Resonant Compton Upscattering in High Field Pulsars and Magnetars

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ABSTRACT

The extremely efficient process of resonant Compton scattering (RCS) in strong magnetic fields is believed to be a leading emission mechanism in high field pulsars and magnetars. In this effort, we develop new analytic developments for resonant Compton scattering, specifically spin-dependent cross sections devised using Sokolov & Ternov electron states. These more technically-correct forms display significant numerical departures from the older Johnson & Lippmann formalism for the cross sections in the resonance, thereby motivating the astrophysical deployment of this updated resonant Compton formulation. Useful approximate analytic forms for the cross section near and at the cyclotron resonance are presented. We highlight the application of these physics calculations in an inner magnetospheric model of the hard X-ray spectral tails in Anomalous X-ray Pulsars (AXPs), recently detected by RXTE and INTEGRAL. Relativistic electrons cool rapidly near the stellar surface, in the presence of intense baths of thermal X-ray photons, where the kinematics dominate and allow thermal photons to easily access the resonance. We present improved RCS electron cooling rates for magnetic fields above the quantum critical value, as functions of the magnetospheric colatitude and altitude. The kinematics provide the framework for an efficient scattering mechanism producing the characteristically flat spectral tails observed in AXPs.

GOALS AND CONTEXT

- We develop compact, analytical expressions to describe resonant, magnetic Compton scattering from relativistic electrons in the neutron star magnetospheres to explore the role of inverse Compton scattering as a mechanism leading to the high-energy tails observed in some magnetars.

- Recent observations reveal the presence of hard X-ray tails in the spectra measured by INTEGRAL, RXTE, XMM and ASCA in Anomalous X-ray Pulsars (Kuiper et al. 2004, 2006; den Hartog et al. 2008a, 2008b) as well as in Soft Gamma-ray Repeaters (Mereghetti et al. 2005; Molkov et al. 2005; Götz et al. 2006; Rea et al. 2009)

- Resonant Compton scattering (RCS) is an efficient mechanism that may interpret these observations. RCS has been studied by several groups (Lyutikov & Gavriil 2006; Rea et al. 2008; Baring & Harding 2007; Baring, Wadiasingh & Gonthier 2011) within this context.

SPIN-DEPENDENT RESONANCE WIDTH

- Relativistic electrons undergo inverse Compton scattering in the strong magnetic fields of magnetars with the soft X-ray photon field from the hot (10^6 K) thermal stellar surface. High-field pulsars may provide similar conditions.

- Given the available phase space, the scattering will occur at the cyclotron resonance where the incident photon is Lorentz boosted into the electron rest frame with an energy equal to B (in units of the quantum critical field of B_{cr} = 4.414x10^{13} Gauss).

- Assuming ground-state-to-ground state scattering with the final state characterized by ℓ = 0, the only contributing intermediate virtual state is in the n = 1 excited Landau state; this generates the resonance at the cyclotron frequency.

- This characterizes the entire available phase space below and at the resonance, while higher excited Landau states become available in the virtual states above the resonance.

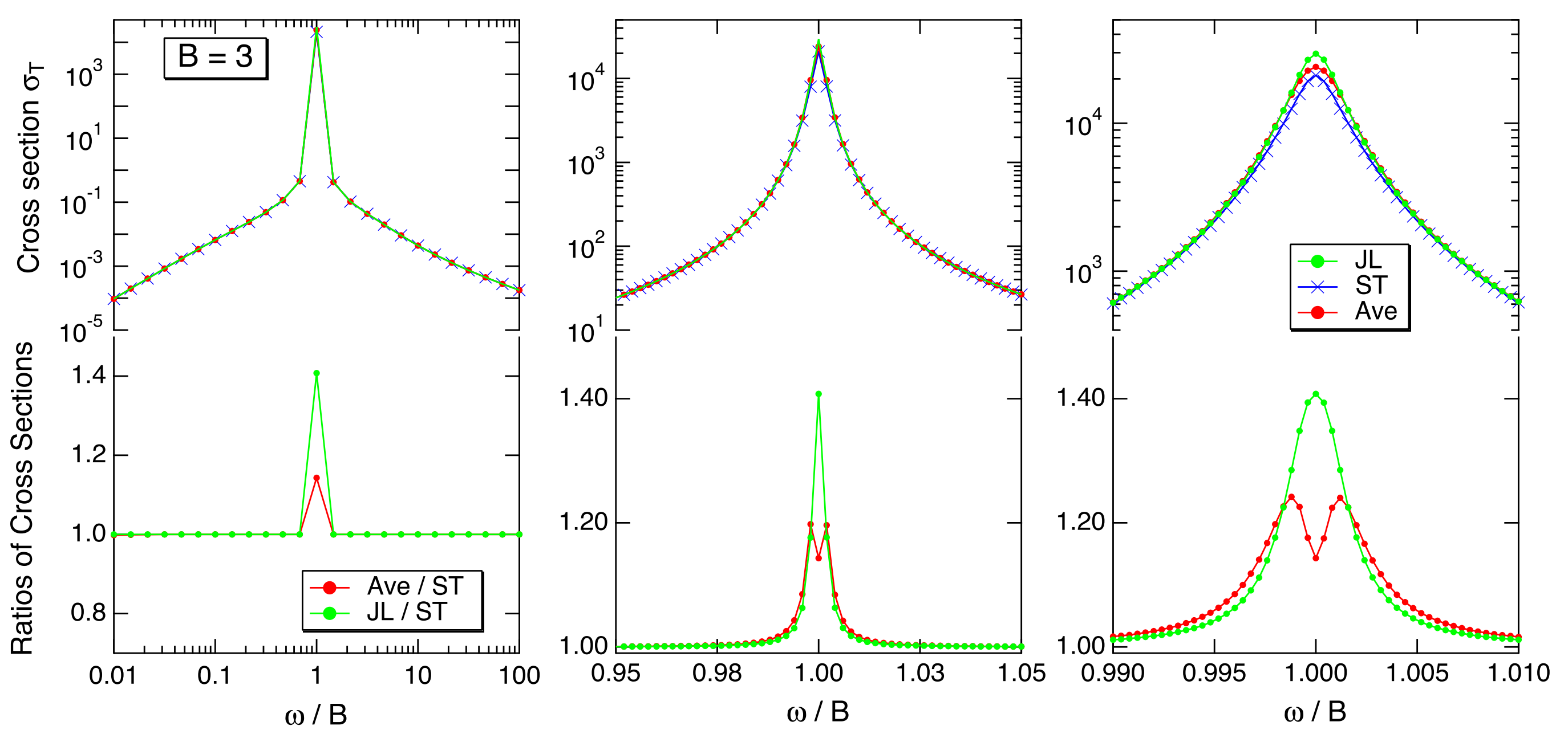
- The lifetime of the excited virtual particle (electron or positron) in the n = 1 state is necessarily dependent on the spin of the state (for example, see Baring, Gonthier & Harding 2005). As a result, to correctly account for resonant Compton scattering in strong fields, the spin-dependence of the resonance must be properly accounted for in terms of proper electron wave functions that behave appropriately under Lorentz transformations along B.

- While the cross section is most easily cast in the electron rest frame, the intermediate virtual particle acquires a component of momentum parallel to B, depending on the Feynman diagram, requiring a Lorentz boost to accurately describe the width of the resonance.

ELECTRON WAVE FUNCTION – BASIS STATES

- We develop the description of Compton scattering with a resonance that is intrinsically spin-dependent within the context of the commonly used Johnson & Lippmann (1949) (J&L) as well as Sokolov & Ternov (1968) (S&T) electron basis states (Gonthier et al. 2011, in preparation).
- As indicated in Baring, Gonthier & Harding (2005), J&L states do not behave appropriately, mixing spin states under Lorentz boosts along the field resulting in the lifetimes of the excited states that are incorrectly characterized. Given the broad use of J&L states in resonant Compton scattering, we proceed in a parallel analysis of both S&T and J&L basis states.
- Commonly used are resonant widths averaged over the spins of the intermediate state (see for example Baring & Harding 2007). One arrives at the same spin-average Compton scattering cross section using either S&T or J&L basis states, as expected.

ANGLE INTEGRATED COMPTON CROSS SECTIONS

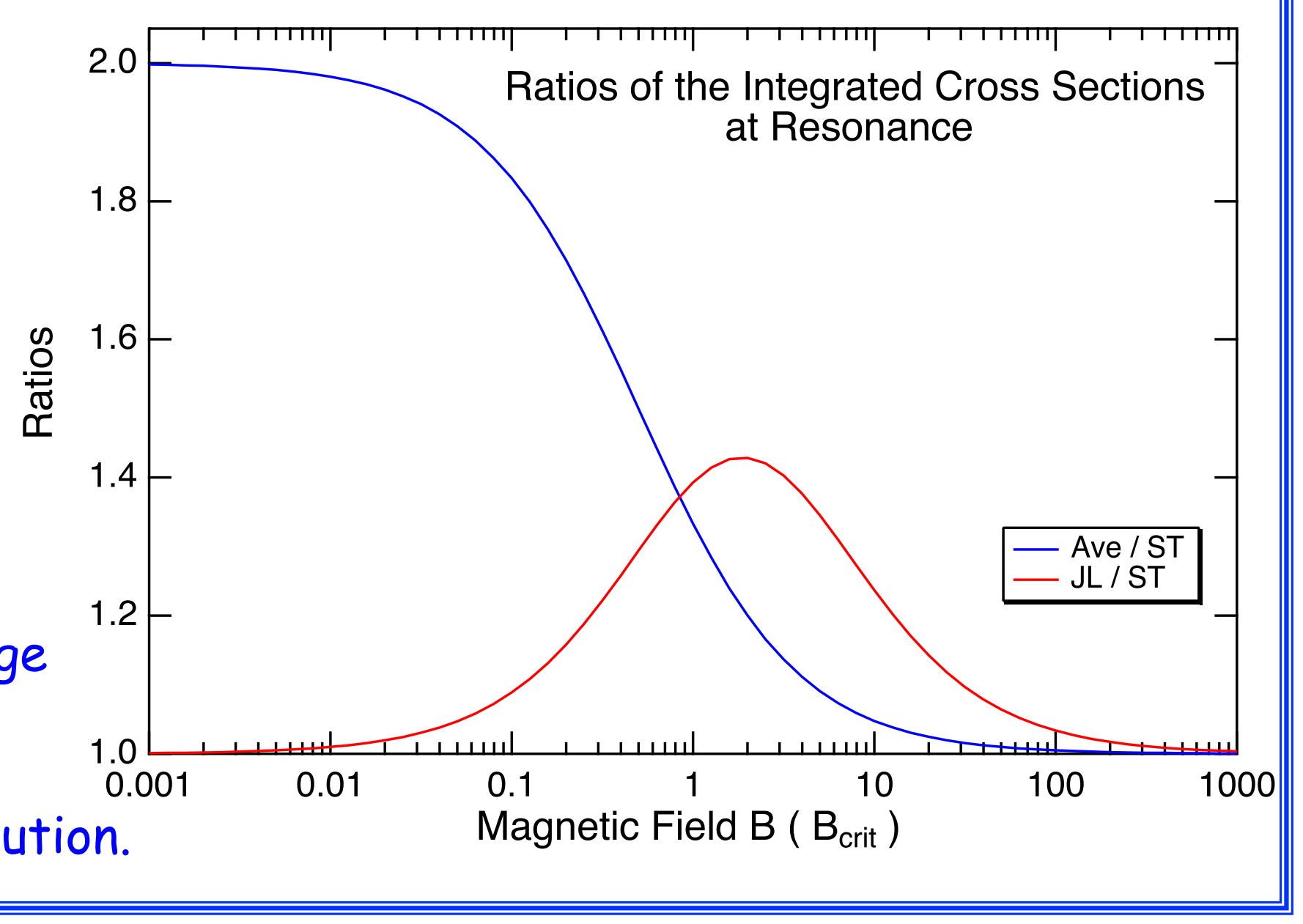


JL – refers to the Compton cross section developed within J&L basis states with a spin-dependent resonance width

ST – cross section is developed within S&T basis states with a spin-dependent resonance width

Ave – is the spin-averaged cross section with an average width (same result in either S&T or in J&L states)

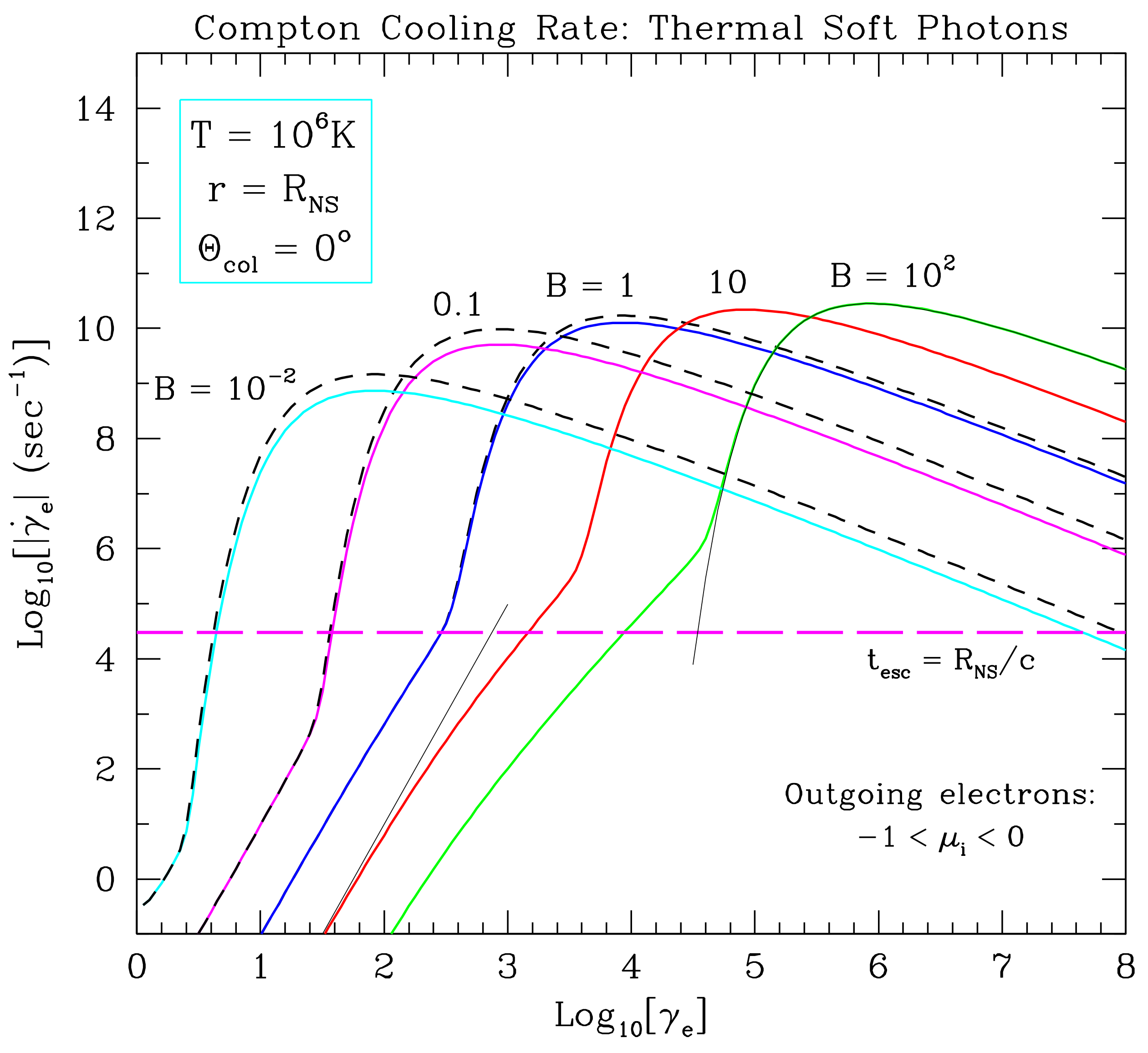
Differences in the formalisms are largest at the resonance. Here the ratio of the resonant cross section of the average and the cross section using J&L spin-dependent width to the cross section using the S&T spin-dependent width is plotted as a function of the magnetic field B. The cross section using the average width is a factor of 2 larger at low B due to the behavior of the perpendicular polarization contribution.



COOLING RATES FOR RELATIVISTIC ELECTRONS

- It is suspected that electrons traveling at relativistic speeds along the magnetic field lines of pulsars and magnetars and interacting with photons during the Compton upscattering process have markedly different cooling rates than non-relativistic electrons undergoing inverse Thompson cooling would demonstrate. This distinction could explain the hard tail X-ray magnetar emission evident in the X-ray spectra.

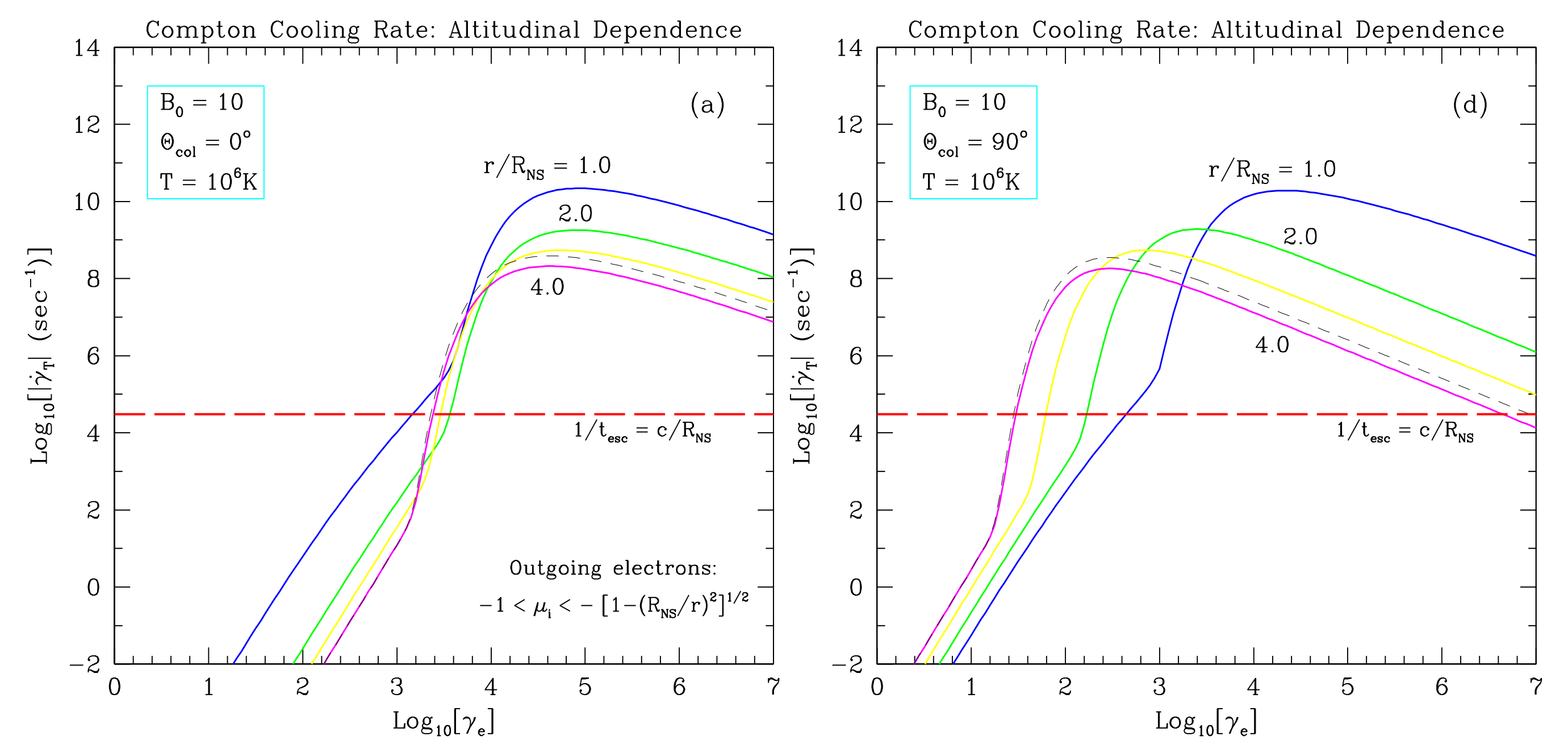
- The kinematics of the Compton interaction govern the electron cooling rates by determining what photon energies sample the resonance embodied in the cross section. Calculations and analytic expressions of the cooling rate use the spin-averaged cross section outside of the resonance and the fully spin-dependent cross section when the resonance is sampled.



- This figure displays the calculated cooling rates for outward propagating electrons for a variety of magnetic field strengths (in units of B_{cr}). The steep increase in cooling rate magnitude occurs when the photon energies begin to sample the resonance.

- The dashed curves in the figure represent the cooling rates for the cross section using the average width. It is apparent that for very high magnetic fields the average cross section is indistinguishable from the cross section using the spin-dependent widths (S&T); for highly-subcritical fields, the difference is approximately a factor of 2.

COOLING RATES – ALTITUDE DEPENDENCE



- Here, the cooling rates are calculated at a variety of altitudes ranging from the stellar surface up to four times the stellar radius. The left panel represents electrons emitted traveling at a colatitude above the magnetic pole, and on the right, electrons at the equator.

- The magnetic field is strongest at the surface, as evidenced in the greater cooling rate magnitudes at that altitude. Higher above the surface along the magnetic axis, the photons predominantly chase electrons from the surface, so the kinematic access to the resonance is not significantly modified by increasing altitudes.

- Electrons at the equator can scatter off photons approaching them at quasi-isotropic angles, so the dependence on altitude is much stronger here.

- The horizontal dashed line represents the light-escape time scaled to the stellar radius, a benchmark for the efficiency of resonant Compton cooling.

- The dashed black curves indicate the cooling rates using the cross section with the average widths as formulated in Baring & Harding (2007) at four stellar radii.

CONCLUSIONS

- The correct formalism of resonance Compton scattering using the spin-dependent resonance width developed with proper Sokolov & Ternov electron wave functions display significant differences with respect to the traditionally used cross section with the average width and lesser differences relative to the resonance cross section using the spin-dependent width using the Johnson & Lippmann electron wave functions.

- Sokolov & Ternov basis states must be used to describe accurate resonant Compton scattering. Sokolov & Ternov states behave correctly under Lorentz boosts along the field, maintaining the spin of the virtual state.

- Inverse resonant Compton scattering in magnetar magnetospheres is an efficient mechanism in the cooling of accelerated relativistic electrons, and subsequent radiation at hard X-ray energies. Preliminary efforts strongly encourage the development of a full radiation model to explain the observed high-energy tails in magnetars in the 100 keV range.

FUTURE EFFORT

- We will soon have full scattered photon spectra resulting from the total scattering within magnetar magnetospheres to be compared to the observed X-ray spectra.
- Such spectra will include self-consistent Compton cooling of electrons along field lines at various altitudes and colatitudes. Preliminary computations of spectra indicate significant sensitivity to the observer's viewing angle with respect to the field lines.

Acknowledgements

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