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396

EMISSION OF EXTREME ULTRAVIOLET RADIATION FROM SOLAR CENTERS OF ACTIVITY

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Abstract: Line emissions at 284 Å, 304 Å and 335 Å in the solar extreme ultraviolet spectrum observed by OSO–1 have been compared with 2800 Mc emission and other indicators of solar activity. Increase in these ultraviolet fluxes can be localized to active regions on the solar disk. Changes in the intensities of the lines are discussed in terms of changes in electron temperature and electron density of the active regions. Certain assumptions made in the calculation of a coronal electron temperature from the relative populations in two stages of ionization of an element are examined, with the conclusion that this calculation may not be valid for the particular case of the solar corona, yielding a fictitiously low value if there is an outward expansion of ions from the base of the corona into a region of higher electron temperature. A non-equilibrium formulation for the distribution of ions is presented which may better describe the actual ion distribution in the corona. An approximate calculation shows that an average radial velocity, outward, and small compared with the average thermal veolcity of the ions, is sufficient to explain the observed increase in height of the maxima of emission of the Fe ion sequence with increasing stage of ionization in the undisturbed corona.

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Резюме: Эмиссия в линиях на 284 Å, 304 Å и 335 Å в крайней части ультрафиолетового спектра Солнца, наблюдавшаяся спутником OSO-1, сравнивалась с эмиссией на 2800 Мгц и другими характеристиками солнечной активности. Возрастания этих потоков ультрафиолета могут быть локализованы в активных областях на солнечном диске. Изменения в интенсивности линий рассматриваются как результат изменений температуры и плотности электронов в активных областях. Анализируются некоторые допущения, сделанные при расчете температуры электронов солнечной короны по относительной плотности в двух стадиях ионизации элемента. Делается вывод о том, что подобные расчеты могут и не быть пригодными для частного случая солненой короны, поскольку могут давать фиктивно низкие значения, если имеет место распространение ионов, направленное наружу от основания солнечной короны в область более высокой электронной температуры. Дана неравновесная форма распределения ионов, которая позволяет лучше описать действительное распределение ионов в короне. Приблизительные расчеты показывают, что направленная наружу и имеющая по сравнению со средней тепловой сокростью ионов небольшую величину средняя радиальная скорость достаточна для того, чтобы объяснить наблюдаемое увеличение высоты максимальной эмиссии ряда ионов железа во время возрастания ионизации в спокойной солнечной короне.

PAGE LIST 3243

1. Introduction

A grazing incidence spectrometer, operating as a pointed experiment on OSO–1, has provided the first observations of variations of solar extreme ultraviolet fluxes due to the presence of solar centers of activity on the sun's surface. In another paper presented at this conference, these variations have been compared with fluctuations observed in other ranges of the solar electromagnetic spectrum; in this paper, the variations in EUV fluxes will be discussed in terms of changes in coronal electron densities and coronal temperatures that may be derived from them. Since the spectrometer has no inherent spatial resolution, our discussion will center around a comparison of EUV fluxes from the entire solar disk, when no disturbed regions are present, with fluxes observed when a well defined center of activity is present on the disk. The discussion is further restricted to three of the more reliably identified lines in the spectral range of the instrument: 284 Å (Fe XV), 304 Å (He II) and 335 Å (Fe XVI).

2. Variations in selected EUV emission lines

A summary of the non-flare variations observed in the abovementioned lines is given in figs. 1 and 2, in which each datum point represents the average of one orbit's observations (six to eight spectral scans). The error bars indicate one standard deviation in the data. The relationship which these observed counting rates have to several ground-based measurements of solar activity is also presented. In fig. 1, the He II Lyman-alpha radiation is compared with daily values of the solar flux at 2800 Mc (National Research Council, Ottawa, Canada) and with the Zurich Provisional Relative Sunspot Number (ZPRSN). Also shown is an estimate of the calcium plage intensity, computed for each day by summing over the observed (fore-shortened) areas of all plages, each area being weighted by the estimated intensity of the plage, on a scale from 1 to 5. Areas were taken in millionths of the solar area. Values for this computation were supplied by the McMath–Hulbert Observatory. A similar presentation is made in fig. 2 for observations of the coronal lines of Fe XV and Fe XVI. Two methods were applied for estimating the instrumental sensitivity at 284 Å and 335 Å. In the first of these, solar fluxes observed at those wavelengths by Hall, Damon and Hinteregger [1], whose instrument had been calibrated, were compared to counting rates obtained by the GSFC instrument on days of comparable solar activity. The 2800 Mc daily flux was used as an index of this activity. In the second, the sensitivity was computed from estimated values of the grating reflectivity and detector efficiency. Sensitivities of 4.2×10^5 photons

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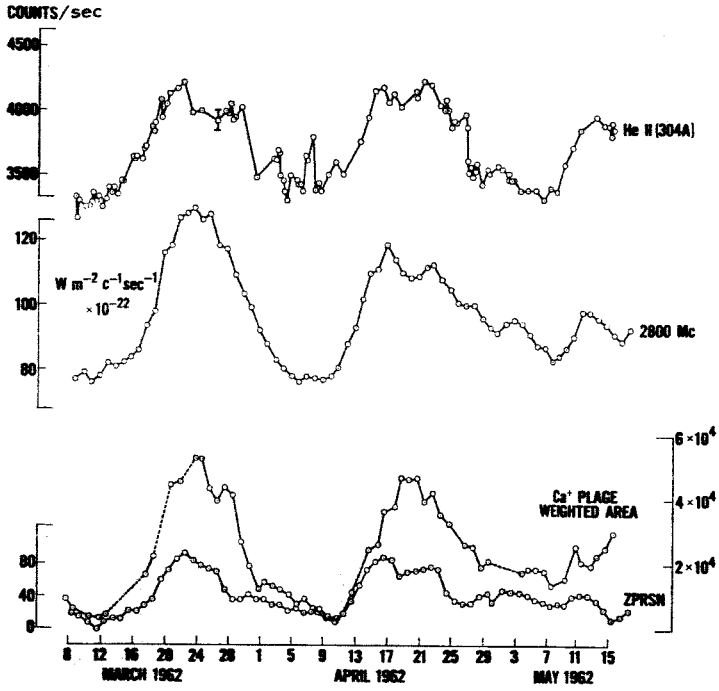

Fig. 1. Comparison of the He II (304 Å) line with measurements made at radio and optical wavelengths.

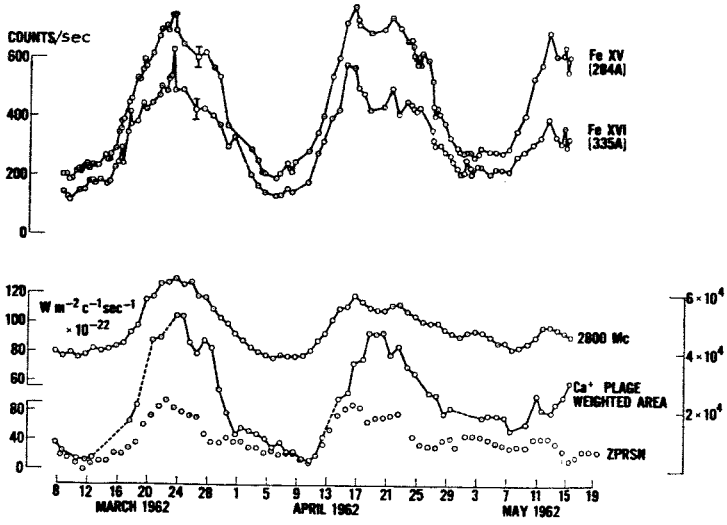

Fig. 2.Comparison of Fe XV (284 Å) and Fe XVI (335 Å) lines with measurements made at radio and optical wavelengths.

cm^{-2} $count^{-1}$ at 284 Å and 8×10^5 photons cm^{-2} $count^{-1}$ at 335 Å, representing averages of the values given by the two methods, were adopted and satisfied the need for a relative calibration at the two wavelengths. Their use as absolute values of the sensitivity is not recommended because of the limited validity of the calibration procedure.

3. Discussion of the data

3.1. Observation of the quiet corona

The use of the Orbiting Solar Observatory as a long-term stable platform has permitted the acquisition of a solar EUV spectrum which can tentatively be associated with a corona not disturbed by visible centers of activity. This situation presented itself for a short period of time on 11 March, when a Zurich Provisional Relative Sunspot Number of zero was reported. The American Relative Sunspot Number was reported as zero on both March 10 and 11. In addition, no large active regions had been associated with the face of the sun turned toward the earth on March 11 during the preceding six months. A careful analysis of the more intense emission lines, made for the period from March 7 to April 5, demonstrates that the lowest counting rates of the period were indeed observed when the sunspot number was near zero and the calcium plage area on the sun was also at a minimum. However, it is also clear from an examination of figs. 1 and 2 that no close correlation can be assumed to exist between the EUV fluxes and any of the ground-based observations. As fig. 2 shows, counting rates from the iron lines were lower on May 1, when the Sunspot Number was 49, than on May 15, when it was at 13. Likewise, although the agreement between the radio data and EUV coronal fluxes is striking at times, as for instance in the interval from April 13 to 25, a period of considerable solar activity, this similarity is not consistent, as the data taken from April 29 to May 15 shows: A small maximum observed at 2800 Mc on May 1 to 5 does not appear at 284 Å whereas on the succeeding days, May 9 to 15, a larger peak is observed at 284 Å than at radio wavelengths. The anomaly can be eliminated, at least in this particular instance, by observing that the flux at each wavelength depends on the age of the center of activity being observed. The region under observation on May 1 to 5 is a center of activity approximately 1 solar rotation old whereas the plage areas observed on May 9 to 15 are remnants of active regions 4–5 rotations old. The trend in the data is consistent with a model for a center of activity (CA) described by De Jager [2], in which the center is initially localized in the lower altitudes of the solar atmosphere and gradually expands into the quiet corona. After

the spot phase of the CA has passed, the region remains as a magnetic bipolar region which may have quiescent filaments and perhaps coronal rays associated with it. The continued enhancement of the Fe XV and Fe XVI lines after all sunspots have vanished in the region may be an indication of remaining coronal rays. In any event, these observations suggest that it is necessary to have knowledge of the recent past history of solar activity as well as current data in order to make a correlation with the EUV radiation.

Having established an emission spectrum corresponding as nearly as the data permit to an undisturbed corona as observed approximately four years after sunspot maximum, it is of interest to compute an electron temperature for the quiet corona which is implied by the observed spectrum. The reason for choosing an undisturbed spectrum for this calculation is that we are forced to make an assumption of spherical symmetry of the corona since the spectrometer has, inherently, no spatial resolution, and this assumption is best satisfied when large scale structures, as evidenced by EUV enhancements, are absent. An electron temperature may be derived (Woolley and Allen [3]) from the observed ratio of intensities of two spectral lines originating from two different ionic species of the same element. Such a calculation has validity only if both radiations originate in the same region of the corona at some well-defined electron temperature, and only if the ionization-recombination equilibrium assumed by the theory is actually present. These assumptions will be examined in the following sections.

The ionization formula used to relate the relative populations in adjacent states of ionization was that of Elwert [4]. Excitation cross sections were computed from the expression derived by Woolley and Allen on the basis of the classical Thompson atom. The oscillator strengths were taken from Varsavsky [5]. It is found that an electron temperature of 1.75 million degrees in that part of the corona assumed to be the source of both the Fe XV and Fe XVI radiations best fits the observed data. The estimated possible error in this value arising from uncertainty in the relative sensitivity of the spectrometer at the two wavelengths is 100 000 °K. This result contrasts sharply with the value of 800 000 °K usually obtained from observation of the forbidden lines of Fe X and Fe XIV. Since both results are ultimately based on the same theory of ionization equilibrium, one is forced either to question the validity of the ionization equilibrium assumed or postulate that a range of electron temperature exists in the corona. Indeed the very observation of six stages of ionization of iron, from Fe X through Fe XV, excepting Fe XII in the visible, coupled with the Fe XVI resonance transitions in the ultraviolet, leads one to the same conclusion.

3.2. EUV Radiation from solar centers of activity

A discussion of the sources of radiation from Fe XV and Fe XVI may be extended to include centers of activity and plages since it appears from the data that emission from these ions is intimately associated with these disturbances. In this section we will consider whether or not a unique change in electron temperature or density or both can be obtained for the corona above plages from the EUV data. A tentative analysis has been made for changes observed in the 284 Å and 335 Å counting rates between March 11 (ZPRSN equal to zero) and March 25 (ZPRSN equal to 74). Although the latter date does not represent the period of greatest deviation of the spectrum from quiet sun conditions, it was chosen because of the relatively well-defined configuration of three plage areas near the central meridian at that time. During this period the Fe XVI radiation increased by a factor of 3.85, the Fe XV radiation by 3.37, and the Fe XIV radiation, as estimated from optical observations of λ 5303, by 2.50. It is obvious that the center of activity represents a more complex change than simply an increase in density in a volume having a uniform and non-changing electron temperature. On the other hand, it is also impossible to explain the changes in emission as exclusively due to an increase in electron temperature in a homogeneous volume of the corona; that is, no one unique increase in electron temperature of the center of activity above that of the quiet corona can explain the observed spectral variations. From the nearly constant Fe XVI/Fe XV ratio one obtains only a small temperature increase, 100 000 °K, whereas the increase implied by the Fe XV/Fe XIV ratio (using λ 5303 data) is more than two and one-half times as large. The inability to obtain consistent results under the assumption of an isothermal center of activity again suggests that not all spectral lines are emitted uniformly from the corona but that those regions (or region) emitting Fe XV and Fe XVI radiation from the quiet corona become relatively more predominant over centers of activity and plages.

4. Effect of a coronal expansion on the calculation of an electron temperature

4.1. Discussion of the ionization equation

The inconsistencies discussed in the foregoing sections, as well as the long standing discrepancy between the electron temperature of the quiet corona obtained from forbidden emission line intensity ratios and other values computed from the electron density gradient has led to an analysis of the ionization theory on which the former value is based. It appears that

a combination of two physical conditions may exist in the corona which may produce this discrepancy. These two factors are:

1) An average time between ionizations (of heavy ions) which is large compared with the time for equipartition of energy between the ions and the coronal plasma.
2) A mass motion of ions through a region having a high electron temperature gradient in a period of time equal to or less than the above mentioned time between ionizations.

We will first consider the existence of each of these effects in the lower corona and then discuss their influence on a theory assuming ionization equilibrium. An estimate of the time between ionizations can be obtained using values of the ionization rates for iron ions given and discussed by Firor and Zirin [6]. These rates are found to increase only slightly with temperature (from 0.21×10^{-12} sec^{-1} cm^3 at 1.0×10^6 °K to 6.4×10^{-12} sec^{-1} cm^3 at 2.6×10^6 °K for Fe XII). The change with stage of ionization at a given temperature is still less sensitive, decreasing, for example, from 5.3×10^{-12} sec^{-1} cm^3 for Fe X to 2.0×10^{-12} sec^{-1} cm^3 for Fe XIV at 2.0×10^6 °K. A measure of the time between successive ionizations is then given by

$$\tau_{\text{ion}} = N_i / N_i N_e S(T) = 1 / N_e S(T),$$

where N_i is the ion density, N_e is the electron density and $S(T)$ is the ionization rate in sec^{-1} cm^3. Taking a value for N_e of 3.5×10^8 cm^{-3} at a height of 1.02 $R_\odot$ ($R_\odot$ being the solar radius) and a value for $S(T)$ of 3.0×10^{-12} sec^{-1} cm^3 one finds that a time of the order of 1000 sec is required to ionize (without recombinations) an assemblage of ions from stage i to stage $i+1$. On the other hand, the time required to establish equipartition of energy between electrons and heavy ions in the coronal plasma is considerably shorter. This characteristic time can be computed from an equation given by Spitzer [7] and is of the order of 20 sec for Fe XIII-electron equilibrium at an electron density of 3.5×10^8 cm^{-3} and temperature of 2.0×10^6 °K. The time for equipartition is again inversely proportional to the electron density, leading to the relation

$$\tau_{\text{ion}} / \tau_{\text{equi}} \approx \text{constant} \gg 1$$

for a given ion anywhere in the solar corona.

In considering the second of the two conditions stated above we must restrict ourselves to regions of low magnetic field, thus permitting an expansion of the corona which results in the corpuscular stream deduced

by Biermann [8] from his work on comet tails and was more recently discussed by Parker [9]. Using the continuity equation one can compute the average solar wind velocity at any height in the corona once its velocity and particle density at another height have been defined. Using as initial parameters (Parker [10]) for $r = 1.43\ R_{\odot}$, a proton density of $1.8 \times 10^7\ \mathrm{cm}^{-3}$ and a solar wind velocity of 66 km/sec, one then finds at $1.02\ R_{\odot}$, where the density is approximately $3.5 \times 10^8\ \mathrm{cm}^{-3}$, a velocity of about 7 km/sec. From these figures we may conclude that an ion may travel radially outward at a distance of 10^3 to 10^4 km in the lower corona before undergoing further ionization.

The result of fulfilling both of the above conditions is that an ion, in traveling along a positive electron temperature gradient, or in crossing a steep gradient representing a large change in electron temperature, very quickly attains an average thermal velocity characteristic of the higher temperature (condition 1) but carries with it, for a much longer time and radial distance, a history of any previous ionization equilibrium (condition 2). Under such circumstances no theory which postulates equilibrium between ionizations and recombinations can furnish a valid value for the electron temperature of the region even if the predominent ionization mechanism is electron impact, and recombination is by radiative capture. A kinetic temperature derived from line broadening may still be valid, however. Because of the large increase in temperature over a distance of 10 000 km or less in the lower solar corona it appears that the situation here described may well occur throughout the lower corona from which most of the coronal radiation is observed.

At any height in the corona one must then replace the equilibrium equation:

$$N_i N_e\, S_i^{i+1}(T) = N_{i+1} N_e\, Q^i{}_{i+1}(T),$$

where $Q(T)$ is the recombination rate in $\mathrm{sec}^{-1}\ \mathrm{cm}^3$, with the more general equation

$$\nabla \cdot \mathbf{F}_i \gtreqless 0$$

where $\mathbf{F}_i$ is the flux of ions, in stage i, of each element.

For an optically thin corona of low density in which photoionizations and three-body recombinations are assumed to be negligible one obtains

$$\nabla \cdot \mathbf{F}_i = N_{i-1} N_e\, S^i{}_{i-1}(T) - N_i N_e [Q_i{}^{i-1}(T) + S_i{}^{i+1}(T)] + N_{i+1} N_e\, Q^i{}_{i+1}(T)$$

for each stage of ionization, i, of each element present, together with

$$N(r) = \sum_i N_i(r),$$

where N_i is the number density in each stage of ionization. The summation is made over all stages of ionization of the particular element being considered.

For a spherically symmetric corona expanding with velocity of magnitude $v(r)$ we have, for the total flux of a particular ion crossing a shell of radius r,

$$F_i = 4\pi r^2 N_i(r) v(r).$$

By requiring a steady state outward flow, all ions moving outward with the same average velocity, we obtain

$$F_0 = \sum_i F_i \approx 4\pi r^2 N_e(r) v(r) = \text{constant}.$$

In this case the summation includes all elements present.

Using the notation P_i, where P_i is the relative population in each stage of ionization:

$$P_i \equiv N_i(r)/N(r),$$

we obtain

$$\frac{d}{dr} P_i = \frac{N_e^2}{F_0/4\pi r^2} [P_{i-1} S^i_{i-1}(T) - P_i(Q_i^{i-1}(T) + S_i^{i+1}(T)) + P_{i+1} Q^i_{i+1}(T)]$$

for each element and each stage of ionization.

It is possible to discuss the general behavior of the system by considering the expansion of an assemblage of ions from a region of low electron temperature of 10^5 °K to a hotter region of 10^6 °K, the change in electron temperature taking place over a distance of only a few thousand kilometers. Examination of the equation for the lowest stage of ionization present at 10^5 °K indicates that the relative population will decrease, in the absence of recombinations, by a factor of $1/e$ in a distance of

$$(F_0/4\pi r^2)/N_e^2 S(T),$$

which is of the order of 10^4 km. Including recombinations will increase this distance. Higher stages of ionization will become more populated with increasing height above the photosphere, reaching an ionization equilibrium characteristic of the higher temperature only in a distance of a few tens of thousands of kilometers. It is precisely in this range of heights that most of the coronal radiation is observed.

4.2. Comparison with observations

A small amount of observational evidence is available which appears to support the scale we have computed. Beginning with the lower stages of ionization of iron observed in the corona, it has been found for the undisturbed corona that:

a. The maximum in Fe XI emission occurs below 10 000 km above the photosphere (Feb. 25, 1952 eclipse) (Athay and Roberts [11]).

b. The maximum in Fe XIV occurs (statistically) at about 18 000 km (Petri [12]).

c. The intensity of the Fe XV line at 7059 Å decreases much more slowly with distance from the limb than do the lines of Fe X (6374 Å) and Fe XI (7891 Å) (Feb. 15, 1961 eclipse) (Wlerick and Fehrenback [13]). Based on the observation by OSO–1 that the intensity of emission from Fe XVI requires emission from 0.1 to 0.5 of the solar corona one might hypothesize, in accordance with the model being presented here, that the maximum in emission of Fe XVI occurs at about 40 000 km. Because of the rapidly decreasing electron density with height in the lower corona the maximum in intensity of an ion may be very broad and need not be coincident with the maximum in relative population.

It is also of interest to reverse the problem, using the experimental data to estimate the radial velocity that would be required to achieve the observed separations of maximum emission assuming again the excitations are primarily produced by electron collisions. Using an average time between ionizations of 1000 sec for stages Fe XI through Fe XIV and 2000 sec for Fe XV and Fe XVI we obtain

a. For the radial velocity of Fe XI through Fe XIV:

$$\bar{v} \approx 10\,000 \text{ km}/3000 \text{ sec} = 3.3 \text{ km/sec}.$$

b. For the radial velocity of Fe XV and Fe XVI:

$$\bar{v} \approx 20\,000 \text{ km}/4000 \text{ sec} = 5 \text{ km/sec}.$$

These values are comparable to the solar wind velocity of the lower corona computed in section 4.1. By comparison, the average thermal velocity for Fe ions at 2.0×10^6 °K is 16 km/sec. Since only limb observations of the corona are possible at visible wavelengths, little or no shift in the emission lines, due to the outward ion velocity should be observable.

5. Summary

Intensity variations of three spectral lines observed in the solar EUV spectrum have been presented together with a discussion of the slowly varying component of solar activity which accompanied these changes. The Fe XV and Fe XVI lines are found to be prominent in the solar spectrum even in the near absence of solar activity, a fact not expected on the basis of

observations of forbidden lines of iron in the visible spectrum. It is found that a general correlation exists with solar activity, with the suggestion that an increase in these coronal radiations occurs subsequent to appearance of a center of activity as observed at 2800 Mc and may linger in the presence of diminishing Ca^+ plages after the cessation of solar activity in an active region. The enhancement at 284 Å and 335 Å is nearly the same, implying little or no temperature increase in active regions having no yellow line (Ca XV) emission. The observations are consistent with a model for active regions which postulates both an increase in electron density together with an increase in the vertical range over which radiation from Fe XV and Fe XVI is emitted. The discrepancy observed between the electron temperature obtained from ion ratios and that inferred from electron density profiles for the quiet corona has led to the suggestion that the former method may yield a fictitiously low value if there is a streaming outward of ions from the base of the corona. An approximate calculation shows that a radial velocity outward, small compared with the average thermal velocity of the ions, is sufficient to explain the observed increase in height of the maximum of emission of the Fe ion sequence with increasing stage of ionization.

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