Monte-Carlo/Fokker-Planck Simulations of Accretion onto Magnetized Neutron Stars

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Abstract

We discuss the results of coupled Monte-Carlo/Fokker-Planck simulations of the thermal/nonthermal radiation and electron acceleration and cooling in the case of accretion onto a magnetized neutron star. Most of the energy release into thermal/nonthermal electrons is assumed to happen in a thin shell near the Alfvén radius, where the radiation from the neutron star surface is reprocessed into thermal/nonthermal high-energy (hard X-ray — γ-ray) emission. We explore the parameter space defined by the accretion rate, stellar surface field and the level of wave turbulence in the shell. Our results are relevant to the emission from atoll sources, transient X-ray binaries containing weakly magnetized neutron stars, and to recently suggested models of accretion-powered emission from anomalous X-ray pulsars.

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1) Introduction

Recent observations of weak-field neutron star binaries, such as low-luminosity, X-ray bursters (atoll sources, e.g., 4U 1608-522: Zhang et al. 1996, 4U 1705-44: Barret et al. 1996), bursting soft X-ray transients (e.g., Aql X-1: Harmon et al. 1996), or pulsar binary systems (e.g., PSR B1259-63: Tavani et al. 1996) indicate that many of them exhibit soft (photon index $\gtrsim 2$) power law tails extending beyond ~ 100 keV, at least episodically, in addition to the thermal component at temperatures of $\sim$ a few keV, which presumably originates from the stellar surface. The luminosity of this high-energy tail appears to be anti-correlated with the soft X-ray luminosity (Barret & Vedrenne 1994, Tavani & Liang 1996).

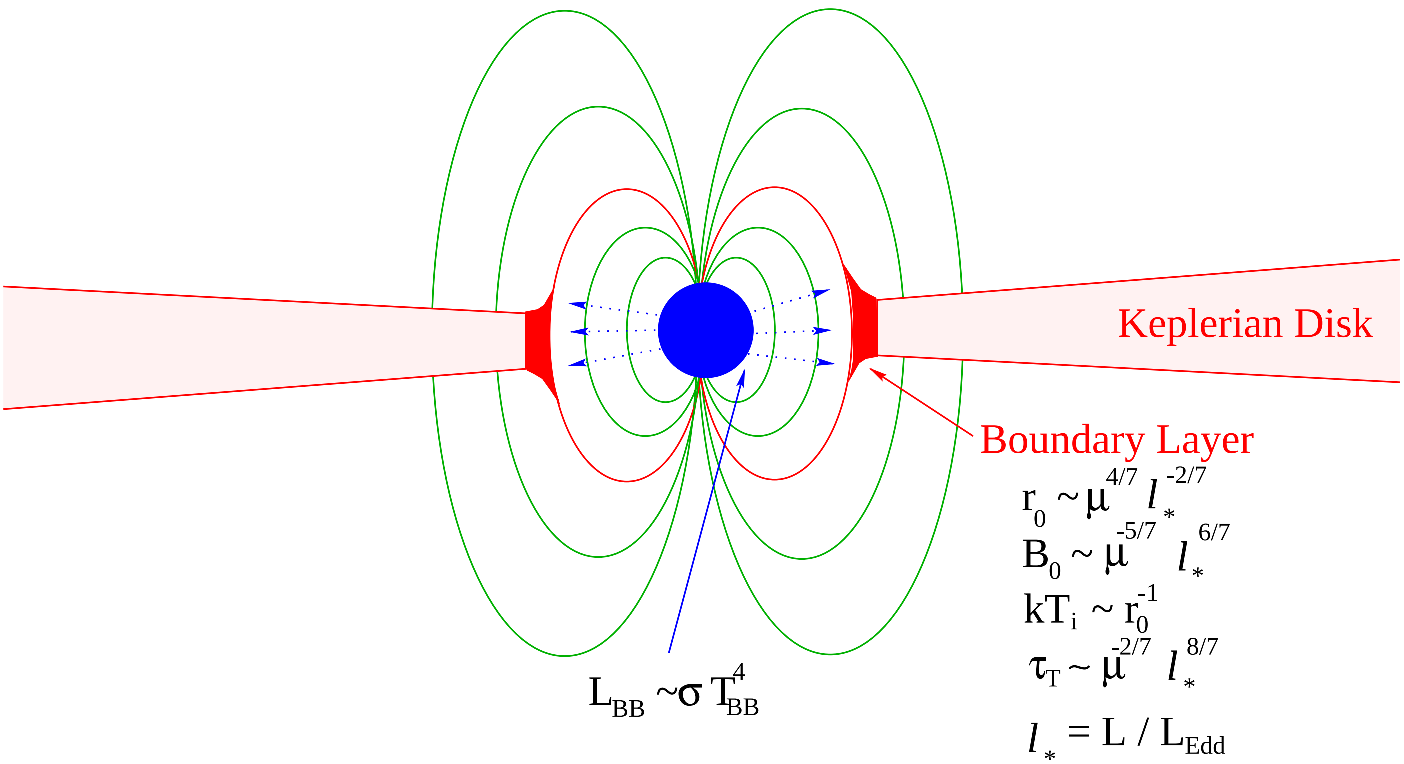
The origin of this high energy tail is unexplained at present. It could be due to thermal Comptonization by a hot coronal plasma, or it could be due to nonthermal emission. Tavani & Liang (1996) examined systematically the possible sites of nonthermal emissions and concluded that the Alfvén surface is the most likely candidate since the dissipation of the rotation energy of the disk is strongest there, due to magnetic reconnection and wave turbulence generation. Here we first focus on particle acceleration by wave turbulence. We assume that the leptons are energized by Coulomb collisions with virial ions and accelerated nonthermally by Alfvén and whistler wave turbulence, and cooled by cyclotron/synchrotron, bremsstrahlung, and inverse Comptonization of both internal soft photons and blackbody photons from the stellar surface. We use our coupled Monte-Carlo/Fokker-Planck code (Böttcher & Liang 2001) to solve self-consistently for the resulting thermal/nonthermal equilibrium electron distribution and radiation transport.

The primary focus of the parameter study presented in Section 3 is the application to weakly magnetized neutron stars with surface magnetic fields of $B_{\rm surf} \lesssim 10^{11}$ G. In particular, we will show that the anti-correlation of the hardness and luminosity of the hard X-ray emission with the soft X-ray luminosity is a natural consequence of the energetics of particle acceleration and cooling near the Alfvén radius. We predict that the nonthermal tails in the hard X-ray spectra of accreting, weakly magnetized neutron stars may extend up to ~ 1 MeV. A solid detection and the measurement of the cutoff energy of these high-energy tails by the INTEGRAL mission, scheduled for launch in 2002, will provide important constraints on accretion-based models for the hard X-ray emission from accreting neutron stars.

In this context, it is interesting to note that Chatterjee, Hernquist, & Narayan (2000; see also Mereghetti & Stella 1995, Wang 197, Chatterjee & Hernquist 2000) have recently proposed a similar type of accretion-powered emission for anomalous X-ray pulsars (AXPs), as an alternative to models based on magnetic-field decay (Thompson & Duncan 1996) or residual thermal energy (Heyl & Hernquist 1997). According to Chatterjee et al. (2000) the X-ray emission from AXPs (which generally consists of a soft, thermal component with $kT \sim 0.3 - 0.4$ keV plus a hard X-ray tail with photon index , $\sim 3 - 4$) is powered by accretion of material from the debris of the supernova which had formed the neutron star, onto a the surface of the neutron star, which possesses a typical pulsar magnetic field of $B_{\rm surf} \sim 10^{12}$ G. Therefore, we extend our parameter study to parameter values relevant to accreting pulsars. However, we point out that in the case of a magnetic field as high as $B_{\rm surf} \sim 10^{12}$ G, the assumed shell geometry and the quasi-isotropy of the emission from the neutron star surface may be a gross over-simplification. However, although consequently the precise parameter values used in this region of the parameter space should not be taken at face value, our parameter study might still provide interesting insight into the dependence of the equilibrium electron and photon spectra on the various input parameters in the high-magnetic-field case.

2) Model setup

Geometry:



(Ghosh & Lamb 1979a,b)

Model parameters:

$l_* = L/L_{\rm Edd} = \dot{M}/\dot{M}_{\rm edd}$	= normalized luminosity / accretion rate
$\mu = 10^{30}\,\mu_{30}$ G cm^3	= Magnetic moment
$\delta^2 = (\delta B/B_0)^2$	= level of Alfvén / whistler wave turbulence
$q = 5/3$	= spectral index of turbulence spectrum

Physical Processes:

- Compton scattering
- Thermal cyclotron emission/absorption
- Nonthermal synchrotron emission/absorption
- Thermal bremsstrahlung emission/absorption
- Coulomb (ep) scattering
- Møller/Bhabha (ee) scattering
- Stochastic electron acceleration by Alfvén/Whistler wave turbulence ($\leftrightarrow$ Landau damping)
- $\gamma\gamma$ pair production and pair annihilation

Assumptions:

- Soft photons: Thermal blackbody from the neutron star surface
- High-energy emission: from energetic thermal/nonthermal electrons in the boundary layer at the Alfvén radius, where the accretion disk is disrupted
- Electrons in the boundary layer are energized by thermal protons and non-thermal acceleration by Alfvén / whistler wave turbulence
- All of the above radiation processes contribute to the emerging photon spectra and radiative cooling of electrons in the boundary layer

3) Parameter Study

Variation of accretion rate, $\delta^2 = 0$:

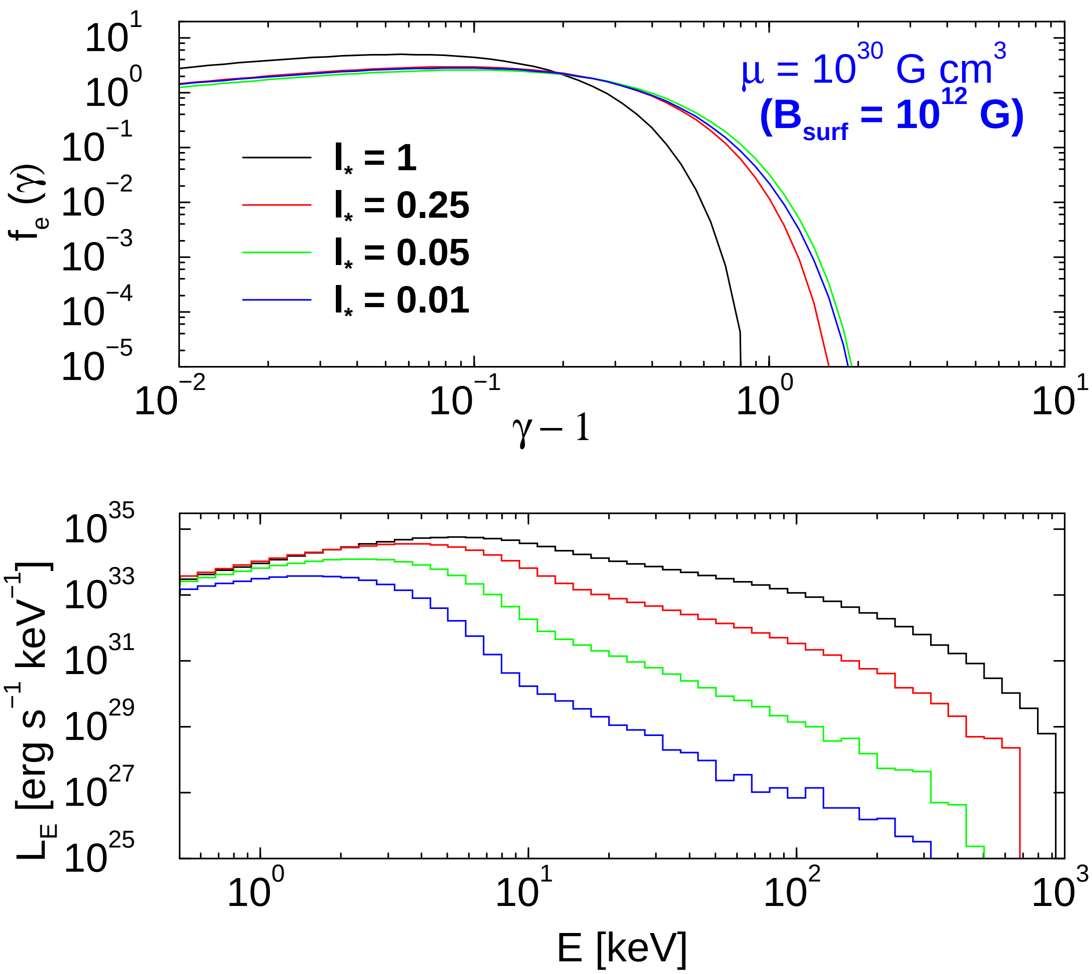


Fig. 2: *Effect of a varying accretion rate in the case of no Alfvén/whistler wave turbulence ($\delta^2 = 0$) and a strong surface magnetic field of the neutron star*

Variation of accretion rate:
($\delta^2 > 0$; weak-field case)

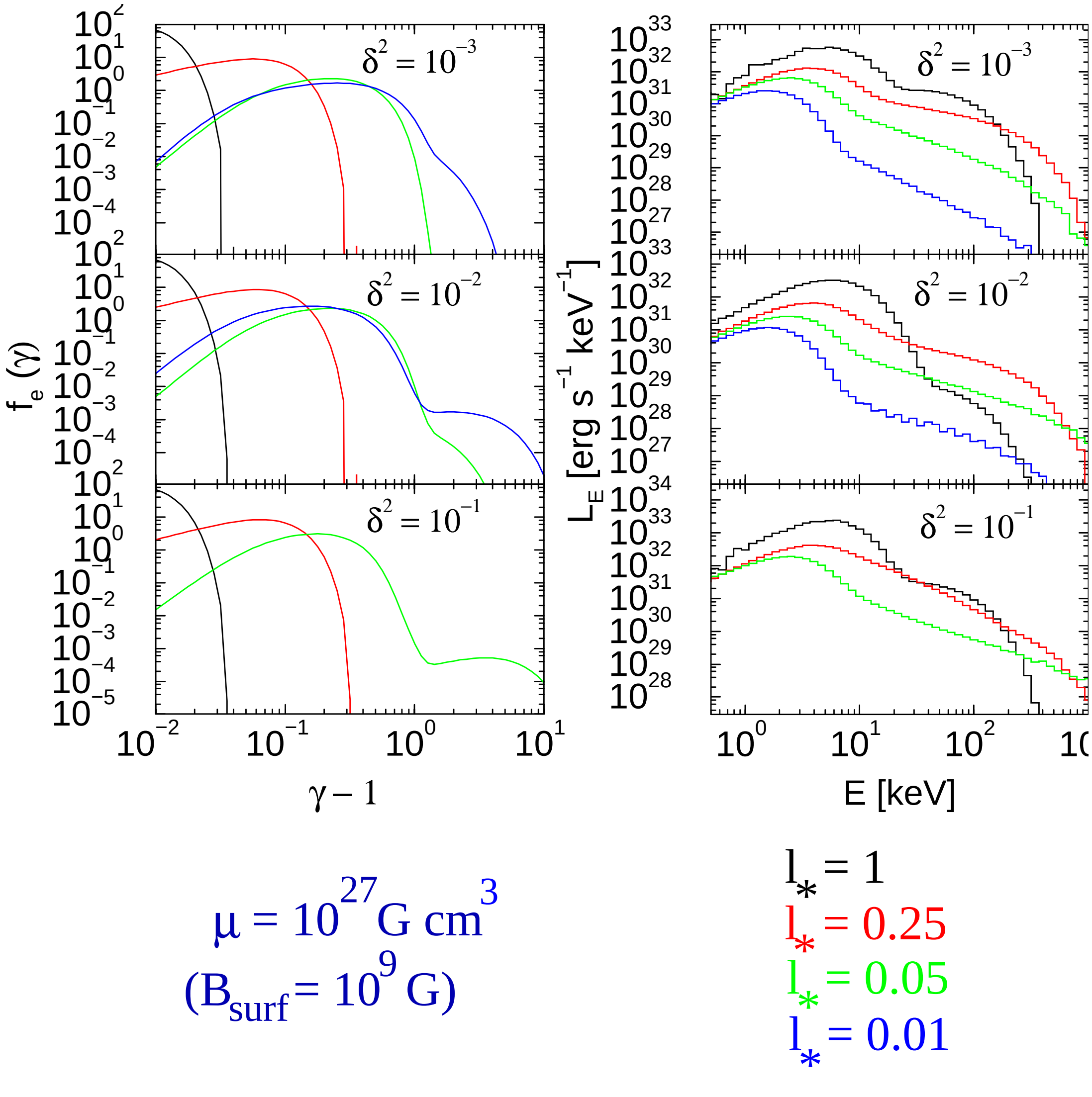


Fig. 3: *Effect of a varying accretion rate and varying turbulence level δ^2 in the case of a weak surface magnetic field*

Variation of accretion rate:
($\delta^2 > 0$; strong-field case)

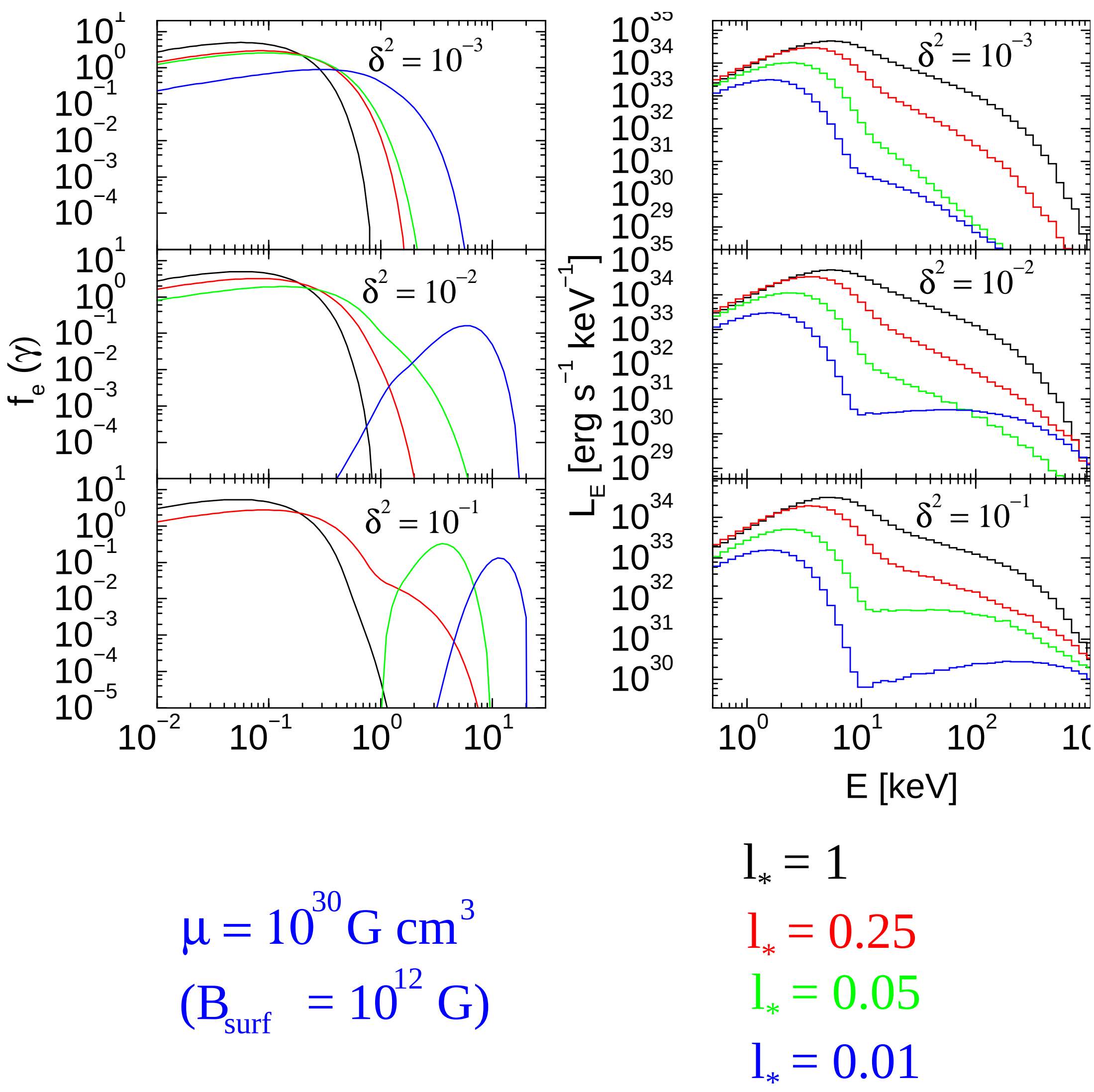


Fig. 4: *Effect of a varying accretion rate and varying turbulence level δ^2 in the case of a strong surface magnetic field*

Variation of magnetic field:
($\delta^2 > 0$; moderate accretion rate)

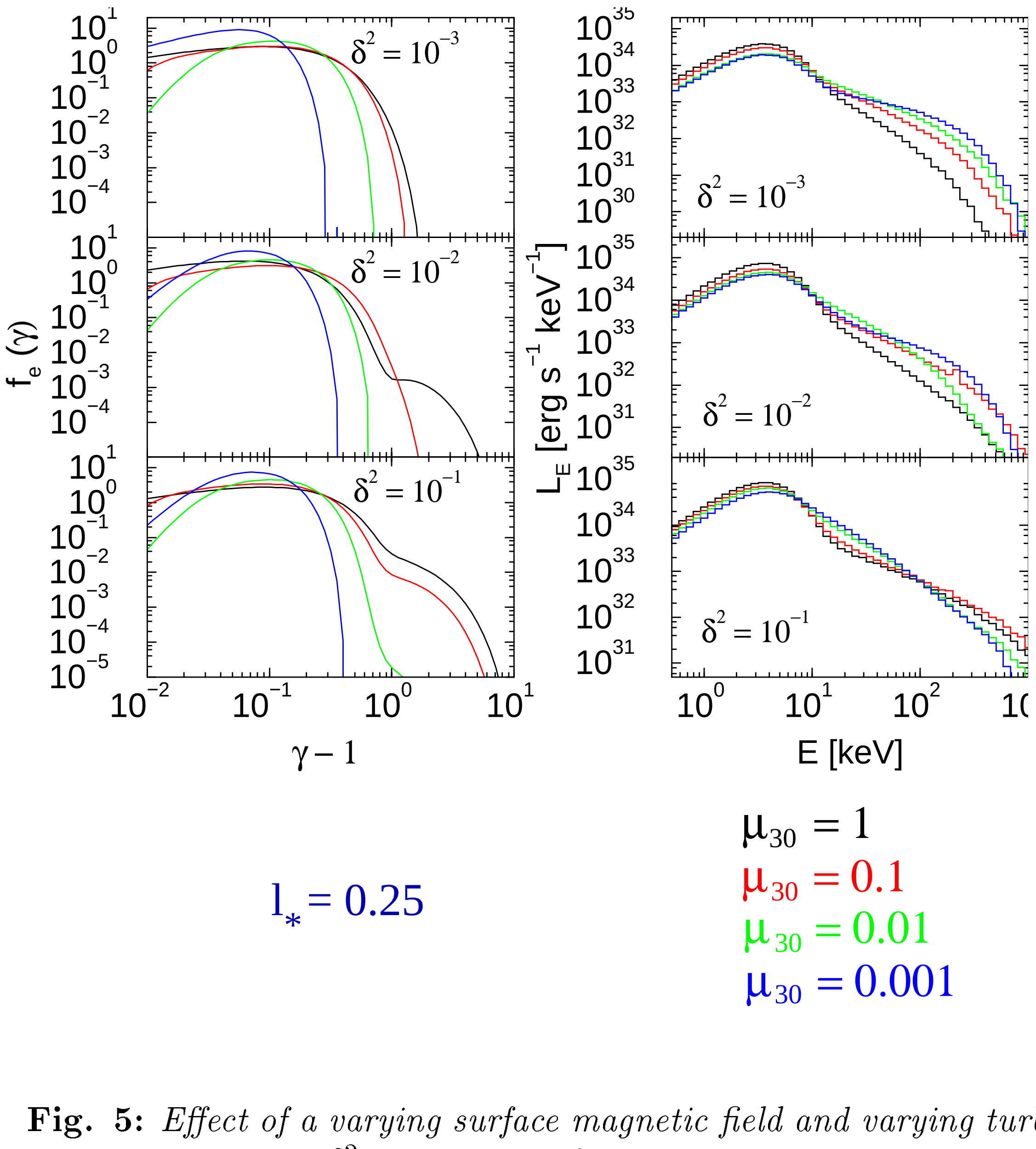


Fig. 5: *Effect of a varying surface magnetic field and varying turbulence level δ^2 in the case of a moderate accretion rate*

4) Results

a) General Results

- l_* decreases $\Longrightarrow$ T_e increases;

  hard X-ray spectrum hardens;

  normalization of hard power-law w.r.t. soft blackbody decreases (transition to low/hard state spectrum)

- δ^2 increases $\Longrightarrow$ nonthermal tails in electron spectra become stronger;

  T_e decreases;

- μ increases $\Longrightarrow$ moderate hardening of X-ray spectra for high accretion rates ($l_* \gtrsim$ a few %);

  no significant effect for low accretion rates

b) Results for Weakly Magnetized Neutron Stars and Anomalous X-ray Pulsars

Weakly magnetized neutron stars:
(atoll sources; soft X-ray transients)

a) Strong hard X-ray tails (, $\sim 2 - 3$) during soft X-ray low states, as observed

b) Prediction: $E_c \lesssim 1$ MeV in low state

c) Prediction: Hard-X-ray tails also in high state; $E_c \sim 100 - 200$ keV

Anomalous X-ray pulsars:

a) hard X-ray spectral index , $\sim 3 - 4$, as observed

b) Prediction: $E_c \sim 100 - 500$ keV

c) Prediction: spectral hardness at hard X-rays only weakly correlated with soft X-ray luminosity (except for very low accretion rate and very high hydro-magnetic turbulence level)

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