Spreading layer illumination of accretion disk around weakly magnetized neutron star: radial profiles of Fe-K$_\alpha$ photoionizing flux

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ABSTRACT

Relativistic Fe-K$_\alpha$ emission line near 6−7 keV is one of the most prominent features of the reflected spectra usually found in low mass X-ray binaries with a black hole or neutron star (NS). In the case of a system with NS, shape and strength of the emission line provide important constrains on the geometry of the inner accretion disk and on the properties of the NS. Existing NS reflection models (e.g. relxillNS; García et al. 2022) provide a detailed treatment of radiative transfer and atomic processes in the disk, but rely on phenomenological prescriptions for the radial illumination profile. We investigate the illumination of a geometrically thin accretion disk by a latitude-dependent spreading layer (SL) on a surface of a weakly magnetized NS. The accreted material heats the NS surface in two symmetric Gaussian-like belts that emit locally as blackbodies, with the SL geometry setting the latitude of peak temperature and the angular extent of the radiating region. Using Monte Carlo ray tracing, we compute the radial profile of the disk-incident energy flux weighted by the efficiency for photoionization of iron above the Fe-K$_\alpha$ edge.

MOTIVATION

The disk emissivity profile is determined by both the incident illumination and the disk's radiative response. While the latter is usually calculated in detail, the illumination is commonly described by phenomenological prescriptions that are not directly linked to the geometry of the illuminating source. Standard choices include a single power law and a smoothly broken power law (SBPL), characterized by two emissivity indices and a break radius. In this work, we connect the SBPL parameters—and its transition to a single power law—to the geometry of the spreading layer (SL) and the compactness of the neutron star.

MODEL - geometry of the system, local radiation and light propagation

We model a geometrically thin, optically thick Keplerian disk extending down to the ISCO of a weakly magnetized neutron star (NS). The star has mass $M = 1.6\,M_\odot$, radius $R_{\rm NS}$, and spin frequency $f_{\rm NS}$. The disk is illuminated by a spreading layer (SL) present on the surface of NS. We assume Schwarzschild spacetime, use geometric units ($G = c = 1$), and approximate photon trajectories with the analytic light-bending prescription of (La Placa et al. 2019).

Latitude θ is measured from the equatorial plane. We approximate the SL angular velocity by a generalized Gaussian,

$$\Omega_{\rm SL}(\theta) = \Omega_{\rm NS} + (\Omega_{\rm max} - \Omega_{\rm NS}) \exp\left[-\frac{1}{2}\left(\frac{|\theta|}{\sigma_{\rm SL}}\right)^n\right], \qquad \Omega_{\rm NS} = 2\pi f_{\rm NS}, \tag{1}$$

where $\sigma_{\rm SL}$ sets the layer width. The index $n = 4$ produces a flatter equatorial region and sharper deceleration than a Gaussian ($n = 2$), in better qualitative agreement with numerical SL models (Suleimanov & Poutanen 2006; Gilfanov & Sunyaev 2014). Conservation of the specific angular momentum carried from the ISCO gives

$$\Omega_{\rm max} = \frac{l_{\rm ISCO}\,(1 - 2M/R_{\rm NS})}{R_{\rm NS}^2}, \qquad l_{\rm ISCO} = \sqrt{\frac{27}{2}}\,M. \tag{2}$$

We define the full SL opening angle by the region in which the excess angular velocity exceeds 5.5% of its maximum,

$$\Omega_{\rm SL}(\theta) - \Omega_{\rm NS} \geq 0.055\,(\Omega_{\rm max} - \Omega_{\rm NS}), \qquad \alpha_{\rm SL} = 2\sigma_{\rm SL}[2\ln(20)]^{1/n}. \tag{3}$$

The local dissipation is assumed to arise from latitudinal deceleration,

$$Q(\theta) \propto |\Omega_{\rm SL}(\theta) - \Omega_{\rm NS}| \left|\frac{d\Omega_{\rm SL}}{d\theta}\right|. \tag{4}$$

It peaks in two symmetric off-equatorial belts at latitudes $\pm\theta_{\rm pk}$. As $\alpha_{\rm SL}$ increases, the belts broaden and move to higher latitude, as expected for increasing accretion rate. Our reference model has $\alpha_{\rm SL} = 50^\circ$ and $\theta_{\rm pk} \approx 15^\circ$, corresponding approximately to $L_{\rm SL} \simeq 0.2 L_{\rm Edd}$ and $\dot{M} \simeq 0.4 \dot{M}_{\rm Edd}$

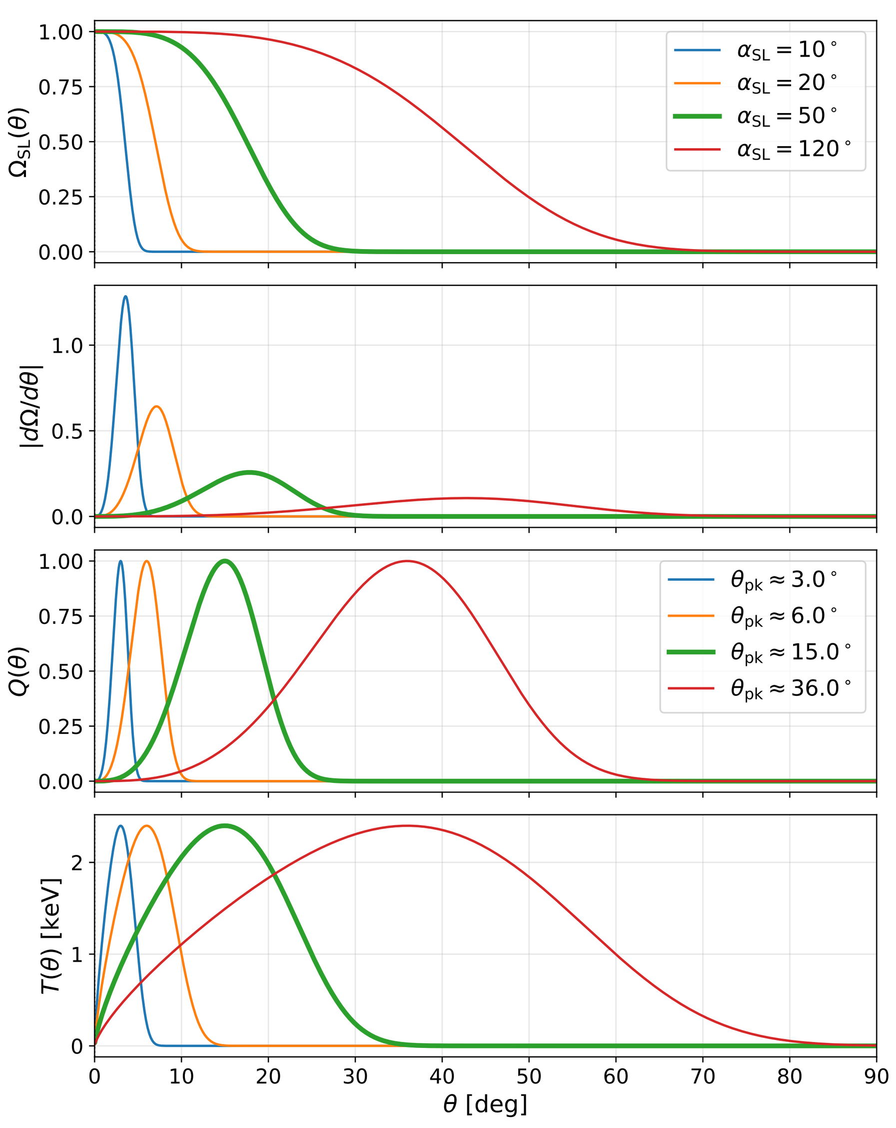
Assuming that the dissipated energy is radiated locally by an optically thick layer,

$$F(\theta) \propto Q(\theta), \qquad F(\theta) = \sigma_{\rm SB} T^4(\theta),$$

and hence

$$T(\theta) = T_{\rm max}\left[\frac{Q(\theta)}{Q_{\rm max}}\right]^{1/4}, \qquad kT_{\rm max} = 2.4\,{\rm keV}. \tag{5}$$

The adopted colour temperature is representative of luminous NS spreading layers (Suleimanov & Poutanen 2006; Gilfanov & Sunyaev 2014), with $f_{\rm NS} = 0$ Hz.



Construction of the SL surface emission profile from the latitudinal angular velocity prescription. From top to bottom, the panels show the angular velocity $\Omega_{\rm SL}(\theta)$, eq. (1), the magnitude of its latitudinal gradient $|d\Omega_{\rm SL}/d\theta|$, the normalized energy dissipation $Q(\theta)$, (3) and the resulting effective temperature profile $T(\theta)$, eq(4). Curves are shown for three values of full opening angle $\alpha_{\rm SL}$ with the reference model highlighted. The figure illustrates how the formation of two symmetric off-equatorial radiating belts arise naturally from the latitudinal deceleration of the spreading flow. The latitude of maximum temperature $\theta_{\rm pk}$ shifts to higher latitudes as the SL broadens.

Each NS surface element emits a local blackbody photon-number spectrum,

$$N_{\rm em}(E_{\rm em}, \theta) \propto \frac{E_{\rm em}^2}{\exp[E_{\rm em}/kT(\theta)] - 1}. \tag{6}$$

Only photons above the Fe K-shell threshold in the disk frame contribute to fluorescence. Their disk-frame energy is

$$E_{\rm disk} = g E_{\rm em}, \qquad g \equiv \frac{E_{\rm disk}}{E_{\rm em}} = \frac{u^\mu_{\rm disk} p_\mu}{u^\nu_{\rm em} p_\nu},$$

where $u^\mu_{\rm em}$ and $u^\mu_{\rm disk}$ are the emitter and disk four-velocities and p_μ is the photon four-momentum.

The condition $E_{\rm disk} \geq E_{\rm th}$ is included through the weight

$$w(\theta, g) \propto \int_{E_{\rm th}/g}^{\infty} N_{\rm em}(E_{\rm em}, \theta)\, \sigma_{\rm Fe}(g E_{\rm em})\, dE_{\rm em}\,.$$

In Schwarzschild spacetime, p_t and p_φ are conserved, so each ray is characterized by the impact parameter

$$b \equiv -\frac{p_\varphi}{p_t} = \frac{R_{\rm NS} \sin\alpha_{\rm em}}{\sqrt{1 - r_s/R_{\rm NS}}}, \tag{7}$$

where $\alpha_{\rm em}$ is the local emission angle. The emission is assumed to be locally isotropic ($dF \propto \cos\alpha_{\rm em}\, d\Omega$). After correcting the initial direction for Schwarzschild light bending (La Placa et al. 2019), we record where 10^8 rays intercept the disk. The photoionization-weighted incident flux in annulus i is

$$F_{\rm MC}(r_i) \propto \frac{1}{\Delta A_i} \sum_{j \in i} g_j^2\, w_j(\theta_j, g_j), \tag{8}$$

where g^2 accounts for the photon-energy shift and the transformation of the arrival rate. Thus, $F_{\rm MC}(r)$ measures the radial disk-incident energy flux capable of producing Fe-K$_\alpha$ fluorescence.

MC simulations and SBPL fits for $E_{\rm th} = 7.1$ keV

The Monte Carlo irradiation profiles were fitted with a smoothly broken power law (SBPL),

$$\epsilon_{\rm SBPL}(r) = \epsilon_0 r^{-q_1}\left[1 + \left(\frac{r}{r_b}\right)^{1/s}\right]^{s(q_1 - q_2)}, \tag{9}$$

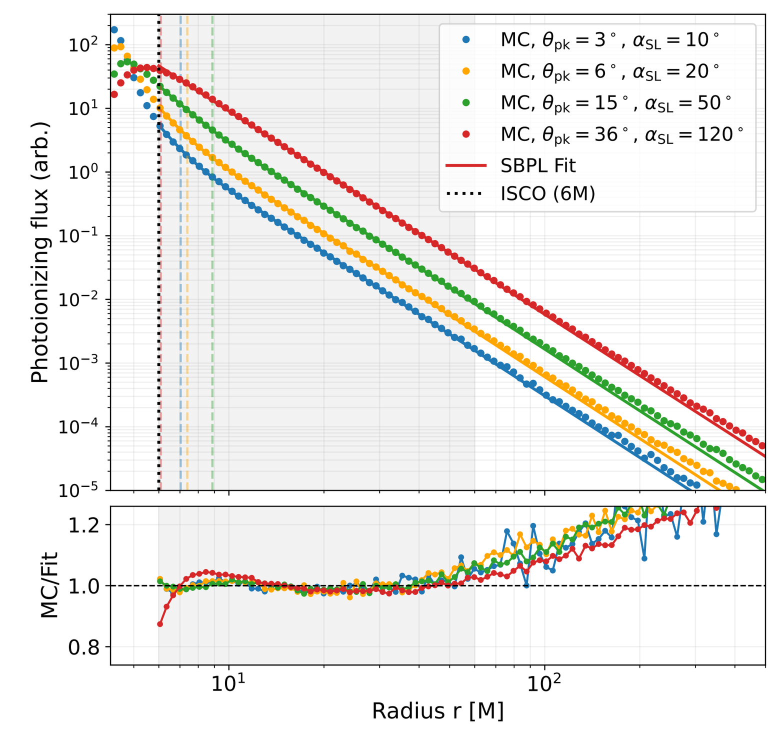
where q_1 and q_2 are the inner and outer emissivity indices, r_b is the break radius, and s controls the transition smoothness. We fixed $s = 0.15$ and allowed

$$2.5 \leq q_1 \leq 15, \qquad 2 \leq q_2 \leq 4, \qquad 6M \leq r_b \leq 60M.$$

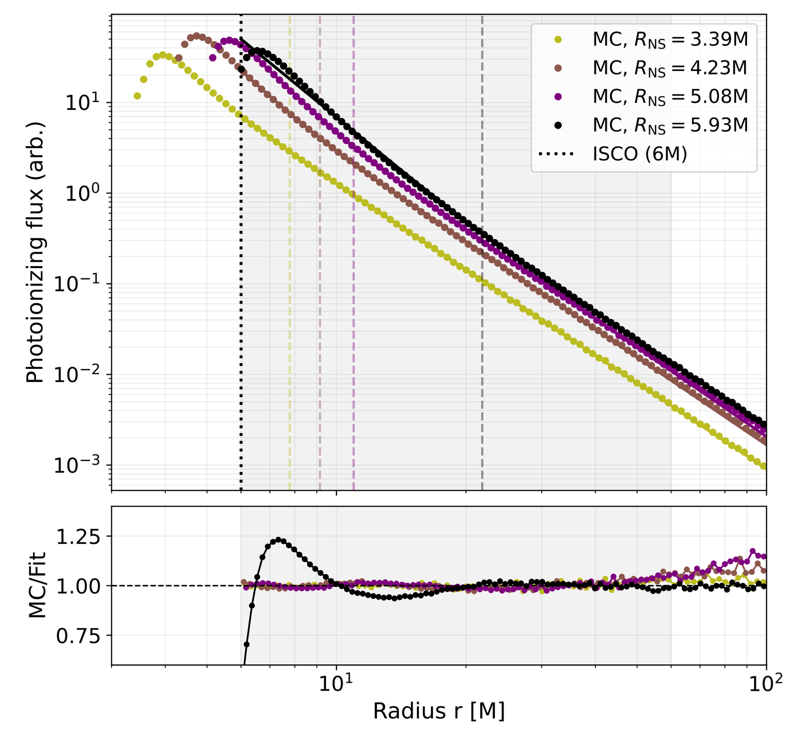
The fit was performed in logarithmic space over $6M \leq r \leq 60M$ by minimizing

$$\chi^2_{\rm w} = \sum_i w_{\rm fit}(r_i)\,[\ln \epsilon_{\rm SBPL}(r_i) - \ln F_{\rm MC}(r_i)]^2\,, \tag{10}$$

with $w_{\rm fit}$ denoting an emphasis on inner disk region, where the irradiation is strongest and most of the relativistically broadened Fe-K$_\alpha$ emission line originates.



Monte Carlo illuminating profiles with SBPL fits. Dependence on SL full openning angle. Colored dashed vertical lines mark the fitted break radii r_b, and the black dotted line indicates ISCO at $r = 6M$. The lower panel shows the ratio of the Monte Carlo profile to the corresponding SBPL fit, demonstrating that the analytic model reproduces the simulated curves to within ∼ 10–20% over most of the fitted radial range. The shaded region indicates the interval used for the fit.



Monte Carlo illuminating profiles with SBPL fits. Dependence on NS compactness. Colored dashed vertical lines mark the fitted break radii r_b, and the black dotted line indicates ISCO at $r = 6M$. The lower panel shows the ratio of the Monte Carlo profile to the corresponding SBPL fit, demonstrating that the analytic model reproduces the simulated curves to within ∼ 10–20% over most of the fitted radial range. The shaded region indicates the interval used for the fit.

Monte Carlo simulations map

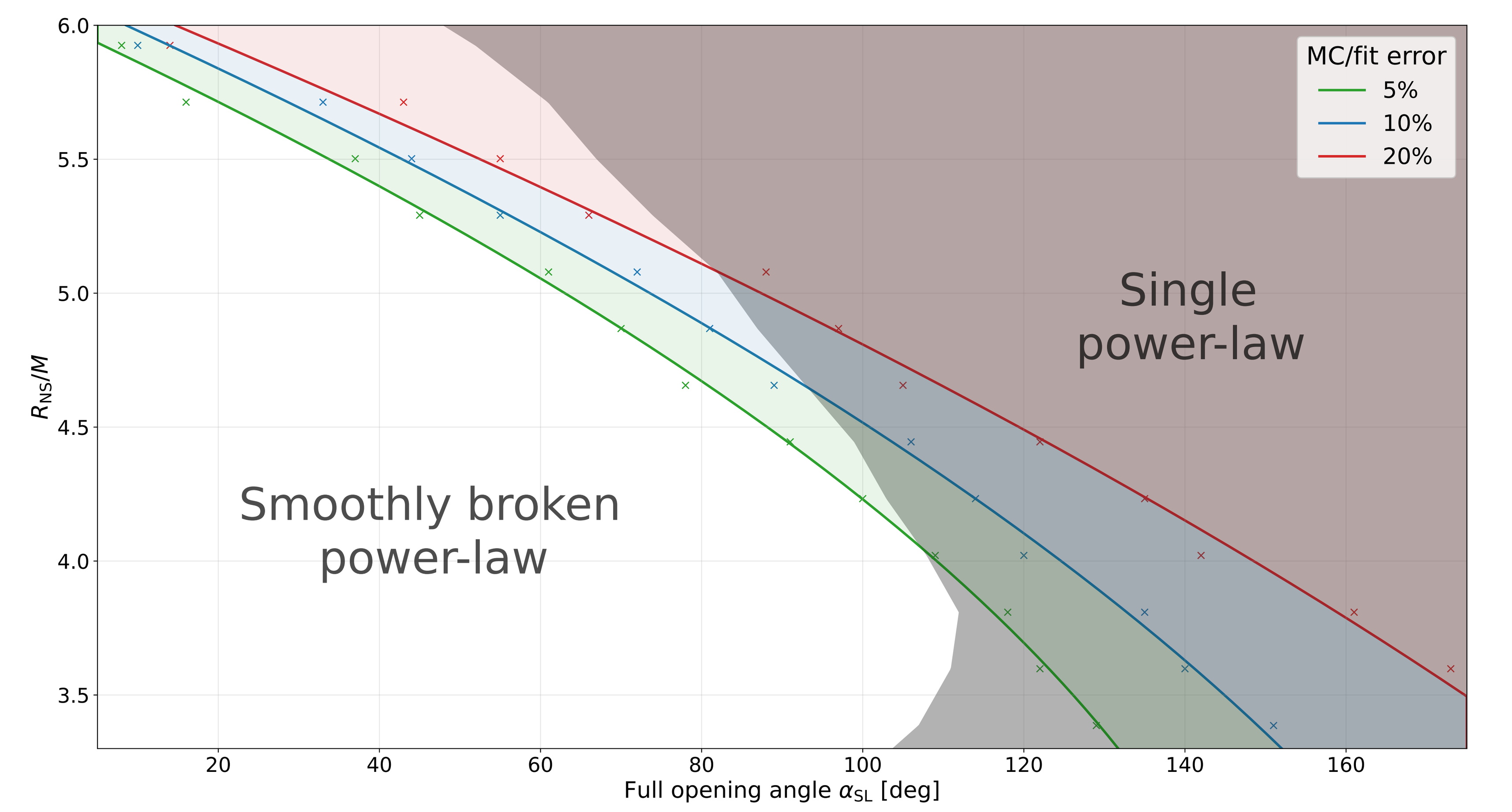


Figure 1: Dependence of the MC/SBPL fit quality on NS compactness, $R_{\rm NS}/M$, and the SL full opening angle, $\alpha_{\rm SL}$. White area represents a region for which the SBPL is a better fitting function then a single power-law. The gray shaded region marks the transition to effectively single power-law profiles, where $q_1 = q_2$. Green, blue, and red curves mark the 5%, 10%, and 20% MC/SBPL mismatch levels, respectively; crosses denote the measured critical points used to construct the smooth curves.

SBPL parameters map

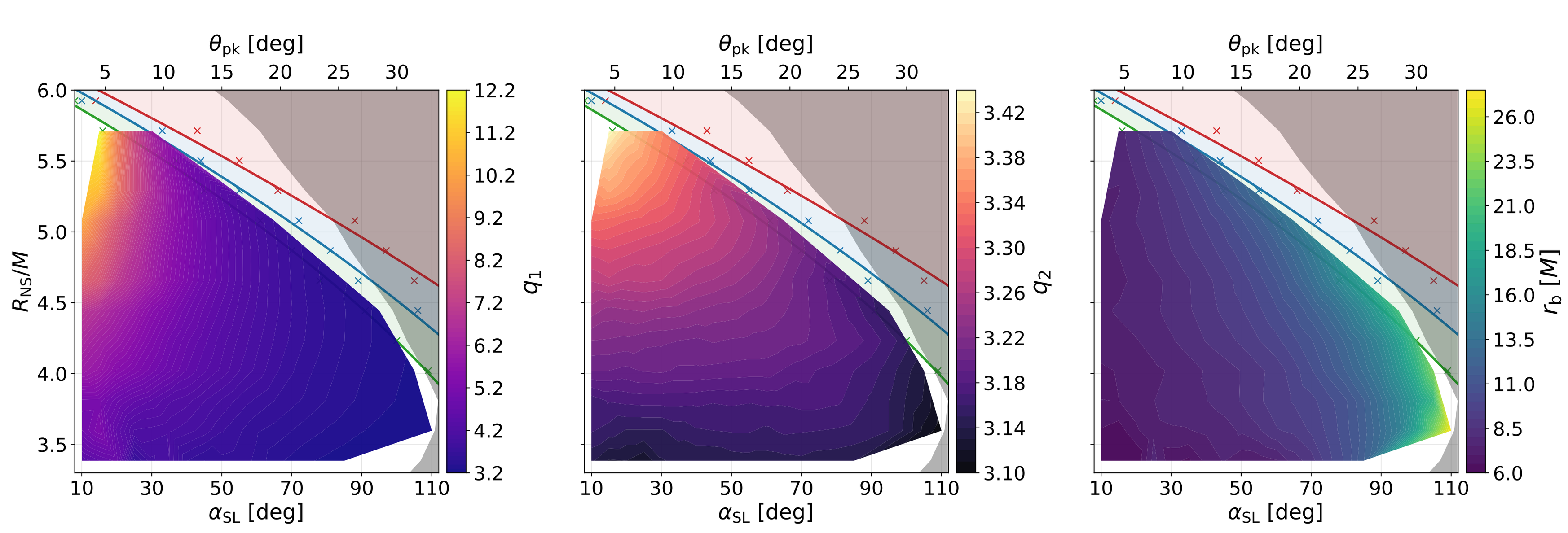


Figure 2: Maps of best-fitting SBPL parameters q_1, q_2, and r_b as functions of the SL opening angle $\alpha_{\rm SL}$ and NS compactness. The upper axes show the corresponding SL flux peak position $\theta_{\rm pk}$. The colored contours are obtained from the SBPL fits to the Monte Carlo irradiation profiles.

DISCUSSION AND CONCLUSIONS

Our results show how SL geometry and neutron-star compactness affect the radial disk-irradiation profile. While current reflection models calculate the disk response in detail, illumination is usually described phenomenologically. The resulting SBPL parametrization offers a physically motivated alternative for modelling reflection in soft-state NS LMXBs.

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