CORONAL ELECTRON TEMPERATURES AS MEASURED BY X-RAY PHOTOMETER

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Abstract: We present here a rather general method for evaluating electron temperatures and emission measures from X-ray energy flux data obtained by satellites. The method enables us to state the range of the thermal X-ray spectrum and is suitable for handling large amounts of data by computers.

On board of Intercosmos 4, Intercosmos 7 and, with slight changes and improvements, on board of the next scheduled Intercosmos solar satellite, there was and will be an X-ray photometer, part of which is described in detail in Dr. Fárník's contribution (see p. 161), the full description being in Valníček et al. (1973). Here we shall speak of an attempt to process the data, obtained from this experiment, and to exploit most of the physical information these data contain.

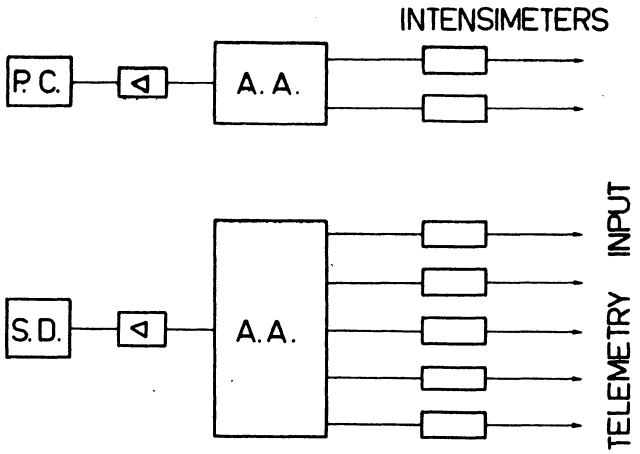

Fig. 1. Block diagram of the photometer (P.C. — proportional counter, S.D. — scintillation detector, A.A. — amplitude analyser).

We will briefly review the signal path (Fig. 1). There are two detectors, a gas-filled proportional counter and a natrium iodine scintillation detector, both with output pulse height proportional to the incident photon energy; after amplification their signals are fed to the amplitude discriminator which sorts them into two and five channels according to this pulse height (Fig. 2 shows the discriminator limits for the scintillation detector) and then each branch passes through a logarithmic intensimeter, whose output voltage (immediately transmitted by analogue telemetry) is nearly proportional to the logarithm of the number of pulses per second.

Suppose we are given the actual spectral distribution $\phi_0(\omega)$ incident upon the detector; it is then subject to the following modifications:

1. It is converted from an energy scale to a number-of-pulses scale:

$$\phi_1 = \phi_0/\hbar\omega .$$

2. It is multiplied by the window area and the spectral efficiency of the detector:

$$\phi_2 = A \,.\, \varepsilon(\omega) \,.\, \phi_1(\omega).$$

3. If the photon is recorded, the detector response need not correspond to the actual photon energy (this is caused, e.g., by the fluctuations of and modifies the spectrum in the following way:

$$\phi_3(\omega) = \int_0^\infty z(\omega, \omega_0) \,.\, \phi_2(\omega_0)\, \mathrm{d}\omega_0 .$$

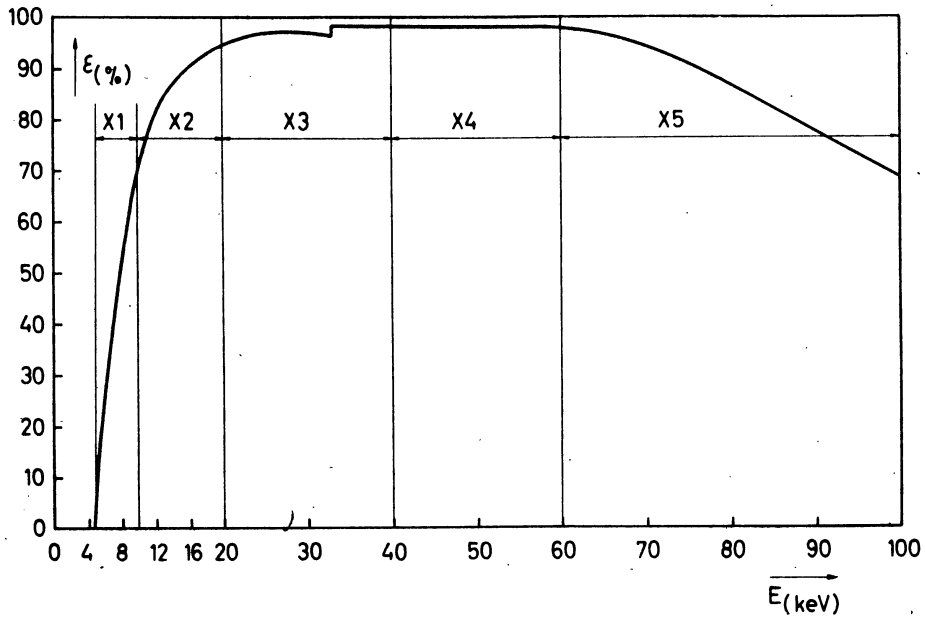

Fig. 2. The spectral efficiency of the scintillation detector and the discrimination levels of the individual channels.

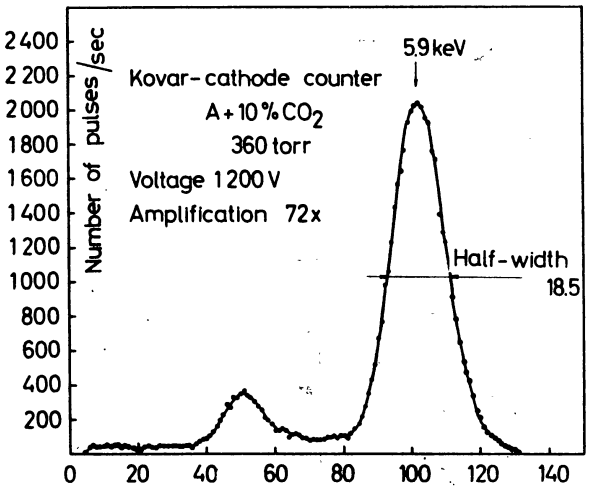

Fig. 3. Function $z(\omega,\omega_0)$ for $\omega_0 = 5.9$ keV.

the gas-amplification factor in the proportional counter). Figure 3 shows the probability density that, on receiving a photon of energy $\hbar\omega_0$, the detector will issue a signal corresponding to another energy $\hbar\omega$. We call this function $z(\omega, \omega_0)$; it is normed to a unit area

$$\int_0^\infty z(\omega, \omega_0)\, \mathrm{d}\omega = 1$$

An ideal detector should have $z(\omega, \omega_0)$ equal to the Dirac delta function of $\omega - \omega_0$. A special disturbing feature of this curve is the so-called "escape", i.e. a relatively high probability that the photon will be recorded as having an energy diminished by the ionization potential of the K-shell of the detecting material (in Ar it is about 3 keV, in NaI it is the iodine K-shell with about 29 keV).

4. The spectrum modified in this way, is then integrated in the amplitude discriminator within bounds, specific for each channel:

$$\phi_4 = \int_a^b \phi_3(\omega)\, \mathrm{d}\omega = \int_0^\infty K_{ab}(\omega_0) \,.\, \phi_1(\omega_0)\, \mathrm{d}\omega_0 ,$$

where

$$K_{ab}(\omega_0) = \int_a^b A \,.\, \varepsilon(\omega_0) \,.\, z(\omega, \omega_0)\, \mathrm{d}\omega .$$

Here, small variations of the supply voltage may cause the discrimination levels to vary rather strongly. No corrections were made for this effect as it was impossible to find out the actual value of such variations.

5. After recording a photon, the counter is insensitive for some time; this is, however, very short (about 1 microsecond) as compared to the

intensimeter dead time which may amount to a hundred microseconds. Therefore, we may carry out the obvious dead-time reduction with the integrated flux ϕ_4 and omit it before integration:

$$\phi_5 = \phi_4/(1+\tau\phi_4).$$

We must be aware, however, that the dead time depends on the input frequency of the pulses, i.e. on ϕ_4. This dependence is not well known to us and had to be disregarded.

6. The pulses in each channel are then converted to a uniform voltage by the logarithmic intensimeter:

$$U = F(\phi_5).$$

It is clear that we cannot obtain more parameters describing the shape of the spectrum than the number of channels we receive, i.e. 7 in our case. We proceed in the following way: expressing ϕ_1 as a simple function of these parameters and ω, we approximate $k_{ab}(\omega_0)$ by another simple function of ω_0, multiply one by the other and integrate analytically. We should then get a function of the chosen parameters which we equate to the (partly reduced) flux measured and solve the set of as many equations (pertinent to the neighbouring channels) as may parameters we seek.

In most cases, the appropriate parameter to describe the spectrum will be the emission measure; another may be the temperature, or the exponent of the photon energy, if we assume the power spectrum, or even others. In our calculations we confined ourselves to two parameters and chose the pair temperature and emission measure, that is, we assumed thermal radiation. The modification to the power spectrum is straight-forward. We accepted the expression of Culhane (1969) for the thermal X-ray free-free and free-bound transition spectra with Gaunt factors, computed according to Karzas and Latter (1961); in the region where our detectors are sensitive the lines are rather sporadic and we sould abandon them. The flux distribution, thus obtained as a function (apart from the obvious emission measure factor), of the temperature and photon energy (for easy scaling we used keV units to measure the photon frequency), we developed into Laguerre polynomials in terms of the temperature, the development coefficients again into Laguerre polynomials in terms of the photon energy, multiplied by an exponential:

$$\phi_1(\hbar\omega) = \\ = \text{E.M.} \sum_{m=0}^{9} \sum_{n=0}^{5} A_{mn} (\hbar\omega)^m \exp(-\hbar\omega) \cdot \\ \cdot T^n \exp\left(-\frac{\hbar\omega}{kT}\right).$$

We used the advantageous Gauss-Langrange integration formula

$$\int_0^\infty f(t) \exp(-t)\, \mathrm{d}t \approx \sum_{i=1}^{n} B^{n,i} f(x^{n,i})$$

to perform the integration, necessary to compute the series coefficients; in this formula we need know the value of the integrand at three points only to get six terms of the development in terms of the T-variable, which saves us from tedious computations, which the relative abundances of various ionization stages of various elements for many temperatures would certainly require. The weight K was approximated by means of a more accurate least-squares fit by means of Chebyshev polynomials, because it was easy to evaluate at many points. Both kinds of orthogonal polynomial series were then assumed into general polynomials and multiplied together; an elementary integration yielded the rational algebraic expression

$$\phi_4 = \text{E.M.} \sum_{m,n} C_{mn} T^n \int_0^\infty (\hbar\omega)^m \cdot \\ \exp\left[-\left(b + \frac{1}{kT}\right)\hbar\omega\right] \mathrm{d}(\hbar\omega) = \\ = \text{E.M.} \sum_{m,n} C_{mn} T^n \left(b + \frac{1}{kT}\right)^{-m-1} \Gamma(m+1),$$

which, equated to the measured flux, was easy to solve numerically.

Unlike Intercosmos 7, to which the present work is specially devoted, the X-ray photometer employed on the next Intercosmos solar satellite will be slightly modified in the following sense:

1. The amplitude discriminator will be calibrated automatically by a reference monochromatic X-ray source; the discrimination levels will then no longer vary in an unpredictable way.

2. There will be but one intensimeter switched cyclically to different discriminator channels; its dead time will be drastically reduced and made intensity-independent.

3. The data will have a digital form during through the whole processing procedure except on telemetry. On receiving the analogue the signal will again be converted into digital form and recorded on computer magnetic tape. Its handling is made as easy as possible in this way.

In spite of all these improvements a consider-

able list of deficiencies in our method still remains:

1. We must supply the assumed spectral distribution, dependent on a small number of parameters only. This is a grave restriction, as we can then get no principally new physical information. Furthermore, the theoretical spectrum, as dependent upon such physical parameters as the temperature, is always liable to errors which may occasionally be serious.

2. Even if the raw data, handed over to us, were strictly correct (and they are not), additional errors of great significance are brought into them in the course of processing such as approximation by polynomials, approximate quadrate formulas, extrapolation of detector characteristics into the region where they cannot be measured, etc. This shows that we are trying to get inappropriate information from the detectors, the kind of information for which they were not constructed, and that the data are not fit for this kind of elaboration.

3. All the distinct spectral features such as lines, edges, etc., which are of great importance for us, if we want to get a deeper insight into the physical conditions responsible for the radiation, are definitely smoothed out and lost to us.

If we want to know these conditions, e.g., the densities, pressures, velocities, fields, etc., we need rather high-dispersion spectrometers and polarimeters, pointed as precisely as possible at the present stage of technical development, which would yield all the information carried by the incident photon: its direction, energy, and polarization.

Therefore, we feel the sense of the X-ray photometer does not lie in determining the shape of the spectrum but rather, e.g., in its connection with instruments producing a large amount of information to help us with preliminary sorting.

References

CULHANE, J. L. (1969): Mon. Not. R. Astron. Soc., *144* (3), 375.

KARZAS, W. J. and LATTER, R. (1961): Astrophys. J. Suppl., *6*, 167.

VALNÍČEK, B., FÁRNÍK, F., HORN, J., LETFUS, V., SUDOVÁ, J., KOMÁREK, B., ENGELTHALER, P., ULRYCH, J., MOUČKA, L., FROŇKA, O., VAŠEK, T., BERÁNEK, I., PLCH, J., and ZDERADIČKA, J. (1972): Bull. Astron. Inst. Czech., *24* (6).