Advances in the Power-Law Correlation between UV/OPT/NIR and X-ray Radiation: Postprint

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Abstract

The radiation in low-mass X-ray binary systems spans from radio to gamma-ray bands. It is generally believed that X-ray radiation originates from the inner region of the accretion disk, radio emission is primarily contributed by jets, while ultraviolet, optical, and near-infrared (UV/OPT/NIR) radiation may be contributed by multiple radiation mechanisms. Determining the dominant mechanism of UV/OPT/NIR radiation in X-ray binary systems can provide very important information for the study of accretion processes. Analyzing correlations between radiation fluxes in different wavebands is an important research method. Previous researchers have investigated the primary origin of UV/OPT/NIR radiation by analyzing power-law correlations between UV/OPT/NIR and X-ray radiation. They have summarized observational results of power-law correlations present in different sources and introduced theoretical models used to explain the origin of UV/OPT/NIR radiation.

Full Text

Research Progress on Power-law Correlation between UV/OPT/NIR and X-ray Emission in Low-Mass X-ray Binaries

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Abstract

Radiation from low-mass X-ray binary (LMXB) systems spans from radio to gamma-ray wavelengths. X-ray emission is generally believed to originate from the inner region of the accretion disk, radio emission is primarily contributed by jets, while ultraviolet, optical, and near-infrared (UV/OPT/NIR) radiation may arise from multiple mechanisms. Identifying the dominant mechanism for UV/OPT/NIR emission in X-ray binary systems provides crucial information for understanding accretion processes. Analyzing correlations between fluxes at different wavelengths represents an important research approach. Previous studies have investigated the primary origin of UV/OPT/NIR radiation by examining power-law correlations between UV/OPT/NIR and X-ray emission. This paper summarizes observational results of power-law correlations found in various sources and introduces theoretical models used to explain the origin of UV/OPT/NIR radiation.

Keywords: low-mass X-ray binary; accreting black hole; accreting neutron star; UV/OPT/NIR radiation; power-law correlation

1 Introduction

Low-mass X-ray binaries (LMXBs) are binary systems composed of a compact object and a companion star with mass typically less than 1 M , where the companion is usually a normal evolved star. Based on the type of compact object, LMXBs can be classified as black hole LMXBs (BH-LMXBs) and neutron star LMXBs (NS-LMXBs). Material from the companion star transfers through the first Lagrangian point onto the compact object, forming an accretion disk. LMXBs include both persistent and transient sources. Most BH-LMXBs are transients, while only about 40% of NS-LMXBs are transient sources. Transient sources remain in quiescence for long periods with luminosities LX 10^{22}-10^{27} $\mathrm{J \cdot s^{-1}}$. During outbursts, optical and X-ray fluxes increase by several orders of magnitude relative to quiescence, with peak X-ray luminosities reaching LX 10^{27}-10^{32} $\mathrm{J \cdot s^{-1}}$. Outburst durations typically range from weeks to months or even longer. The physical mechanism for such outbursts is generally explained by the thermal-viscous disc instability model (DIM).

Based on X-ray spectral and timing properties, BH-LMXB outbursts are divided into different states, broadly categorized as low-hard state (LHS), intermediate state (IMS), and high-soft state (HSS). In typical outbursts, the state evolution follows the sequence LHS→IMS→HSS→IMS→LHS. Detailed spectral and timing properties of each state can be found in references [**?**, **?**]. During outbursts, q-shaped evolutionary tracks are typically observed in hardness-intensity diagrams (HID). Some outbursts evolve only in the hard state without reaching the soft state; these are called failed outbursts.

NS-LMXBs can be classified as Z sources and Atoll sources based on their evolution in color-color diagrams and timing properties. Z sources exhibit Z-shaped tracks in color-color diagrams with three branches: horizontal branch (HB), normal branch (NB), and flaring branch (FB). Atoll sources show three branches in their evolutionary tracks: island state (IS), lower banana state (LB), and upper banana state (UB). Detailed information about each state can be found in references [**?**, **?**].

LMXBs emit radiation across all wavelengths. X-ray radiation consists of two components: a soft thermal component and a hard power-law component. The soft thermal component is generally believed to originate from thermal radiation of an optically thick, geometrically thin accretion disk, with peak temperatures typically in the range 0.1–2.5 keV. The hard power-law component is produced in a corona composed of hot electron plasma, with temperatures of tens to hundreds of keV. The corona may be distributed around the compact object or in the disk. Low-energy soft photons are inverse Compton scattered by high-energy electrons in the corona, producing hard X-ray radiation. Because neutron stars have solid surfaces, material accumulating on the neutron star surface undergoes thermonuclear reactions, contributing to X-ray radiation. Radio to submillimeter radiation is produced by synchrotron radiation processes from charged particles in jets. Since UV/OPT/NIR bands lie at the intersection of multiple radiation mechanisms, the origin of UV/OPT/NIR radiation is less understood than that of X-ray and radio bands. The companion star in LMXBs may contribute, but generally the companion is faint, and its contribution is overwhelmed by the outburst component during outbursts. UV/OPT/NIR radiation is generally thought to originate from: intrinsic thermal radiation from the outer accretion disk (viscous heating process), reprocessing of X-ray irradiation on the accretion disk, synchrotron radiation from jets, and synchrotron radiation from hot accretion flows.

The diversity of radiation mechanisms in UV/OPT/NIR bands requires determination of the dominant mechanism. Broadband spectral fitting can be used to analyze primary radiation mechanisms in each band, but simultaneous broadband data are often difficult to obtain. Previous observational studies of multiple LMXBs have found ubiquitous power-law correlations between UV/OPT/NIR and X-ray radiation fluxes. This paper introduces a method for studying the dominant radiation mechanism in the UV/OPT/NIR band of LMXBs by analyzing correlations between UV/OPT/NIR and X-ray radiation fluxes.

Such correlation studies exist on long timescales (>1 day) and short timescales (<1 day). This paper focuses on long-timescale studies. Section 2 summarizes the main models used to explain UV/OPT/NIR radiation. Section 3 introduces observations and studies of UV/OPT/NIR and X-ray correlations in different sources. Section 4 discusses current observational results and models, and provides prospects for studying the origin of UV/OPT/NIR radiation.

2 Theoretical Explanations for the Origin of UV/OPT/NIR Radiation

Using power-law correlations between UV/OPT/NIR and X-ray radiation (LUV=OPT=NIR L_X^β), four main theoretical models currently explain UV/OPT/NIR radiation: the viscous heating disk model, X-ray reprocessing model, jet radiation model, and hot accretion flow model. We introduce each model below.

2.1 Viscous Heating Disk Model

The accretion disk in BH-LMXBs is typically described by a multi-color blackbody disk. The inner disk region contributes soft X-rays, while the outer disk has lower temperatures and primarily contributes UV/OPT/NIR radiation through intrinsic thermal radiation produced by viscous heating in the accretion disk. If this process dominates UV/OPT/NIR radiation, a corresponding power-law relationship exists.

Assuming a steady-state thin disk with temperature-radius relation [**?**]:

$$T(R) = T_{\rm in}\left(\frac{R}{R_{\rm in}}\right)^{-n},$$

where $\dot{M}$ is the accretion rate, and $T_{\rm in}$ and $R_{\rm in}$ are the inner temperature and inner radius of the accretion disk, respectively. UV/OPT/NIR radiation is generally considered to be in the Rayleigh-Jeans (RJ) limit and flat-spectrum portion of the multi-color blackbody disk spectrum. When $h\nu \ll kT$ (Rayleigh-Jeans limit), the disk radiation luminosity relates to accretion rate as:

$$L_\nu^{\rm RJ} \propto \dot{M}^m.$$

For the flat-spectrum portion:

$$L_\nu^{\rm flat} \propto \dot{M}^{2m/n}.$$

In radiatively efficient and inefficient accretion systems, the relationship between X-ray luminosity and accretion rate is [**?**, **?**, **?**]:

$$L_X \propto \dot{M}, \quad L_X \propto \dot{M}^2.$$

BH-LMXBs are typically radiatively inefficient in the hard state and radiatively efficient in the soft state, while NS-LMXBs are generally radiatively efficient. From equations (2)-(4), for hard-state BH-LMXBs:

$$L_\nu^{\rm RJ} \propto L_X^{m/n}, \quad L_\nu^{\rm flat} \propto L_X^{m/2}.$$

For NS-LMXBs and soft-state BH-LMXBs:

$$L_\nu^{\mathrm{RJ}} \propto L_X^{2m/n}, \quad L_\nu^{\mathrm{flat}} \propto L_X^{2m/n}.$$

For viscous heating-dominated disks, $m = 1/4$, $n = 3/4$ [?]. Since UV/OPT/NIR radiation lies between the Rayleigh-Jeans limit and flat-spectrum portion of the multi-color blackbody disk spectrum, the theoretically expected power-law index range is $0.13 < \beta < 0.33$ for hard-state BH-LMXBs and $0.25 < \beta < 0.67$ for NS-LMXBs and soft-state BH-LMXBs [?, ?]. Russell et al. [?] reached similar conclusions for the hard state, with theoretical expectations for the power-law index β of $0.15 < \beta < 0.30$ in BH-LMXBs and $0.30 < \beta < 0.60$ in NS-LMXBs.

2.2 X-ray Reprocessing Model

van Paradijs & McClintock [?] proposed that X-rays from the inner accretion disk irradiate and heat the outer disk, with the heating process dominating the disk temperature. The thermal radiation from the heated disk then dominates the optical band. This process is called X-ray reprocessing. The model assumes a simple axisymmetric, optically thick, geometrically thin accretion disk. Defining a series of surface elements on the disk grid, the apparent disk luminosity is expressed as:

$$L_V = \sum_i S_i A_i \cos\phi_i,$$

where S_i is the surface brightness of each element i, A_i is the area of element i (proportional to the square of the binary orbital separation a), and ϕ_i is the angle between the line of sight and the normal to element i.

Assuming each element radiates as a blackbody isotropically and the disk temperature is dominated by irradiation from the inner X-ray source:

$$S_i = (1-\epsilon) L_X \cos\xi_i / (4\pi d_i^2),$$

where ϵ is the X-ray albedo, L_X is the X-ray luminosity from the inner accretion region, ξ_i is the angle between the line connecting element i to the X-ray source (at distance d_i) and the normal to the element. Letting $d_i = a\rho_i$, where ρ_i is the distance from element i to the X-ray source in the model, the disk temperature can be written as:

$$T_i = \left[(1-\epsilon)\cos\xi_i/(4\pi\rho_i^2)\right]^{1/4} (L_X/a^2)^{1/4}.$$

In LMXB accretion disks, the apparent surface brightness of blackbody radiation varies with temperature approximately as [?]:

$$S_V \propto T^{\alpha}, \quad \alpha \approx 2.$$

Combining these relations yields:

$$L_V \propto L_X^{1/2} \sum_i w_i \cos\xi_i \cos\phi_i / (4\pi\rho_i^2),$$

where w_i is the relative area of element i in the accretion disk model. Since the summation is independent of disk size, equation (11) can be written as:

$$L_V \propto L_X^{1/2} a.$$

Equation (12) shows that when X-ray reprocessing dominates optical radiation, a power-law correlation exists between the V band and X-ray band with a theoretically expected power-law index $\beta = 0.5$. Shahbaz et al. [**?**] argued that the power-law coefficient increases with decreasing wavelength. From the assumptions of van Paradijs & McClintock' s model, the power-law index β relates to the disk surface brightness as $\beta = \alpha/4$. Through simulated calculations of steady-state accretion disk spectra, Shahbaz et al. found $\beta \approx 0.9$ ($\alpha \approx 3.7$) in the UV band, $\beta \approx 0.7$ ($\alpha \approx 2.7$) in the V band, and $\beta \approx 0.3$ ($\alpha \approx 1.2$) in the K band. Neither van Paradijs & McClintock nor Shahbaz et al. considered differences between hard and soft states, so this model applies to both.

Additionally, Coriat et al. [**?**] analyzed this model in the soft state. Similar to the viscous heating disk model, they assumed a steady-state thin disk with temperature-radius relation [**?**]:

$$T(R) \propto R^{-n},$$

with UV/OPT/NIR radiation between the Rayleigh-Jeans limit and flat-spectrum portion of the multi-color blackbody disk spectrum. For the Rayleigh-Jeans limit, the disk radiation luminosity relates to frequency ν and temperature T as:

$$L_\nu^{\mathrm{RJ}} \propto T\nu^2.$$

For the flat-spectrum portion:

$$L_\nu^{\mathrm{flat}} \propto T^{n-3/2}\nu^{3-2n}.$$

In the soft state, the accretion disk typically dominates X-ray radiation, so $L_X \propto T^4$ [**?**], giving:

$$L_\nu^{\mathrm{RJ}} \propto L_X^{1/4}, \quad L_\nu^{\mathrm{flat}} \propto L_X^{1/2n}.$$

In the X-ray reprocessing model, the accretion disk is irradiation-heated, with $n = 1/2$, yielding a theoretically expected power-law index range of $0.25 < \beta < 1$ in the soft state. As shown above, the power-law index increases with decreasing observational wavelength (from Rayleigh-Jeans limit to flat-spectrum portion), consistent with Shahbaz et al.' s calculations.

2.3 Jet Radiation Model

Synchrotron radiation from charged particles in jet magnetic fields produces UV/OPT/NIR radiation. If jets dominate UV/OPT/NIR radiation, a corresponding power-law correlation exists between UV/OPT/NIR and X-ray bands. Russell et al. [?] derived the power-law correlation between UV/OPT/NIR and X-ray luminosities through relationships between multi-wavelength luminosities and accretion rate.

In compact, steady jet models, total jet power correlates with radio luminosity [?]:

$$L_{\mathrm{radio}} \propto L_{\mathrm{jet}}^{1.4},$$

and for hard-state BH-LMXBs and NS-LMXBs, total jet power correlates linearly with accretion rate [?, ?, ?]:

$$L_{\mathrm{jet}} \propto \dot{M}.$$

As mentioned in Section 2.1, X-ray luminosity in hard-state BH-LMXBs scales with accretion rate squared, while in NS-LMXBs it scales linearly. Combining equations (17) and (18) gives:

$$L_{\mathrm{radio}} \propto L_{\mathrm{jet}}^{1.4} \propto \dot{M}^{1.4} \propto L_X^{0.7} \quad \text{(BH-LMXBs)},$$

$$L_{\mathrm{radio}} \propto L_{\mathrm{jet}}^{1.4} \propto \dot{M}^{1.4} \propto L_X^{1.4} \quad \text{(NS-LMXBs)}.$$

Gallo et al. [?] and Migliari & Fender [?] observed such relationships in BH-LMXBs and NS-LMXBs, respectively. Flat, optically thick jet spectra extend from radio to NIR and optical bands [?], and even to UV [?], giving:

$$L_{\mathrm{UV/OPT/NIR}} \propto L_{\mathrm{radio}} \propto L_X^{0.7} \quad \text{(BH-LMXBs)},$$

$$L_{\mathrm{UV/OPT/NIR}} \propto L_{\mathrm{radio}} \propto L_X^{1.4} \quad \text{(NS-LMXBs)}.$$

Thus, when jets dominate UV/OPT/NIR radiation, the theoretically expected power-law index β is 0.7 for BH-LMXBs and 1.4 for NS-LMXBs. Since jets are weak and nearly undetectable in the soft state, the jet model explanation applies only to the hard state.

Note that equations (21) and (22) are derived based on the $L_{\rm radio}$-L_X correlation and the assumption of a flat jet spectrum. Recent observations [?] have found radio-weak BH-LMXBs showing broken power-law correlations: shallower at low L_X and steeper at high L_X. For example, Coriat et al. [?] found $L_{\rm radio} \propto L_X^{1.4}$ in BH-LMXB H1743-322 at high hard-state L_X. Carotenuto et al. [?] found $L_{\rm radio} \propto L_X^{0.6}$ at low L_X and $L_{\rm radio} \propto L_X^{0.95}$ at high hard-state L_X in BH-LMXB XTE J1118+480. Different $L_{\rm radio}$-L_X correlations thus yield different $L_{\rm UV/OPT/NIR}$-L_X correlations.

Russell et al. [?] assumed UV/OPT/NIR radiation originates from optically thick regions of jets. For optically thin cases, only Coriat et al. [?] discussed GX 339-4 to explain its broken power-law in NIR, but no general form was given.

2.4 Hot Accretion Flow Model

Veledina et al. [?] proposed a hot accretion flow model to explain UV/OPT/NIR radiation origin. Optical excess relative to standard accretion disk spectra has been observed in many sources [?], and the hot accretion flow model plays an important role in explaining this phenomenon. Electrons in hot accretion flows are typically assumed to follow a thermal distribution. Due to strong self-absorption, synchrotron radiation contributions are not significant in BH-LMXB hot accretion flows [?]. Veledina et al. [?] argued that besides thermal electron distributions, non-thermal electron distributions exist in hot accretion flows, and their synchrotron radiation may dominate OPT/NIR radiation. The hot accretion flow model is typically applied to the hard state.

Kosenkov et al. [?] explained power-law correlations in the hard state based on this model. Assuming the UV/OPT/NIR-X-ray spectrum consists of broken power-laws, UV/OPT/NIR luminosity ($L_{\rm UON}$) can be related to X-ray luminosity (L_X) by:

$$L_{\rm UON} = L_{\nu_t}\left(\frac{\nu_{\rm UON}}{\nu_t}\right)^{\alpha_{\rm UON}}, \quad L_X = L_{\nu_t}\left(\frac{\nu_X}{\nu_t}\right)^{\alpha_X},$$

where ν_t is the break frequency, $\alpha_{\rm UON}$ and α_X are spectral indices in UV/OPT/NIR and X-ray bands, and $\nu_{\rm UON}$ and ν_X are frequencies in UV/OPT/NIR and X-ray bands. The ratio of X-ray to UV/OPT/NIR luminosity can be written as:

$$\frac{L_X}{L_{\rm UON}} = \left(\frac{\nu_X}{\nu_{\rm UON}}\right)^{\alpha_X} \nu_t^{\alpha_{\rm UON}-\alpha_X} \nu_{\rm UON}^{\alpha_{\rm UON}-\alpha_X}.$$

From equation (24), the UV/OPT/NIR-X-ray power-law correlation index is:

$$\beta \equiv \frac{\partial \lg L_{\mathrm{UON}}}{\partial \lg L_X} = 1 - \gamma(\alpha_{\mathrm{UON}} - \alpha_X),$$

where $\gamma \equiv \partial \lg \nu_t / \partial \lg L_X$. The break frequency ν_t relates to magnetic field strength B and Thomson optical depth τ as:

$$\nu_t \propto B^{p+4} \tau^{p+4},$$

where p is the power-law index of the electron distribution. Assuming $B^2 \propto \rho$, electron density proportional to accretion rate ($\rho \propto \dot{M}$), and optical depth proportional to accretion rate ($\tau \propto \dot{M}$), we obtain:

$$\nu_t \propto \dot{M}^{2(p+4)}.$$

In radiatively efficient and inefficient accretion flows, X-ray thermal luminosity scales with accretion rate $\dot{M}$ and $\dot{M}^2$, respectively [**?**, **?**]. For these cases:

$$\gamma \equiv \frac{\partial \lg \nu_t}{\partial \lg L_X} = \frac{p+6}{2(p+4)}, \quad \gamma = \frac{p+6}{4(p+4)}.$$

Thus, when parameters α_{UON}, α_X, and p are obtained from observations, the power-law correlation index β between UV/OPT/NIR and X-ray radiation can be determined.

Besides these main radiation mechanisms, other possibilities exist. For example, magnetic reconnection in the accretion disk may contribute to optical radiation in black hole systems [**?**], and interaction between pulsar relativistic winds and inflowing material may produce optical radiation in neutron star systems [**?**].

3 Observational Power-law Correlations between UV/OPT/NIR and X-ray Radiation

Studying multi-wavelength correlations requires simultaneous multi-wavelength observational data. Power-law correlations between UV/OPT/NIR and X-ray radiation can be observed in both BH-LMXBs and NS-LMXBs. Radiation in each band is typically expressed as luminosity L or flux F, with power-law correlations expressed as $L_{\mathrm{UON}} \propto L_X^{\beta}$ or $F_{\mathrm{UON}} \propto F_X^{\beta}$. Different sources show different power-law indices β, displaying clear linear relationships in log-log coordinates, with some sources showing steeper and others flatter correlations. We now detail power-law correlations in different sources, focusing on BH-LMXBs and NS-LMXBs. Some X-ray binaries contain compact objects that are not dynamically confirmed black hole candidates (BHCs) but exhibit spectral and timing properties similar to black holes; we collectively refer to these as BH-LMXBs.

The radiation origins corresponding to different β values can be referenced in the detailed model descriptions in Section 2.

3.1 BH-LMXBs

3.1.1 GX 339-4 GX 339-4 is a frequently outbursting BH-LMXB that has experienced 20 outbursts since its discovery in 1972 [?], exhibiting multiple outburst types [?, ?], making it important for BH-LMXB research. The black hole mass is $11.24^{+0.59}_{-1.25}M_{\odot}$ [?], with a giant K-type companion star [?] that is relatively faint, so quiescent optical radiation is believed to originate from the accretion disk. The binary orbital period is 42.1 h [?]. Homan et al. [?] analyzed RXTE X-ray data and YALO 1 m telescope NIR (H band) and optical (I, V band) data spanning over 8 months, covering the initial X-ray rise and transition from hard to soft state. They found two distinct correlation patterns between OPT/NIR flux density and 3-100 keV X-ray flux. A strong correlation exists in the hard state [Figure 1: see original paper], spanning three orders of magnitude in X-ray flux, with power-law indices $\beta = 0.53 \pm 0.02$, 0.48 ± 0.02, and 0.44 ± 0.03 for H, I, and V bands, respectively. Although these β values are close to X-ray reprocessing model predictions, broadband spectral energy distribution (SED) analysis revealed that NIR radiation in the hard state originates mainly from optically thin synchrotron radiation in jets, while OPT radiation has contributions from jets, the accretion disk, and a compact corona. No correlation was found in the soft state, with data distributions clearly deviating from the hard-state correlation (lower right of Figure 1). They discovered a 2-week delay of X-ray relative to NIR radiation in the soft state, suggesting OPT/NIR radiation in the soft state is dominated by viscous heating of the accretion disk.

Coriat et al. [?] analyzed OPT/NIR and 3-9 keV X-ray correlations in GX 339-4 during four outbursts from 2002-2007. X-ray data came from RXTE and optical data from SMARTS. Overall analysis of the four outbursts [Figure 2: see original paper] revealed clear correlations in both hard and soft states, connected by intermediate-state data. In the hard state, the NIR-X-ray correlation is described by a broken power-law with $\beta_1 = 0.68 \pm 0.05$ at higher fluxes and $\beta_2 = 0.48 \pm 0.01$ at lower fluxes, while the OPT-X-ray correlation follows a single power-law with $\beta = 0.44 \pm 0.01$. In the soft state, both NIR and OPT follow simple power-laws with $\beta = 0.34 \pm 0.01$ and 0.45 ± 0.04, respectively. They found that if X-rays originate from jet synchrotron self-Compton processes and the break frequency variation range of the jet spectrum is considered, the broken power-law relationship and corresponding indices for NIR-X-ray flux can be well explained, suggesting NIR radiation in the hard state is dominated by jet emission. Through SED and time-delay analysis, they concluded OPT radiation in the hard state is mainly dominated by viscous heating of the accretion disk. By comparing observed power-law correlations with model predictions, they suggested OPT/NIR radiation in the soft state originates from the accretion disk, but could not determine whether it is dominated by viscous heating or

X-ray irradiation heating.

Yan & Yu [?] analyzed UV and 0.4–10 keV X-ray correlations during the 2010 outburst [Figure 3: see original paper]. X-ray and optical data came from SWIFT' s XRT and UVOT detectors. During the UV flux rising phase, a power-law correlation with $\beta = 0.50 \pm 0.04$ was found. This appears consistent with X-ray reprocessing model expectations, but during the UV flux decay phase, X-ray flux continued increasing, contradicting the reprocessing model. The UV flux decay trend during the hard-to-soft transition resembles radio, NIR, and optical flux decays, suggesting a common origin. Therefore, they concluded UV radiation during the rising phase of this outburst primarily originates from jets.

3.1.2 XTE J1817-330 XTE J1817-330 is a BH-LMXB with a BHC compact object. Gierliński et al. [?] estimated its orbital period at ~20 h, and Sala et al. [?] estimated a black hole mass of $6.0^{+4.0}_{-2.5} M_\odot$. SWIFT provided simultaneous UV and X-ray observations of the 2006 outburst covering 160 days, including evolution from high-soft to low-hard state. Rykoff et al. [?] analyzed UV and 2–10 keV X-ray correlations [Figure 4: see original paper], finding a significant power-law correlation with best-fit index $\beta = 0.47 \pm 0.03$, consistent with X-ray reprocessing model predictions. Spectral fitting of the decay phase revealed $L_X \propto T^4$, where T is the disk temperature, indicating a geometrically stable accretion disk during decay. Rykoff et al. compared UV and X-ray light curves, finding UV flux follows the X-ray power-law component rather than the disk component. Broadband spectral analysis showed UV flux far exceeds extrapolated values from the viscous heating disk model at lower wavelengths. King & Ritter [?] found that when OPT/UV radiation is dominated by X-ray reprocessing, the OPT/UV light curve e-folding time (τ) is about twice that of the X-ray light curve. Rykoff et al. analyzed $\tau_{\rm UV}$ and τ_X, finding $\tau_{\rm UV}/\tau_X \approx 1.7 - 2.0$, consistent with theoretical predictions. Based on these three analyses, they concluded UV radiation in this outburst is dominated by reprocessing of hard X-rays on the accretion disk.

3.1.3 XTE J1752-223 XTE J1752-223 is a BH-LMXB with a BHC compact object, black hole mass $(9.6 \pm 0.9) M_\odot$, orbital period ~6.8 h, and an M-type companion [?]. The source experienced an outburst in 2009–2010. The optical light curve during decay did not decline exponentially directly to quiescence but first decayed exponentially, then remained stable for ~40 days before final decay. Both hard and soft states were observed during decay. Russell et al. [?] analyzed OPT flux density and X-ray count rate correlations using RXTE 3–20 keV X-ray data, Faulkes telescope optical (i , R, V, B bands) data, and SWIFT/UVOT optical (v, b bands) data, with simultaneous observations spanning ~80–180 days [Figure 5: see original paper]. Faulkes observations were mostly in the hard state, with power-law indices of 0.24 ± 0.04 (R and i bands), 0.35 ± 0.03 (B band), and 0.29 ± 0.04 (V band). UVOT observations were mostly in the soft state, with v and b band indices of ~0.4–0.5. These indices fall in the $\beta < 0.5$ range. The authors suggested OPT radiation may originate from the accretion disk but could not determine whether from viscous heating or X-ray irradiation heating, and could not rule out jet contributions during decay.

3.1.4 SWIFT J1357.2-0933 SWIFT J1357.2-0933 is a BH-LMXB with a BHC compact object, orbital period 2.8 h [?], and mass >9.3 $M_\odot$ [?], classified as a very faint X-ray transient. The source remained in the hard state during 2011 and 2017 outbursts. Armas Padilla et al. [?] analyzed UV/OPT and X-ray correlations in the 2011 outburst using SWIFT simultaneous observations covering 7 months [Figure 6a: see original paper]. They found significant correlations between UV/OPT flux density and 0.5–10 keV and 2–10 keV X-ray fluxes, with power-law indices of 0.20–0.37 and 0.19–0.36, respectively, and β increasing with decreasing wavelength. These results are basically consistent with viscous heating disk model predictions, suggesting UV/OPT radiation is dominated by viscous heating, though higher β values may indicate minor contributions from jets or irradiated disks.

Beri et al. [?] also analyzed UV/OPT and X-ray correlations in the 2017 outburst using SWIFT simultaneous observations covering 4.8 months [Figure 6b: see original paper]. They found significant correlations between UV/OPT and 2–10 keV X-ray radiation with indices of 0.17–0.35, also showing β increasing with decreasing wavelength. They similarly concluded UV/OPT radiation is dominated by viscous heating. Due to the short orbital period, the disk lies closer to the X-ray source, receiving more X-ray heating and having higher average temperature, so Beri et al. suggested X-ray reprocessing may contribute to UV radiation.

3.1.5 SWIFT J1753.5-0127 SWIFT J1753.5-0127 is a BH-LMXB with a BHC compact object, orbital period ~3.24 h [?], and black hole mass >7.4 $M_\odot$ [?]. After exponential decay, the source maintained low-level outburst activity, remaining in the hard state long-term, occasionally entering the hard-intermediate state, and only briefly entering a low-luminosity soft state in 2015 before returning to the hard state and ending 12 years of activity with two mini-outbursts. Shaw et al. [?] analyzed UV/OPT and 2–10 keV X-ray correlations during the mini-outbursts [Figure 7: see original paper], finding power-law indices of $0.20 < \beta < 0.30$ that increase with decreasing wavelength, consistent with viscous heating disk models. However, fitting X-ray light curves and UV/OPT/NIR SEDs with an X-ray irradiated disk instability model revealed high fractions of X-ray irradiation on a truncated, cooling, shrinking disk. While the UVW2 band correlation ($\beta = 0.52^{+0.14}_{-0.10}$) matches X-ray reprocessing expectations, the fit is heavily influenced by low-flux data points with large errors. Shaw et al. concluded UV/OPT radiation during mini-outbursts has multiple origins, possibly including both outer disk X-ray reprocessing and coronal synchrotron radiation, yielding smaller β than pure reprocessing models.

We also analyzed UV/OPT and X-ray correlations during the source’ s 12-year activity using SWIFT simultaneous observations, finding significant correlations in the hard state but less clear correlations in the soft state. In the hard state, power-law indices range from $0.24 < \beta < 0.33$ for UV/OPT vs. 0.3-10 keV X-ray flux, and $0.26 < \beta < 0.37$ for UV/OPT vs. 2-10 keV X-ray flux, with β increasing with decreasing optical wavelength, consistent with viscous heating disk models.

3.1.6 GS 1354-64 GS 1354-64 is a BH-LMXB with black hole mass 7.47 $M_{\odot}$, orbital period 2.5 days (long period), and a G0-5 III companion [?, ?]. Koljonen et al. [?] studied the 2015 outburst using Faulkes, SMARTS, and SWIFT UV/OPT and X-ray observations. The outburst lasted ~120 days, remained in the hard state throughout, and reached peak luminosity $L_X > 0.15L_{\text{Edd}}$, the brightest hard state observed in any black hole X-ray binary. They analyzed UV/OPT and X-ray correlations [Figure 8: see original paper], finding $\beta \approx 0.4-0.5$. They concluded UV/OPT radiation is dominated by X-ray irradiated disks, possibly with minor contributions from viscous heating that makes the correlation slightly shallower than pure reprocessing predictions. Uncertain UV/OPT extinction prevents further SED analysis of jet contributions.

3.1.7 MAXI J1348-630 MAXI J1348-630 is a BH-LMXB with black hole mass $(11 \pm 2)M_{\odot}$ [?, ?]. Weng et al. [?] analyzed UV/OPT flux density and 1-10 keV X-ray power-law component correlations during the 2019 outburst using Insight-HXMT X-ray data and SWIFT/UVOT UV/OPT data [Figure 9: see original paper], finding $\beta \approx 0.37 - 0.41$, slightly lower than X-ray reprocessing model predictions. Weng et al. suggested this deviation may arise from more complex coronal geometry or non-negligible contributions from non-thermal electron synchrotron radiation in the corona.

3.1.8 4U 1957+11 BH-LMXB 4U 1957+11 is a persistent source with a BHC compact object, orbital period 9.33 h [?], and has remained in the soft X-ray state since discovery [?]. Russell et al. [?] used 3-year optical (V, R, i bands) monitoring from the Faulkes North and South telescopes combined with RXTE All-Sky Monitor (ASM) 1.5-12 keV X-ray data to analyze optical flux density and X-ray count rate correlations. They found the strongest correlation using 7-day averaged ASM rates, yielding power-law indices $\beta \approx 0.5-0.6$ in $F_{\text{OPT}} \propto F_X^{\beta}$, with the i-band correlation having the highest significance (4.5σ) [Figure 10: see original paper]. This matches both X-ray reprocessing ($\beta \approx 0.5$) and jet radiation ($\beta \approx 0.7$) model predictions. However, the optical SED index is blue ($\alpha \approx +1.0$, $F_\nu \propto \nu^\alpha$), inconsistent with jet synchrotron origin. Optical-X-ray cross-correlation analysis revealed optical lags of -14 to $+4$ days. Positive lags suggest X-ray heated disk origin, while negative lags indicate viscous heating origin (accretion flow propagating from outer optical-emitting disk to inner X-ray-emitting disk). Russell et al. concluded optical radiation may originate from either viscous or X-ray heated disks, requiring higher signal-to-noise data to constrain the mechanism.

3.1.9 XTE J1550-564 XTE J1550-564 is a BH-LMXB with black hole mass $(9.1 \pm 0.6)M_\odot$ and orbital period 1.54 days [?]. During the 2002 outburst decay, X-ray flux decayed exponentially to quiescence, while OPT/NIR first decayed exponentially, then flared when returning to the hard state, before final decay. Russell et al. [?] argued OPT/NIR during exponential decay originates from thermal disk radiation, while the OPT/NIR flare is non-thermal. By extrapolating the exponential decay trend, they estimated the jet's additional contribution to OPT/NIR radiation from the flare excess. Using RXTE 3-10 keV X-ray data and YALO optical (V, I bands) and NIR (H band) data, they analyzed correlations between non-thermal radiation luminosity and X-ray luminosity during the OPT/NIR flare, with simultaneous observations spanning ~20 days, finding a near-linear relation $L_{\mathrm{OIR}} \propto L_X^{0.98\pm0.08}$, steeper than jet model predictions. The OPT/NIR jet spectral index ($\alpha \approx -0.6$ to -0.7) matches optically thin synchrotron radiation, leading Russell et al. to attribute the OPT/NIR flare to optically thin synchrotron radiation from jets. However, Poutanen et al. [?] found the evolution and spectral shape of the non-thermal component during the flare difficult to explain with jet models, instead using non-thermal electron synchrotron radiation in hot accretion flows.

3.1.10 MAXI J1820+070 MAXI J1820+070 is a BH-LMXB with a BHC compact object, mass $8.48^{+0.79}_{-0.72}M_\odot$ [?]. Shidatsu et al. [?] used MAXI/GSC and SWIFT/BAT X-ray data and MITSuME telescope g -band observations to study correlations between 2–10 keV X-ray and optical luminosities during the March–October 2018 outburst, with simultaneous observations spanning ~70 days. They found a strong correlation in the intermediate and high-soft states: $L_{\mathrm{OPT}} \propto L_X^{0.51\pm0.03}$, leading them to conclude optical radiation originates from X-ray reprocessing on the accretion disk.

3.2 NS-LMXBs

3.2.1 Cyg X-2 Cyg X-2 is a persistent NS-LMXB and Z source with orbital period ~9.8 days [?]. Rykoff et al. [?] analyzed UV and X-ray correlations using 4 months of SWIFT simultaneous observations. They found no correlation between UV flux density and XRT soft X-ray flux [Figure 11a: see original paper], but an anti-correlation with BAT hard X-ray flux [Figure 11b: see original paper]. This anti-correlation is inconsistent with X-ray reprocessing models and may be related to Cyg X-2' s high inclination or disk thickening.

3.2.2 SAX J1808.4-3658 SAX J1808.4-3658 is a NS-LMXB and millisecond pulsar [?] with a semi-degenerate companion [?, ?] and 2-hour orbital period [?]. The source typically shows low-luminosity reflares after main outbursts, remaining in the hard state throughout [?]. SWIFT observed two reflares simultaneously for 12 and 11 days. Patruno et al. [?] analyzed UV/OPT/NIR and X-ray correlations [Figure 12: see original paper], finding power-law indices of 0.15–0.30. Although these β values are smaller than viscous heating disk model predictions for NS-LMXBs, the wavelength-dependent increase in β

matches viscous heating models. Expected values for jet- or X-ray heated disk-dominated optical radiation are larger than observed. Patruno et al. concluded NIR/OPT/UV radiation is dominated by viscous heating of the accretion disk.

3.2.3 PSR J1023+0038 PSR J1023+0038 is a NS-LMXB and millisecond pulsar [?] with 4.754-hour orbital period and late G5-type companion [?]. Shahbaz et al. [?] used SWIFT simultaneous observations from October 18, 2013 to June 11, 2014 to analyze UV and 0.5–10 keV X-ray luminosity correlations [Figure 13: see original paper], finding $\beta \approx 1.0$. This matches X-ray reprocessing model predictions, leading them to conclude UV radiation is dominated by X-ray reprocessing in the accretion disk.

3.2.4 Aql X-1 Aql X-1 is a NS-LMXB and very active transient, outbursting approximately annually [?], with 19-hour orbital period and K-type companion [?]. López-Navas et al. [?] analyzed UV/OPT and X-ray correlations during 2013, 2014, and 2016 outbursts. Correlations were steeper during decay (soft state) than rise (hard-to-soft transition). During rise, indices were $\beta \approx 0.6 - 1.1$ (2013) and $\beta \approx 0.2 - 0.4$ (2014). López-Navas et al. concluded 2013 rising-phase UV/OPT radiation is dominated by X-ray reprocessing, while 2014 is dominated by viscous heating, though caution is needed due to spectral state transitions during rise. During decay, $\beta \approx 0.7 - 1.5$, which cannot be explained by a single X-ray reprocessing model, indicating multiple mechanisms contribute to UV/OPT radiation, such as viscous heating or hot accretion flows. Limited observational bands and model assumptions may also cause deviations from theoretical predictions.

3.3 Comparison of Power-law Correlations between BH-LMXBs and NS-LMXBs

Bernardini et al. [?] studied correlation differences between BH-LMXB V404 Cyg and NS-LMXB Cen X-4 during outburst and quiescence. During outburst, V404 Cyg' s optical luminosity is 160–280 times higher than Cen X-4' s at given X-ray luminosity; in quiescence, V404 Cyg is also brighter. After accounting for major differences (compact object mass, disk size, jet contributions in BH hard states, neutron star surface X-ray emission) and using X-ray thermal luminosities, the two systems show similar correlation distributions [Figure 14: see original paper]. Incomplete overlap may result from other system differences such as inclination. Bernardini et al. concluded optical luminosity differences may arise from: (1) BH-LMXBs having jet-dominated states in hard states while NS-LMXBs generally do not [?]; (2) differences in accretion disk scales (including compact object and companion masses, orbital periods), where $L_{\mathrm{OPT}} \propto L_X^{1/2}(M_p + M_c)P^{2/3}$ for binary systems, with BH-LMXBs typically having larger parameters than NS-LMXBs; (3) neutron stars having solid surfaces while black holes do not; and (4) inclination differences, where low-inclination systems produce brighter optical luminosities via X-ray reprocessing than high-inclination systems at given X-ray luminosity. Russell et al. [?] previously found

BH systems are ~20 times optically brighter than NS systems at given X-ray luminosity, possibly due to differences in disk scale and central object mass.

3.4 Observational Summary of Power-law Correlations

Using OPT/NIR and X-ray power-law correlations, Russell et al. [?] studied OPT/NIR radiation origins. They statistically analyzed multi-wavelength data from 15 hard-state BH-LMXBs, 9 soft-state BH-LMXBs, and 8 hard-state NS-LMXBs. Over 8 orders of magnitude in X-ray luminosity, hard-state BH-LMXBs show a strong L_{OIR}-L_X correlation ($L_{\mathrm{OIR}} \propto L_X^{0.61\pm0.02}$) [Figure 15a: see original paper]. Soft-state BH-LMXBs deviate from this hard-state correlation [Figure 15b: see original paper]. Over 7 orders of magnitude, hard-state NS-LMXBs show a similar L_{OIR}-L_X relation ($L_{\mathrm{OIR}} \propto L_X^{0.63\pm0.04}$) [Figure 16: see original paper], but BH-LMXBs are ~20 times brighter in OIR at given X-ray luminosity. Russell et al. compared these results with theoretical models. For BH-LMXBs, both X-ray reprocessing and jet models can explain hard-state OIR radiation, with jets contributing ~90% to NIR at high luminosities. For NS-LMXBs, hard-state OIR radiation is dominated by X-ray reprocessing, possibly with viscous heating contributions and jet contributions at high luminosities. Russell et al. [?] later studied low-magnetic-field ($B < 10^{11}$ G) hard-state NS-LMXBs, including Atoll sources, Z sources, and millisecond pulsars. Through OIR SED analysis and comparison of model-derived correlations, they found that for Atoll sources and millisecond pulsars, optically thin synchrotron radiation from jets dominates NIR ($L_X > 10^{29}\ \mathrm{J \cdot s^{-1}}$) and OPT ($L_X > 10^{30}\ \mathrm{J \cdot s^{-1}}$) at high luminosities. For Z sources, optically thick jet spectra sometimes dominate OIR radiation. Russell et al. concluded that OIR-X-ray power-law correlations roughly quantify accretion disk and jet contributions to OIR radiation, though precise estimates may be sensitive to other parameters such as disk size and jet spectral shape.

TABLE 1 summarizes existing power-law correlation studies for individual LMXBs, including 11 transients and 3 persistent sources. Some observed correlations match theoretical expectations well (e.g., SWIFT J1357.2-0933' s two outbursts match viscous heating predictions; XTE J1817-330 matches reprocessing predictions), making β a useful diagnostic for radiation origin. However, some observations disagree with models (e.g., GX 339-4' s 2002 H-band β is smaller than jet model predictions). Some sources cannot be explained by single mechanisms (e.g., GX 339-4' s 2002 optical I/V bands, Aql X-1' s three outbursts, MAXI J1348-630' s 2019 optical emission all show multiple mechanism contributions). Due to UV/OPT/NIR radiation complexity, β alone cannot serve as a sole criterion. Further analysis requires broadband SED and multi-wavelength time-delay analysis.

We analyzed P-β (orbital period) and M-β (compact object mass) relationships [Figure 17: see original paper], using only transient hard-state data with low-energy X-ray bands (0.4–10 keV) for consistent comparison. Different studies use different statistical methods (luminosity-luminosity, flux-flux, flux density-flux, count rate-count rate, flux density-count rate), but the first three yield identical β values, so we used only those. Based on previous observations, we found no correlation between compact object mass and β, but P-β suggests short-period systems may have smaller β values. Limited multi-wavelength correlation analyses for long-period systems prevent firm conclusions.

4 Summary and Outlook

Multi-wavelength observations advance accretion process studies. UV/OPT/NIR and X-ray power-law correlation characteristics can help identify dominant UV/OPT/NIR radiation mechanisms. Model-predicted β values represent idealized single-mechanism dominance. When multiple mechanisms contribute comparably or other mechanisms exist, observed β may deviate from theory. Observed β may also be affected by limited observational bands, requiring careful band selection. Theoretical models are mostly based on simple assumptions, making it difficult to explain complex observations as data increase. In the X-ray reprocessing model, the basic assumption that observed X-ray flux varies with inner X-ray luminosity can be affected by state evolution and X-ray emission region geometry, yielding different correlations. Some researchers consider the model' s V-band prediction $\beta = 0.5$ applicable to all UV/OPT/NIR bands, while others argue β varies with wavelength. In the jet radiation model, the basic assumption of an optically thick, self-absorbed flat spectrum depends on the break frequency, which may differ between sources and outbursts, causing observational-theoretical inconsistencies. Models thus require improvement.

We must consider these factors causing β deviations from theory. When analyzing UV/OPT/NIR radiation mechanisms, broadband SED and time-delay analyses are also needed, making extensive simultaneous multi-wavelength observations crucial. FIGURE:17 suggests possible correlations between orbital period and β, but few studies exist for individual sources, especially NS systems during outburst and long-period systems. Future work should expand samples to confirm whether orbital period correlates with β.

UV/OPT/NIR monitoring programs can better study X-ray binary radiation origins. For example, Russell et al. [**?**] developed the X-ray Binary New Early Warning System. Where and how LMXB outbursts are triggered remains unresolved, partly due to lack of early rise-phase data. Since disk instability models predict optical brightening before X-ray outbursts, early optical detection can trigger X-ray observations. Russell et al. use the Las Cumbres Observatory (LCO) global telescope network to continuously monitor ~50 X-ray binaries. The Faulkes telescopes, the world' s largest fully robotic optical telescopes and part of LCO, plus nine additional 1 m telescopes, enable long-term flux monitoring. When a source brightens, the warning system automatically processes data and triggers multi-wavelength observations, particularly during early outburst rise. This program may obtain simultaneous optical and X-ray data during early outburst phases, advancing LMXB outburst mechanism studies and providing extensive simultaneous multi-wavelength data for systematic studies of X-ray binary UV/OPT/NIR radiation mechanisms from broadband spectral and correlation perspectives.

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