gaunt factor of unity.

The calculations were done originally for hydrogen-like ions in a plasma which had no external radiation incident upon it. The methods and results of this circulation have been published elsewhere (Hearn 1966). These calculations were modified very easily to include the effect of the photospheric radiation, but the large labour involved in recalculating the line intensities using cross-sections for hydrogen atoms instead of hydrogen-like ions was not undertaken because differences between these cross-sections cannot affect the principal conclusions of this interpretation. The important cross-sections are those for ionization from the ground level and excitation from the ground level to the first three excited levels and they were taken from the Coulomb-Born calculations of Burgess (1961). A comparison of the rate coefficients used in this calculation with those obtained from the theoretical work of Gryzinski (1959) for hydrogen atoms shows that in the range of temperatures of interest here the ionization rate coefficient from the ground level is about four times greater than that obtained from Gryzinski's theory and the excitation rate coefficients from the ground level to the first and second excited levels are two to four times greater. Changing these rate coefficients would alter the electron temperature by about 10% only. The details of the rate coefficients used in this calculation are given by McWhirter and Hearn (1963).

It was assumed that the lines are Doppler broadened and that the atom and electron temperatures are equal. Differences between these two temperatures may be included by the scaling laws described by Hearn (1966). The numerical methods used for solving the equation of transfer are suitable only for finite atmospheres and the accuracy of the calculation decreases as the optical thickness of the atmosphere increases. For the Lyman α line for example, the error of the solution for an atmosphere of optical thickness 10 is 5% or less but for an optical thickness of 100 this has grown to perhaps 30%. Since the error in the intensity of Lyman β is affected in a somewhat similar fashion, the error in the ratio of the intensities of the two lines will be rather less.

The contribution of the photospheric radiation to photo-excitation at the wavelengths of the main Balmer and higher lines may be added directly to the statistical equilibrium equations since the calculations show that the atmospheres in this interpretation are optically thin in these lines. It was not possible to include this photo-excitation term for all levels in the calculation, but it was found that when it was added for all lines up to level 5 the effect of higher levels was not significant. The most important effect is photo-excitation between levels 2 and 3 by radiation at the Balmer α wavelengths. The shape of the Balmer α Fraunhofer line has been measured by White (1964). The line is wide and flat-bottomed with a central intensity of 0.155 of the background continuum. When combined with the absolute continuum measurements of Minnaert (1924) this shows that the central intensity corresponds to a black body intensity of 4,000°K. Measurements of the other Fraunhofer lines involved in this calculation are not available and they were all included at a black body intensity of 4,000°K

3. THE RESULTS

The most interesting result of the calculation is the variation of the ratio of the intensity of the Lyman β line to the Lyman α line with optical thickness of the atmosphere for various electron densities. This is shown in Fig.1 for an electron temperature of 32,000°K. The main features of the variation are essentially similar for the other temperatures of interest. To illustrate the effect that the radiation from the photosphere has, the original results obtained with no external radiation incident on the atmosphere are shown in continuous lines and the results including the radiation from the photosphere are shown in dotted lines.

Consider, first of all, the ratio of the intensity of Lyman β to Lyman α from an atmosphere which has an electron density less than 10^9 cm^{-3} and which has no radiation falling on it from the photosphere. Here the electron density is so low that collisional processes between excited levels are not important and the rate of emission of photons from an excited level equals the rate of collisional excitation from the ground level. If the atmosphere is optically thin then the ratio of the intensity of Lyman β to Lyman α is given by

$$\frac{I_\beta}{I_\alpha} = \frac{h\nu_{13}}{h\nu_{12}} \frac{K(1,3)}{K(1,2)} \frac{A_{31}}{(A_{31} + A_{32})} \qquad (1)$$

where $K(1,2)$ is the rate coefficient for collisional excitation from the ground level to level 2 defined so that the number of excitations is given by $n(1)\ n(c)\ K(1,2)\ \mathrm{cm}^{-3}\ \mathrm{sec}^{-1}$ where $n(1)$ is the ground level population density and $n(c)$ is the electron density. The rate coefficients are a function of electron temperature only. The ratio of the spontaneous transition probabilities A_{31} and A_{32} allows for the emission of Balmer α photons competing with the emission of Lyman β photons. The ratio of the two intensities for a low electron density and optically thin atmosphere is therefore a function of electron temperature only and for the range of temperatures of interest here say $16{,}000^{\circ}$K to $128{,}000^{\circ}$K it varies from 3.7×10^{-2} to 1.3×10^{-1}.

To explain the observed ratio of 9.6×10^{-3} by this mechanism alone would require a temperature as low as $8{,}000^{\circ}$K and then the rate of collisional excitation is so low that it is impossible to obtain the observed total intensity of the Lyman α line.

As the atmosphere becomes increasingly optically thick the ratio of the intensities goes down, and this is caused by the differences in the processes competing with the emission of photons in the two lines. Each time photons are absorbed and re-emitted, the number of photons is reduced by processes competing with the spontaneous emission of the photons. For Lyman α photons these processes are so slow that all the photons generated by collisional excitation eventually leave the atmosphere unless the optical thickness is 10,000 or more. Thus the intensity of the Lyman α line grows linearly with the optical thickness of the atmosphere.

For Lyman β photons the situation is quite different, for at each scattering a fraction $A_{32}/(A_{32} + A_{31})$ is lost by the emission of a Balmer α photon which is not absorbed by the atmosphere. As a result the intensity of the Lyman β line does not increase linearly with the optical thickness but falls very rapidly below it, so that as the optical thickness of the atmosphere increases the ratio of the intensity of Lyman β to Lyman α becomes smaller. Since the departure from linearity of the Lyman β line depends only on transition probabilities in a low electron density atmosphere, the variation of the intensity ratio with optical thickness is independent of the electron density.

The effect of the radiation from the photosphere is to increase the population of level 3 by photo-excitation from level 2 by Balmer α wavelengths. This increases the intensity ratio and to restore its former value the optical thickness of the atmosphere must be increased.

As the electron density increases, the ratio of the two intensities eventually becomes larger than the ratio for a low electron density and optically thin atmosphere. This results from a change in the mode of populating the low excited levels from collisional excitation direct from the ground level for low electron densities to a process populating from the continuum through the higher excited levels resulting from three body recombination, collisional de-excitation and spontaneous emissions. At high electron densities collisional processes dominate and the population densities of the bound levels are given by the Saha-Boltzmann population and the ratio of the line intensities may be obtained from curve of growth analyses.

This change in the mode of populating the levels places an upper limit on the electron density for which the observed ratio of the intensity of Lyman β to Lyman α can be obtained from the calculations. At 32,000°K this is somewhere between 10^9 and 10^{10} cm^{-3}. The existence of this limit shows the importance of high bound levels for moderate electron densities. A model atom of three bound levels plus continuum would conceal its existence. It could possibly be important in the interpretation of plages. If the intensity of Lyman β relative to Lyman α is observed to be brighter than about 1 to 10, this would suggest that the electron density of the plage had risen to at least 10^{11} cm^{-3}.

The observed ratio of the intensity of the Lyman β to the Lyman α line and the observed total absolute intensity of the Lyman α line may be used to find the optical thickness of the atmosphere at the centre of the Lyman α line and the electron density for any assumed electron temperature of the atmosphere. They are shown plotted against the electron temperature in Figs.2 and 3. The calculations show that the electron density required over most of the range of electron temperature is small enough for the atmosphere to be in the regime where the ratio of the intensity of Lyman β to Lyman α is independent of electron density. For an electron temperature of 16,000°K however the electron density required to give the observed intensity of Lyman α is high enough to cause the ratio of the two intensities to vary with the electron density, but the calculations still yield a unique fit for an assumed electron temperature.

The two observed intensities have been used in determining the optical thickness and electron density of the atmosphere and it is clear that another observation is necessary for a unique interpretation of the electron temperature. The calculations show that the geometrical size of the atmosphere that emits the observed intensities of the Lyman α and β lines is very sensitive to the electron temperature. The relation between them is shown in Fig.4. This figure shows that doubling the electron temperature from 16,000°K to 32,000°K increases the geometrical size by over four orders of magnitude. The rapidity of this variation comes from the dependence of the geometrical size on the product of the rate coefficient for collisional ionization $K(1,c)$ from the ground level and the rate coefficient for collisional excitation $K(1,2)$ from the ground level to the first excited level. Since each of these is varying rapidly with electron temperature their product varies very rapidly indeed.

The scaling laws developed for this calculation (Hearn 1966) show that the geometrical size is proportional to the atom temperature. It is assumed that the atom temperature equals the electron temperature. If the atom temperature corresponding to the Doppler width of these layers is twice the electron temperature for example, then the geometrical size will be doubled too, but this represents a very small error in the temperature derived from the geometrical size assuming that the atom and electron temperatures are equal.

Unfortunately there is no direct measurement of the geometrical size of these layers, but rocket observations during eclipses may be interpreted to give an upper limit. At the total eclipse of the sun on 12th October, 1958, Friedman and others flew rockets from the Danger Islands in the South Pacific to measure the intensity of the Lyman α line during totality (Friedman 1963). They found that during the totality the Lyman α flux was reduced to 0.05% of the uneclipsed value. Friedman also states that this measurement was repeated by Mandelshtam, Tindo, Voronko, Shurygin and Vasilyev during the eclipse of 15th February, 1961 in the Crimea with substantially the same results.

If it is assumed that the layer emitting the two Lyman lines lies between the photospheric limb of the sun and the projection of the moon's limb onto the sun, then the difference between the two gives a maximum size for the layer. From the circumstances of these eclipses given in the American Ephemeris and Nautical Almanac, the maximum distance between the two limbs is 30,000 km for the 1958 eclipse and 19,000 km for the 1961 eclipse. Fig. 1 shows that a maximum geometrical size of 19,000 km represents a maximum electron temperature of $30,000^{\circ}K$ and this together with Figs. 2 and 3 gives a minimum electron density of 10^9 cm^{-3} and a maximum optical thickness in Lyman α of 480.

There is no clear evidence for the minimum electron temperature which will provide the observed intensities in this interpretation. At $16,000^{\circ}K$ the geometrical size of the layer is only 2.5 km which is probably too small to be acceptable and so this may be regarded as a lower limit. At this temperature the electron density has to be fairly high to obtain the observed total intensity of the Lyman α line and the ratio of the intensity of the Lyman β line to the Lyman α line is sensitive to the electron density which has almost reached the level where the mode of populating level 3 changes from collisional excitation from the ground level to processes populating from the continuum through the higher excited levels. It is clear that at some temperature not far below 16,000^{O}K this change will occur and the solution for the observations will disappear. This presents a true lower limit to the electron temperature but it has not been pursued because of the very small geometrical size already obtained at 16,000^{O}K.

4. DISCUSSION

The maximum electron temperature of 30,000^{O}K contrasts sharply with the interpretation of the Lyman α profile by Morton and Widing (1961) which suggests temperatures in the region of 70,000 to 90,000^{O}K. Their interpretation is essentially a deduction of the Doppler width with the assumption that the equivalent atom temperature and electron temperature are equal.

This is a good indication that in further work on the interpretation of the Lyman α and β profiles, it should not be assumed that the Doppler temperature and the electron temperature are the same. This suggestion does not contradict the work of Bhatnagar, Krook, Menzel and Thomas (1955) who showed that significant differences cannot exist between the electron temperature and the atom temperature in the chromosphere. It does not contradict it because there is a great difference in the distance scales involved in the two problems. Their calculation considers the random energy of the atoms and electrons measured relative to the centre of mass of the particles in the limit as the volume of matter becomes very small. Whereas in determining the Doppler width, the velocities of the atoms over a distance equivalent to a unit optical depth are contributing. At 32,000^{O}K for example this corresponds to a distance in the atmosphere of 50 to 100 km. The Doppler width is determined not only by the random velocities of the atoms relative to their centre of mass but also by the distribution of the velocities of the centres of mass over distances perhaps up to 100 km.

At present there is no direct measurement of the geometrical size of the layers emitting the Lyman α and β lines. Measurements of this to give a unique interpretation to the intensities seem rather difficult. A simple spectroheliogram in Lyman α will not show the size of the spherical shell emitting Lyman α because it is optically thick. If the shell were optically thin a spectroheliogram would show limb brightening from which the size of the shell could be determined by an Abel transform. A shell emitting Lyman α radiation will be optically thin in the wings of the line, which suggests that a spectroheliogram taken only in the wings of the Lyman α line might show limb brightening which could be used to give the geometrical size of the layer. One possible difficulty is that if there are substantial variations of the Doppler width through the layer, they could cause misleading results.

An alternative method would be to take spectroheliograms in the higher Lyman lines. If these lines are emitted by the same layers as the Lyman α and β lines then some of them will be optically thin and will show limb brightening. If the optical thickness of the layer in Lyman α is 400, one has to go as high as Lyman 11 or 12 to obtain an optical depth of unity. These lines are very faint and it would be very difficult to get a spectroheliogram from them and there is the added difficulty that the population densities of the higher levels are increasingly determined by the radiation from the photosphere and their interpretation would be uncertain. However, so little information is available that spectroheliograms in the lower Lyman lines would be useful even if they show no limb brightening since they give information about the minimum optical thickness in the layer in Lyman α.

It has been assumed in these calculations that the atmosphere is uniform, whereas the interpretation based on a finite atmosphere depends on the temperature increasing outwards. These systematic variations of the electron temperature through the layer may cause errors in two ways: by separating in space the two regions which are contributing most of the photons formed by the basic excitation process in each of the two lines, and by the effect of the transfer of these photons in an atmosphere where the distribution of the primary production of the photons is asymmetric.

The spatial separation of the layers generating the photons is perhaps smaller for Lyman α and β than for any other important pair of lines since the energy separation of the two excited levels is small compared with that of the excited levels and the ground level. Figure 5 shows the variation with the electron temperature in the rate of collisional excitation to levels 2 and 3 from the ground level whose population density is determined by the ionization balance. The two curves are normalised to unity at the maximum. The density of electrons plus neutral atoms was assumed to be constant and low enough for radiative recombination and collisional ionization from the ground level to be the dominant processes in determining the ionization balance. Any variations in the total density would have to be superposed on the temperature variations. These curves show that there is very little separation of the regions producing the photons by collisional excitation and this will cause no significant error in the interpretation. The production of Lyman α and β photons peaks very sharply at about $16{,}000^{\circ}$K so that if the chromosphere had a constant density and a uniform temperature gradient, the interpretation would be dominated by the region at $16{,}000^{\circ}$K and this temperature would be deduced from the observations. If a temperature other than $16{,}000^{\circ}$K is obtained it would be consistent with the sharp gradients and plateaux of electron temperature and density suggested by other investigations of the chromosphere.

It is difficult to estimate the effect of the transfer of Lyman α and β photons in an atmosphere where the distribution of the primary excitation is asymmetric, but a temperature increasing outward is the situation least likely to cause significant errors.

If the Lyman lines were emitted by the spicules, the plane parallel geometry used in these calculations should be replaced by a long cylinder or cylindrical shell. However this would not alter the main form of the results. The solution of the equation of transfer in a long cylinder of diameter L is not greatly different from that obtained from a finite plane parallel atmosphere of thickness L. This is illustrated by the similarity of the expressions derived for the imprisonment factor for an infinite cylinder and plane parallel enclosure by Holstein (1951) for Doppler broadened lines. The basic problem of the interpretation remains that in the range of temperatures of 16,000 to 64,000°K the ratio of the collisional excitation rate coefficients from the ground level to levels 3 and 2 are about 1 to 10 whereas the observed ratio of the intensity of Lyman β to Lyman α is about 1 to 100. This ratio can be attained by having sufficient optical thickness in the Lyman β line to convert photons to Balmer α photons which escape. This cannot be done by increasing the electron density because the change in the mode of populating the levels prevents this. If the temperature is lowered to 8,000°K where the ratio of the excitation rate coefficients is about 1 to 100 the electron densities required to obtain the observed total intensity of Lyman α is so high, around 10^{16} cm^{-3}, that collisional processes through the higher excited levels are again dominant and the ratio of the intensity of Lyman β to Lyman α is forced back to 1 to 10.

The difficulty is made even worse when the small area of the sun covered by spicules is included. For example, if 5% of the sun's surface is covered by spicules, which is a rather high estimate, the specific intensity of the lines emitted must be increased 20 times to preserve the mean intensity emitted by the whole sun. At 16,000°K the electron density of the interpretation would have to be increased 20 times to something over 10^{12} cm^{-3} and at these electron densities a solution yielding the correct ratio would again cease to exist and some electron temperature higher than 16,000°K would be required.

The optical thickness at the centre of the Balmer α line of the plane parallel atmosphere emitting the observed intensities of the Lyman α and β lines is shown in Fig.6 plotted against the electron temperature. These optical thicknesses are all 0.01 or less which shows that the treatment of the photo-excitation by the photospheric radiation is consistent. The intensity emitted by the layer at the centre of the Balmer α line is shown in Fig.7. This is the intensity emitted by the finite atmosphere alone. Where the effect of photo-excitation by the photosphere has been included it has been used to calculate the excited level population density in the atmosphere, but the background intensity is not included in Fig.7. The observed intensity at the centre of the Balmer α Fraunhofer line is 6.57×10^{-6} Ergs cm^{-2} sec^{-1} cps^{-1} $sterad^{-1}$, so that the emission of the atmosphere itself is less than 10% of the intensity of the photosphere at the centre of the Fraunhofer line.

Once again if 5% of the sun's surface were covered by spicules and a cylindrical geometry were used, these optical thicknesses and intensities would have to be increased 20 times, but they would still be inconsistent with observations of spicules which suggest they are optically thick in the Balmer α line.

5. CONCLUSION

Absolute measurements of the total intensities of the Lyman α and β lines of hydrogen and measurements of the intensity of the Lyman α line at a total eclipse of the sun give an interpretation for the mean electron temperature and density of the layers emitting the lines. The mean electron temperature in the interpretation cannot exceed 30,000°K nor be much less than 16,000°K. The mean electron density must be in the range 10^9 to 10^{11} cm^{-3}.

6. ACKNOWLEDGEMENTS

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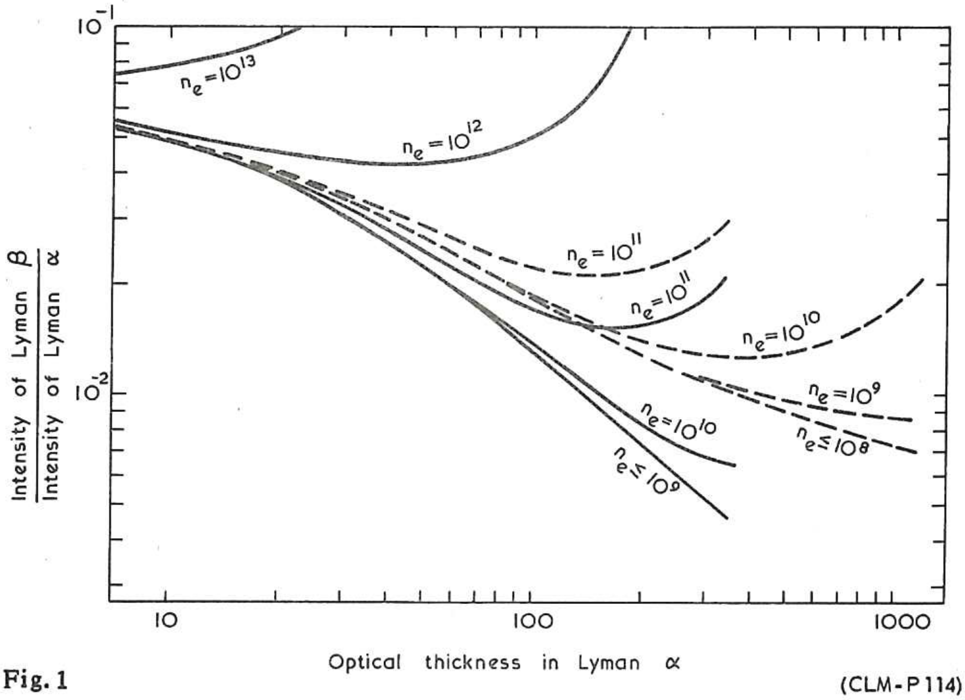

Fig. 1 (CLM-P 114)

The ratio of the intensity of the Lyman β line to the Lyman α line is plotted against the total optical thickness at the centre of the Lyman α line of a finite atmosphere for various electron densities for an electron temperature of 32,000°K The continuous lines are for an atmosphere isolated from external radiation, and the dotted lines include the effect of radiation from the photosphere

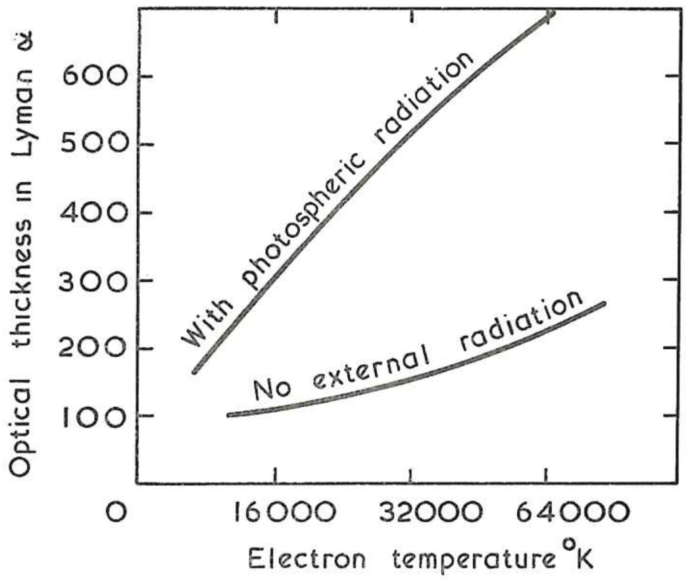

Fig. 2 (CLM-P 114)

The optical thickness of the atmosphere in Lyman α required to give the intensities of the Lyman α and β lines observed from the sun plotted against the electron temperature with and without the contribution of radiation from the photosphere

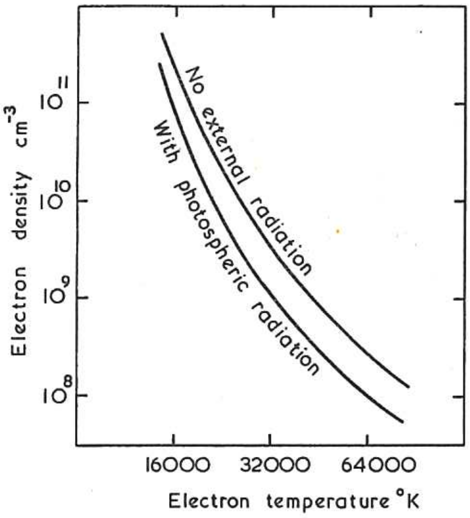

Fig. 3 (CLM-P114)
The electron density of the atmosphere required to give the intensities of the Lyman α and β lines observed from the sun plotted against the electron temperature with and without the contribution of radiation from the photosphere

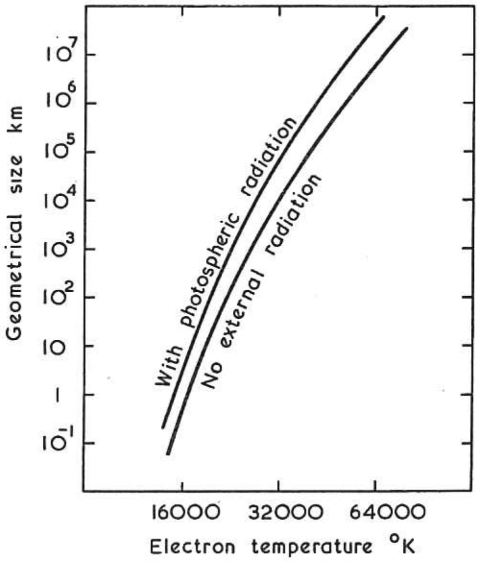

Fig. 4 (CLM-P114)
The geometrical size of the atmosphere required to give the intensities of the Lyman α and β lines observed from the sun plotted against the electron temperature with and without the contribution of radiation from the photosphere

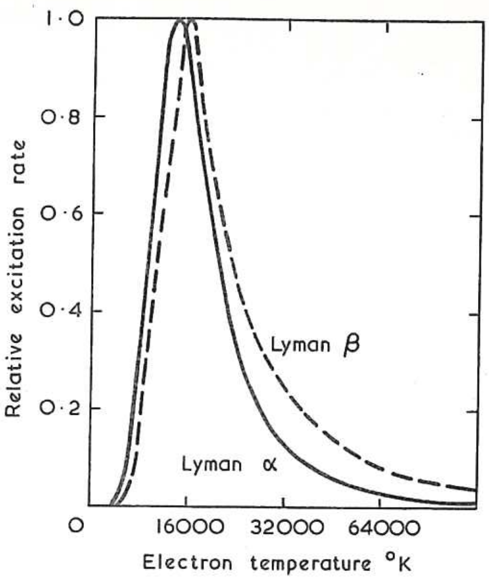

Fig. 5 (CLM-P114)
The variation with electron temperature of the rate of collisional excitation of Lyman α and β photons in a low electron density atmosphere. The curves are normalised to unity at the maximum

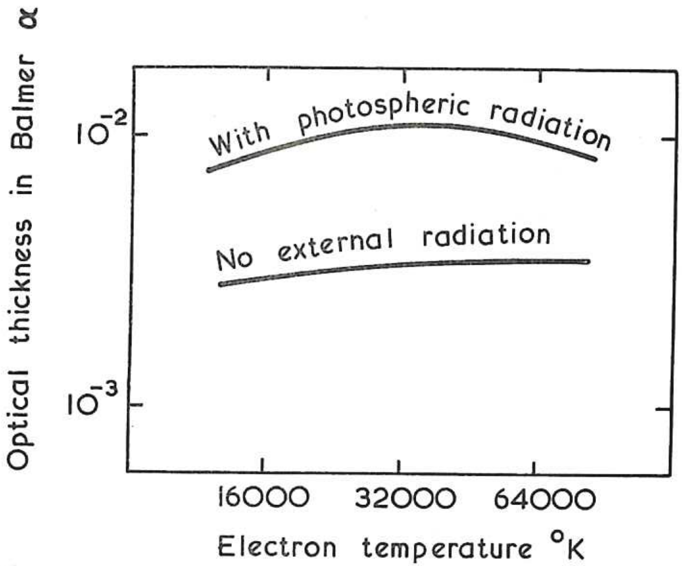

Fig. 6 (CLM-P114)
The optical thickness of the atmosphere measured at the centre of the Balmer α line with and without the contribution of radiation from the photosphere

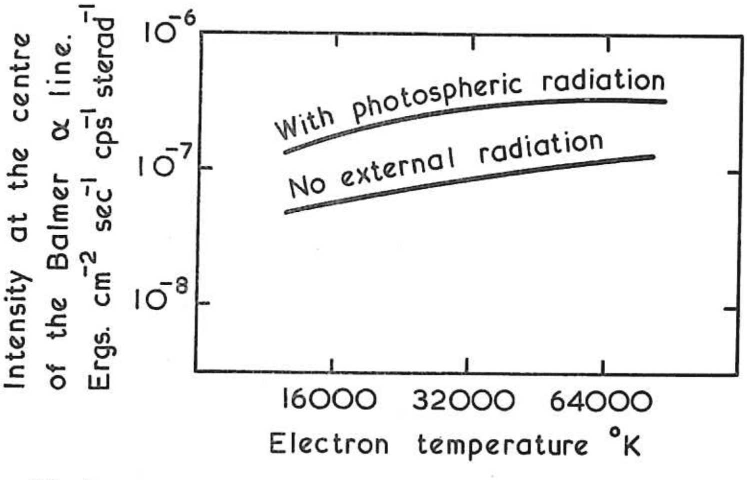

Fig. 7 (CLM-P114)
The intensity at the centre of the Balmer α line emitted by the finite atmosphere alone, but with and without the