X-ray Polarimetry as a Probe of Emission Geometry In Compact Objects

Lev Titarchuk (GMU/NRL/GSFC)

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Why X-ray Polarimetry? How?

<u>Black holes are central, fundamental, but hard to study.</u>
1. BH have no pulsations: *QPOs = best signature*alternatives to QPOs : spectra, jets, maybe
someday imaging and X-ray polarimetry
Spectra, timing and X-ray Polarimetry is a perfect combination

2. Then, need to validate understanding of BH spectra and timing *on other sources* - **use neutron stars ; try to bring BH and NS within one** *Comprehensive Spectral Formation and Timing Theory*

- 3. Approach it as aproblem of Radiative Hydrodynamics
 - fluid accreting onto compact object (NS, BH)
 - no new *fluid* physics peculiar to this problem, so far.
 - Radiative Transfer in the hot plasma. *Polarization Effects*.
 - use families of QPOs as the data
 - treat QPOs mainly as eigenvalues of fluid dynamics problems
 - treat X-ray polarimetry as a probe of accretion geometry

Spectral states in BH candidates

- Steep power-law state: Black body like bump, extended power law with index, 2.5-3
- Low/hard state: Thermal Comptonization Spectrum (electron temperature 50 keV and Thomson optical depth a few, index 1.5-1.8)
- Intermediate state in between these distinct states



Grove et al. (1998)



Model Terminology for NS, BH cases: Transition Layer (TL) and Adjustment Radius (R_{adj})

- Transition Layer as an adjustment of Kepler disk to sub-Keplerian rotated central object (either NS or BH); change from Keplerian to sub-Keplerian flow occurs at R_{adj}.
- The adjustment is not smooth and shock occurs at R_{adj}. Hot matter is lifted from the disk forming the Compton cloud around the central object.
- Disk model features near the adjustment radius correlated with features of the power spectrum, i.e, QPO frequencies in formulae are evaluated at R_{adi}
- Scaling of other frequencies relative to frequency K is predicted by model



The TL adjustment) radius, R_{adj} is determined by an equation of angular momentum radial transport and inner and outer boundary conditions (Titarchuk, Lapidus & Muslimov 1998):

$$\gamma \frac{d}{dR}(\omega R^2) = \frac{d}{dR}(R^3 \frac{d\omega}{dR}) \text{ and } \gamma = \frac{\dot{M}}{4\pi\eta H} \text{ is}$$

the Reynolds number- inverse of the SS α -parameter

$$\omega(R_{NS}) = \Omega_{NS}$$
 and $\omega(R_{adj}) = \omega_{K}(R_{adj}), \omega'(R_{adj}) = \omega'_{K}(R_{adj}).$

Index-QPO frequency correlation: Observational evidence for the bounded configuration (TL)



Data points of power-law photon index vs QPO centroid frequency for GRS 1915+105. From Vignarca, et. al. 2003. The theoretical correlations are predictions of the TL model (TLM98, T& Fiorito 2004).

This data shows that the index may be saturating to the BMC critical value of 2.7 ± 0.1 when the QPO frequency increases which is a result of an increase of the mass accretion rate.

Radiative Transfer Formalism of the Polarized Radiation

The equation of Transfer for Polarized radiation (see e.g. Pomraning 1973)

Ω.•**V I**(ν, **Ω**)=**S**(ν)- σ (ν)**I**(ν,**Ω**)+primary sources.

Here $I(\mathbf{r},\mathbf{v},\mathbf{\Omega})$ is a four component vector $[I_1; I_r; U; V]$, and $\mathbf{S} = \mathbf{S}(\mathbf{r},\mathbf{v})$ is a source Vector with components $[S_1; S_r; S_U; S_V]$, describing the polarization state of the photons arising from spontaneous emission.

Comptonization of the soft photons

T & Lyubarsky (1995) show that the Green's function of this full kinetic equation can be factorized for the Thomson scattering regime and for energies when the recoil effect can be neglected. Namely, $G(v,v_0, r, \Omega) = v^{-\alpha} J_{\alpha}(r, \Omega)$.

Polarization of the Comptonized radiation is independent of energy!

Results of Calculations of X-ray Polarization



Fig. 4. Angular distribution of hard radiation from the disk computed for different τ_0 . The $\tau_0 = 10$ case practically coincides with the solution of the classical problem about the escape of radiation from the atmosphere when electron scattering is predominant



Fig. 5. Hard-radiation polarization degree for different τ_0 . When $\tau_0 = 10$ it is close to the solution of the classical problem

Sunyaev & T 1985

Summary

BLACK HOLE and NEUTRON STAR X-ray POLARIZATION and TIMING FROM VIEW POINT OF FUTURE OF X-RAY MISSION

This picture views polarization and timing primarily as Radiation Hydrodynamics under extreme conditions – *an important enough task for a successor mission to RXTE, XMM, Chandra*

Analytic treatment, supported by numerical simulations is a good beginning, to formulate the problem for future X-ray polarization measurements.

Black holes are the starting point and also simplest, most elegant case, while neutron stars have symmetry- breaking.

There is continuity of the physics treatment of X-ray spectral formation and Timing from BH to NS (and even to WD).