Measuring X-ray polarization in the presence of systematic effects

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We describe a mathematical formalism for determining the 1 and 2 parameter errors in the magnitude and position angle of X-ray polarization. The formalism includes a treatment of systematic effects, such as background and instrumental bias.

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Introduction (1)

Despite the recent cancelation of the GEMS x-ray polarimetry mission, there remains a scientific need to probe the most energetic and exotic astronomical objects—especially neutron stars and black holes. With calibrated x-ray detectors that can make significant and accurate polarization measurements, a dedicated x-ray-polarimetry observatory will provide another dimension to the study of cosmic x-ray sources. This will significantly enlarge the observational phase space and uniquely address fundamental questions concerning high densities, high temperatures, nonthermal particles, strong magnetic and electric fields, and possibly strong gravity.

At this juncture, it is appropriate to examine rigorously uncertainties in polarization measurements, taking into account realistic conditions.

- What exactly does minimum detectable polarization (MDP) mean?
- What is the uncertainty in measuring polarization?
- What role do systematic effects play?
- Can instrumental systematics be "calibrated out"?

A simple example of systematic effects and their impact on sensitivity (2)

Consider a measurement of (normally distributed) counts (N) due to source (S) plus background (B).

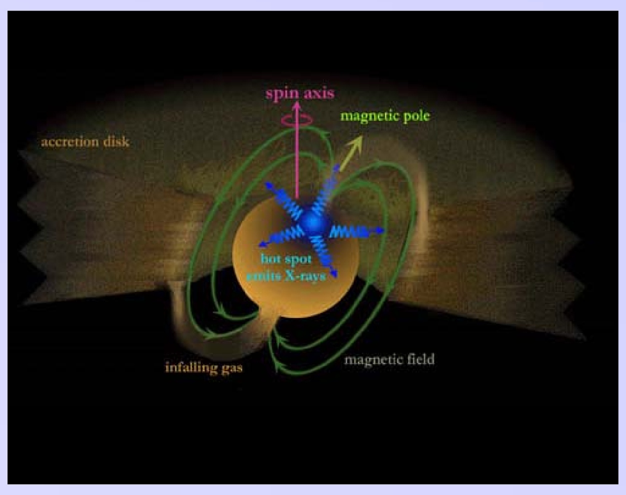
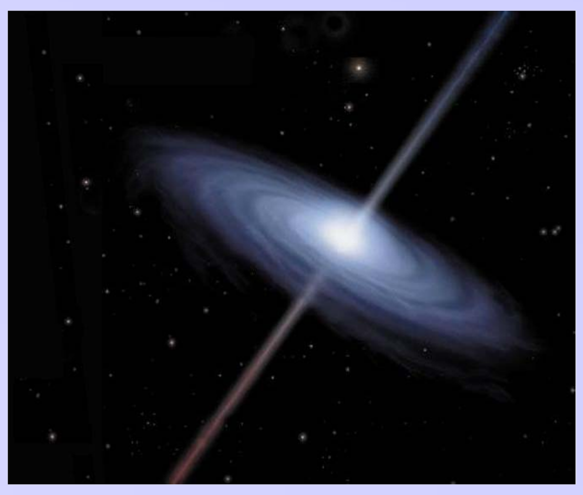
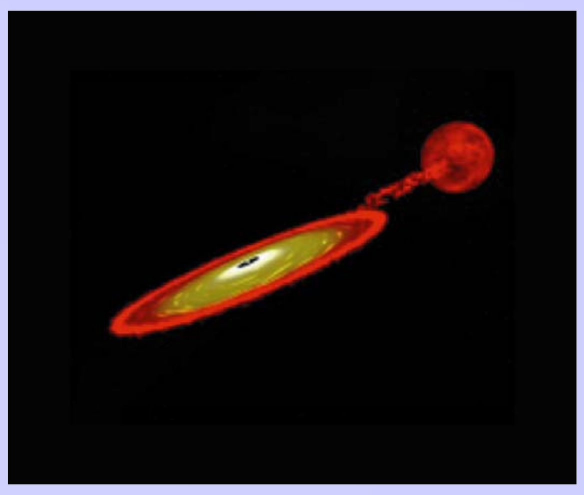
- The detector records N counts.
- The background's expectation value $\underline{B}$ is known.
- The number of source counts is $S = (N-\underline{B}) \pm \sqrt{N}$.
- The fractional source-count error is $\sqrt{N}/(N-\underline{B})$.

Consequently, even if the background's expectation value is perfectly known, its statistical uncertainty significantly affects source sensitivity unless $\underline{B} \ll N$.

Description of our paper (3)

We have derived exact equations for statistical uncertainties in measured polarization parameters, under these assumptions:

- Counts are normally distributed, as polarization detection typically requires numerous counts.
- The expectation value of the unpolarized background is constant and precisely known.
- The expectation value of any polarized background or polarization-signature (2φ) systematic effect is precisely known in amplitude and phase.

A polarimetry mission with ***appropriate sensitivity*** will provide unique data to address key questions:

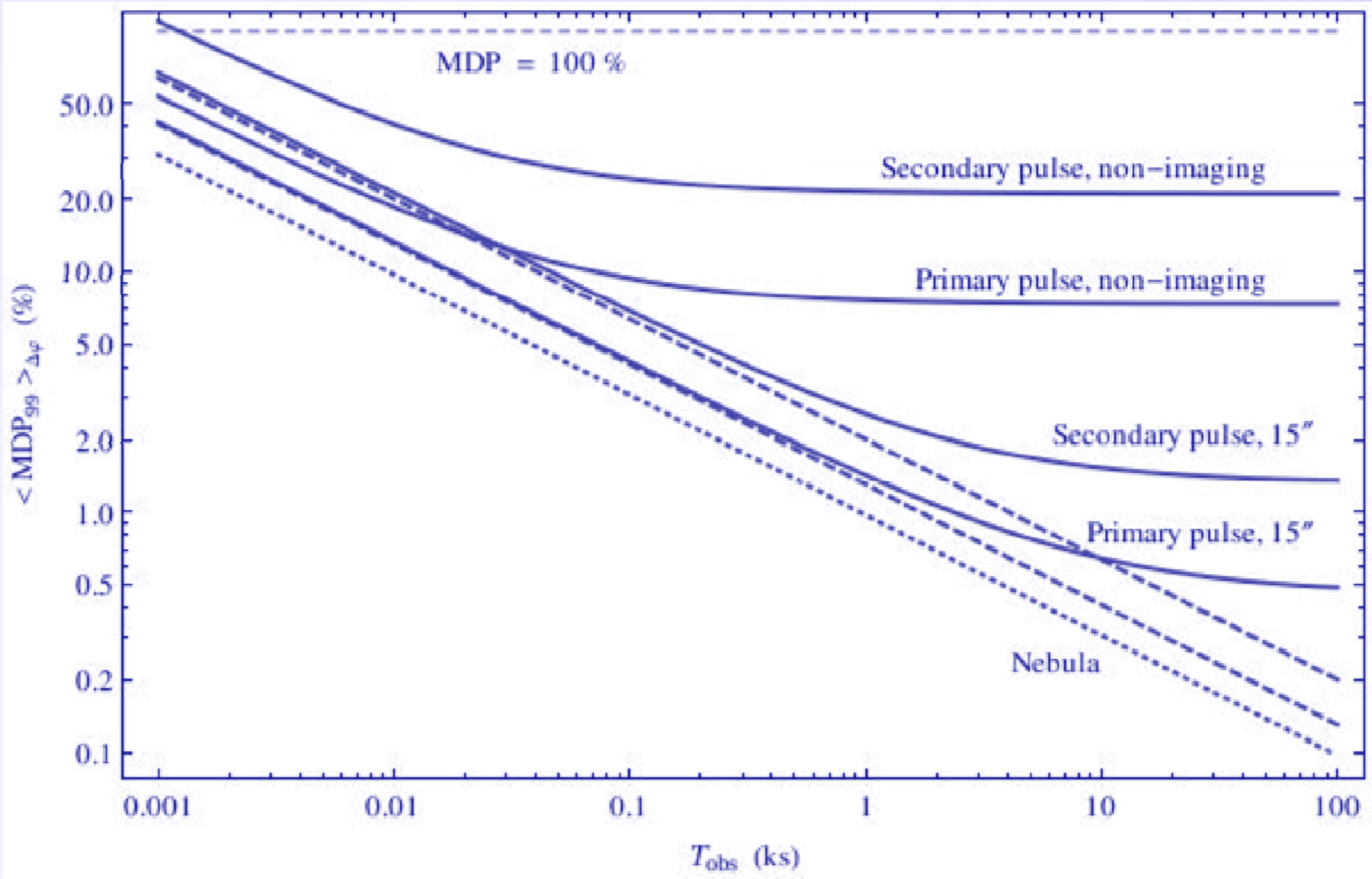
- What are the geometries and emission mechanisms of AGN and microquasars?
- What are the magnetic-field geometry and strength in magnetars and accreting x-ray pulsars?
- What is the origin of x rays from radio pulsars?
- What are the magnetic-field topology and particle spectrum in Pulsar Wind Nebulae (PWNe)?
- Are predictions of GR and QED effects correct?

Equations you will find in the paper (4)

- Treatment of uncertainties due to (unpolarized and polarized) background and to systematic effects.
- The minimum detectable polarization for a given polarization angle (new) or averaged over angle.
- Uncertainties in polarization measurements

Example consequence (5)

Accurate measurement the Crab pulsar's polarization must deal with the polarization of the Crab's nebula, unless the polarimeter can perfectly resolve the pulsar from the nebula.



99%-confidence Minimum Detectible Polarization of the Crab pulsar primary or secondary pulse, for a 15" imaging polarimeter and for a non-imaging polarimeter of the same area. The dotted line is MDP_{99} for the full Nebula; the two dashed lines, for sub-arcsecond imaging of the pulsar.

Properly determining the expected uncertainties in polarimetric measurements is essential for realistically evaluating the expected outcome of prospective missions.