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Interpretation of Extreme Ultraviolet Emissions from the Sun

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Interpretation of extreme ultraviolet emissions from the Sun

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1. Introduction

The purpose of this review is to consider the analysis of extreme u.v. space observations for the interpretation of the Quiet Sun (Q.), active regions (a.r.) and flares (fl.). The three components must be segregated from one another using the observational data that exists. We cannot count on having every type of observation for every occasion. It becomes necessary to make some simple assumptions concerning the components Q, a.r. and fl. in order that they can be measured consistently. I give below some descriptive models which are complete enough to represent the complex varying Sun at all times but simple enough to be expressed quantitatively in a few numbers. The aim will be to interpret all extreme u.v. observations on the basis of these models and to regard them as the norm. Exceptional phenomena would be regarded as variations from the models.

Ideally all intensity and flux measurements would be made within individual spectrum lines or in continua at specified wavelengths. However, many valuable observations are based on broad spectral regions and it is necessary to devise methods for interpreting them.

2. Model descriptions

Quiet Sun (Q)

Time scale of variations ≃ 1 year.
Some smooth variation with sunspot cycle.
Limb brightening.
Polar darkening at sunspot minimum.
Some intensity irregularities but a useful smoothed mean available.
Extends a little beyond visible limb.

Active regions (a.r.)

Time scale of variations ≃ 1 day.
A one-to-one relation between extreme u.v. sources and a.r. (sunspots and plages).
Considerable variety in intensity of both extreme u.v. sources and a.r. (as expressed at their maxima).
A change of character with age.
Source sizes similar to plages.
Sources can extend beyond the limb.

Flares (fl.)

Time scale of variations ≃ 1 min.
Mainly sudden bursts, but also occur in the form of persistent minor flaring.
Associated with optical flares, centimetre-wave radio bursts, and s.i.d.

Very great variations in size, flux, spectrum, etc.

Emission wavelengths are short and source atoms are highly ionized.

X-ray emissions are harder at flare commencement and for the brighter flares.

Sources can occur at considerable heights.

Most of the items in the above descriptions lend themselves to quantitative statements and measurements.

3. Segregation

Segregation of the Quiet Sun from a.r. sources

(i) *Using extreme u.v. images*

A glance at a well stabilized extreme u.v. image shows that the Quiet Sun with its limb brightening can be readily distinguished from the small bright active regions. Using photometric scans it is possible to estimate the Q. intensity level, which must be smoothed for obtaining model measurements, and must be known in order to provide a base for the a.r. photometry. The errors in the segregation of a.r. from Q. are mainly associated with the irregularity of Q. The difficulty is greatest at the limb where a.r. and Q. may have a similar intensity. Nevertheless image photometry provides the most accurate method of determining Q. and a.r. intensities and fluxes on a particular occasion.

(ii) *Using total flux statistics*

The two clouds of points in figure 1 are intended to represent correlations of extreme u.v. flux $\mathscr{F}$ against solar activity (e.g. sunspot number R) in a year near sunspot minimum and a year near sunspot maximum. By extrapolating linear solutions to $R = 0$ we can determine $\mathscr{F}_Q$ both for minimum and maximum; thus we can find the slow change of $\mathscr{F}_Q$ with the sunspot cycle. On any day $\mathscr{F}_{a.r.}$ (day) is given by $\mathscr{F} - \mathscr{F}_Q$. It will be noticed that if $\mathscr{F}$ had been plotted against R for the whole sunspot cycle the correlation would be represented by the broken line, but such a plot would not give a segregation of $\mathscr{F}_{a.r.}$ from $\mathscr{F}_Q$.

In the above argument it has been assumed that there is a linear proportionality between R and $\mathscr{F}_{a.r.}$. This is justified by the fact that both R and $\mathscr{F}_{a.r.}$ are additive over the existing active regions. Unfortunately the correlation between R and $\mathscr{F}_{a.r.}$ is not always as good as one would like for the above application, and a worse correlation may be expected in periods when the Sun is dominated by one exceptional a.r. Such periods should be avoided if one is seeking standard values of $\mathscr{F}_Q$.

Segregation of flare emission from a.r. sources

Usually flare changes are sudden and dramatic enough for the changes themselves to define the flare emission; also coincidence with optical flares, radio bursts and S.I.D. can be used. However, in X-ray wavelengths it is often desirable to discriminate between persistent minor flaring and the steady a.r. emission. The existence of the minor flaring can be sometimes detected by rapid flux variability but this does not separate the a.r. and fl. components quantitatively. A method of segregating based on routine flux recording (e.g. from Iowa Catalogue, Drake *et al.* 1969) is to plot minimum flux for each day against sunspot number. The nature of the result is illustrated in figure 2. For most of the time there is a reasonably good relation between daily R and $\mathscr{F}$ but in periods where flares are more active $\mathscr{F}$ tends to be larger than normal. It might be presumed that the linear relation connects R with the steady a.r. emissions while the extra emissions are associated with flaring. More analysis is needed to test this reasonable assumption and in particular to find what are the spectroscopic characteristics of this minor flaring.

At wavelengths where fl. and a.r. components may both be present there is not likely to be any significant Q. emission, and the $\mathscr{F}$–R correlation can be expected to pass through the origin.

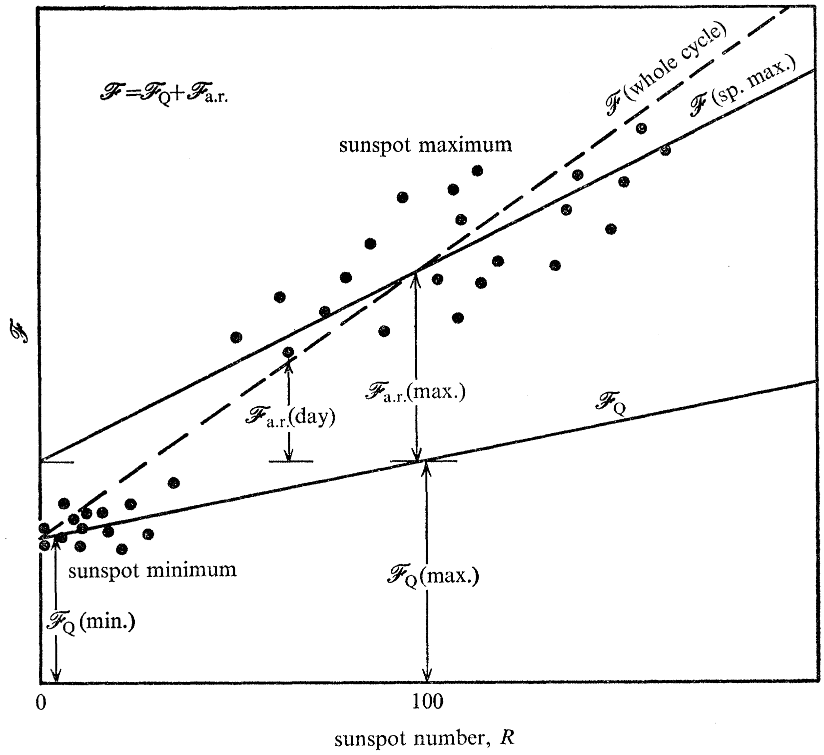

FIGURE 1. Correlation of extreme u.v. flux $\mathscr{F}$ with sunspot number R near both sunspot minimum and sunspot maximum.

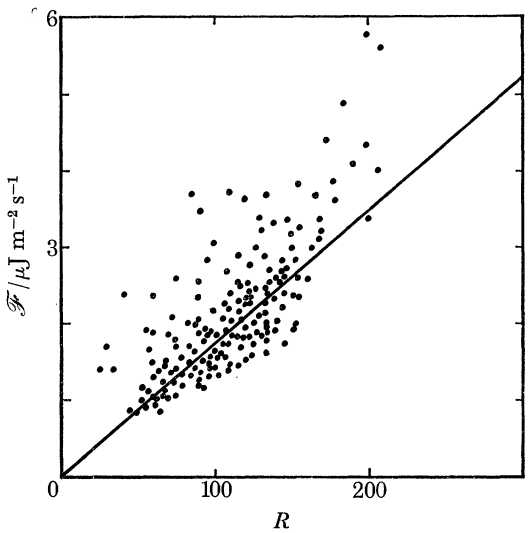

FIGURE 2. The relation between X-ray flux and sunspot number R. 1968 Iowa data, supplied by Goddard Space Flight Center. 0.2 to 1.2 nm.

4. Interpretation

The first approach used for interpreting extreme u.v. emissions is to assume that each photon emitted is associated with a collision excitation from a ground-level ion. This leads to an expression (see, for example, Allen 1965) of the form

$$\mathscr{F}_1 = 2.4 \times 10^{-43} f T^{-\frac{1}{2}} a i 10^{-5040 W/T} \int_T N_e^2 \mathrm{d}V$$

connecting $\mathscr{F}_1$ the line flux at the earth (in cgs) with oscillator strength f, emission region temperature T, abundance (relative to H) a, ionization fraction i, and excitation energy (in eV) W. The last term expresses the squared electron density over the volume where the temperature is within a defined range of T. In this expression f and W are usually known, i and T are interrelated and determined from the line identification, $\mathscr{F}_1$ is measured, and

$$a \int_T N_e^2 \mathrm{d}V$$

is the interpreted result. Using measurements from various atoms both the abundances a, and the N_e^2 integral can be determined.

Similar information on N_e^2 can be obtained from the groups of lines in a band but the results are more confused. Because of the significance of T in these applications it is usual to label ions and their spectrum lines by the temperature T at which they have their greatest i and therefore greatest line emission. It is sometimes necessary to determine a mean T to represent an observed spectral region. Tables suitable for determining T are available (see, for example, Jordan 1969).

In the well-ionized lines of the extreme u.v. the emission losses resulting from self absorption can usually be neglected. Calculated optical depths τ are of the order of one or less, and moreover those photons that are affected are not absorbed but scattered. Consequently they eventually leave the source and contribute to the measured $\mathscr{F}$ of the whole object. It is only when one is interested in the interpretation of an intensity distribution that τ must be considered.

Quiet Sun, Q.

Total $\mathscr{F}_1$ measurements segregated to represent Q. give good evaluations of

$$a \int_T N_e^2 \mathrm{d}V$$

for a range of T and the whole volume visible from the earth. By fitting such results to other coronal observations, and assuming pressure equilibrium, model atmospheres can be determined.

From the observing point of view it is convenient to regard the Q. emission as (i) a constant intensity disk D, plus (ii) a limb brightening feature L (with $L+D$ = Q.). If the emission layer were both physically and optically thin the flux from the limb $\mathscr{F}_L$ would equal the disk flux $\mathscr{F}_D$. However, the measured ratio $\mathscr{F}_L/\mathscr{F}_D$ is usually less than unity. It can be shown that the ratio is affected by the optical depth τ and by the spicule absorption (Withbroe 1970). It also depends on the scale height H and the amount of polar darkening (Allen 1969). To some extent the measured limb brightening can be segregated into these factors. However, the limb brightening is not very sensitive to such variables and it should be possible to set up an empirical relation between limb brightening and mean wavelength of a spectral region. This could be useful for interpreting extreme u.v. images, based on wide spectral bands. Often the limb is the only part of the Q.

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emission that can be detected and the limb brightness ratio can be useful to convert limb measurements into total $\mathscr{F}_{\mathrm{Q}}$ by such an empirical relation.

Active regions

The spectrum line flux measurements for active regions can lead to estimates of N_{e}^2 distributed over the a.r. volume. Such estimates could be consolidated only if it were possible to define a standard a.r. that could sometimes be well observed. Probably the most reproducible and available standard of solar activity is the total activity for $R = 100$ (but avoiding exceptional sunspots) and this should be used for establishing $\mathscr{F}_{\mathrm{a.r.}}$ relations. But it does not represent any typical single a.r.

For individual a.r. correlations it should be sufficient to express the activity by two constants: (i) the intensity of the maximum (using maximum sunspot area or number, plage area, coronal 530.3 nm flux, etc.) and (ii) the age (which could conveniently be expressed in terms of the duration of the visible sunspots). Evaluations of

$$\int_T N_{\mathrm{e}}^2 \mathrm{d}V$$

as a function of T, and these two activity constants, could go far to establishing the model of an a.r. and its changes with age.

Flares

As with the Q. and a.r. components the extreme u.v. emissions from flares (X-rays in this case) can lead to estimates of flare temperature and density. The interpretation is complicated by the fact that continua are produced as well as lines so that the physical arguments must be extended. Moreover, there are nonthermal components in the emissions which confuse the estimates of temperature. As might be expected temperatures are higher for the more intense flares and tend to decrease during the flare's life.

Flare observations can be standardized to some extent by relating them to the Hα flares of importance 1, 2, and 3. However, there is great interest in the exceptionally bright and energetic flares that come beyond this range and need detailed individual interpretation.

Flares can be very small and faint but still have the sudden flare characteristics. However, it is still unknown whether the rapid small variations of X-ray emissions can really be called minor flares or whether they are a class of activity that comes between our fl. and a.r.

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