# 9. Fascinating observations. But how much is well understood?

9.1. X-ray binaries

We already learnt something about binaries and about accretion in lectures 3 and 5. Neutron stars are more abundant than BHs. In most X-ray emitting binary systems the compact component is a neutron star. Astronomers distinguish between high mass x-ray binaries (HMXB) and low mass x-ray binaries (LMXB). NSs have always been found with a mass of nearly $1,4 M_{sol}$, so the notation high and low mass refers to the normal (optical observable) primary star. In HMXB systems the normal star is often of spectral type B, a hot very luminous star with several times the solar radius. The orbital period is a few weeks till months. The B-star has an effective temperature between $1-3 \cdot 10^4 K$ and masses $M > 10 M_{sol}$. B-stars rotate rapidly and emit strong winds of stellar matter (especially strong emitters are of type Be) which surrounds the star as a cloud or ring. When the NS on its orbit passes the cloud accretion takes place accompanied by strong X-ray and optical outbursts. The brightest X-ray source belongs to this class. It carries the notation A0538-66 and is located in the Great Magellan Cloud. During its active phase the system shows outbursts in a 16,6 day cycle. An active phase lasts months, the quiet phase years without any regularity. A model of this system is shown in fig.9.1. The accreted infalling matter is forced to travel
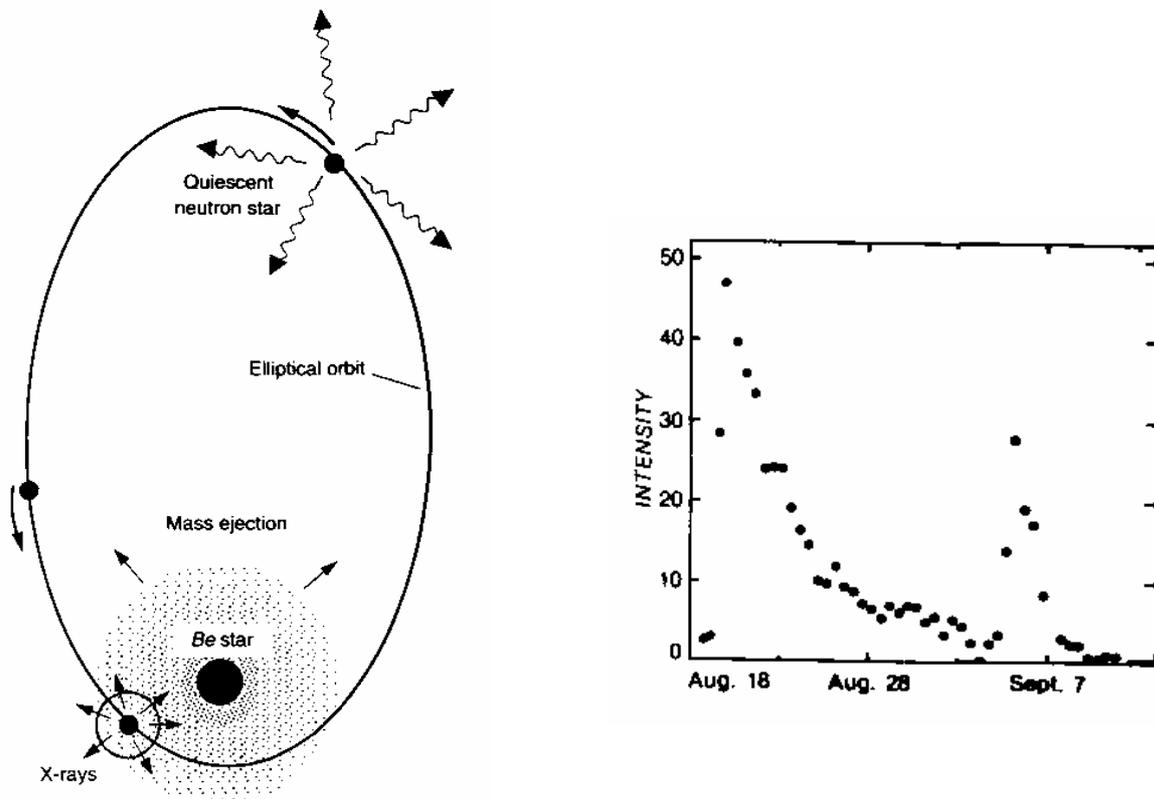
Fig. 9.1.a) An excentric orbit model of A0538-66. When the NS passes through the extended matter cloud of the Be-star accretion occurs and an X-ray and optical outbursts starts.

b) X-ray outburst of A0538-66 observed by the X-ray satellite Ariel 1988. The intensity is given in units of the Crab.
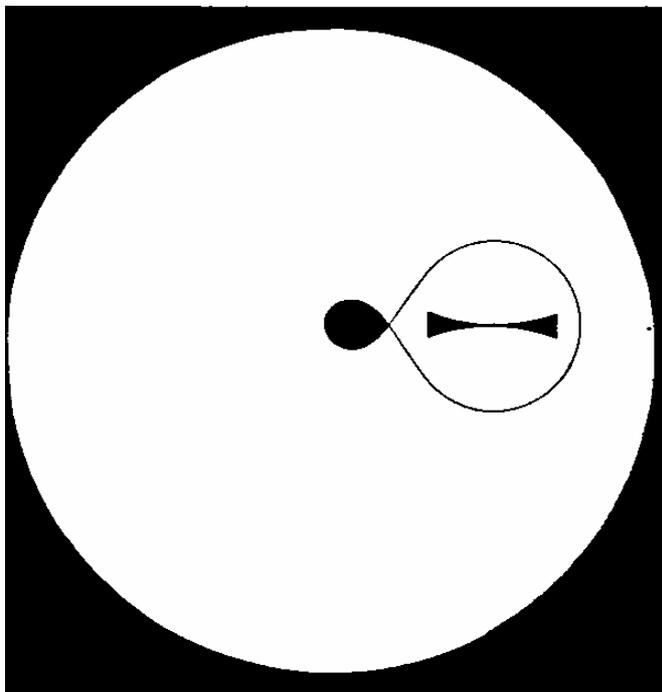**Credit: Ph. A. Charles and F,D, Seward, Exploring the X-ray universe. Cambridge Univ. Press 1995**

along the magnetic field lines to the polar caps of the NS. If the accretion rate decreases, the gas pressure falls and the magnetosphere with its field pressure can expand. When at the edge of this enlarged magnetosphere matter should move with higher speed than in its respective Kepler orbit. Thus it cannot enter the magnetosphere, i.e. an accretion barrier has been built up and stops further accretion processes.

Source	Spectral type	V (mag)	P_{spin} (s)	P_{orb} (days)	e	L (peak) erg s^{-1}
A0538-66	B2IIIe	15	0.069	16.65	0.7	10^{39}
4U0115+63	Be	16	3.6	24.3	0.34	8×10^{36}
V0332+53	Be(?)	15.5	4.4	34	0.31	?
2S1553-542	?	?	9.3	30.6	<0.09	?
A0535+26	B0Ve	9	104	111	0.3	2×10^{37}
GX304-1	B2Ve	14	272	133	?	3×10^{36}
4U1154-61	B1Ve	9	292	188	?	6×10^{36}
X Per	O9.5III-Ve	6	835	580(?)	?	10^{34}

Table 9.1. A collection of X-ray emitting HMXB systems with a primary Be-star. The upper line contains source, spectral type, visible magnitude V, spin period in seconds P_{sin}, orbital period in days P_{days}, excentricity e and luminosity L (peak radiation power, 10^{37} erg·s^{-1} = 10^{30} Watt. Credit: Ph. A. Charles and F,D, Seward, Exploring the X-ray universe. Cambridge Univ. Press 1995

Pulsar activity although not a really abundant phenomna in HMXB is generally more likely observable with X- or γ- rays than with radio frequencies. Obviously high energy electromagnetic radiation from pulsars is far less beamed than radiowaves. Their narrow cone has to pass our line of sight to make the pulsar observable. In the last years satellite supported X-ray and γ- ray observations have been extended. Higher sensitivity and larger observation angles have increased the number of detected pulsars considerably.


Fig.9.2. a) The size of an LMXB with notation 4U1626-76 relative to the sun. Credit: Ph. A. Charles and F,D, Seward, Exploring the X-ray universe. Cambridge Univ. Press 1995
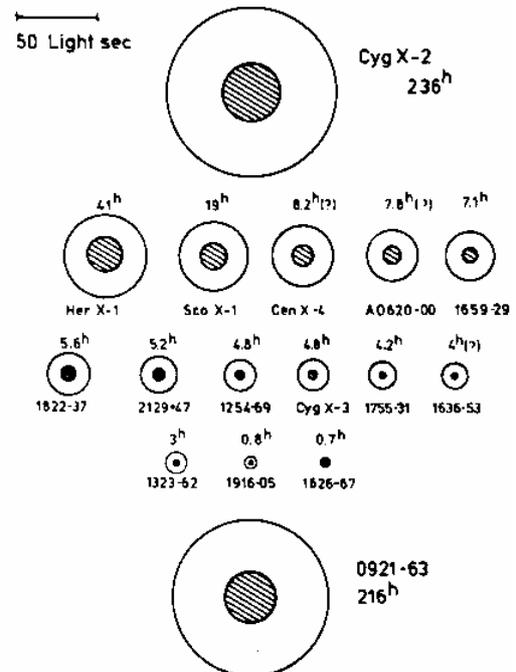
b) Relative sizes of the primary star, the size of the orbit of the compact companion and orbital period.

Another important class of objects are low mass X-ray binaries (LMXB). The primary stars are usually normal dwarf stars. They have masses smaller than one solar mass, short orbital periods of some hours or even less and the orbital diameter smaller than the sun (s. fig.9.2.). These have usually developed an accretion disk and show all phenomena of eclipsing if observable under appropriate inclination.
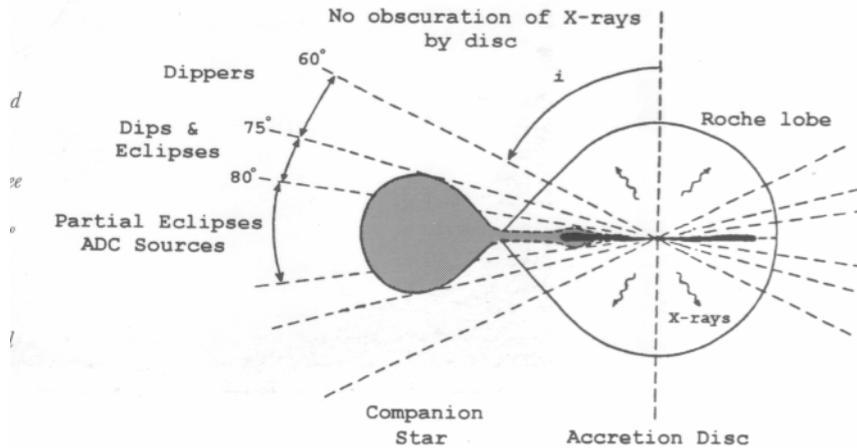
Fig. 9.3. Roche lobe and accretion disk lead to shadowing or eclipsing effects. In the shadowed region the X-ray central source is not visible. Credit: Ph. A. Charles and F,D, Seward, Exploring the X-ray universe. Cambridge Univ. Press 1995

9.2. X-ray burster and thermonuclear burning on the surface.

These objects could have been discovered in the early seventies by the Vela satellite. However, this satellite was designed to check for nuclear tests and therefore the Vela observations were kept classified. More than 10 years later the European satellite EXOSAT
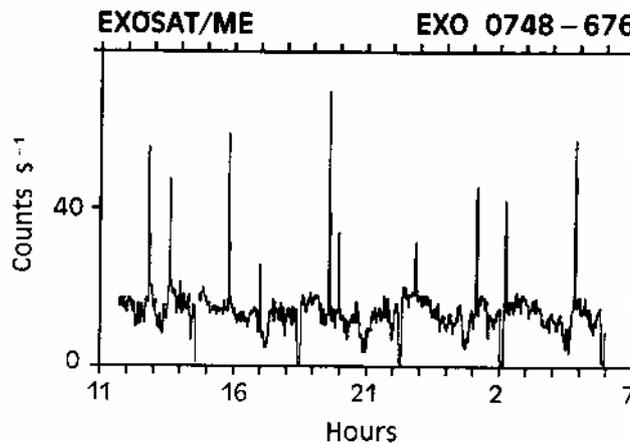
Fig. 9.4. A single 20 hour observation of the LMXB system EXO 0748-676 by EXOSAT. Credit: Ph. A. Charles and F,D, Seward, Exploring the X-ray universe. Cambridge Univ. Press 1995

observed X-ray burster continuously over several hours. The succession of bursts seems erratic. But if the total burst energy is plotted versus recurrence time the data points are found

on a straight line. For a stronger burst the system needs more time to accrete more material. The burst spectra are in good approximation black body emission

$$L = 4\pi R^2 \sigma T^4 \, \text{Watt} \tag{9.1}$$

The X-ray flux F_X received by the instrument of the satellite in a distance D from the source is then

$$F_X = \frac{L}{4\pi D^2} \, \text{W/m}^2 \tag{9.2}$$

This relation was used to estimate the radius of the NS. The result depends on the square of the distance of the source which is in most cases not accurately enough known. Nevertheless

9.5. **Temporal evolution of flux, temperature and radius of the NS during a burst. The system shown is MXBI 608-72 observed by EXOSAT. After initial expansion of the radiating area it cools in about one minute and settles down to its original radius. Credit: Ph. A. Charles and F,D, Seward, Exploring the X-ray universe. Cambridge Univ. Press 1995**
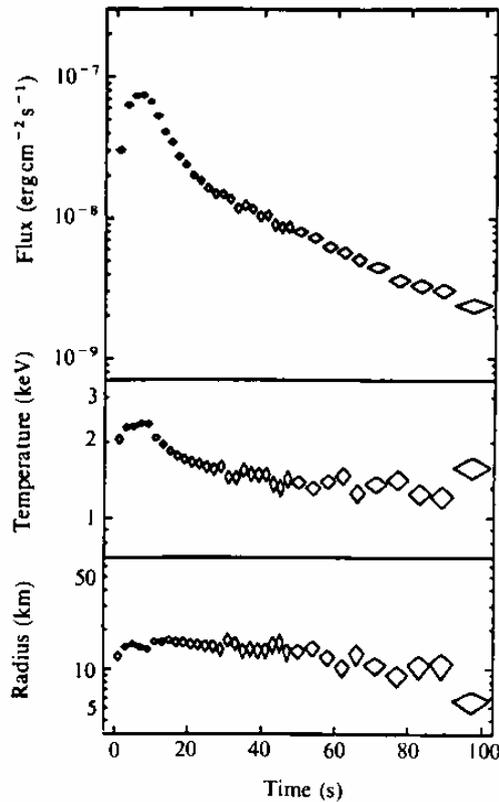

if the temperature is known from the spectral profil the radius may be derived as is shown in fig. 9.5.A burst model has to consider fusion reactions on the surface of the NS. The most abundant element is hydrogen from the accretion disk with 25weight % He. Hydrogen will form a surface layer which burn in a fusion process (the CNO process) and generates helium.

The high surface acceleration keeps hydrogen separate above the helium layer. When the helium density and temperature reach a critical value Helium fusion by the 3-α-process starts explosively

$$^4He + {}^4He \rightarrow {}^8Be^*; \quad {}^8Be^* + {}^4He \rightarrow C^{12} \tag{9.3}$$
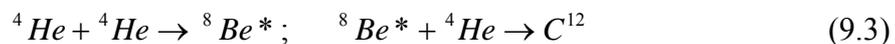
The energy gained in this process is 7,275 MeV. The notation $^8Be*$ denotes a beryllium state with very short life time ($2,6 \cdot 10^{-16}$ s) and therefore the ignition of the 3-α-process needs high densities ($\rho > 10^6 \ g \cdot cm^{-3}$) After the nuclear burst the accretion and burning of hydrogen continues so that after a certain amount of time, not always the same, the next bursts starts. From the observation of dozens of bursters there seems to exists a maximum burst power of $1,8 \cdot 10^{31}$ Watt. This can be understood to be due to the Eddington luminosity of a NS with well known surface area of $A = 4\pi(11)^2 \ km^2$. In favourable cases the burst spectra offer some more information..
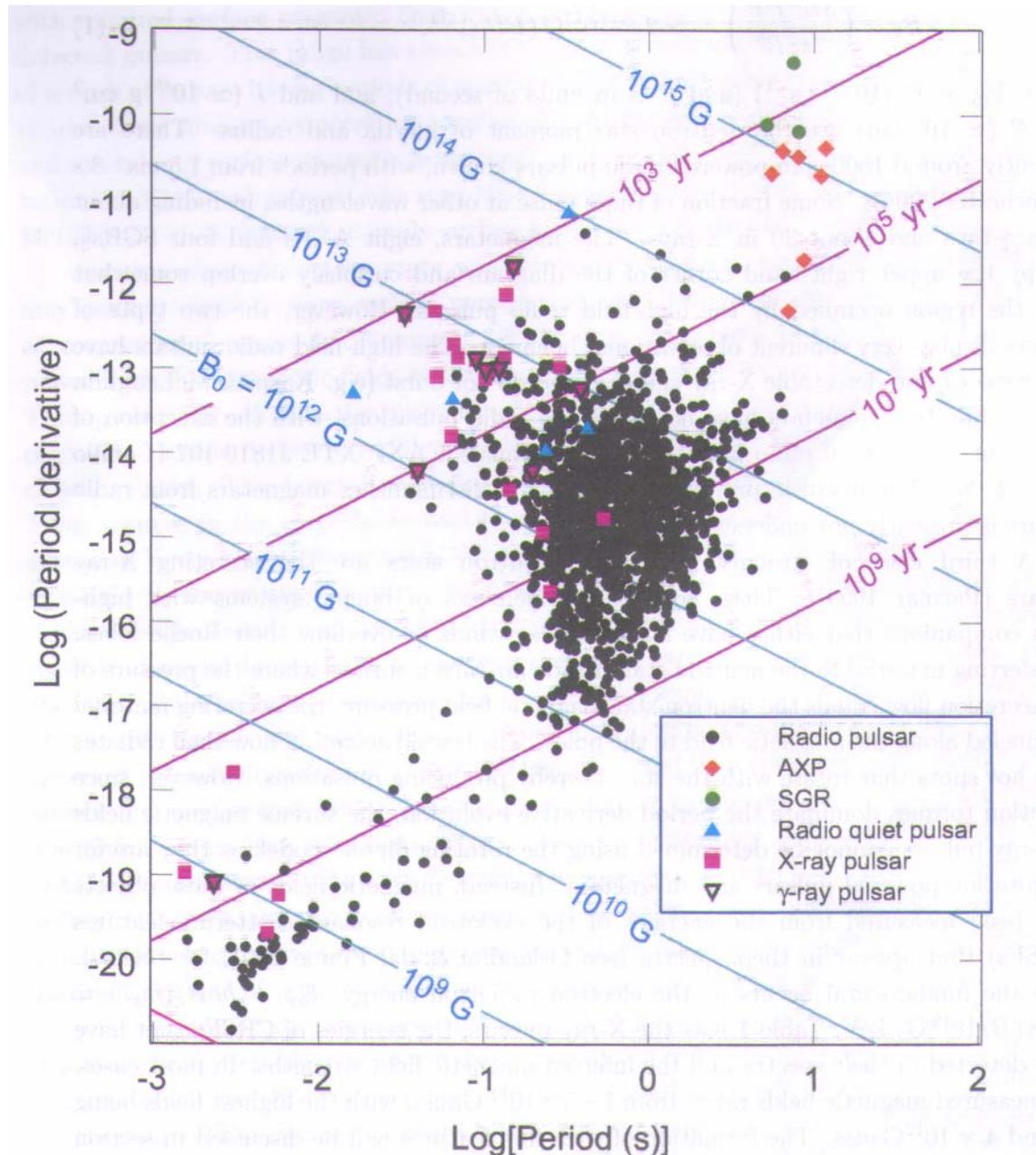
Fig.9.5. At present about 2 000 pulsars are known. A representative subset is plotted in this t_P-$\dot{t}_P$-diagram. Pulsars with the highest b-fields are found with long period t_P and large derivative $\dot{t}_P$ in the upper right corner of the diagram. Figure taken from Alice K. Harding and Dong Lai: "Physics of strongly magnetized neutron stars". **http://arxiv.org/astro-ph/0606674**

In some cases the $K\alpha$ iron line at 6,7 keV is observed redshifted to 5 keV. This allows to determine *2M/R* the compactness factor from the gravitational redshift. In the last years gravitational redshift of spectral lines from other elements have observed.

Other observation already mentioned in the last lecture are quasi periodic oscillations (QPO) which are now interpreted as star quakes. The assignment of the succession of frequencies is attempted by comparison with model calculation. They are used to test models of the internal structure of NSs

9.4. Ultrahigh magnetic fields. Magnetars.

In many pulsars the dipole magnetic fields are in the range of $10^8 - 10^{12}$ Gauss (1Tesla = 10^4 Gauss). The field strength can be obtained from equ. (8.9) of the preceding lecture

$$B\sin\alpha = 3\cdot 10^{15}\left(t_P\ \dot{t}_P\left[\frac{I}{10^{38}kg\cdot m^2}\right]\right)^{\frac{1}{2}}\ Tesla \qquad (8.9)$$

When cyclotron resonance scattering can be observed a direct measurement of the surface field strength is possible using

$$E_C = \hbar\omega_C = \hbar\frac{eB}{m_e} = 11{,}58\cdot\left(\frac{B}{10^{12}\,Gauss}\right)keV \qquad (9.4)$$

In order to find the objects with highest field strength we should search for those with large pulse period t_P and large derivative $\dot{t}_P$. For this purpose we present a t_P-$\dot{t}_P$ diagram (9.5) and look for systems at the upper right. There are 2 kinds of data points, black filled circles and red squares. The first belong to the class of **Soft Gamma Repeters** (SGR). They are transient sources which undergo repeted bursting of subsecond duration. Sometimes they exhibit luminous superflares lasting some 100 seconds but their repetition has not yet been observed. The other class of high field objects are the **Anomalous X-ray Pulsars** (AXP).They were discovered as pulsating X-ray sources with spin periods in the narrow range of 5 – 11 s. The NSs of both groups are probably variations of the same object called **magnetar** with fields $B > 10^{13}$ *Gauss*. Only few magnetars have been observed which may be due to the fact that they are most time in the quiet state. Since their spinning is comparatively slow it is assumed that their energy is stored in the high magnetic field. The analysis of strong bursts in magnetars and their decay exhibited quasi periodic oscillations (QPO). Some frequencies have been assigned to star quakes of the crust (see also Ch. 8.4). This opens the field of asteroseismology for NSs a method already well developed for normal stars and white dwarfs.

Gamma Ray Bursts (GRB) are energetic events. Those with the duration of seconds are connected with the death of a massive star and the emergence of a BH. However the source of one recent event was a magnetar. The energy of the Gamma ray burst must have been stored in the magnetic field.

The carrier of information for the astrophysicist is the electromagnetic radiation. Therefore a study of electrons in high B-fields and their interaction with radiation will be important for the

interpretation of magnetar bursts. If cyclotron energy is considerably larger than Coulomb interaction a first step is to consider free electrons in magnetic fields. There is a quantum critical field strength which separates the nonrelativistic from the relativistic range

$$B_Q = \frac{m_e^2 c^2}{e\hbar} = 4,414 \cdot 10^{13} \ Gauss \tag{9.5}$$

It is obtained by dividing the rest energy of the electron by its cyclotron energy. As long as $B < B_Q$ the energy in the field is given by the Landau energy

$$E_L = (n_L + 1/2)\hbar\omega_C + \frac{p_z^2}{2m_e} \qquad\qquad n_L = 0, 1, 2....... \tag{9.6}$$

The motion perpendicular to the field $\vec{B} \equiv (0,0,B)$ is quantized. When the spin energy is included we have for the magnetic splitting

$$E_S = g\,\mu_B\,(\vec{\sigma}\cdot\vec{B}) = g\,\mu_B B(\pm 1/2) \tag{9.7}$$

Noting that $2\mu_B B = \hbar\omega_C$ we take both together we obtain

$$E_L + E_S = E_n = \hbar\omega_C\, n + \frac{p_z^2}{2m_e} \qquad\text{with}\quad n = n_L + \frac{1}{2}(1+\sigma_z) = 0, 1, 2.. \tag{9.8}$$

In the relativistic case for $B \geq B_Q$ the Dirac equation has to be solved for a homogeneous B-field. The result is

$$E_n = \left[c^2 p_z^2 + m_e^2 c^4 \left(1 + 2n\frac{B}{B_Q} \right) \right]^{\frac{1}{2}} \tag{9.9}$$

Higher harmonics of the cyclotron resonance with $\Delta n > 1$ are also observed. They are forbidden transitions at low fields but become strong at high fields. With high radiative transition probabilities the deexcitation of Landau levels by cyclotron emission is much faster than the collision rate. Therefore radiative transitions control the population of Landau states and they dominate in general over collision in astrophysical sources with strong magnetic fields. It will also lead to a prevalence of scattering processes (2nd order) over pure absorption or emission.

High fields not only polarize the plasma surrounding the NS but also the vacuum. Virtual excited electron-positron pairs contribute to the dielectric tensor and add to the magnetic dichroism.

In order to compare the magnetic energies with the Coulomb interaction in atoms or solids we first write the binding energy of hydrogen E_0 in terms of the fine structure constant $\alpha = 1/137$

$$E_0 = \frac{1}{2}\alpha^2 m_e c^2 = 13,6 \ eV \tag{9.10}$$

Then a dimensionless field strength is introduced

$$b = \frac{B}{B_0} \qquad \text{with} \quad B_0 = \alpha^2 B_Q \qquad (9.11)$$

In strong fields when $b \gg 1$ the stationary states of hydrogen are specified by two quantum numbers (m, v) where m measures the mean transverse separation between electron and proton and v gives the number of nodes of the wave function along the z-direction. The hydrogen atoms take on strange shapes like whiskers with a length of the wave function

$$L_z = \left[\ln \frac{b}{2m+1} \right]^{-1} \qquad (9.12)$$

The corresponding energy is

$$E_{m0} = -0{,}16 \cdot A \left[\ln \frac{b}{2m+1} \right]^2 \qquad (9.13)$$

The prefactor A is of the order "1". Finally the ground state or ionisation energy of the magnetized hydrogen atom becomes $E_{00} = 160 \ eV \ at \ 10^{12} \ G$ and $E_{00} = 540 \ eV \ at \ 10^{14} \ G$ respectively.

After all these details and strange features found under the extreme conditions of NSs I am afraid you will feel a bit confused. I am sorry! All these many faces belong to this same object that we call neutron star. I use here the singular deliberately since it is now believed that there exists only one kind of neutron star instead of various species. The individuals may slightly differ in mass, they may be solitary or in binaries, rotating fast or slow with high magnetic fields or even extremely high fields. It seems very likely that they all have the same internal structure and practically the same composition. Certainly a NS has many more important parameters than a BH. It is not just a giant nucleus but a real star with a lot of gravitational energy. However the most surprising experience is this, that NSs have "so many faces" which have mocked astrophysicist over the last more than 40 years. Although there exists meanwhile an overwhelming amount of data there are still many open questions which shows that the extrapolations of our natural laws to these extreme conditions is not as simple and straight forward as we might have suggested.

9.5. Problems

At a distance of 1 kpc a NS in a binary swallows matter streaming off the companion star. The matter is accelerated in the gravitational field and channelled along magnetic field lines on to the magnetic poles where it releases its kinetic energy forming hot spots on the surface of the NS. The spots have an area of about 1 km^2. They emit X- and γ-radiation with a spectral maximum at 10,000 eV.
  1. Consider the emission as blackbody. What is the temperature of the hot spots?
  2. What is the luminosity? Compare it with that of the sun.
  3. A satellite detector has an area of 1 m^2. What is the received power from the NS?

4. What is the counting rate of the detector?

You need Wien's law in the following form $h\nu = 2{,}898 \cdot k_B T$ and the following conversions:

1 eV = 11 604 Kelvin   1 eV = $1{,}602 \cdot 10^{-19}$ Joule

1 pc = $3{,}086 \cdot 10^{16}$ m

Comment: X-ray astronomists use both units eV and temperature, whereas $\hbar\omega[eV] = 11604 \cdot k_B T[Kelvin]$. The Boltzmann constant is always ignored.

References

Ph. A. Charles and F,D, Seward, Exploring the X-ray universe. Cambridge Univ. Press 1995

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