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Flux modulation from non-axisymmetric structures in accretion discs

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Abstract

Non-axisymmetric accretion discs can lead to flux variability. Here we provide an analytic framework for modeling non-axisymmetric structures like hotspots and spiral waves and their influence on observed timing measurements. The presently unexplained low-frequency quasi-periodic oscillations (LFQPO), observed in X-ray binaries and cataclysmic variables, could be the result of such discs. Our framework serves as a guide to quantify the properties that non-axisymmetric structures produced by nonlinear accretion disc models must have in order to explain observed features such as LFQPOs. The results from our microquasar applications also provide analogous predictions for X-ray modulation in active galactic nuclei. The formalism and physical interpretation is of practical use for generic non-axisymmetric accretion disc systems.

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1. Introduction

X-ray emission from accreting black holes in binary stellar systems varies on time scales ranging from milliseconds to years. Variability on time scales longer than days appears to be driven by changes in the accretion rate onto the black hole, and is often manifested as transient outbursts in which the luminosity of a source changes by a million-fold Lasota (2001). At the shortest time scales, quasi-periodic oscillations (QPOs) are observed in the X-ray emission. The highest frequency

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QPOs (>100 Hz) are consistent with those expected from general relativistic orbits near the innermost stable orbit around the black hole, and they are likely caused by inhomogeneities in the inner accretion flow (Remillard et al., 2002; Stella and Vietri, 1998). However, the cause of low frequency QPO (LFQPO)s 0.1–20 Hz is still a mystery. This motivates the work herein. For neutron star X-ray binaries, low frequency QPOs can be subdivided into more precise categories (e.g., Psaltis et al., 1999). Here we focus on a basic paradigm for the modulation and leave explanations of possible harmonic relations and phase lag behavior Varnière (2005) for further work. Black hole microquasars avoid the role of any solid stellar surface, and offer a purer probe of the accretion process without interaction with a stellar surface. The basic properties of LFQPOs that any model needs to explain are these:

(1) LFQPOs often appear to be present in widely spaced observations, over a period of weeks, with fractionally narrow frequency widths ($\Delta\nu/\nu \approx 1/30$) (Morgan et al., 1997; Remillard et al., 1999). Although the observations are not continuous, the fact that the LFQPO are observed to be the same (within a very small variation) over several observations within the same week/month, suggest that the QPO are likely always present during that time, at least when averaged over such long time scales within the hard state; there are periods where the LFQPO appear and disappear on timescale of a few seconds. If LFQPOs result from inhomogeneities orbiting at a Keplerian speed in the accretion disc they are constrained to a narrow range of radii.

(2) LFQPO amplitudes are typically 5–10% RMS (root mean squared), but can reach 20% RMS. Given that the X-ray luminosities of black hole binaries approach 10^{39} erg s^{-1}, LFQPOs involve an enormously energetic fraction of the accretion flow.

(3) On the other hand, LFQPOs are transient features, so the spectral properties of the X-ray emission when LFQPOs are present and absent can be used to constrain the LFPQO origin (Muno et al., 1999; Sobczak et al., 2000).

(4) The 0.1–20 Hz LFQPOs only appear when the non-thermal component of the X-ray spectrum is strong, and their fractional amplitudes increase with energy between 2 and 20 keV. However, a thermal component that contributes ~10% of the X-ray emission at lower energies must also be present, and the frequencies of the LFQPO appear to be correlated best with this. The energy output of accreting black holes can generally be decomposed into a ~1 keV thermal component (thought to originate from the optically thick accretion disc) and a non-thermal component with a power-law spectrum extending beyond 100 keV (thought to result from inverse-Compton scattering of cool photons by a corona of hot electrons.) Thus, it appears that the 0.1–20 Hz QPOs either originate in the boundary between the disc and the corona, or are part of the mechanism which accelerates the hot Comptonizing electrons.

As mentioned, LFQPOs can be further subdivided (Psaltis et al., 1999), but the above represents a basic set of characteristics that a zeroth order LFQPO flux modulation model should explain.

Two different conceptual paradigms for LFQPOs have been proposed in this regard: (1) In the centrifugal pressure supported boundary layer model (CENBOL, Chakrabarti and Manickam, 2000; Molteni et al., 1996), a QPO is produced by a shock in the accretion flow where it makes a transition from a Keplerian disc to a hot Comptonizing region. If the cooling time of the post-shock region is resonant with the free-fall time at the shock, the shock can oscillate radially with a frequency on order a Hz. The QPO is, in principle, produced because the shock modulates the flux of seed photons that reach the Comptonizing post-shock region. In this model, the LFQPO would represent a global radial oscillation that modifies the emitted flux. (2) A second paradigm for LFQPOs is non-axisymmetric structures in the disk. Their motion around the black hole would lead to flux modulation. These structures could move at the Keplerian speed, a precession speed (such as Lense-Thirring) or a phase velocity associated with a structural instability. One example occurs in the accretion-ejection instability model (AEI, Caunt and Tagger, 2001; Tagger and Pellat, 1999; Varnière and Tagger, 2002). Here a spiral shock forms in an accretion disc threaded by a vertical magnetic field. The dispersion relation is sim-