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Magnetars – the Universe's strongest magnetic fields

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Introduction

Neutron stars are a melting pot of some of the most extreme physical conditions known, with densities exceeding those of an atomic nucleus. One particular class of neutron star is also distinguished by extreme magnetic fields, thought to exceed 10^{15} gauss. These are the magnetars: volatile neutron stars seen most spectacularly in their X/γ-ray flaring. With their slow rotation, magnetars are believed to be magnetically-powered: their chief source of free energy comes from their ultra-strong field.
A main strand of research of the Theoretical Astrophysics (TAT) group in Tübingen has been to understand the behaviour of these objects through theoretical modelling; in particular, the challenges associated with magnetic-field phenomena.

Steady-state models

To understand magnetar dynamics one needs knowledge of the interior, not directly accessible from observations. Instead we resort to theory, producing equilibrium models[1]. For stability reasons [2], it is thought that a long-lived magnetar field contains both poloidal and toroidal components; see Fig. 1. There is a complication, however: the protons in a magnetar are expected to be superconducting, making the governing equations more complicated and harder to solve [3, 4, 5].

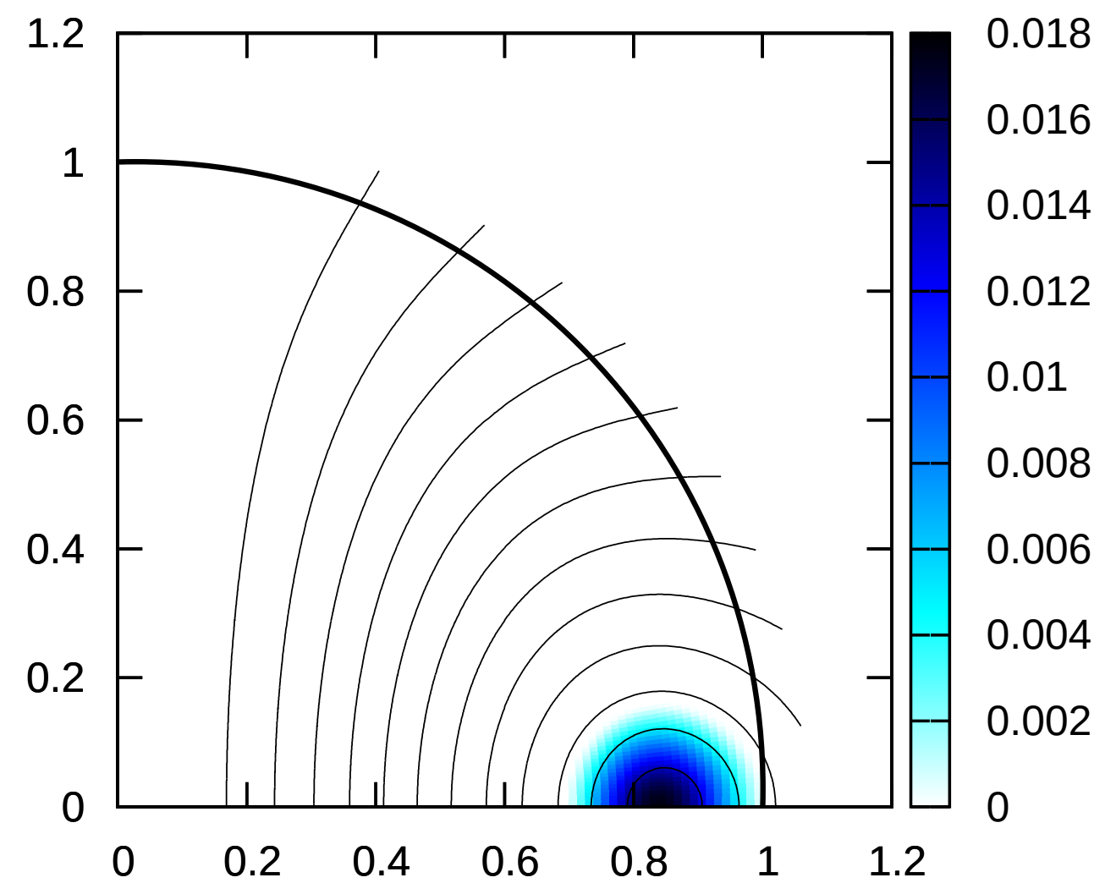

Figure 1: Equilibrium of a normally-conducting magnetar. The lines show the direction of the poloidal field and the colour scale the magnitude of the toroidal field.

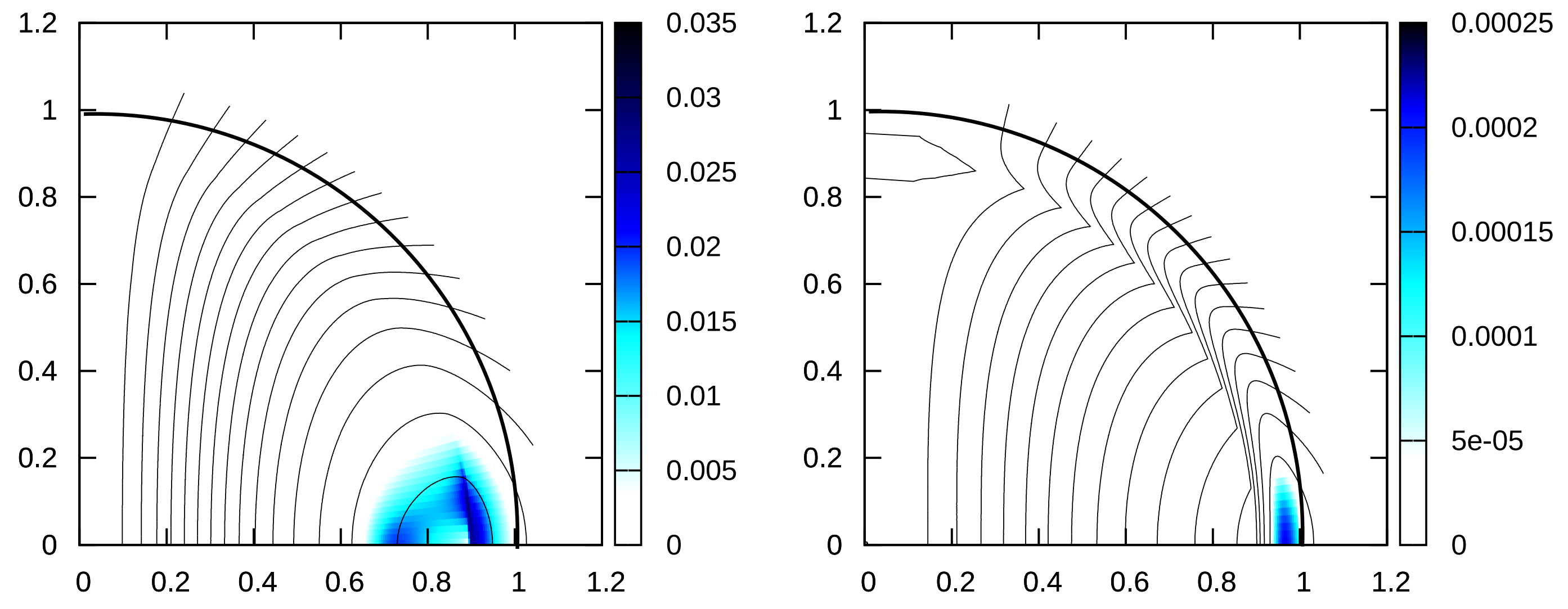

Figure 2: Magnetar models with a superconducting core and a normal crust, showing poloidal/toroidal field as before. *Left*: a magnetar model, $B = 2 \times 10^{15}$ G, *right*: a pulsar or weak-field magnetar, $B = 5 \times 10^{13}$ G.

Giant flares

Magnetar giant flares are among the most energetic astrophysical phenomena known; they are believed to represent a huge release of magnetic energy from the star. The trigger mechanism for a giant flare and the subsequent dynamics remain open questions. By modelling the flare as the onset of a hydromagnetic instability, TAT members have used nonlinear MHD simulations to follow the dynamics of the instability and subsequent post-flare field rearrangement [6]. A giant flare might even excite magnetic modes strongly enough to produce detectable gravitational waves [7].

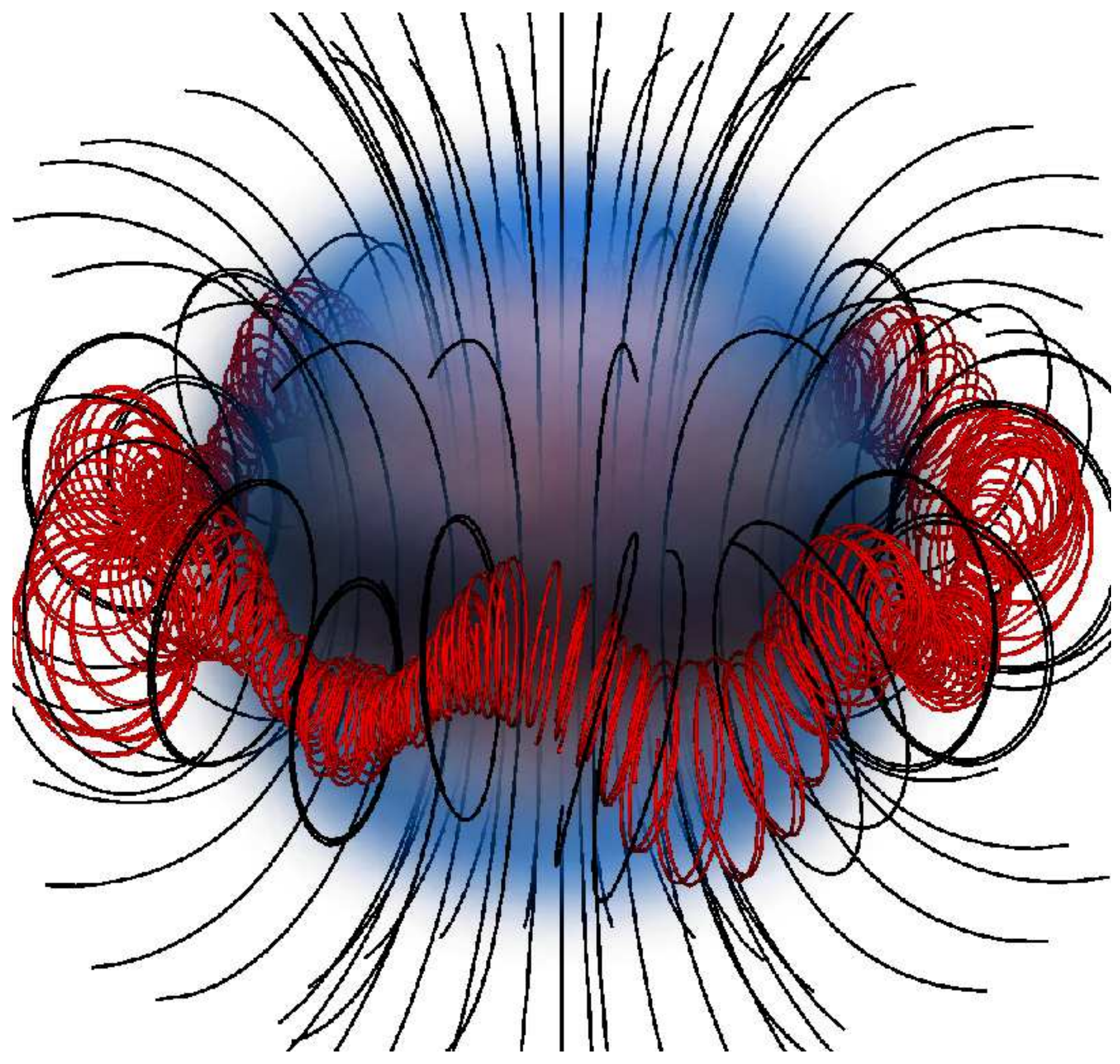

Figure 3: Unstable 'kinking' motion of closed field lines (red) in a magnetar. The inner region of the star is shaded blue and the outer region left white. As the instability saturates the field rearranges, releasing energy; this represents a simple giant flare model.

Oscillations

The giant flares described above are followed by an X-ray tail, in which quasi-periodic oscillations have been detected. These are believed to represent oscillations of the star itself, and offer a tantalising opportunity to probe its interior physics — if we can work out what specific oscillations are excited. The TAT group has been building increasingly sophisticated models to understand this complex problem: including the effects of relativity [8, 9], the elastic crust [10], more complex field configurations [11] and the presence of superfluid neutrons in the core [12, 13]. In addition to this theory work, the group has been involved in reanalysing the original flare data, discovering several new QPOs [14].

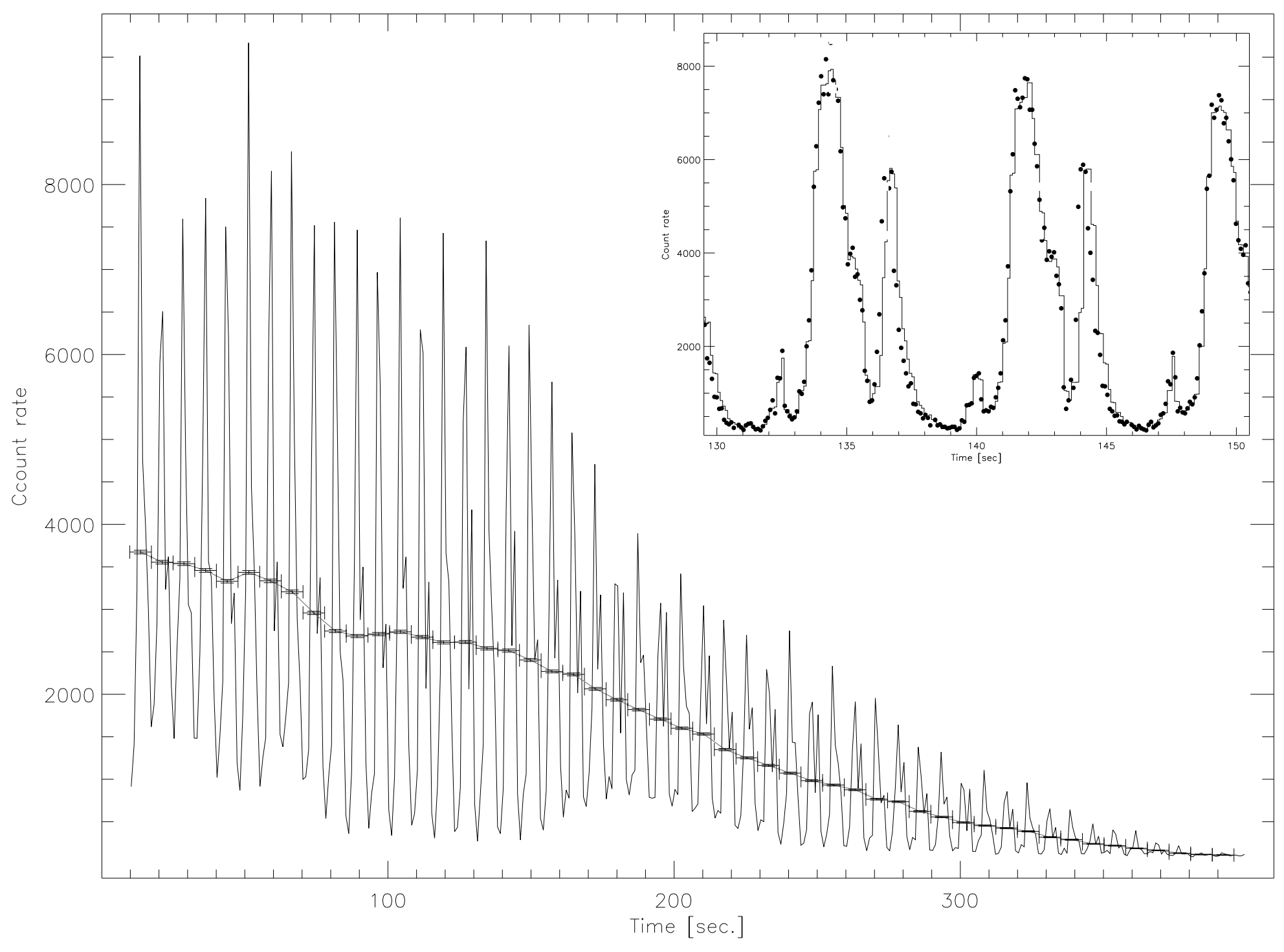

Figure 4: X-ray tail following the giant flare of SGR 1806-20. The visible oscillations represent rotational modulation of the star; data analysis is needed to extract the QPOs within this signal.

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