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**Abstract**

**Full Text**

**Astronomy**

**G. M. Nikolsky**

**Soft X-Ray Radiation of Stars**

*(Presented by Academician V. G. Fesenkov, March 9, 1963)*

The rapid development of rocket methods for studying space has made topical the questions concerning the radiation of stars in the far ultraviolet region of the spectrum. Attempts to measure the X-ray radiation of stars, undertaken in 1960, made it possible only to estimate the upper limits of the radiation fluxes:  $2 \cdot 10^{-7}$  erg/cm<sup>2</sup>·sec in the region 8–18 Å and  $5 \cdot 10^{-7}$  erg/cm<sup>2</sup>·sec for 44–60 Å <sup>(1)</sup>. There is no doubt that such measurements will soon be carried out with more sensitive apparatus. Therefore, here we shall estimate the expected radiation flux from stars in the region  $\lambda < 100$  Å.

For most bright stars, absorption by interstellar hydrogen beyond the Lyman series is substantial. For example, for a star located relatively nearby, at a distance of 10 pc, the spectral region  $\lambda \simeq 300$ –912 Å is completely absorbed in the interstellar medium. Therefore, observations from the solar system can access only the extreme regions of the short-wavelength spectrum of stars:  $\lambda \gtrsim 1000$  Å and  $\lambda \lesssim 100$  Å. Even for hot stars, radiation at  $\lambda < 100$  Å is determined by the upper atmosphere (corona), since the continuous radiation of the photosphere is negligibly small in this spectral region.

Our calculations pertain to the “quiet” radiation of stationary stars. Such radiation arises as a result of three processes: 1) “free-free” transitions of electrons, 2) photorecombination of electrons with highly ionized atoms, and 3) excitation of these ions by electron impacts (line radiation). It can be shown that the last process is the most significant, of course in the case where ions are present that give lines in the spectral region under consideration. The existence of various ions is determined by the electron temperature of the stellar corona. For example, for the Sun the X-ray radiation with  $\lambda > 20$  Å is predominantly line radiation <sup>(2)</sup>.

If excitation of the initial level is due to electron impact, then the radiation flux in a line of wavelength  $\lambda$  Å is determined by the expression

$$F = \frac{10^{-8}}{\lambda} \varkappa f_{12} W' \Delta\varphi \frac{\text{erg}}{\text{cm}^2 \cdot \text{sec}}, \quad (1)$$

Here  $\varkappa$  is the abundance of the given ion relative to hydrogen <sup>(3)</sup>;  $f_{12} T^{-3/2} W'$  is the probability of excitation by electron impact <sup>(2)</sup>,  $f_{12}$  is the oscillator strength;

$\Delta\varphi = \int n_e^2 T^{-3/2} dh$  is the generalized emission measure for the region in which the given ion exists, i.e., for that layer in the stellar atmosphere whose electron temperature lies, according to (3), within the limits (0.7 ÷ 1.3) of the ionization temperature of the ion considered. Formula (1) is valid in the absence of self-absorption, which is true for any star at  $\lambda < 100 \text{ \AA}$ .

In our work (4), the structure of transition regions and stellar coronae was considered. The principal result of (4) is the construction of the generalized emission measure of the stellar atmosphere as a function of electron temperature

$$\varphi(T) = \int_{h(T)}^{\infty} n_e^2 T^{-3/2} dh.$$

The quantities we need,

$$\Delta\varphi(T_i) = \varphi(0.7T_i) - \varphi(1.3T_i) \simeq \varphi(0.7T_i),$$

will be taken from (4).

To determine the radiation at  $\lambda < 100 \text{ \AA}$ , we shall consider only some of the most intense resonance lines, listed in Table 1. The total flux in all existing lines is, in order of magnitude, determined by these lines (it may be larger by a factor of 3).

In Table 1, for the ions of the isoelectronic sequences H I and He I,  $f_{12} \approx 0.4$ ; for all other lines we have taken  $f_{12} \sim 0.2$ .

In Table 2 the initial data are given: Sp—the spectrum with luminosity subclass (I—supergiants, III—giants, V—main-sequence stars);  $m_v$ —photovisual stellar magnitude;  $r$ —distance in parsecs—all according to (5);  $\tau$ —the optical thickness of the interstellar gas at  $\lambda = 100 \text{ \AA}$ , calculated under the assumption of an isotropic distribution of hydrogen with  $n_H \approx 0.5 \text{ cm}^{-3}$  in the vicinity of the Sun;  $R/R_\odot$ —the stellar radius, and  $T_k$ —the mean temperature of the stellar corona, taken from our paper (4). The final result of the calculations is the values  $L$ —the radiation power of the star—and  $f$ —the flux from it, taking account of interstellar absorption in four spectral intervals. The values of  $f$ , in accordance with the remarks made above, turned out to be  $\sim 10$  times larger than the recombination radiation (4).

**Table 1**

$\lambda_0 - \lambda_1, \text{ \AA}$	Ion	$\lg T_i$	$\lambda, \text{ \AA}$
100-60	Fe X	5.80	94-97
100-60	Fe XII	6.00	80
100-60	Fe XIII	6.05	75
60-40	Fe XIV	6.12	59
60-40	Fe XV	6.20	52.9

$\lambda_0 - \lambda_1, \text{ \AA}$	Ion	$\lg T_i$	$\lambda, \text{ \AA}$
60-40	Fe XVI	6.30	50.5
60-40	C V	6.14	40.3
40-20	C VI	6.30	33.8
40-20	N VII	6.40	24.8
40-20	O VII	6.40	21.6
<20	O VIII	6.50	19.0
<20	Ne IX	6.50	~ 14
<20	Ne XI	6.75	10.0

According to Table 2, the photon flux from bright stars in the region 20-100  $\text{\AA}$  is on average  $\sim 10^{-3}$  photon/cm<sup>2</sup> · sec. To detect such a flux, a combination of a counter with a collimator\* of effective area up to 1 m<sup>2</sup> is necessary. More effective may be an advance into the region

**Table 2**  
**X-ray radiation of bright stars**

Star	$m_v$	Sp	$r,$ pc	$\tau,$ 100 $\text{\AA}$	$\lambda =$ $\lg R/R_\odot$	$T_k$	$L,$ erg/sec				$f,$ erg/cm <sup>2</sup> /sec			
							100- 60 $\text{\AA}$	60- 40 $\text{\AA}$	40- 20 $\text{\AA}$	<20 $\text{\AA}$	100- 60 $\text{\AA}$	60- 40 $\text{\AA}$	40- 20 $\text{\AA}$	<20 $\text{\AA}$
$\alpha$	-1.43	A1	2.7	0.02	0.36	6.30	3 · 10 <sup>27</sup>	3 · 10 <sup>27</sup>	3 · 10 <sup>27</sup>	-	2 · 10 <sup>-12</sup>	2 · 10 <sup>-12</sup>	2 · 10 <sup>-12</sup>	-
C		V												
Ma														
$\alpha$	0.37	F5	3.5	0.03	0.5	6.0	10 <sup>28</sup>	10 <sup>27</sup>	-	-	4 · 10 <sup>-12</sup>	4 · 10 <sup>-13</sup>	-	-
C		IV												
Mi														
$\alpha$	1.36	B8	26	0.25	0.44	6.35	5 · 10 <sup>27</sup>	5 · 10 <sup>27</sup>	2 · 10 <sup>28</sup>	-	1 · 10 <sup>-14</sup>	2 · 10 <sup>-14</sup>	7 · 10 <sup>-14</sup>	-
Leo		V												
$\alpha$	1.00	B1	72	0.07	0.86	6.44	10 <sup>29</sup>	10 <sup>29</sup>	10 <sup>29</sup>	-	5 · 10 <sup>-14</sup>	10 <sup>-13</sup>	8 · 10 <sup>-13</sup>	-
Vir		V												
$\alpha$	0.04	A0	8	0.08	0.35	6.32	2 · 10 <sup>27</sup>	3 · 10 <sup>27</sup>	3 · 10 <sup>27</sup>	-	2 · 10 <sup>-13</sup>	2 · 10 <sup>-13</sup>	2 · 10 <sup>-13</sup>	-
Lyr		V												
$\alpha$	0.80	A7	4.8?	0.04	0.20	6.24	8 · 10 <sup>26</sup>	2 · 10 <sup>27</sup>	2 · 10 <sup>27</sup>	-	1 · 10 <sup>-13</sup>	2 · 10 <sup>-13</sup>	2 · 10 <sup>-13</sup>	-
Aql		V												
$\alpha$	1.26	A2	50?	0.5	1.63	5.74	6 · 10 <sup>31</sup>	-	-	-	6 · 10 <sup>-11</sup>	-	-	-
Cyg		I												
$\mu$	2.40	B5	100?	0.9	1.45	6.10	2 · 10 <sup>29</sup>	5 · 10 <sup>28</sup>	-	-	2 · 10 <sup>-14</sup>	2 · 10 <sup>-14</sup>	-	-
C		I												
Ma														

Star	$m_v$	Sp	$r$ , pc	$\tau, \lambda =$			$\lg R/R_\odot$	$T_k$	$L$ , erg/sec	$L$ , erg/sec	$L$ , erg/sec	$L$ , erg/sec	$f$ , erg/cm <sup>2</sup> /sec	$f$ , erg/cm <sup>2</sup> /sec	$f$ , erg/cm <sup>2</sup> /sec	$f$ , erg/cm <sup>2</sup> /sec
				100 Å	100 Å	100 Å										
$\beta$	1.65	A0	26	0.25	0.55	6.20	8 · 10 <sup>27</sup>	8 · 10 <sup>26</sup>	8 · 10 <sup>26</sup>	8 · 10 <sup>26</sup>	8 · 10 <sup>26</sup>	8 · 10 <sup>26</sup>	4 · 10 <sup>-14</sup>	5 · 10 <sup>-15</sup>	5 · 10 <sup>-15</sup>	5 · 10 <sup>-15</sup>
Car		III					10 <sup>26</sup>	10 <sup>26</sup>	10 <sup>26</sup>	10 <sup>26</sup>	10 <sup>26</sup>	10 <sup>26</sup>	10 <sup>-15</sup>	10 <sup>-15</sup>	10 <sup>-15</sup>	10 <sup>-15</sup>
$\zeta$	1.70	B0	200	1.9	1.3	6.6	10 <sup>30</sup>	10 <sup>30</sup>	10 <sup>30</sup>	10 <sup>30</sup>	10 <sup>30</sup>	10 <sup>30</sup>	2 · 10 <sup>-13</sup>	2 · 10 <sup>-13</sup>	2 · 10 <sup>-13</sup>	2 · 10 <sup>-13</sup>
Ori		I											10 <sup>29</sup>	10 <sup>29</sup>	10 <sup>29</sup>	10 <sup>29</sup>
$\varepsilon$	1.78	O9	140?	1.3	1.26	6.7	4 · 10 <sup>30</sup>	2 · 10 <sup>30</sup>	2 · 10 <sup>30</sup>	2 · 10 <sup>30</sup>	2 · 10 <sup>30</sup>	2 · 10 <sup>30</sup>	3 · 10 <sup>-13</sup>	4 · 10 <sup>-13</sup>	4 · 10 <sup>-13</sup>	4 · 10 <sup>-13</sup>
Ori		I					10 <sup>30</sup>	10 <sup>30</sup>	10 <sup>30</sup>	10 <sup>30</sup>	10 <sup>30</sup>	10 <sup>30</sup>	10 <sup>-13</sup>	10 <sup>-13</sup>	10 <sup>-13</sup>	10 <sup>-13</sup>

$\lambda \sim 200\text{--}300 \text{ \AA}$ , where the flux is higher; however, only nearby stars such as Sirius, Canopus, Vega are then accessible. Recently <sup>(6)</sup>, with the aid of a counter raised on a rocket, a flux  $\sim 5 \text{ photons/cm}^2 \cdot \text{sec}$  was detected in the spectral region  $2\text{--}8 \text{ \AA}$  from an extended region ( $\sim 10^\circ \times 10^\circ$ ) located approximately in the direction of the galactic center\*\*. In addition, an isotropic background of  $\sim 1.7 \text{ photons/cm}^2 \cdot \text{sec}$  ( $\sim 10^{-8} \text{ erg/cm}^2 \cdot \text{sec}$ ) was recorded.

In this connection it is of interest to estimate the total X-ray radiation due to all the stars in the Galaxy. Such an estimate was made by Clark <sup>(7)</sup>, who assumed that, on the average, all stars radiate in the same way as the Sun. According to <sup>(7)</sup>, for  $\lambda = 8\text{--}20 \text{ \AA}$  the radiation flux is  $\sim 10^{-12}\text{--}10^{-10} \text{ erg/cm}^2 \cdot \text{sec}$ . From this, in <sup>(7)</sup> the conclusion was drawn that the observations <sup>(6)</sup> may be due to

\* For example, a mirror operating in the grazing-incidence mode.

\*\* There are, however, some grounds for considering this radiation to be a flux of electrons ( $\sim 10 \text{ keV}$ ).

by synchrotron radiation of cosmic electrons ( $\sim 10^{14} \text{ eV}$ ) in the galactic magnetic field. V. L. Ginzburg and S. I. Syrovatskii <sup>(8)</sup> showed, however, that synchrotron radiation at  $\lambda < 8 \text{ \AA}$  can give only a flux of  $\sim 3 \cdot 10^{-4} \text{ quanta/cm}^2 \cdot \text{sec}$ .

Let us calculate the flux of X-ray radiation in the Galaxy on the basis of the data in Table 2. If we consider only the stars of the galactic disk (dimensions  $25 \text{ kpc} \times 0.2 \text{ kpc}$ ), then  $f \approx NL/S$ , where  $N$  is the total number of radiating stars,  $L$  is their luminosity in the X-ray region of the spectrum, and  $S = 5 \cdot 10^{45} \text{ cm}^2$  is the area of the galactic disk. In the region  $\lambda < 40 \text{ \AA}$ , stars of classes O-B radiate effectively; their density <sup>(5)</sup> is  $\sim 10^{-4} \text{ pc}^{-3}$ , and the mean value of  $L_{(40\text{--}20 \text{ \AA})}$  for these same stars, according to Table 2, is  $\sim 10^{29} \text{ erg/sec}$ . With these data we find  $f \sim 3 \cdot 10^{-10} \text{ erg/cm}^2 \cdot \text{sec}$  ( $\sim 3 \text{ quanta/cm}^2 \cdot \text{sec}$ ). However, in the region  $\lambda < 8 \text{ \AA}$  the radiation flux must be substantially lower; for example, for the Sun, according to rocket measurements <sup>(9)</sup>, the radiation at  $\lambda < 8 \text{ \AA}$  is approximately 1.5 orders of magnitude less than at  $\lambda = 20\text{--}40 \text{ \AA}$ . Making the very rough assumption that this ratio is valid for stars of classes O-B, we find

$f(\lambda < 8 \text{ \AA}) \sim 0.1 \text{ quanta/cm}^2 \cdot \text{sec}$ . Let us recall that this number refers to the radiation of a star in the “quiet state.” If we assume that flares occur on O-B stars with the same frequency, duration, and relative power as on the Sun, then we can estimate (apparently, the lower limit) the radiation due to “stellar activity.” If for  $\sim 10^{-3}$  of the total time the Sun’s radiation at  $\lambda < 8 \text{ \AA}$  is enhanced by a factor of  $10^2$ - $10^3$  <sup>(9)</sup>, then the radiation due to flares on stars is also, in order of magnitude,  $0.1 \text{ quanta/cm}^2 \cdot \text{sec}$ .

In summary, let us note that the total flux of X-ray radiation ( $\lambda < 8 \text{ \AA}$ ) calculated by us may also be larger by an order of magnitude, and then the observations <sup>(6)</sup> may be explained by the radiation of stars; however, for a more precise answer to the question posed one should also take into account the contribution of novae, which may turn out to be significant. Consideration of this question lies beyond the scope of the present article.

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*Note: Figure translations are in progress. See original paper for figures.*

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