Properties of magneto-dipole X-ray lines in different radiation models

G.S. Bisnovatyi-Kogan

IKI RAN and MEPHI (Moscow)

In collaboration with Y. Lyakhova

THESEUS CONFERENCE
March 23-26, 2021

The X-ray pulsar Her X-1, discovered in 1971 by the ***Uhuru satellite***, is one of the best studied X-ray sources. Her X-1 is the first source in the X-ray spectrum of which the line feature in the 39–58 keV energy range was observed by **Truemper et al. (1978).** This could not be identified with any chemical element and was suggested to be a cyclotron line. This feature was observed later by **Tuelle, et al. (1984); Voges, et al. (1982); Ubertini, et al. (1980); Gruber, et al. (1980).** Similar features have been observed in the X-ray spectra of some other X-ray sources, **Santangelo et al. (1999).** When this feature is interpreted as a cyclotron line, the magnetic field strength may be calculated from the non-relativistic formula

$$B = \frac{m_e c \omega}{e}$$

In this case, the magnetic field strength should be of the order of (3–5) × 10^12 G. However, values as large as this come into conflict with some theoretical reasoning, and simulation of pulse variability during the 35-day cycle in observations from the satellites ***ASTRON, Ginga and RXTE,*** see **Sheffer et al. (1992); Scott, et al. (2000); Deeter, et al. (1998)**. Obscuration of X-ray beams during the 35-d cycle is used there to explain the periodic X-ray high–low state transitions of Her X-1 during accretion disc precession. If the obscuring material is the inner edge of the accretion disc, then the inner disc must be tilted out of the binary plane and be precessing to produce periodically varying obscuration. In such a situation, occultation of the neutron star would occur twice in each precession cycle, leading to a decline in flux and termination of the main and short high states. This scheme was successfully extended to explain pulse profile evolution by a reflection of the light in the off state by the inner edge of the accretion disc. The value of the dipole magnetic field of the neutron star, which determines the radius of the inner edge, coinciding with the radius of the Alfv´en surface, was estimated in this model as 10^10–10^11 G, see Fig.1 from **Sheffer et al(1992).**

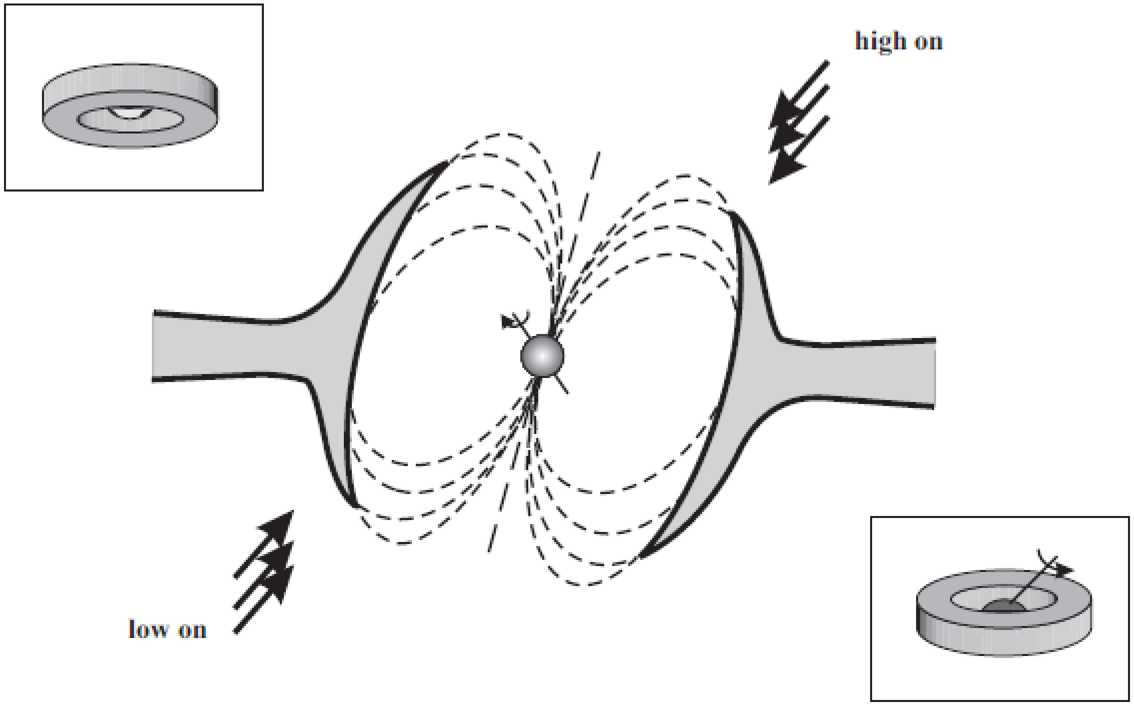


Fig.1

To solve this discrepancy problem, another model for interpretation of the observed X-ray line was proposed.

It was suggested by **Baushev & Bisnovatyi-Kogan (1999)** that the observed features could be explained by the relativistic dipole radiation of electrons having a strongly anisotropic distribution function, with ultrarelativistic motion along the magnetic field lines and nonrelativistic motion across it.

Such a distribution function is formed when the accretion flow into the magnetic pole of the neutron star is stopped in a non-collisional shock wave **(Bisnovatyi-Kogan & Fridman 1969)** and a rapid loss of transversal energy in the strong magnetic field leads to a strongly anisotropic momentum distribution in the region behind the non-collisional shock **(Bisnovatyi-Kogan 1973),** see Fig.2 from **(Bisnovatyi-Kogan 2002)**.

Schematic structure of the accretion column near NS magnetic pole

a)

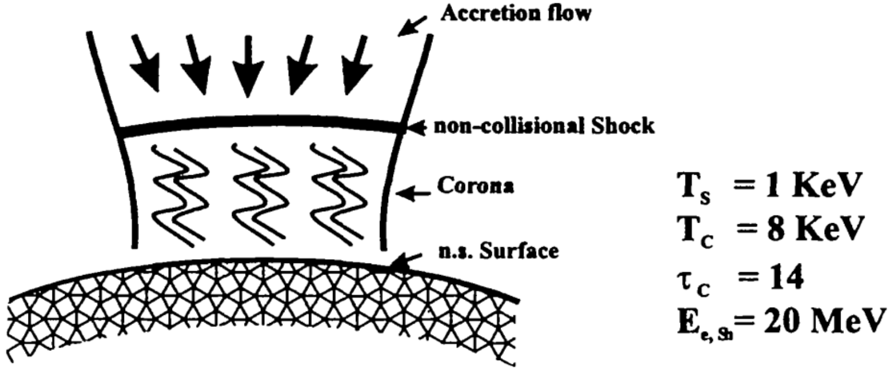


Fig. 2

b)

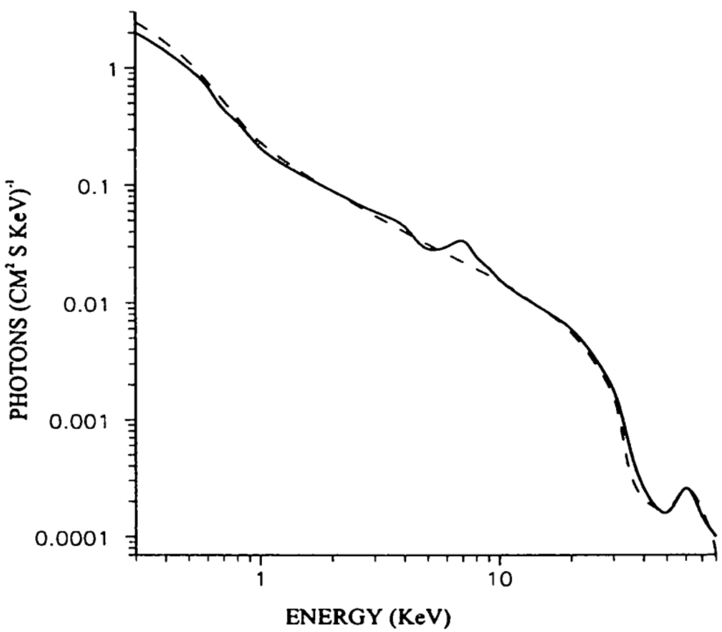


Fig. 2. Comparison of the observational and computational X-ray spectra of Her X-1. The solid curve is the observational results taken from McCray et al. (1982), the dot curve is the approximation with $T_s = 0.9$ KeV, $T_e = 8$ KeV, $\tau_e = 14$, $a = 7 \cdot 10^{-4}\ \frac{eV \cdot s}{cm}$, $\sigma = 10^{-4}\ \frac{eV \cdot s}{cm}$, $B = 4 \times 10^{10}$ Gs.

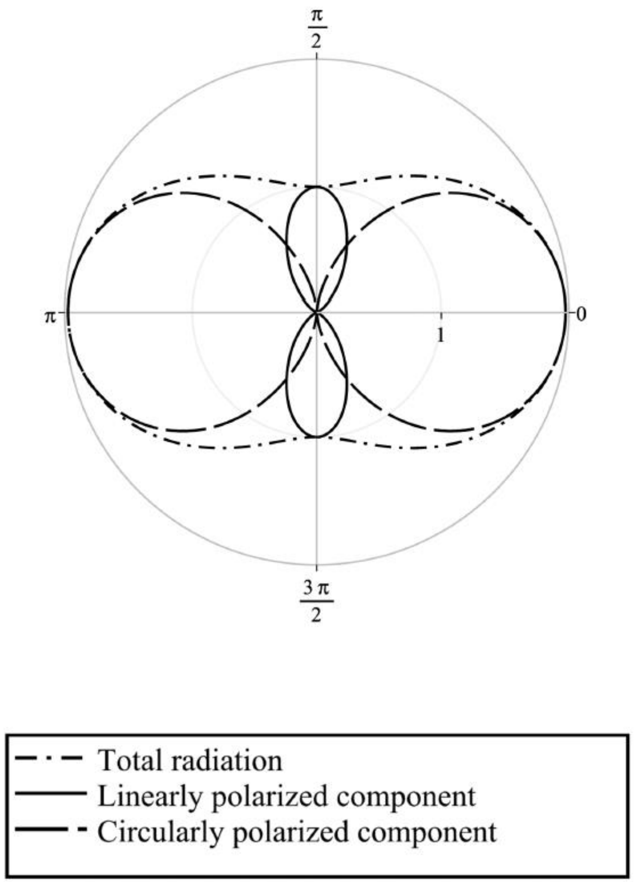
It is not possible for the moment to make a definite choice between these two models. There are other models explaining the change of X-ray beam during a 35-d period without obscuration of the beam by the inner edge of the accretion disc. **(Postnov et al., 2013; Staubert et al., 2013).** Therefore only observational criteria permit us to make a choice between the models.

The relativistic dipole and cyclotron radiation have different polarization properties, so its measurements could solve this problem **(Bisnovatyi-Kogan and Lyakhova, 2016).**

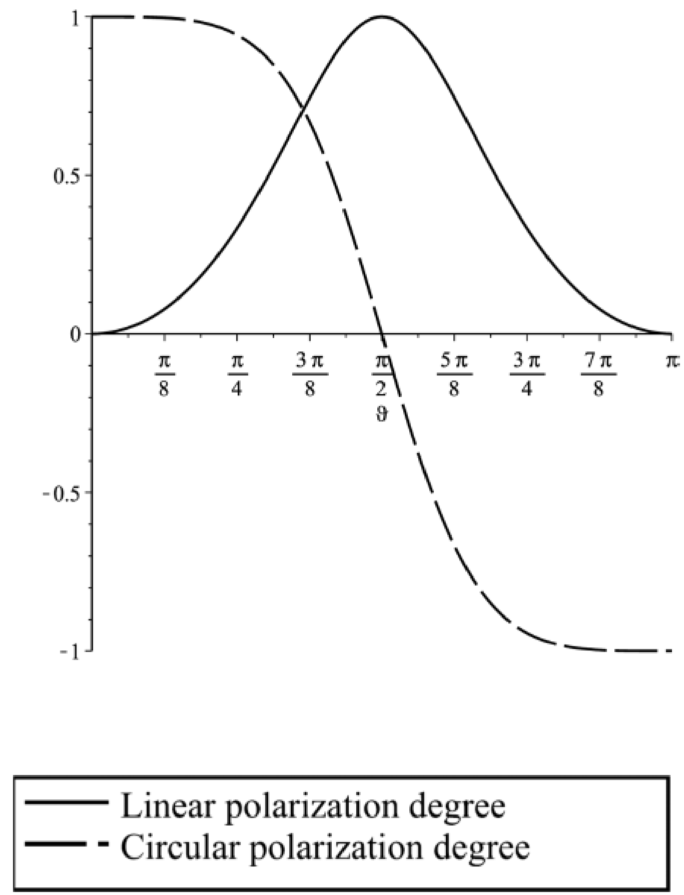
Polarization properties of the radiation produced by cyclotron and magneto-dipole radiation, at different level of anisotropy in the electron distribution, were studied by **Epstein (1973).**

The cyclotron radiation of a single electron is totally polarized. The cyclotron radiation along the direction of the magnetic field is fully circularly polarized and in the plane perpendicular to the magnetic field it's fully linearly polarized. If the lines observed in some X-ray sources are produced by a cyclotron mechanism the observed radiation in the line should be circularly polarized, if it is arriving in the beam along the magnetic field lined from magnetic poles at small angles, see Fig.3, from (Bisnovatyi-Kogan and Lyakhova, 2016).

POLARIZATION AND EMISSIVITY OF CYCLOTRON RADIATION



1.a)



1.b)

Fig. 3. (a) Angular distribution of CR polarization components and (b) angular dependence of the linear and circular polarization degrees.

Let's consider an electron in the magnetic field, with the following values of the velocity components in the laboratory frame

$$v_{\|} \simeq c, \qquad \gamma_{\|} = \frac{1}{\sqrt{1 - \frac{v_{\|}^2}{c^2}}} \gg 1,$$

$$v_{\perp} \ll c\sqrt{1 - \frac{v_{\|}^2}{c^2}} = \frac{c}{\gamma_{\|}}.$$

The trajectory of the electron is helical, with the helix step signfiicantly larger than it's radius

The radiation provided by such system is called Relativistic Dipole (RDR). The polarization properties of RDR have been considered in detail in **Epstein (1973).** The calculations of the angular distributions of RDR emissivity power, and both types of polarization in the laboratory frame, where the electron is moving along the magnetic field to the observer with the $v_{\|}$ velocity are calculated by making Lorentz transformation in formulas for a cyclotron radiation.

The emission of RDR is monochromatic in the laboratory frame in any given direction, with the frequency and polarization depending on the angle.

Angular dependencies of the polarization degrees in the laboratory frame derived by **Epstein (1973),** are plotted in Fig.4 for two Lorentz parameters, from (Bisnovatyi-Kogan and Lyakhova, 2016).

POLARIZATION OF RELATIVISTIC DIPOLE RADIATION

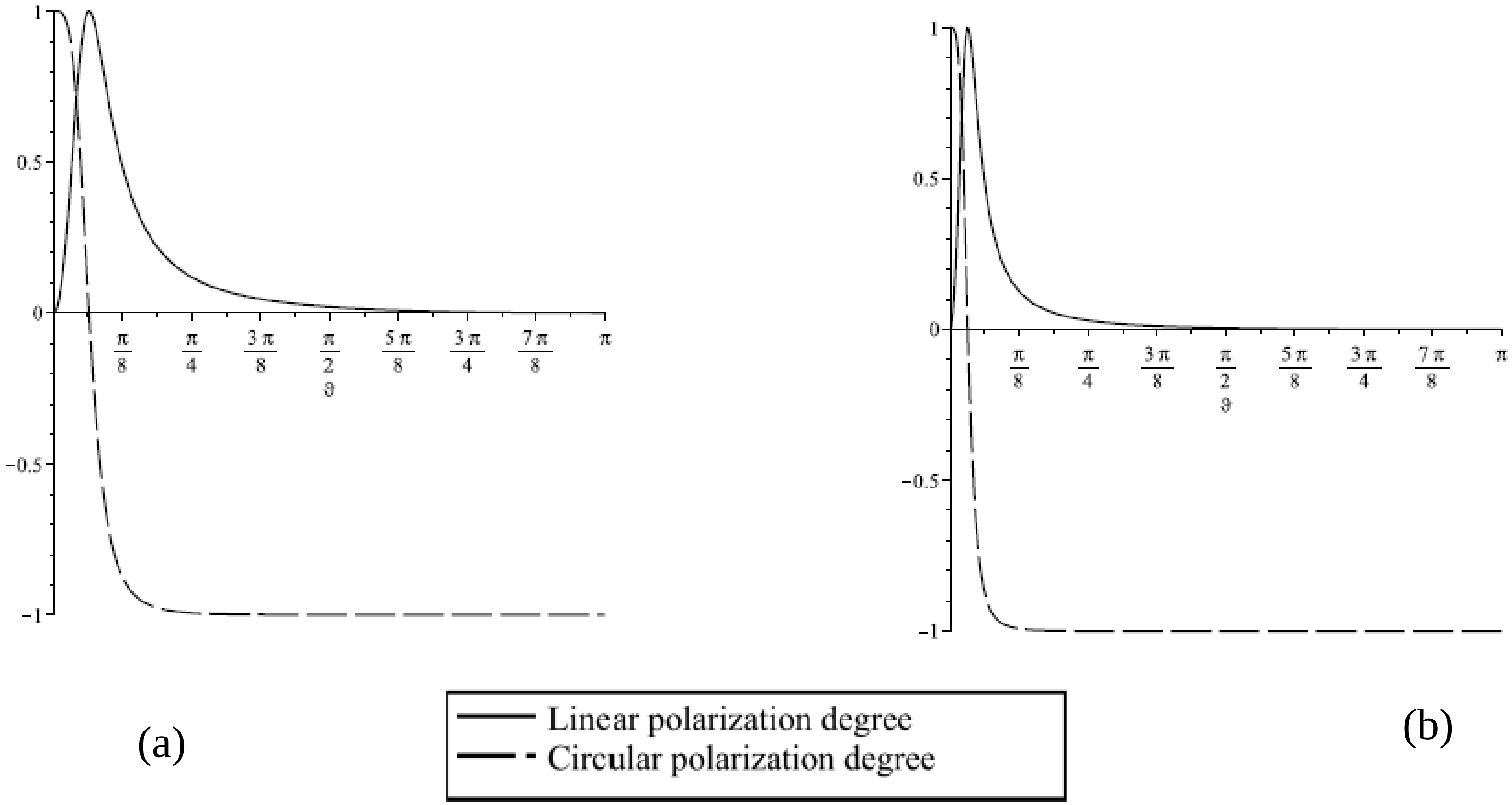


Fig.4

Angular dependence of the linear and circular polarization degrees for different values of Lorentz parameters:
(a) $\gamma_{\|}$ = 3.0; (b) $\gamma_{\|}$ =10.0.

CONCLUSIONS

1. The most distinct difference between the cyclotron and RDR mechanisms of the line formation may be seen in their polarization features. The measurements of the hard X-ray polarization are discussed for more than 40 years, but still there is no space mission for these measurements. The linear X-ray polarization should be close to zero for the cyclotron radiation from the hot magnetic pole, while the radiation produced in RDR model should have about 35% of the linear polarization in the line integrated over the beam (Bisnovatyi-Kogan and Lyakhova, 2016). The first source Her X-1 with the detected magnetic dipole line is probably the best target for this investigation.

2. The line emitted by non-relativistic electrons in the magnetic field has the same cyclotron frequency. Its harmonics are highly suppressed at $kT \ll m_e c^2$, what is expected in the accretion disk and in the accretion column. The observed line width originating from photons of the relativistic dipole radiation coming from different angles has a rather broad spectrum, contrary to separate harmonics in the cyclotron model. The second harmonic in the case of relativistic dipole radiation should form another line of almost the same width at double energy. There is still not clear whether the second "cyclotron" harmonics is present in the X-ray spectrum of Her X1 (Truemper at al., 1978; Enoto et al., 2008; Fuerst et al., 2013).

REFERENCES

Baushev A.N., Bisnovatyi-Kogan G.S. (1999) Astronomical Reports, **43**, 241

Bisnovatyi-Kogan G.S. (1973) AZh, **50**, 902

Bisnovatyi-Kogan G.S. (2002) Memorie della Soc. Astron. Italiana,, **73**, 318

Bisnovatyi-Kogan G.S., Fridman A.M. (1969) AZh,, **46**, 721

Bisnovatyi-Kogan G.S., Lyakhova Ya.S. (2016) MNRAS, **456,** 3186

Deeter J.E., et al.(1998) ApJ, **502**, 802

Enoto T., et al. (2008) Publ. Astron. Soc. Japan 60, S57

Epstein R. (1973) ApJ, **183**, 593

Fuerst F., et al. (2013) ApJ, 779, 69

McCray, R.A., Shull, J.M., Boynton, P.E., et al.: 1982, *Astrophys. J.* **262**, 301

Gruber D.E., et al.(1980) ApJ.(Letters), **240**, L27

Postnov K., et al. (2013) MNRAS, **435**, 1147

Santangelo A. et al., 1999, ApJ, **523**, L85

Staubert R., et al. (2013) A&A, **550**, A110

Scott D.M., Leahy D.A., Wilson R.B. (2000) ApJ, **539**, 392

Sheffer E.K., et al.(1992) AZh, 1992, **69**, 82

Truemper J., et al.(1978) ApJ lett. **219**, L105

Tueller J., et al. (1980) Proc. 17th Int. Cosmic-Ray Conf., Paris, **1**, 99

Ubertini P., et al. (1980) Proc. 17th Int. Cosmic-Ray Conf., Paris, **1**, 99

Voges W., et al. (1982) ApJ, **263**, 803