OBSERVABILITY OF ATOMIC LINE FEATURES IN STRONG MAGNETIC FIELDS[1]

G. WUNNER, H. RUDER, AND H. HEROLD
Institut für Theoretische Physik, Universität Erlangen-Nürnberg
West Germany

J. TRÜMPER
Max-Planck-Institut für Physik und Astrophysik,
Institut für Extraterrestrische Physik, Garching,
West-Germany

ABSTRACT

As an application of our comprehensive investigations of the physical properties of atoms in superstrong magnetic fields $B \sim 10^{10} - 10^{13}$ G, characteristic of neutron stars, we discuss the possibility of detecting magnetically strongly shifted atomic lines in the spectra of magnetized X-ray pulsars. Careful estimates of the relevant parameters lead us to the conclusion that it would be profitable to look for magnetically strongly shifted Fe XXVI Lyman lines in rotating neutron stars of not too high luminosity using spectrometers working in the energy range 10 - 20 keV, with sensitivities $\geq 10^{-4}$ photons per cm^2 and second, and resolution $E/\Delta E \sim 10$-100.

The observation of cyclotron features in the X-ray spectra of accreting neutron stars has confirmed the existence of superstrong magnetic fields of the order of $B \sim 10^{11} - 10^{13}$G (cf. Trümper et al. 1977). The discovery of further lines in the spectra of atomic origin for example, would provide an independent check on both the strengths of the magnetic fields and the assumptions of the physical conditions prevailing there. From the source temperatures kT $\sim$

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10 - 30 keV, derived from the observed spectra, it follows that the emitting matter is almost completely ionized, with a small fraction of hydrogen-like ions. The cosmic abundance of elements then implies that the lines with the largest possible energies and the highest intensities are members of the Lyman-series of Fe XXVI.

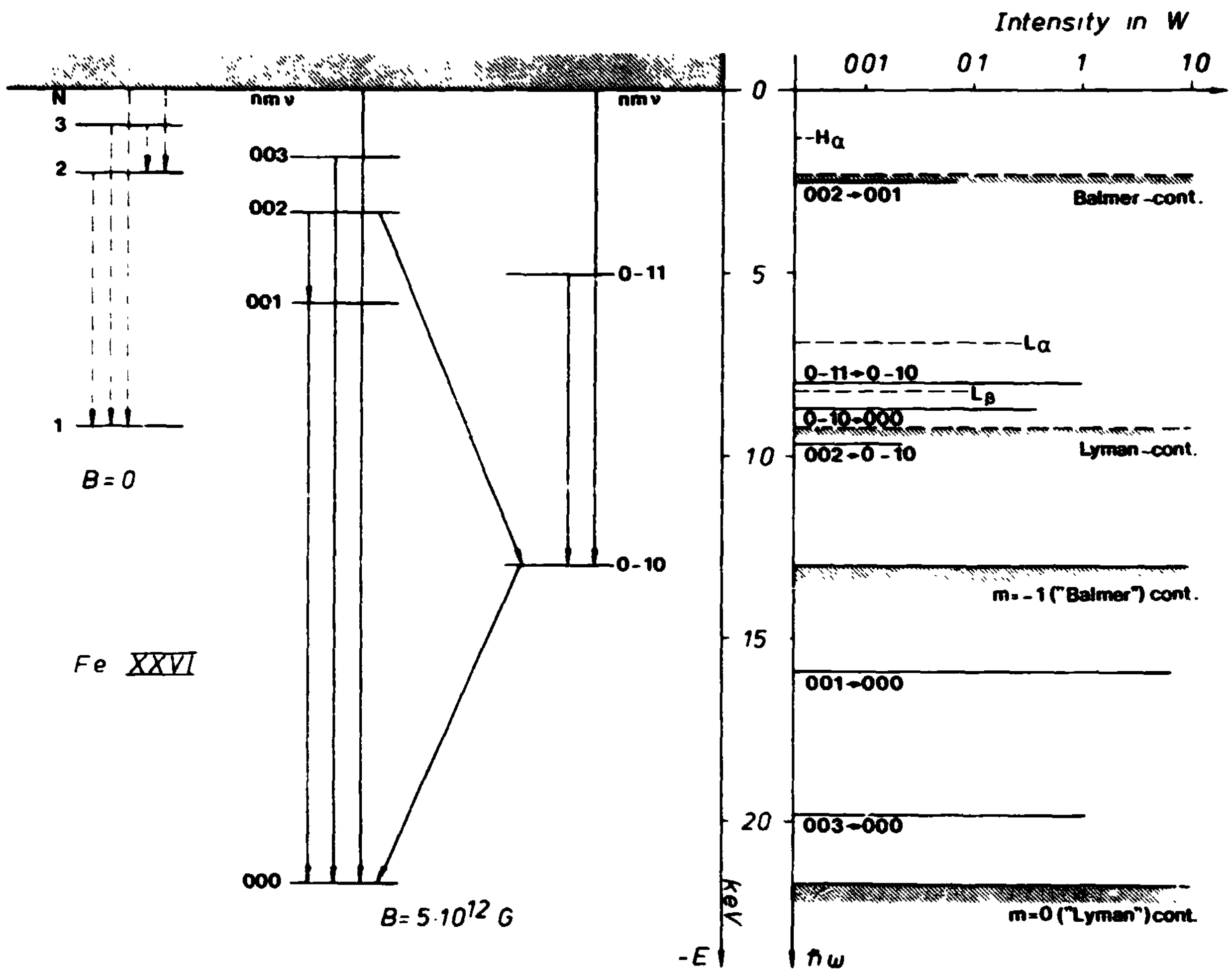

Fig.1. Level scheme for Fe XXVI and the photon spectrum resulting from the drawn transitions for $B = 5 \cdot 10^{12}$G in comparison with B = 0 (dashed lines). The states are labelled by the usual field-free quantum numbers N,l,m, and by the quantum numbers n,m,ν of the adiabatic approximation. The intensities have been obtained assuming an average occupation number of one electron in the excited state. The onset of the continua is marked by hatching.

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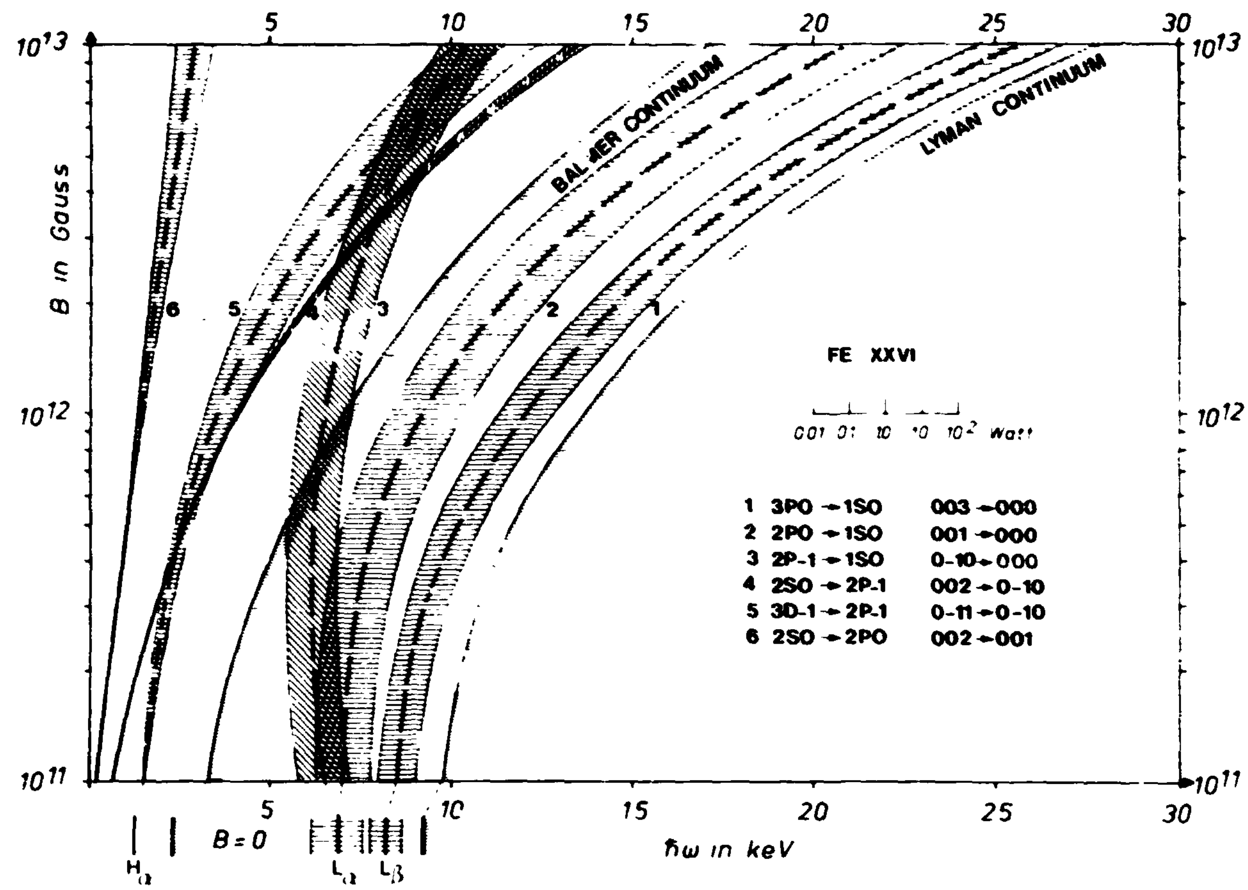

Fig.2. Energies and intensities of Fe XXVI lines as continuous functions of B in the range 10^{11} - 10^{13} G. The dashed lines represent the energetic positions of the lines, the widths of the corresponding corridors are proportional to the logarithms of the intensities in units of 10^{-2} W.

	B in Gauss							
	0	10^{11}	$5\cdot10^{11}$	10^{12}	$5\cdot10^{12}$	10^{13}	$5\cdot10^{13}$	10^{14}
Energies of γ's in keV	6.9	7.0	7.9	9.3	15.9	21.0	39.7	52.2
Numbers of γ's in 10^{15} s^{-1}	0.28	0.31	0.54	0.82	2.58	4.22	12.5	18.3

Tab.1. Energies and numbers of γ-quanta of the transition corresponding to L_α in the field-free case for Fe XXVI assuming one excited atom on the time average.

Using the scaling laws (Surmelian and O'Connell 1974, Wunner et al. 1981) of the one-electron energies E_m, $E_m(Z,B) = Z^2E_m(Z=1,B/Z^2)$, (Z nuclear charge, m eigenvalue of the component of the angular momentum parallel to the magnetic field), and of the oscillator strengths, $f_{\tau\tau'}(Z,B) = f_{\tau\tau'}(Z=1,B/Z^2)$, the energy levels, oscillator strengths,transition probabilities, etc. of Fe XXVI in magnetic fields of arbitrary strength can immediately be derived from our comprehensive calculations (Wunner and Ruder 1980, Wunner et al. 1981) of the continuous B-dependence of these quantities for the H atom. Fig.1 shows the level schemes of Fe XXVI at B = 0 and $5\cdot10^{12}$ G and the resulting line spectra. The magnetic field dependence of both the energies and intensities of these lines over the whole regime of interesting field strengths can be seen from Fig.2. It is clearly exhibited that from B $\cong 10^{11}$ G onward for Z = 26 the magnetic forces begin to outweigh the Coulomb forces, to the effect that the structure of the spectrum changes from the field-free form to the magnetic-field-dominated shape. Furthermore one recognizes that L_α (asymptotically 001 → 000) remains the strongest transition. In Tab.1 we therefore provide, for this transition, the numerical values of the energies, and the numbers of γ-quanta emitted per second.

The observability of iron lines in the X-ray spectra of accreting magnetized neutron stars depends on a number of parameters such as plasma temperature and density, abundance of iron, source dimensions, magnetic field strength, and, of course, source distance. In addition, to be detectable the lines should be sufficiently narrow ($\Delta E/E \lesssim 0.1$). Doppler broadening should be negligible for iron lines at the typical temperatures of these sources ($kT \sim 10$ keV), and collision broadening effects can be estimated to be less than ~ 1 keV at the prevailing temperatures and densities. However, a nontrivial condition is that the Thomson optical depth of the emitting plasma should be $\tau \lesssim 1$, in order to avoid too large line smearing by Comptonization.

The appropriate conditions may be found in accreting magnetic neutron stars of low luminosity, such as 4U900-40. Here one can expect that the interaction between the infalling gas and the radiation produced via Thomson scattering is small, and the material remains in free fall down to the stellar surface. If it is stopped there by Coulomb or nuclear collisions (Basko and Sunyaev 1975, Pavlov and Yakovlev 1976) the heated layer will have a thickness of 50 g/cm², viz., $\tau \sim 20$. However, recent computations by Kirk and Galloway (1981) show that plasma effects will considerably reduce the stopping length to values of the order of a few g/cm², which means $\tau \sim 1$ for the heated layer.

To arrive at a quantitative estimate, let us consider a radiating hot spot of area 10^{10} cm² and a thickness 2.5 g/cm² (corresponding to a total number of protons $1.5 \cdot 10^{34}$), a temperature of 10^8K, and $B = 5 \cdot 10^{12}$G. Starting from the Saha equation in a magnetic field (Gnedin et al. 1974), for these conditions the fraction of Fe XXVI ions in the first excited m = 0 state is calculated as $1 \cdot 10^{-4}$, which leads, together with the cosmic Fe abundance $3 \cdot 10^{-5}$, to $4.5 \cdot 10^{25}$ excited Fe ions on the time average. Using

Tab.1 and assuming a source distance of 1 kpc, we arrive at a line flux of iron L_α-photons of $1.0 \cdot 10^{-3}$ $cm^{-2}s^{-1}$, which should be detectable with X-ray spectrometers available at present. Actually, the iron line flux from the hot polar spot may be much higher than the above estimate, if the radiating plasma contains a substantial fraction of "stirred up" surface material, which should consist of pure iron.

Of course the detailed shape and width of the line feature are sensitively affected by the physical conditions in the accretion column (cf. Yahel 1981). For example it can be imagined that due to resonance scattering line trapping occurs, and a possible emission feature above the continuum background is changed into an absorption feature. At any rate, we conclude that it would be profitable in future X-ray explorer missions to look for magnetically shifted iron line features in magnetic neutron stars, using spectrometers working in the energy range 10 - 20 keV with sensitivities of $10^{-4}cm^{-2}s^{-1}$ and energy resolutions $E/\Delta E \sim 10$-100.

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