The cyclotron emission of anisotropic electrons in the X-ray pulsars

A.N.Baushev*and G.S.Bisnovatyi-Kogan†

Abstract

The spectrum of cyclotron radiation is calculated for anisotropically distributed relativistic electrons with a nonrelativistic velocity scattering across the magnetic field. It is shown that if such electrons are responsible for a formation of the "cyclotron" line in the spectrum of Her X-1, then the value of its magnetic field $(3-6)\cdot 10^{10}$ Gs following from this interpretation is in a good agreement with some other observations and theoretical estimations. Observations of a time dependence of the energy of this "cyclotron" line in the spectra of several X-ray pulsars is explained by a variability of the average longitude energy of the electrons, decreasing with increasing of the liminocity due to radiational braking of the accretion flow.

1 Introduction.

There are a lot of observations of the cyclotron resonance structure in the X-ray spectrum of pulsar Her X-1 [18, 17, 20, 9, 19, 14] at 39-58 KeV (see Table). This singularity is interpreted as a cyclotron line, and the magnetic field intensity was usually calculated from the non-relativistic formula

$$H = \frac{mc\omega}{e}, \tag{1}$$

where ω is the cycle frequency of the photons, m is the mass of the electron. It was obtained to be of the order of $(3-5)\cdot 10^{12}$ Gs. But as large as this value comes into conflict with some theoretical reasonings like interpretation of the observations of pulsar spin acceleration [5], condition for the transparency for the outgoing of the directed radiation [2, 3], consideration of the interrelation between radio and X-ray pulsars [6], simulation of the 35-days cycle variability [15], see also [10]

*Space Research Institute, Profsoyuznaya, 84/32, Moscow 117810, Russia
†Space Research Institute, Profsoyuznaya, 84/32, Moscow 117810, Russia, E-mail: gkogan@mx.iki.rssi.ru

It seems likely that the reason of this conflict is an unsuitability of the non-relativistic formula in this case. According to [4], the temperature of the electrons emitting a cyclotron line could be $\sim 10^{11} K$, and therefore they are ultrarelativistic. By this means the mean energy of the cyclotron line is broadened and shifted relativistically by a factor of $\gamma \simeq \frac{kT}{mc^2}$. In this article the spectrum profile of the cyclotron line is calculated for various electrons distributions. Furthermore, the model of the hot spot on the pulsar is considered and it is shown that the overall observed X-ray spectrum (from 0.2 to 120 KeV) can arise under the fields near the pulsar surface ($\approx 5 \cdot 10^{10}$ Gs) which are well below then those, obtaind from (1).

2 The cyclotron radiation of the anisotropic relativistic electrons

According to [8, 2], in the magnetic field near the pulsar the cross component of a momentum emits rapidly, while the parallel component remains constant. Hence the momentum distribution of the electrons is anisotropic

$$p_{\perp}^2 \ll p_{\parallel}^2, \tag{2}$$

where $p_{\perp} \ll mc$, $p_{\parallel} \gg mc$. In this article we assume for simplicity that the transverse electron distribution is two-dimensional Maxwellian

$$dn = \frac{N}{T_1} \exp\left(-\frac{mu^2}{2T_1}\right) d\frac{mu^2}{2}, \tag{3}$$

where $T_1 \ll mc^2$. Let us calculate the cyclotron emission of N such particles that move at a rate V along the magnetic field.

For a single particle, having the transverse velocity u, we find [7]:

$$j(\theta) = \frac{e^4 H^2 u^2 (1 - \frac{V^2}{c^2})^2 [(1 + \cos\theta)(1 + \frac{V^2}{c^2}) - 4\frac{V}{c}\cos\theta]}{8\pi c^5 m^2 (1 - \frac{V}{c}\cos\theta)^5}, \tag{4}$$

where θ is an observational angle in a laboratory frame of reference. Integrating over the distribution (3), we obtain for N particles:

$$J(\theta) = \int j(\theta) dn = N \frac{e^4 H^2 T_1 (1 - \frac{V^2}{c^2})^2 [(1 + \cos\theta)(1 + \frac{V^2}{c^2}) - 4\frac{V}{c}\cos\theta]}{4\pi c^5 m^3 (1 - \frac{V}{c}\cos\theta)^5}. \tag{5}$$

For the spectrum we find:

$$\omega(\theta) = \omega_H \frac{\sqrt{1 - \frac{V^2}{c^2}}}{1 - \frac{V}{c}\cos\theta}, \quad \omega_H = \frac{eH}{mc}. \tag{6}$$

When $V \simeq c$ the cyclotron radiation is highly directed and diagram has a pencil beam along V ($\theta \simeq 0$). Under these conditions ($\theta = 0, V \simeq c$) we obtain from (5),(6):

$$J(0) = \frac{2Ne^4H^2T_1}{\pi c^5 m^3 (1 - \frac{V}{c})}, \tag{7}$$

$$\omega(0) = \omega_H \sqrt{\frac{1 + \frac{V}{c}}{1 - \frac{V}{c}}} \approx 2\omega_H \frac{E_\parallel}{m_e c^2}, \tag{8}$$

what gives

$$1 - \frac{V}{c} = \frac{2\omega_H^2}{\omega^2}. \tag{9}$$

Let us consider the parallel momentum distribution of the electrons as:

$$dn = f(p_\parallel)\, dp_\parallel. \tag{10}$$

Substituting of dn for N and using

$$p_\parallel = \frac{mc}{2}\frac{\omega}{\omega_H}; \quad 1 - \frac{V}{c} = \frac{2\omega_H^2}{\omega^2}, \tag{11}$$

we obtain for the spectral density:

$$J_\omega = \frac{e^2T}{2\pi c^2 \omega_H}\omega^2 f\left(-\frac{mc}{2}\frac{\omega}{\omega_H}\right) d\omega. \tag{12}$$

Let us consider two important cases. When f is a relativistic Maxwell:

$$f = \frac{n_0 c}{T_2}\exp\left(-\frac{p_\parallel c}{T_2}\right), \quad T_2 \gg mc^2 \gg T_1, \tag{13}$$

where n_0 is a number of emitting electrons. Then the spectrum is:

$$J_\omega = \frac{n_0 e^2}{2\pi c \omega_H}\frac{T}{T_2}\omega^2 \exp\left(-\frac{mc^2\omega}{2\omega_H T_2}\right) d\omega. \tag{14}$$

This spectrum has a single maximum at

$$\frac{\omega}{\omega_H} = \frac{4T_2}{mc^2}. \tag{15}$$

In the second case consider the function f as

$$f = \frac{n_0}{\sqrt{\pi}\sigma}\exp\left(-\frac{(p_\parallel - a)^2}{\sigma^2}\right). \tag{16}$$

The spectrum of radiation is

$$J_\omega = \frac{n_0 e^2}{2\pi c^2 \omega_H} \omega^2 \exp\left(-\frac{(\frac{mc}{2}\frac{\omega}{\omega_H} - a)^2}{\sigma^2}\right) d\omega. \tag{17}$$

When $\sigma \ll a$ this spectrum has a single maximum at

$$\omega \simeq \frac{2a}{mc}\omega_H. \tag{18}$$

Notice that in all cases the maximum is shifted to

$$\frac{\omega}{\omega_H} \sim \frac{\bar{E}_e}{mc^2}. \tag{19}$$

It is a common property of relativistic cyclotron line, that is independent of the particular form of f. We had approximated experimental spectrum taken from [12] (solid line) by (14),(17) (dot line in fig. 1 and 2), and spectrum [11] by (17) only (fig. 3). Setting (in accordance with [4]) the longitude electron temperature as $\sim 2 \cdot 10^{11}$ K, that is $T_2 = 2 \cdot 10^{11}$ K and $a = 7 \cdot 10^{-4}\ \frac{\text{eV}\cdot\text{s}}{\text{cm}}$, we obtain for the magnetic field strength $B = 4 \cdot 10^{10}$ Gs, $8 \cdot 10^{10}$ Gs, and $4 \cdot 10^{10}$ Gs respectively. Here we estimate the spectral form of the cyclotron line averaged over the pulsar period, supposing uniform distribution of $f(p \parallel)$ over the polar cap. In this model the beam of the cyclotron feature is determined by the number distribution of the emitting relativistic electrons, moving predominantly along the magnetic field, over the polar cap.

3 Model of the X-ray spectrum of Her X-1.

In order to obtain the whole experimental spectrum of the Her X-1 the following model of the hot spot is considered. A collisionless shock wave is generated in the accretion stream nearby the surface on the magnetic pole of a neutron star. In it‘s front the ultrarelativistic electrons are generated. It’s worth mentioning that according to [2, 8] these electrons when generated can possess only small pitch-angle values and the condition (2) is fullfilled automatically. Under the shock there is a hot turbulent zone with a temperature T_e, and optical depth τ_e, and under this zone a heated spot on the surface of the neutron star with a smaller temperature is situated.

The whole X-ray spectrum of pulsar Her X-1 is represented on fig.3 by the solid line. It was taken from [11]. There are three main regions in it: a quasi-Plankian spectrum between 0,3 and 0,6 KeV, that is generated near the magnetosphere of the X-ray pulsar; power-law spectrum $(0.6 \div 20)$ KeV with a rapid decrease at 20 KeV, and the cyclotron feature.

The power-law spectrum area appears as follows. A surface emits the black-body spectrum with a temperature T_s. Travelling through the turbulent zone

Date	Article	$\omega_{\max}$(KeV)	Width(KeV)
1978,May	[17]	58	11^{+26}_{-11}
1977,Sep.	[20]	51	21^{+9}_{-7}
1978,Feb.	[9]	48	28 ± 7
1980,Apr.	[9]	54	11^{+14}_{-11}
1980,May.	[19]	49.5	18^{+6}_{-3}
1980,Sep.	[18]	39	27^{+21}_{-20}

this radiation is comptonized. This comptonized spectrum has been calculated according to [16]. Setting the neutron star radius equal to 10 km, distance from the X-ray pulsar 6 Kps, hot spot area $S = 2 \cdot 10^{12}$ cm^2, we have found the best approximation conditions at $T_s = 1$ KeV, $T_e = 8$ KeV, $\tau_e = 14$. The best approximation of the X-ray spectrum of the pulsar Her X-1 is represented in fig.3 by the dot line. It agrees nicely with the experimental curve.

4 Discussion.

The observation of the variability of the cyclotron line is reported in [13]. Ginga detected the changes of the cyclotron energies from 4 pulsars. The change is as much as 40 % in the case of 4U 0115+63. Larger luminosity of the source corresponds to smaller average energy of the cyclotron feature. These changes might be easily explained in our model. The velocity of the accretion flow decreases with increasing of the pulsar‘s luminosity because localy the luminosity is close to the Eddington limit. As a result the shock wave intensity drops as well as the energy of the ultrarelativistic electrons in it‘s front. The cyclotron energy decreases in accordance with (19).

5 Conclusion.

X-ray pulsar Her X-1 is one of the most interesting and most investigated of this kind of objects. In the spectra of the other pulsars there is also observed the cyclotron line, but these observations were less reliable. In all of these cases the magnetic field intensity turned out to be too large, if it is calculated according to the non-relativistic formula. The way to overcome this difficulty is proposed in this article. So the relativistic formula for the cyclotron line yields for the magnetic fields the value that is consistent with other observational data and many theoretical estimates.

References

[1] Basko,M.M., Sunyaev,R.A., 1976, MNRAS, **175**, 395

[2] Bisnovatyi-Kogan,G.S. 1973, AZh, **50**, 902

[3] Bisnovatyi-Kogan,G.S. 1974, AZh, **51**, 443

[4] Bisnovatyi-Kogan,G.S., Fridman,A.M. 1969, AZh, **46**, 721

[5] Bisnovatyi-Kogan,G.S., Komberg,B.V. 1973, Astron. cirk., No. 784, 721

[6] Bisnovatyi-Kogan,G.S., Komberg,B.V. 1974, AZh, **51**, 373

[7] Ginzburg,V.L. 1975, Theoretical physics and astrophysics, "Nauka", Moscow

[8] Gnedin,Yu.N., Sunyaev,R.A. 1973, Astron.Ap., **25**, 233

[9] Gruber,D.E., et al. 1980, Ap.J.(Letters), **240**, L27

[10] Lipunov,V.M. 1987, Astron. Zh., **64**, 321

[11] McCray,R.A., Shull,J.M., Boynton,P.E., et al. 1982, Ap.J., **262**, 301

[12] Mihara,T., Makishima,K., Ohashi,T. et al. 1990, Nature, **346**, 250

[13] Mihara,T., Makishima,K., Nagase,F. 1997, Proceedings of an international Workshop "All-sky X-ray Observations in the Next Decade", March 3-5, 135

[14] Sheepmaker,T., Jansen,F.A., Deerenberg,A.J.M., et al. 1981, Space Sci. Rev., **30**, 325

[15] Sheffer E.K., Kopaeva I.F., Averintsev M.B., et.al. 1992, AZh, **69**, 82

[16] Sunyaev, R.A., Titarchuk, L.G. 1980, Astron.Ap., **86**, 121

[17] Trümper,J., Pietsch,W., Reppin,C., et al. 1978, Ap.J., **219**, 105

[18] Tueller,J., Cline,T.L., Teegarden,B.J. et al. 1984, Ap.J., **279**, 177-183

[19] Ubertini,P., Bazzano,A., LaPadula,C.D., et al. 1980, Proc. 17th Int. Cosmic-Ray Conf.,Paris, **1**, 99

[20] Voges,W., Pietsch,W., Reppin,C. et al. 1982, Ap.J., **263**, 803

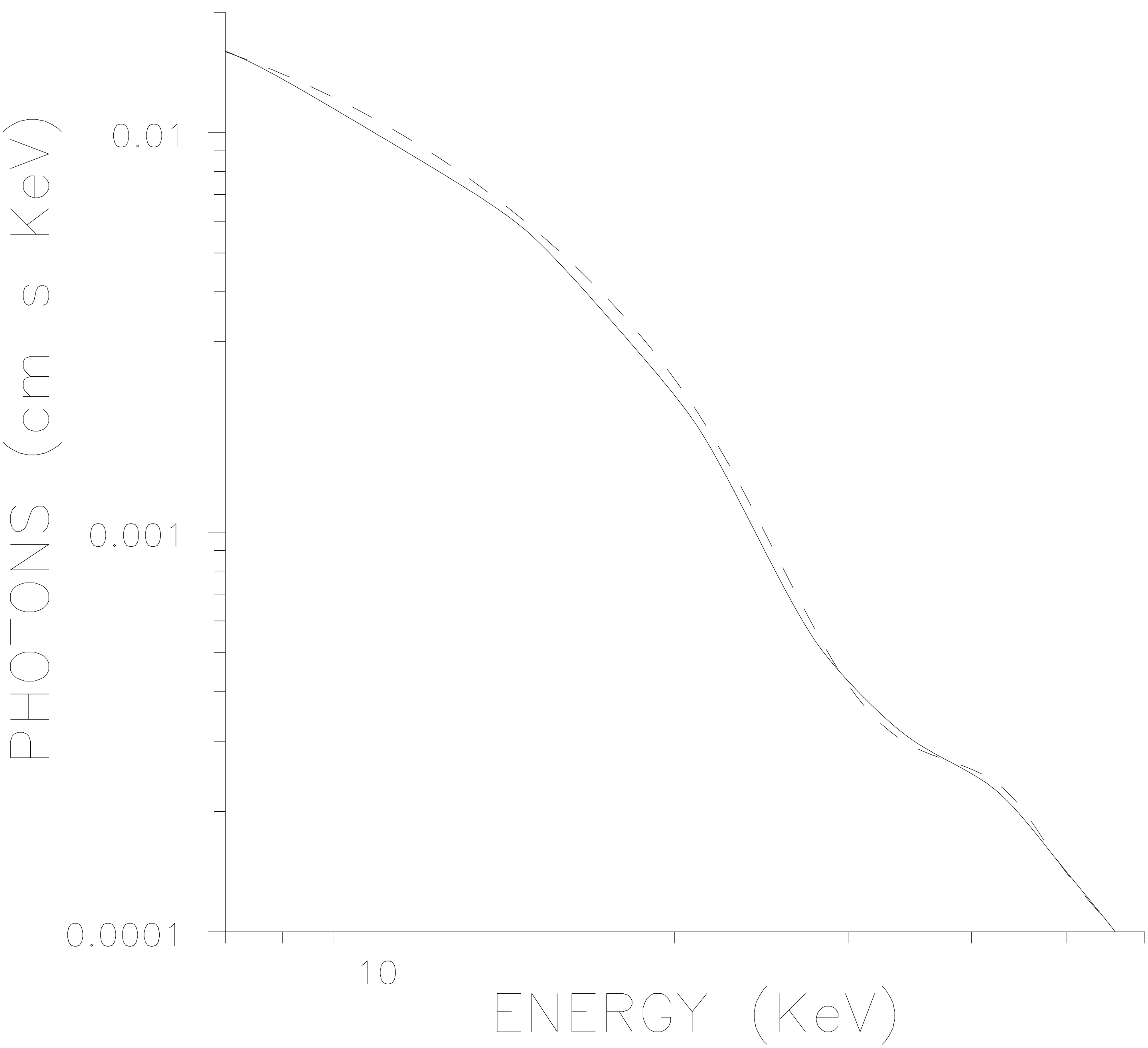
[21] Zel'dovich,Ya.B., Shakura,N.I. 1969, AZh, **46**, 225;

Figure captions

fig.1 Comparision of the observational and computational spectra of the cyclotron line. The solid curve is the observational results taken from [12], the dot curve is the approximation by the comptonized spectrum, and feature (14) with $T_2 = 2 \cdot 10^{11}$ K.

fig.2 Comparision of the observational and computational spectra of the cyclotron line. The solid curve is the observational results taken from [12], the dot curve is the approximation by the comptonized spectrum, and feature (17) with $a = 7 \cdot 10^{-4}\ \frac{\mathrm{eV \cdot s}}{\mathrm{cm}}$, $\sigma = 2 \cdot 10^{-4}\ \frac{\mathrm{eV \cdot s}}{\mathrm{cm}}$.

fig.3 Comparision of the observational and computational X-ray spectra of Her X-1. The solid curve is the observational results taken from [11], the dot curve is the approximation with $T_s = 0.9$ KeV, $T_e = 8$ KeV, $\tau_e = 14$, $a = 7 \cdot 10^{-4}\ \frac{\mathrm{eV \cdot s}}{\mathrm{cm}}$, $\sigma = 10^{-4}\ \frac{\mathrm{eV \cdot s}}{\mathrm{cm}}$.



0.01
0.001
0.0001
10
ENERGY (KeV)
PHOTONS (cm s KeV)

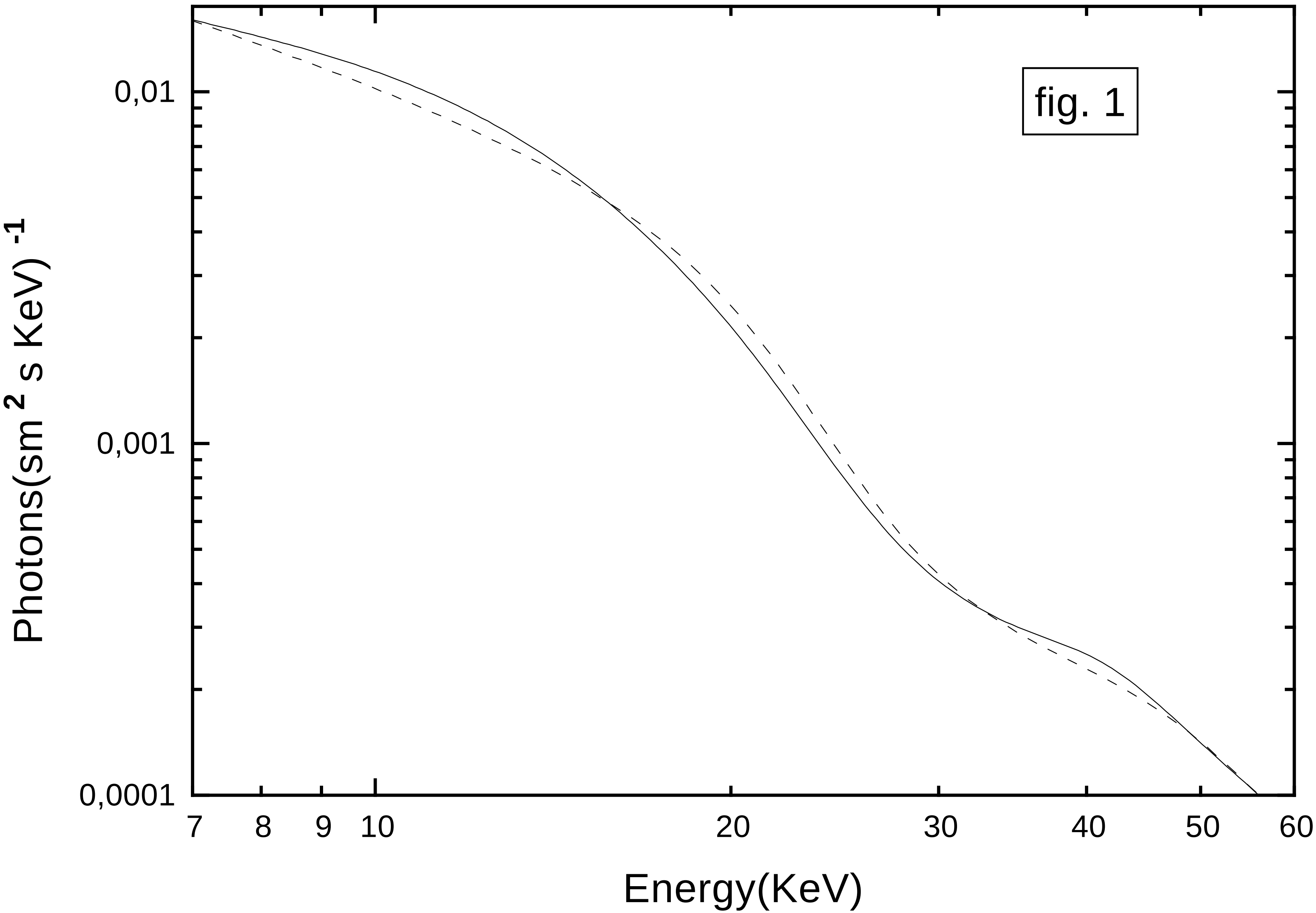
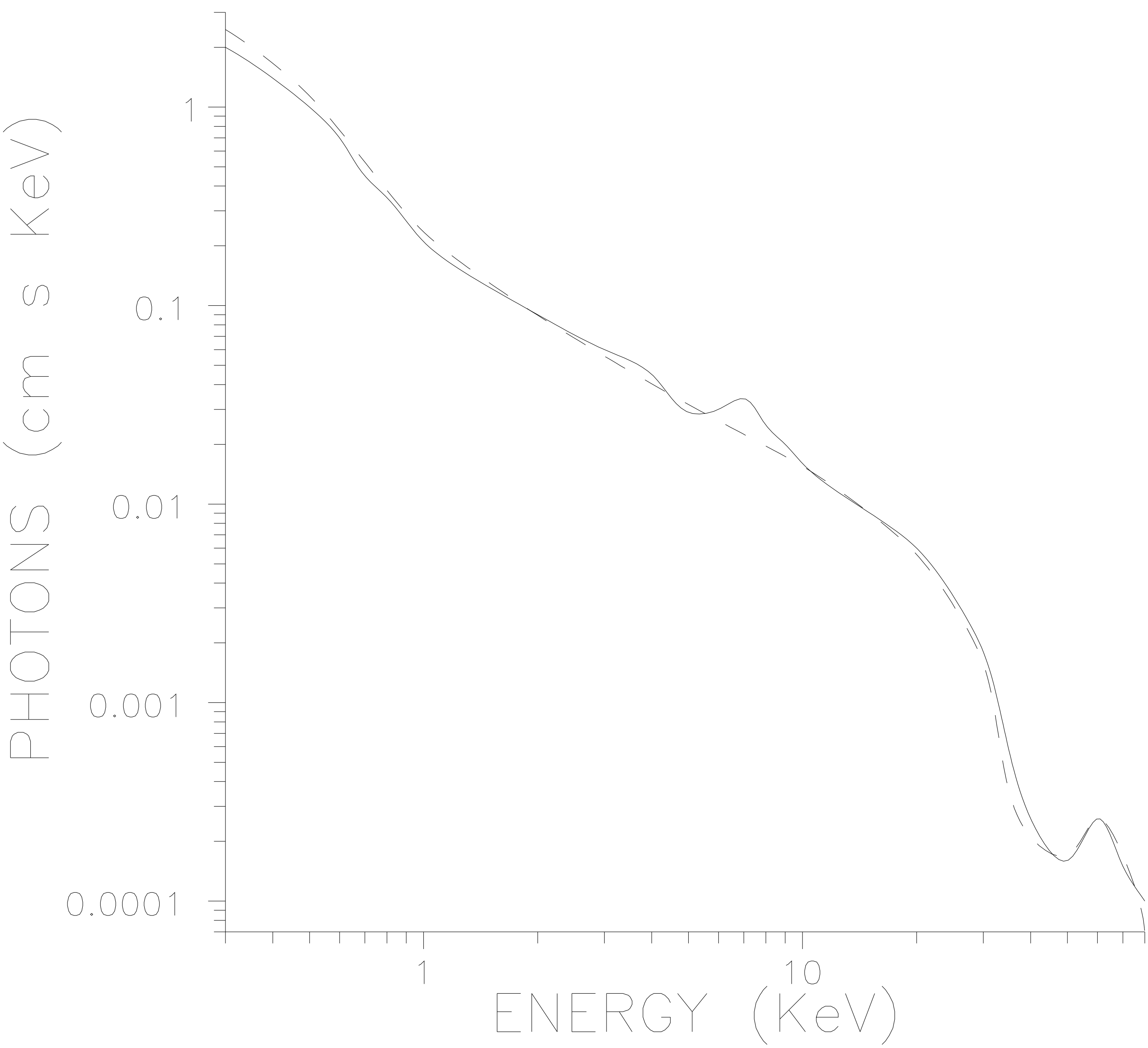


fig. 1
Photons(sm ^{2} s KeV) $^{-1}$
0,01
0,001
0,0001
7
8
9
10
20
30
40
50
60
Energy(KeV)


PHOTONS (cm s KeV)
1
0.1
0.01
0.001
0.0001
1
10
ENERGY (KeV)