ATOMIC IONIZATION AND OPACITIES IN PULSAR ATMOSPHERES

Hydrogen Atmospheres

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Abstract. In the strong magnetic fields of typical radio pulsars atomic lines and photoionization edges lie in the soft X-ray part of the spectrum giving the dominant contribution to the opacity. Improved photoionization cross sections are presented for a hydrogen atmosphere and magnetic fields of $10^{11} - 10^{13}$ G, exhibiting novel Beutler–Fano resonance features due to the contribution of autoionizing atomic levels. The effect of atomic motion transverse to the magnetic field is discussed in detail.

1. Introduction

Thermal radiation from radio pulsars in the soft X-rays has been extensively documented in the recent years following the deployment of ROSAT (Greiveldinger et al., 1996; Trümper, 1997; Becker, 1997; Page, 1997). Most nearby and young pulsars have thus been detected, often clearly displaying a sinusoidal-like modulation at the neutron star's rotation frequency. This has prompted renewed extensive studies of the neutron star's outer atmospheric layers which are expected to leave their spectral signature in the emitted radiation (see e.g. Pavlov et al., 1995; Zavlin et al., 1995, 1996;

Rajagopal and Romani, 1996; Rajagopal et al., 1997; Shibanov et al., 1997). The influence of the pulsar magnetic field on the expected spectral signatures is profound as it displaces the frequencies and alters the width and shape of spectral line features (e.g. Pavlov and Mészáros, 1993; Pavlov and Potekhin, 1995, hereafter PP95).

2. Thermal Motion

One of the least understood aspects in modeling the pulsar's emitting photosphere has been the fact that thermal atomic motion transverse to the pulsar strong magnetic field results in the deformation of the atom which loses its cylindrical symmetry under the action of induced $\mathbf{v} \times \mathbf{B}$ forces, also becoming less bound. This has been found to change the spectral behaviour of the overall opacity in major ways. We report here on the progress in our understanding of these phenomena achieved during the past three years.

As is well known (Canuto and Ventura, 1977; Ruder et al., 1994), the external strong magnetic field dominates the transverse motion of atomic electrons, confining them to within a typical magnetic length scale, $\lambda = (\hbar c/eB)^{1/2}$, in a deep two-dimensional harmonic oscillator potential, with the Coulomb force acting as a weak perturbation on this. In the absence of transverse atomic motion, both the Coulomb and harmonic forces share the same axis of symmetry, and the resulting atomic wave function is thus cylindrically symmetric. Transverse motion, however, results in the Coulomb center being displaced relative to that of the harmonic force, thus resulting in a *decentered* electron wave function, which is pulled away from the ion in the $\mathbf{B} \times \mathbf{v}$ direction.

For the hydrogen atom, a measure of this decentering is shown in Fig. 1 (left panel) taken from the calculation of Potekhin (1994). The atom here is assumed to be moving along the y-axis, while the proton is located at $x = 0$. The atomic transverse motion is measured by its generalized momentum denoted by $\hbar K_\perp$. For small values of $K_\perp$ ($\lesssim \lambda^{-1}$) the atomic wave function is only moderately decentered (upper left), while decentering becomes extreme, reaching the value $\lambda^2 K_\perp$, at high values of $\lambda K_\perp$ (lower left). The corresponding reduction in the atomic binding energy for different values of $K_\perp$ can be seen in Fig. 1b.

3. Photoionization Opacity

Using the above atomic description, improved photoionization opacities were recently obtained (Potekhin and Pavlov, 1997, hereafter PP97). Fig. 2 gives the photoionization cross section for photons of various polarizations. Several effects discussed previously (Kopidakis et al., 1996, hereafter KVH) are seen here again: The reduction of the photoionization threshold for in-

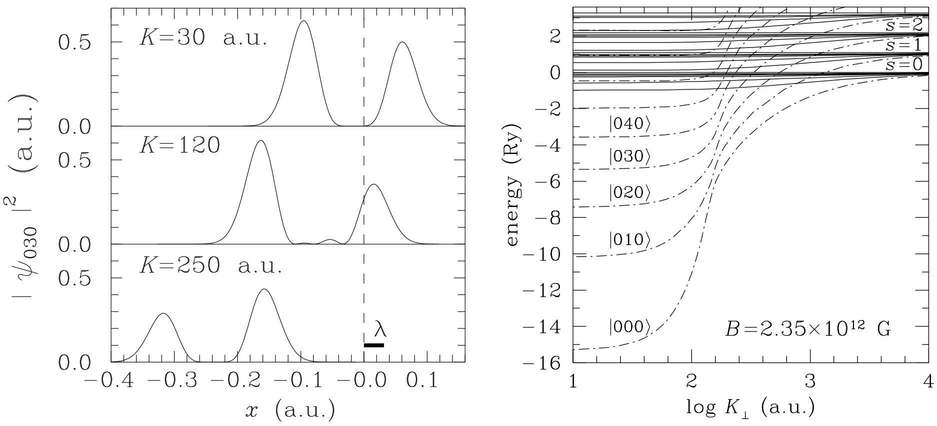

Figure 1. The modulus squared of the wave function for the electron's position relative to the proton is seen to be pulled to the left, as the atom's transverse momentum, $\hbar K_\perp$, increases (left panel). Indicative of the electron's transverse spread is the magnetic length λ, also shown on the graph for the magnetic field $B = 2.35 \times 10^{12}$G assumed. The corresponding value of the atomic energy for different $\hbar K_\perp$ can be read off the graph in the right panel: As the decentering increases, the atomic binding energy decreases. The curves (dot-dashed for tightly-bound states and solid for hydrogen-like states) are labeled with the quantum numbers, $|0s\nu\rangle$. At high values of $K_\perp \gtrsim 375$ atomic units (a.u.) the state $|030\rangle$ ($s = 3$), considered, passes into the $s = 0$ continuum and may autoionize emitting a photon.

creasing $K_\perp$ is quite remarkable, as it decreases from ~ 15.2 Ry to ~ 1.35 Ry reflecting the reduced atomic binding as $K_\perp$ increases from 20 to 1 000 a.u. One further sees for large $K_\perp$ the appearance of additional spikes corresponding to $\Delta s \neq 0$ transitions which do not preserve l_z, the longitudinal component of the angular momentum. These would be "forbidden" transitions for $K_\perp = 0$, which are now allowed due to the breaking of the moving atom's cylindrical symmetry. The above results have corrected a deficiency of the KVH opacities derived in the adiabatic approximation which has been proved inadequate for obtaining the cross section of transverse photon polarizations (Potekhin et al., 1997, hereafter PPV). In addition, they include thermal averaging to obtain final results for the opacity.

Autoionizing States. By going beyond the commonly used adiabatic approximation, and including excited electron Landau levels in the atomic wave function, PPV were further able to give an accurate description of the photoionization cross sections in the vicinity of autoionizing states. Autoionizing excited states are inherent to magnetic atoms because of the peculiar free electron (and proton) phase space, which is a combination of a one-dimensional continuum and a discrete set of quantized two-dimensional

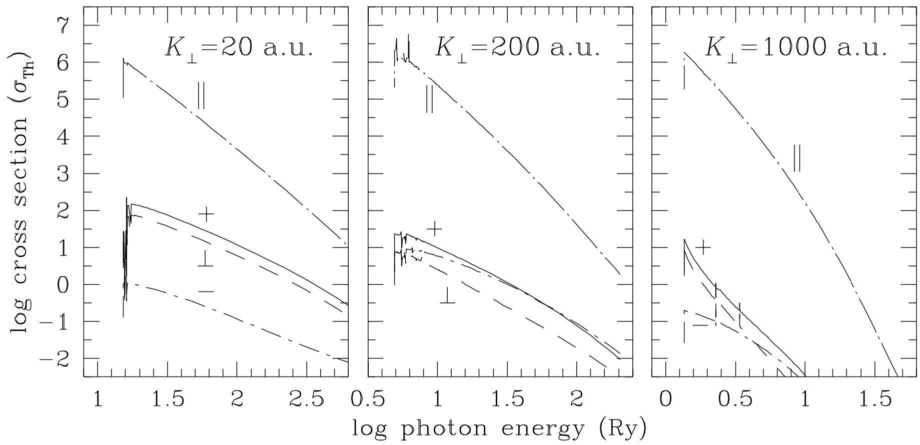

Figure 2. Total photoionization cross section for the moving hydrogen atom at different values of $K_\perp$ in a magnetic field $B = 2.35 \times 10^{12}$G. Solid and dash-dot lines correspond to right (+) and left (−) circular polarization of photons propagating along the magnetic field. Long-dash-dot and dashed lines correspond to the linear polarizations parallel, and perpendicular to the field for transverse propagation, averaged over the photon direction in the transverse plane.

harmonic oscillator states. By exciting the electron's principal quantum number to $n = 1$, one thus has a set of Landau-excited discrete atomic states placed just below the $n = 1$ continuum. All of these are superimposed onto the $n = 0$ continuum, and therefore can autoionize.

Fig. 3 gives an example of the PPV cross sections corresponding to the non-moving atom, i.e. $K_\perp = 0$. The left panel shows the photoionization edges corresponding to the lowest two electron Landau levels. Dashed lines correspond to the adiabatic approximation of Potekhin and Pavlov (1993) which turns out to be accurate just above the thresholds but rather poor below them. Within the energy interval $\sim$ 20 Ry just below the $n = 1$ threshold resonant structures arise, too narrow to be resolved in this scale. The right panel shows the cross section within this range, displaying the characteristic Beutler–Fano resonances corresponding to $n = 1$ bound atomic states. Two such resonances are seen here just below the threshold to the $n = 1$, $s = -1$ free electron continuum, actually occurring at photon energy $\simeq$ 2 014.2 Ry. The resonances arise at energies corresponding to the quasibound states $|110\rangle$ and $|120\rangle$. A similar resonance corresponding to the state $|100\rangle$ at a slightly lower energy is also present but is too weak to be discerned here, as it corresponds to a forbidden transition (due to a "transverse-dipole" selection rule). Resonances corresponding to the hydrogen-like states $|11\nu\rangle$ ($\nu \geq 1$) occur within 1 Ry below the $n = 1$, $s = 1$ continuum threshold (2 016.4 Ry); they are not seen in Fig. 3 since they

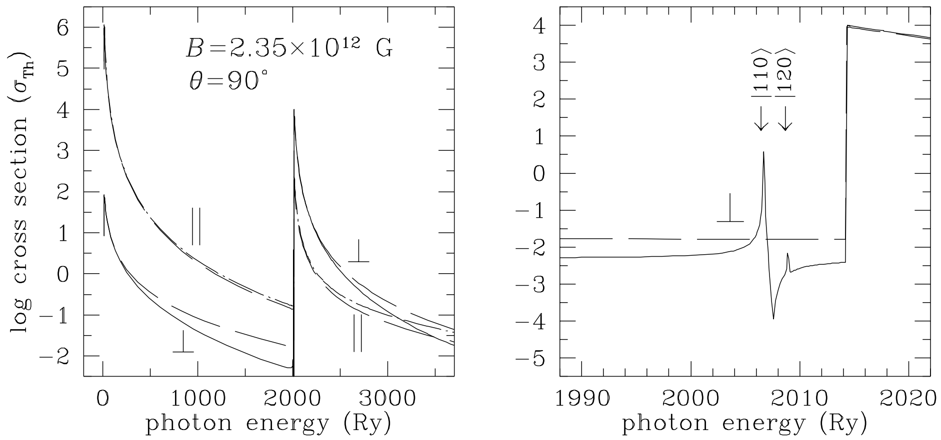

Figure 3. Photoionization cross section for $K_\perp = 0$ and propagation perpendicular to the magnetic field ($\theta = 90°$). Solid lines (transverse polarization) and dash-dotted lines (longitudinal polarization): accurate results; dashed lines: adiabatic approximation (Potekhin and Pavlov 1993). The atom is assumed initially in the ground state. The left panel gives the cross section for photon polarization parallel and perpendicular to **B**. The graph shows two photoionization edges (solid lines) corresponding to electron Landau levels 0 and 1. The $n = 0$ edge occurs at photon energy $\simeq 15.3$ Ry, corresponding to the atomic binding energy. The $n = 1$ edge near 2 000 Ry has a fine structure shown in detail in the right panel.

merge into the strong $n = 1$, $s = -1$ photoabsorption.

Beutler–Fano resonances are actually to be expected immediately below every ns-continuum. Similar effects would thus also occur at much lower photon energies of a few Ry, corresponding to the energy differences (from ground state) in Fig. 1. These transitions to the bound states $|0s0\rangle$ are "transverse"-dipole-forbidden in the non-moving atom, and thus are not seen in Fig.3 where $K_\perp = 0$. They do occur, however, for $K_\perp \neq 0$ (the sharp spikes seen in Fig. 2).

Though interesting in principle, these resonances tend to be rather weak and narrow, and are not expected to influence the overall photon opacities, as they will be superseded by resonant scattering processes which can alternately be described in the adiabatic approximation as bound-bound (b-b) transitions (PP95). PP95 have further shown that b-b transitions will also contribute in a major way to the continuum opacity as a result of the very extensive magnetic broadening present at typical pulsar photosphere temperatures (see also PP97).

4. Discussion

We can finish this report on a positive note by remarking that, as a result of the opacity work pursued over the last five years, we presently have an essentially complete picture of the opacity for hydrogen pulsar photospheres over a wide range of magnetic fields between 10^9 and 10^{13} G. Similar work concerning the presence of helium in pulsar photospheres now being pursued will bring us a significant step forward in interpreting present and future space-borne observations of isolated neutron stars.

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