APPENDIX B

X-RAY EMISSION MECHANISMS

...catch the very light.
(Yes 1971)

B.1. THERMAL PROCESSES

The processes of astrophysical interest which allow the production of X-ray emission can be divided into two broad classes: **thermal processes** and **non-thermal processes**, depending on whether matter is in thermal equilibrium with radiation or not.

In this Appendix we will shortly review these processes, starting from those in which radiation and matter are in equilibrium; these will be dealt in this Section.

The first one among these, and the most common one in astronomy, is the **blackbody emission** mechanism. In this case, the radiation spectrum emitted by a body with high optical thickness (and therefore in which the photons absorbed or emitted by it could interact, and reach the equilibrium, with matter) only depends on the temperature T of the body according to the **Planck law**

$$B_\nu(T) = \frac{2h\nu^3}{c^2}\frac{1}{e^{\frac{h\nu}{kT}} - 1}, \tag{B.1}$$

in which B_ν it is the brilliance (i.e. the power emitted from the body in the surface, solid angle and frequency units), c the speed of the light, ν the frequency of the considered emission, h the Planck constant, and k the Boltzmann constant. The black body spectrum (Fig. B.1) has a peculiar shape, well known by the astronomers, and the characteristic frequency of the emission (i.e. the one corresponding to the maximum brilliance) is, according to the **Wien displacement law**,

$$\nu_{\max} = 5.88\cdot 10^{10}T \quad \text{Hz}; \tag{B.2}$$

it is thus clear that, in order for $\nu_{\max}$ to fall in the X-ray band (0.1÷100 keV), temperatures of the order of some millions (or some tens of millions) of degrees Kelvin are needed, even if substantial X-ray emission is observed from bodies with lower temperatures. Temperatures of this type are reachable in the inner zones of accretion disks around compact objects; it is however needed that the gas density is sufficiently low, otherwise thermonuclear processes within the disk can occur.

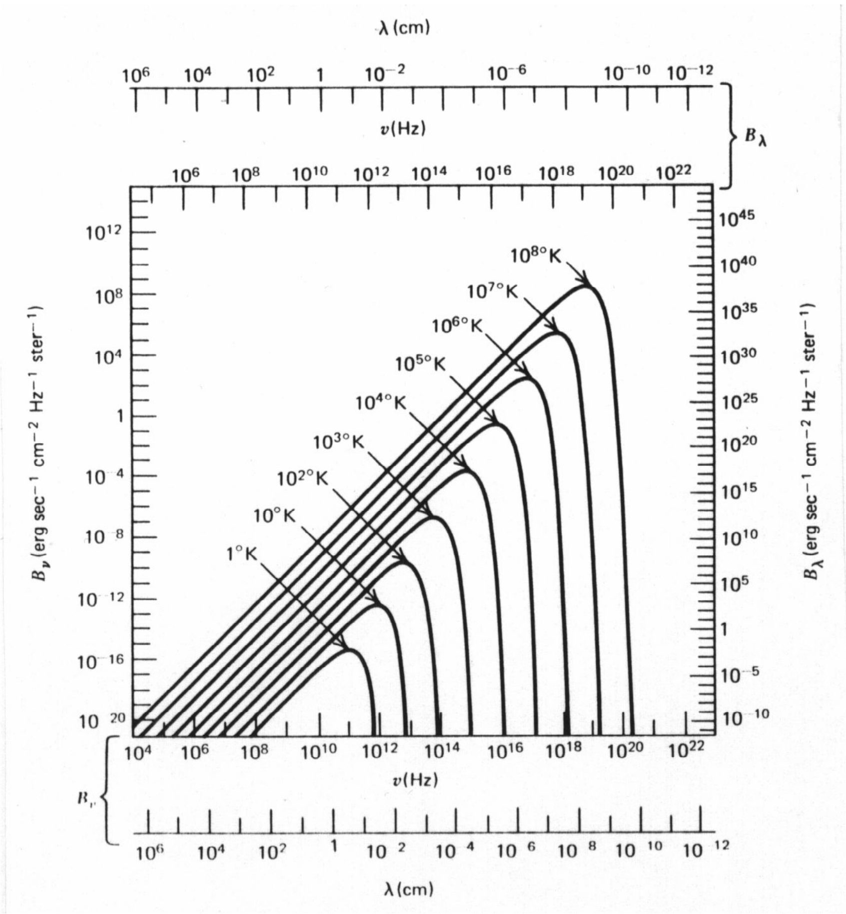

Fig. B.1. Blackbody radiation spectra characterized by different temperatures (from: Rybicki & Lightman 1979).

A second X-ray emission mechanism is the **gas thermalization**, that is, the conversion of the kinetic energy of the gas particles in radiating energy, according to the equation

$$\frac{1}{2}m\mathrm{v}^2 \approx kT \tag{B.3}$$

(with m the gas particle mass); from this equation it can be concluded that, in the case of a proton gas, velocities of some thousands of km s^{-1}, neglecting the relativistic effects, are enough to produce X-ray emission; actually, the energy conversion taking place in the gas because of this mechanism never leads to an immediate and total transformation of the kinetic energy into radiation, as part of the energy will be dissipated in other ways during the phenomenon. Therefore it is needed that the gas velocity at the beginning of the process is at least few times larger than the value computed with Eq. (B.3) in order to produce appreciable X-ray emission. Of course, the collisions among particles must take place in an optically thin atmosphere, otherwise the matter itself will reprocess the radiation by lowering its frequency.

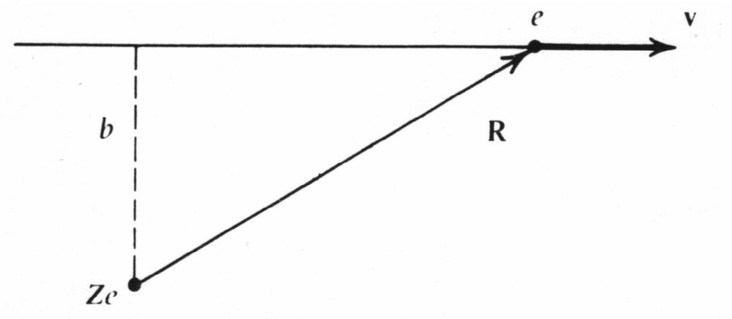

Fig. B.2. Diffusion geometry of an electron emitting via the bremsstrahlung mechanism in the field of an ion with electric charge *Ze* (from: Rybicki & Lightman, 1979).

A mechanism lying midway between the two classes, since it can be both thermal and non-thermal, and which can be considered a generalization of the previous one, is the **bremsstrahlung** or **free-free emission**. It is produced (recalling the physical principle according to which a charged particle radiates if accelerated) by an electron deviated, during its motion, by the coulomb field of an ion. This emission is therefore named after the fact that the electron is "braked" by the ion field (*bremsstrahlung* is indeed a German word that means "braking radiation") and it thus emits radiation while remaining free (i.e. it is not captured by the ion) in spite of this energy loss. The encounter of course produces an acceleration on both charged bodies but, being the electron much lighter than the ion, only the former one will be deviated and will emit in an appreciable way. Indeed, as it will be shown in Eq. (B.4), the emission power depends on the inverse squared mass of the particle.

It is therefore possible to describe the problem in such way to consider the ion as at rest during all the process, inside of an inertial system, with the electron that cresses its electrostatic field. In non-relativistic terms, and within the approximations according to which the electron is deviated of a small angle and it is moving along rectilinear trajectories before and after the deviation, we have, for a single event, an emission per unit cycle of the emitted radiation equal to (Rybicki & Lightman 1979)

$$\frac{dE(b)}{d\omega}=\begin{cases}\dfrac{8Z^2e^6}{3\pi c^3 m_e{}^2 \mathrm{v}^2 b^2} & b<<\dfrac{\mathrm{v}}{\omega}\\ 0 & b>>\dfrac{\mathrm{v}}{\omega}\end{cases} \tag{B.4}$$

in which b is the impact parameter of the electron, v its velocity modulus, e its charge, m_e its mass, Ze the ion charge (see Fig. B.2) and $\omega = 2\pi\nu$, where ν it is the frequency of the emitted radiation.

Now, in order to determine the spectrum of this emission, we need to know the numbers N_I of ions (mostly protons) and N_e of electrons per unit of volume, and the number of collisions that will occur in the unit of time; it is then obtained, by integrating over the impact parameter,

$$\frac{dE}{d\omega dVdt}=\frac{16e^6}{3c^3 m_e{}^2 \mathrm{v}}N_e N_\mathrm{I} Z^2 \log\left(\frac{b_\mathrm{max}}{b_\mathrm{min}}\right). \tag{B.5}$$

Using appropriate values for b_max and b_min (Rybicki & Lightman 1979), and introducing a correction factor of relativistic type, the **Gaunt factor** g (generally of order unity), the final expression of the bremsstrahlung emission spectrum will be in the following form:

$$\frac{dE}{d\omega dVdt}=\frac{16\pi e^6}{3\sqrt{3}c^3 m_e{}^2 \mathrm{v}}N_\mathrm{e} N_\mathrm{I} Z^2 g_\mathrm{ff}(\mathrm{v},\omega); \tag{B.6}$$

the index at the foot of the Gaunt factor indicates that it is referring to a free-free emission.

This process is particularly interesting when the electron velocity distribution is thermal, i.e. when it follows the Maxwell-Boltzmann law (**thermal** bremsstrahlung). In this case, Eq. (B.6) will be modulated by such a law in the following form (Rybicki & Lightman 1979):

$$\frac{dE}{d\omega dVdt}=\frac{2^5\pi e^6}{3m_e c^3}\left(\frac{2\pi}{3m_e k}\right)N_e N_{\mathrm{I}} Z^2 e^{-\frac{h\nu}{kT}}\overline{g}_{\mathrm{ff}}, \tag{B.7}$$

in which the Gaunt factor also is averaged over the Maxwell-Boltzmann thermal distribution of velocities.

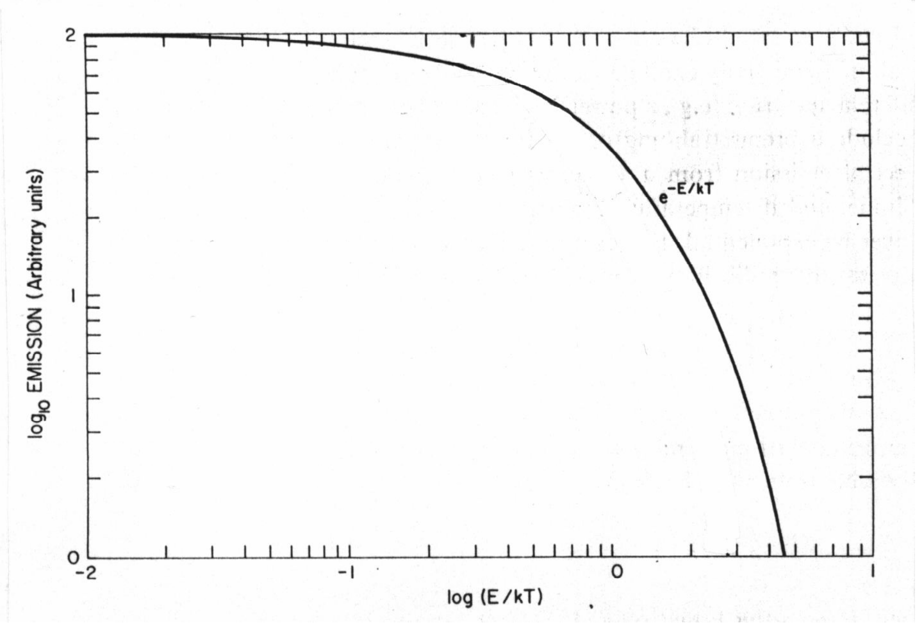

Fig. B.3. Thermal bremsstrahlung emission spectrum. The units along both axes are arbitrary (from: Blumenthal & Tucker, 1974).

The thermal bremsstrahlung emission spectrum is ‘flat’ (Fig. B.3), that is, nearly constant for a wide range of frequencies (in a bilogarithmic diagram), and eventually shows a cutoff at an energy *h*ν ~ *k*T (this occurs if the plasma is optically thin; in the opposite case, self-absorption effects appear): in such a way, from the spetral shape, the gas temperature can be determined. In order to have X-ray emission produced by thermal bremsstrahlung, temperatures ranging from tens to hundreds of millions degrees Kelvin are needed; these are reachable, as said before, in the inner parts of the accretion disks around compact objects.

If the electron velocities do not follow this distribution but, rather, other ones (for example, a power law), **non-thermal** bremsstrahlung emission will take place, which is however a less frequent case in close X-ray binary systems.

B.2. NON-THERMAL PROCESSES

Let us now review the processes which originate in occurrences in which matter is not in equilibrium with radiation.

The first important non-thermal processes that we will consider are the **cyclotron emission** as well as its relativistic extension, the **synchrotron emission**. They too, as we saw for the bremsstrahlung mechanism before, take advantage of the electron acceleration in order to produce radiation; this time, however, a centrifugal force will act on the charged particle. This because the electron is moving inside a magnetic field which, through the Lorentz force, imposes to the electron itself (Fig. B.4) a spiral motion around the field lines.

Assuming that in both cases the magnetic field is uniform, in the cyclotron case we will have, by imposing the centrifugal force equal to the Lorentz force, an angular velocity along the spiral trajectory corresponding to

$$\omega_{\mathrm{g}} = \frac{eB}{m_e c}, \tag{B.8}$$

called **gyration frequency**, in which B is the magnetic field modulus. The associated emission is therefore monochromatic, with frequency

$$\nu_{\mathrm{g}} = \frac{\omega_{\mathrm{g}}}{2\pi} = \frac{eB}{2\pi m_e c}. \tag{B.9}$$

In contrast, because of relativistic effects, the **synchrotron frequency** is

$$\omega_{\mathrm{s}} = \frac{eB}{\gamma m_e c}, \tag{B.10}$$

in which

$$\gamma = \frac{1}{\sqrt{1-\frac{\mathrm{v}^2}{c^2}}}, \tag{B.11}$$

with v the modulus of the electron velocity.

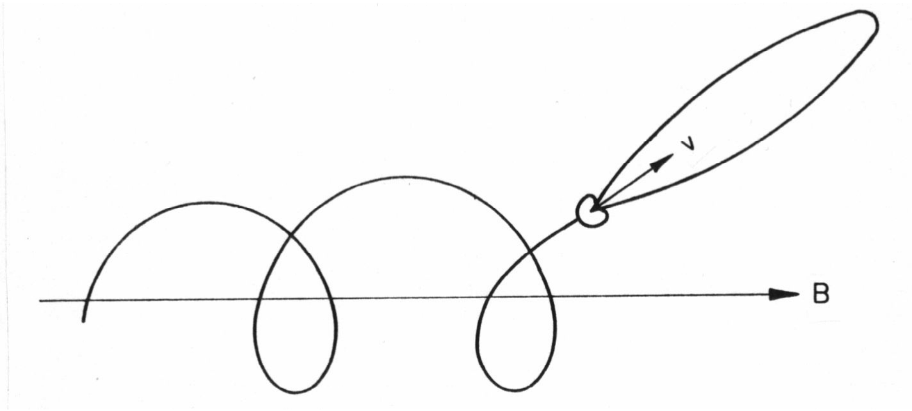

Fig. B.4. Motion of a relativistic charged particle in an uniform magnetic field (from: Blumenthal & Tucker 1974).

These same relativistic effects, however, make the synchrotron emission from a single electron not monochromatic (Rybicki & Lightman 1979), but rather with a spectrum like the one reported in Fig. B.5.

From this same figure it can be noticed that it exists a characteristic pulsation for the emission, which is equal to

$$\omega_{\mathrm{c}} = \frac{3}{2}\gamma^3 \omega_{\mathrm{s}} sen\alpha, \tag{B.12}$$

and which in turn defines a characteristic frequency

$$\nu_{\mathrm{c}} = \frac{3}{4\pi}\gamma^3 \omega_{\mathrm{s}} sen\alpha: \tag{B.13}$$

these quantities characterize a cutoff value beyond which the synchrotron spectral power drops in an exponential fashion. In these expressions, α is the **pitch angle**, that is, the angle between the electron velocity vector $\vec{\mathrm{v}}$ and the magnetic field vector $\vec{B}$.

Therefore, by considering such a frequency and having given an average value to the sine of α, it can be seen that, in order to obtain synchrotron X-ray emission, a magnetic field with intensity at least of the order $10^{12}/\gamma^3$ gauss is needed (and therefore, given that in these cases γ is 10^2 - 10^3, the modulus of $\vec{B}$ will have to be at least 10^6 - 10^8 gauss), while, in the case of the cyclotron, the magnetic field should be around 10^{12} gauss or more.

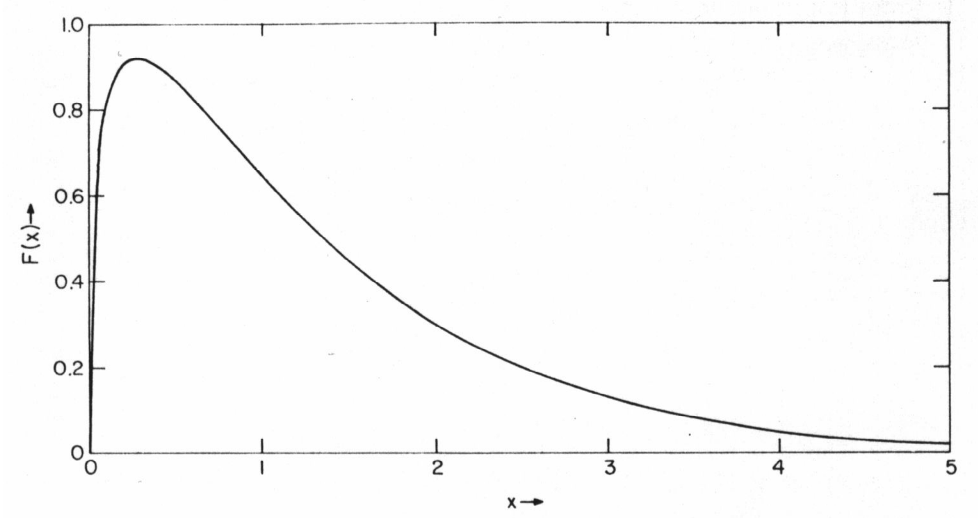

Fig. B.5. Synchrotron spectrum emitted by an electron moving in an uniform magnetic field. The parameter x corresponds to ω/ω_c (from: Blumenthal & Tucker 1974).

The other non-thermal mechanism of well known astrophysical importance for the production of X-ray emission is the **Inverse Compton effect**.

The direct Compton effect is produced by the relativistic scattering off of an electron at rest by a highly energetic photon; the Inverse Compton effect, instead, occurs when a relativistic electron crosses, during its motion, a region populated by low- or medium-frequency photons: in this case it is possible that the particle scatters some of them and transfers to them part of its energy, making them to become more energetic; indeed if, in the system in which the electron is at rest, the Thomson scattering condition is valid, i.e. $h\nu << m_e c^2$ (so that relativistic corrections are negligible in this system), the photon, after the scattering, will find its own energy increased by a factor γ^2. On the contrary, if such approximation does not hold, quantistic and relativistic effects that reduce the efficiency of the mechanism will take place.

Thus, the Inverse Compton effect is responsible of the bulk of cases in which hard X-ray (above 20 keV) and gamma emissions are detected, since the collision between optical photons (having energy of about 1 eV) and electrons with $\gamma \approx 10^2$ can already produce radiation with energies in the tens of keVs range.

Synchrotron and Inverse Compton are considered non-thermal processes because the electrons that produce them are relativistic and they do not follow a distribution of thermal (Maxwell-Boltzmann) type; rather, and more likely, they follow a power law distribution that cannot be associated with any temperature and that moreover produces a shaping effect on the spectrum, making it also in the form of a power law (Fig. B.6), i.e. with the emission flux proportional to the frequency raised to an exponent $-\alpha$ called **spectral index**.

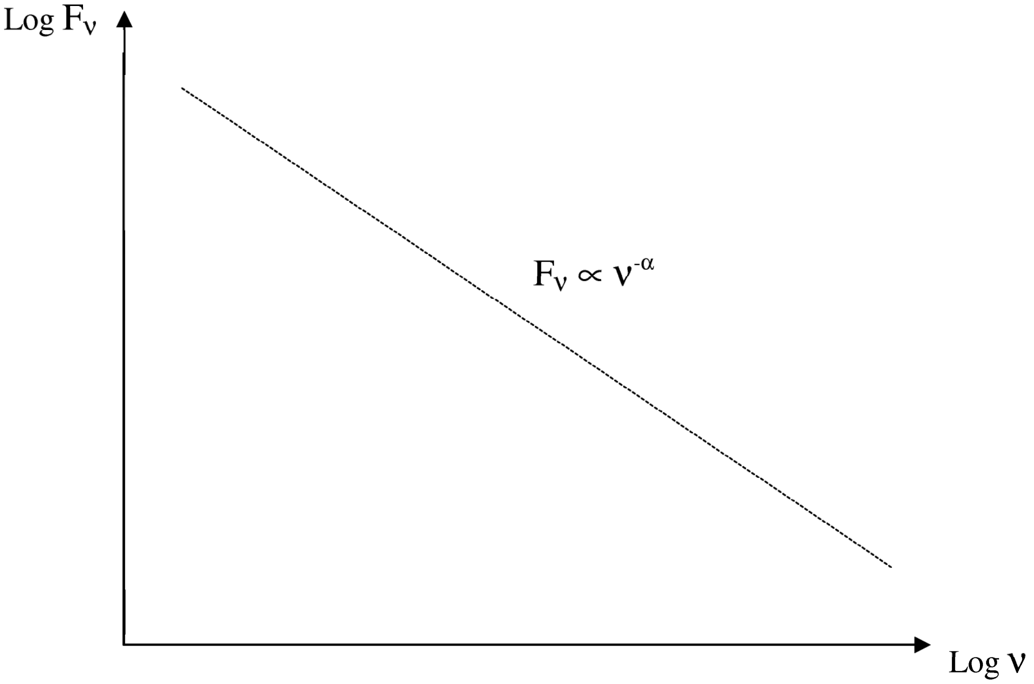

Fig. B.6. Schematic representation of a power-law spectrum. The plot is in bilogarithmic scale and the units are arbitrary.

B.3. DISCRETE X-RAY EMISSION

All emission mechanisms reviewed up to now, with the exception of the cyclotron emission, produce a spectral continuum: it is however possible to observe, in accretion discs or in astrophysical plasmas rich in heavy chemical species, X-ray emission in the form of single discrete lines (Fig. B.7) produced by electrons of strongly ionized atoms. These atoms are at first collisionally excited or further ionized, and then de-excite or recombine through emission of X-rays at a well determined frequency when the electrons return to the fundamental level. A typical example of this kind of emission in X-ray astronomy is the Fe K$_\alpha$ line emission (in practice, the Lyman-α line of the hydrogen-like iron), located at 6.7 keV and observed in AGNs and several accreting X-ray systems, among which some SXTs also (see Ch. 8). A complete description of this emission mechanism can be found in Blumenthal & Tucker (1974).

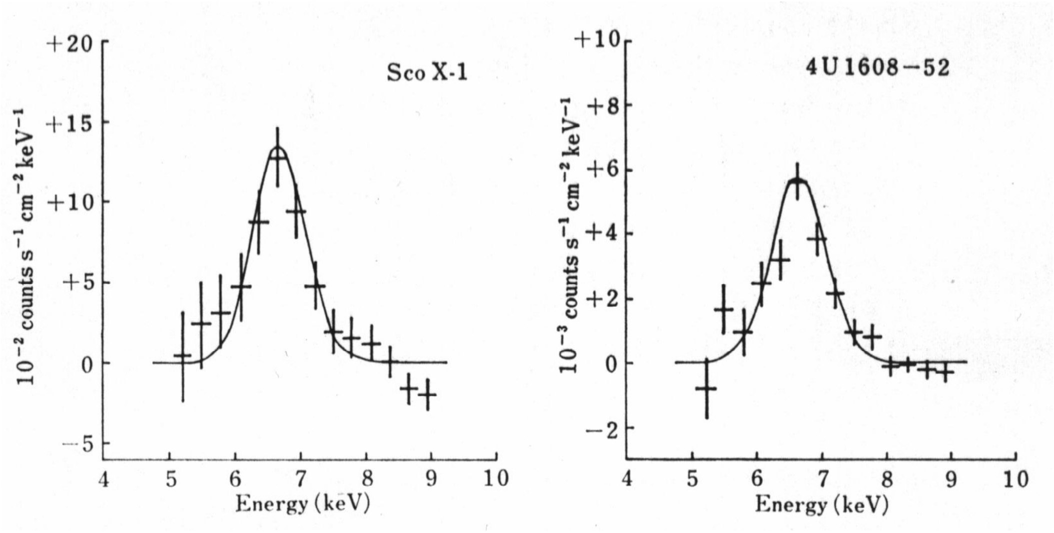

Fig. B.7. Emission lines of highly-ionized iron observed in the spectra of two X-ray binaries (from: Suzuki et al. 1984).

REFERENCES OF APPENDIX B

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